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Charles Care

Technology for Modelling

Electrical Analogies, Engineering Practice, and the Development of Analogue Computing

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For Rachel

Preface

This book is based on research I undertook for my Ph.D. at the University of Warwick. Its motivation began when, as an undergraduate, I completed a research project on the history of planimeters and mechanical integrators. That project was my first journey into the history of analogue computing, and left me with more unanswered questions than I started with. I wanted to understand the relationship between analogue and digital computing, and what that meant for contemporary users. I found it fascinating that some historians portrayed analogue computing solely as a precursor to digital, whereas others were stressing that analogue computing existed well after 1940. Early on in my research it became clear that historians had different views of the core identity of analogue computing. In fact, it quickly became evident that even within contemporary sources, there was a spectrum of understanding around what constituted analogue computing. It was at that point I began restructuring the history around how the technology was used.

This study investigates the technologies, the concepts, and the applications of analogue computing. It is argued that analogue computing must be thought of as not just a computing technology, but also as a modelling technology. The first half of the book demonstrates how the history of analogue computing can be understood in terms of the two parallel themes of calculation and modelling, and describes how the technology evolved. The second half of the book focuses on a number of detailed case studies: examining analogue modelling in academic research, oil reservoir modelling, aeronautical design, and meteorology. Many of these case studies discuss so-called ‘direct’ analogues—analogue computers that used a direct physical analogy. Because they were not used as *calculators*, direct analogues rarely receive prominence in computing history. However, these were the analogue devices that persisted the longest.

Exploring the history in the context of modelling technology encourages us to see analogue computing in terms of its use. Rather than presenting analogue and digital as alternatives, this approach considers them complementary. The challenge is to not simply consider analogue and digital as separate technologies, but to consider the continuity of practice that spanned the two. This practice was a practice of modelling. This book is not the first account to identify a close relationship between analogue computing and modelling technology. That relationship is evident in the sources. However, it is my aim to bring that relationship to the forefront of our historiography.

The central thesis is to demonstrate that the history of analogue computing is broader than just the technology or the machines, but must also include how it was used and applied. When we look at the history of analogue computing, we find that different people had different definitions of what analogue meant. Many histories of computing have discussed historical episodes when users debated the relative merits of analogue and digital. However, this book proposes that these 'debates' should be framed around application rather than technology. Because the dominant applications of analogue computing were as a modelling technology, the book argues that digital computing only became truly dominant once it too had become a practical modelling tool.

Oxford, UK Charles Care

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The research behind this book is the result of three years full-time study 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 Ph.D. 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, Prof. Martin Campbell-Kelly, has always provided excellent advice and support.

Interactions with fellow research students and academics at Warwick have been invaluable. Thanks go to Meurig Beynon, Steve Matthews, Russell Boyatt, Eric Chan, Ant Harfield, Karl King, Dorian Rutter and Ashley Ward. Other historians of computing also offered support and encouragement, special thanks go to David Anderson, Chris Bissell, Janet Delve, James Sumner and Doron Swade. Acknowledgement should also be made to Peter Housego and Joanne Burman of the BP archives, Jackie Bishop and Paul Lilley at EMI Archives, and Jane Wess at the Science Museum. Alan Charlesworth, once 'Senior Hybrid Programmer' at University of Bath, agreed to be interviewed; and Paul Ceruzzi, Peter Lynch, and Brian Randell provided helpful correspondence.

Also, I would like to formally acknowledge the librarians and archivists at the following institutions: Library and Modern Records Centre, University of Warwick; The British Library; Bristol University Library; Imperial College Library; the Royal Society Library; the IET Library; The Bodleian Library; Birmingham Central Library; Birmingham University Library; King's College London Library; University of London Senate Library; Cambridge University Library; Manchester University Library; and The National Archives, Kew.

In addition, I am indebted to the people and institutions who have granted permission to reproduce quotations, images and photographs. Credits are acknowledged throughout the book, but I am particularly grateful to the Association for Computing Machinery, American Meteorological Society, BP Plc, Cambridge University

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Contents

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Acronyms

AC	Alternating Current (electricity)
ACA	Automatic Control Analyzer (machine)
ACE	Automatic Computing Engine (machine)
ACM	Association for Computing Machinery (professional body)
ADI	Alternating Direction Implicit (a mathematical method)
ARC	Aeronautical Research Council (British organisation)
BINAC	Binary Automatic Computer (machine)
CAT	College of Advanced Technology (type of British college)
CEGB	Central Electricity Generating Board (organisation)
CNRS	Centre National de la Recherche Scientifique (French institution)
DC	Direct Current (electricity)
DDA	Digital Differential Analyser (type of machine)
DFT	Discrete Fourier Transform (mathematical method)
DSIR	Department of Scientific and Industrial Research (British institution)
EAI	Electronic Associates Incorporated (company)
EAL	Electronic Associates Limited (company)
EDSAC	Electronic Delay Storage Automatic Calculator (machine)
EDVAC	Electronic Discrete Variable Automatic Computer (machine)
EMI	Electric and Musical Industries (company)
EMIAC	EMI Analogue Computer (machine)
ENIAC	Electronic Numerical Integrator And Computer (machine)
FAU	Friends Ambulance Unit (Quakers in World War I)
FRS	Fellow of the Royal Society of London
GAP/R	George A. Philbrick Researches (company)
GPAC	General Purpose Analog(ue) Computer (type of machine)
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 (machine)
MIT	Massachusetts Institute of Technology

MoS	Ministry of Supply (British government organisation)
MU	Machine Unit (analogue computing term)
NACA	National Advisory Committee for Aeronautics (US organisation)
NASA	National Aeronautics and Space Administration (US organisation)
NDRC	National Defense Research Committee (US organisation)
NPL	National Physical Laboratory (British organisation)
OED	Oxford English Dictionary
ONERA	Office National d'Etudes et de Researches Aeronautique
ONR	Office of Naval Research (US organisation)
OR	Operational Research
RAE	Royal Aeronautical Establishment (British institution)
Rep-Op	Repetitive Operation (analogue computing term)
RSSA	Royal Scottish Society of Arts
SBAC	Society of British Aircraft Constructors
TNA	The (British) National Archives (Kew Gardens)
TRE	Telecommunications Research Establishment (British institution)
TRIDAC	Three-Dimensional Analogue Computer (machine)
UGC	University Grants Committee (British committee)
UMIST	University of Manchester Institute of Science and Technology
WPNP	Weather Prediction by Numerical Process (Richardson 1922b)

Part I
Modelling, Calculation and Analogy: The Themes of Analogue Computing

Chapter 1
Introduction: Analogue Computers in the History of Computing

Modern life can appear to revolve around the computer. We have them at home and at work. We routinely use them to communicate, to learn, to be entertained. But what is a computer? What is computing? At first glance, the answer to these questions may seem obvious. Say ‘computer’ to most readers of this book and they will probably think of a desktop device, or possibly something a little more portable: maybe a ‘laptop’ or ‘notebook’ computer. Today, the Personal Computer (or PC) appears to be the definitive cultural icon of computer technology.

Notwithstanding the importance of this modern personal computing, computers represent a far broader class of technology. At one end of the scale there are large computers such as mainframes, super-computers, and the server ‘farms’ that power enterprise and Internet-scale applications. In contrast, consider the far smaller machines that provide embedded computing in our cars, washing machines, televisions and entertainment systems. We also have our mobile devices, many of which are nearly as powerful as the computers we routinely use on our desktops. And if modern computing encompasses a broad spectrum of technology and applications, the range of technologies relevant to the history of computing is broader still. Many of the ‘computers’ discussed in this book might, at first, appear quite different and unfamiliar when compared to modern technology. They are, nonetheless, part of the history of computing.

There is no doubt that the computer is one of the major technical inventions of the modern world. Just as the steam engine was the enabling technology of the Industrial Revolution, the invention of computing technology during the twentieth century initiated a new revolution. For over half a century, society has used language such as ‘computer revolution’ or ‘computer age’. More recently, it is common to find references to the ‘information revolution’ or the ‘digital revolution’. For the historian of technology, it is fascinating when highly technical terms such as ‘information’ or ‘digital’ become part of cultural discourse. When technologists first used these words, they were technical terms and had very precise meaning. However, as cultural jargon, the terminology has assimilated a whole collection of meanings. The history of the computer provides an opportunity to explore where this jargon came from and how it evolved.

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This book addresses the history of a different kind of computer technology: one commonly known as 'analogue computing'. Once a common alternative to the now-dominant digital computer, analogue technology was used for a whole variety of calculating and modelling applications. Analogue computing devices have a long history, although it is important to note that the phrase 'analogue computing' was only coined during the mid-twentieth century. As we begin to define what an analogue computer is, we discover that there is no single definition of what constitutes an analogue computer. The boundaries of classification are fuzzy.

The meaning of technical terms such as 'analogue', 'digital', 'computer', and 'modelling'—ironically, almost every word that could be used to define the scope of this book—have, through time, evolved and changed. This presents a challenge: should the historian investigate analogue computing as it was defined *then*, or should we use the terms as they are defined *now*? Clearly it is important to always be aware of context, but historians still have to draw boundaries around a study. Boundaries are necessary to decide what to investigate, and more crucially, what to exclude. Assuming that the meaning of 'analogue computing' has significantly evolved through time, how do we identify the technologies that are part of the history? Equipped with a copy of the *Oxford English Dictionary*, a dictionary that publishes actual quotations of usage, it is possible to investigate the etymology of these words. Through doing so, it becomes evident that these shifting meanings are not just an inconvenient fact of life, rather they are an important component of the history of this technology. The people who invented, used, and improved analogue computing: these were the same people who shaped the usage of these terms. We must acknowledge that analogue and digital computing were not always distinct categories, and we need to recognise that the formation of these categories is part of the overall story.

Today, the word 'digital' is a familiar cultural keyword. We commonly use phrases such as 'digital culture', 'digital society', or 'digital economy'. Implicit in this rhetoric is the idea that, as a society, we are moving from an analogue 'world' into a digital one. Although this book discusses the narrow history of one particular technology, investigating the history of analogue computing provides an opportunity to discover exactly where this analogue–digital terminology came from. Because of its role in shaping the use of these words, the development of analogue computing impacts on a much broader history than just the history of the computer.

1.1 Analogue Computers: Another Class of Computing Technology

Today, modern computers are based on digital technology. Information is represented as bits and bytes, sequences of binary 1s and 0s. Fundamental to the technology is the idea of on and off, of true and false. So fundamental is this concept of discrete (or digital) state, that it is difficult to imagine how computers could be non-digital, or even if non-digital computers would be computers. History, however, forces us to consider such technology, for during the decades between 1940 and 1970, digital computers were complemented by the separate technology of analogue computing. In order to investigate the history of analogue computing, it is first necessary to understand what analogue computing is.

Analogue computers are machines that allow a user to model a complex problem through interacting with another, analogous, physical system. A good illustration of this is the Phillips machine. In 1949, a young economist called Bill Phillips built an analogue model of a nation's economy based on hydraulics. Phillips engineered a complex network of tubes, tanks and pumps to represent the flow of money as a flow of liquid. Various storage tanks represented economic funds, and specially engineered valves allowed the flow between them to be diverted and regulated based on different factors. Hydraulic flow was *analogous* to monetary flow—the machine was an 'analogue'.[1] Not all analogues had such a direct modelling function. Many prominent analogue computers modelled systems of equations, and these were often referred to as 'indirect analogue computers'. The classic example of this type of machine is the differential analyser. Invented during the 1930s by Vannevar Bush, a famous American scientist, the differential analyser solved systems of differential equations using mechanical shafts and gears.

As examples, the Phillips machine and the differential analyser highlight some of the technology's key features. However, analogue computers were not limited to hydraulic or mechanical technology. Many twentieth century analogue computers were electronic and used electrical circuits to establish an analogous model. Electronic versions of the differential analyser were also a common computing tool between 1950 and 1980.

In terms of representing information, analogue and digital computers are fundamentally different. In an analogue 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 key difference was the cognitive support provided by analogue machines. Bush had a rich vision of blending empirical and analytical investigation, and described the differential analyser as providing a 'suggestive auxiliary to precise reasoning'.[2] Rather than placing emphasis on automation, an analogue 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 analogue computer provides an opportunity to explore the context of a superseded technology. In fact, the history of analogue computing is often presented as simply the predecessor of digital computing. Many histories of computing describe a period of analogue 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, this book will argue that analogue computing was certainly not *just* a precursor to digital. Since 1990, a num-

[1] See Leeson (1994) p. 612, Morgan and Boumans (2004), Hally (2005) pp. 185–205. The Phillips machine, and whether it really should be called a computer, is discussed further in Sect. 4.2.4, p. 83, below.

[2] Bush (1936) p. 649.

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

ber of scholars have noted that the history of post-World War II analogue computing has been under-represented. These historians revisit the analogue story and show that analogue and digital co-existed well after the late 1940s. For instance, in *The Analogue Alternative*, James Small argues that the technology was a 'real alternative' to digital, and he presents the analogue and digital computers of the period 1950 to 1980 as competing technologies.[4]

Much of the scholarship re-visiting the analogue story emphasises that it is important for historians to consider technologies that, in hindsight, appear unsuccessful. This has become known as the 'failure studies' approach. Discussing the history of superseded technologies is certainly important, but it is also important to investigate similarities between the old and the new. Although there are significant distinctions between analogue and digital hardware, at an application level many of the key features of analogue computing, such as support for interactive visualisation or rapid modelling, are now provided by digital computers.[5] Thus in the language of failure, the history of analogue computing provides an example of partial, not complete, failure. Take a closer look, and we find that the replacement of the older underlying technology was accompanied by a continuity of practices and methods.

As discussed above, the connections between the words 'analogue', 'digital', 'computer', 'model', and 'continuous', are complex, intriguing and previously not studied in great depth. The initial chapters of this book consider the history of these terms and the classifications they define. It is then possible to understand the key elements of the analogue identity—what made an analogue computer (the technology) *analogue*, and more importantly, what made analogue computing (the culture) *analogue*. Analogue culture is central to the social shaping of analogue computing. Chapter 4 will consider how that culture—a network of inventors, users, ideas, machines, and applications—was established.

In order to properly understand the history, it is necessary to understand the different applications and various types of use that the technology supported. Many users of analogue computing also used digital techniques, so we have to accept that

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[4]Small (2001). For the traditional pre-war account see either Bromley (1990) or Campbell-Kelly and Aspray (1996). Recognition of post-war analogue 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 analogue 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 analogue 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. The major recent studies re-visiting analogue history are Small (1994, 2001) who investigated the electronic analogue 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.

[5]This is discussed in Sect. 3.3.1, pp. 64–72, below.

the users of analogue have also shaped the history of digital. As well as exploring the origins of the analogue–digital distinction, we will be investigating what it meant to be a user of analogue computing. It is therefore important to understand the relationship between analogue and digital, both in terms of technology and also in terms of practice. To investigate this practice, the remaining chapters of the book focus on actual applications of analogue computing.

Before beginning this study, two observations of analogue computing must be introduced. First, that the term 'analogue computer' is complex to define; second, that a major use of analogue computing was modelling.

1.2 Analogue Computer: A Challenge to Define

Throughout its history and historiography, there have been many attempts to define analogue computing and each is deficient in capturing the full breadth of contemporary usages and associations. As a further complication, the meaning of 'analogue' has shifted since 1940. Although modern technical use of 'analogue' refers to continuous state, this was not always so. A look at the primary sources exposes that far from using continuity to make an analogue–digital distinction, many contemporary actors used the idea of continuity to contrast between different types of analogue.[6] As the following insightful quote from George Philbrick, himself an analogue computer pioneer, suggests, the meaning of 'analogue' 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.[7]

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 early history of analogue computing is 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

[6] 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 analogue). See Karplus and Soroka (1959), p. ix.

[7] Philbrick (1961), p. 1. Philbrick also highlighted the philosophical concern of the example where a first differential of an analogue (so continuous) function would be considered discontinuous (so not analogue) by the mathematician. However, when analogue computers differentiated functions, they clearly did not convert from analogue to digital. Philbrick was emphasising that pursing an academic definition of analogue computing based solely on technical characteristic is not a fruitful way to understand these machines.

chronology, however, carries with it the danger that a diverse range of artefacts become the defining content of analogue computing. To combat this, we will follow the actual characters through the history and attempt to understand the definitions employed by those who used, developed, and wrote about analogue computing.

Through looking at the textbook literature from the 1950s and 1960s, we can explore what 'analogue' really meant for its users. One helpful definition dating from the early 1960s comes from Stanley Fifer, the director of Dian Laboratories, an analogue computer manufacturer based in New York. In 1961 Fifer published an extensive four volume work covering every aspect of analogue computing, including a historical review of its development.[8] Identifying that analogue 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.)[9]

Note that, for Fifer, analogy is the first characteristic of analogue computing, whereas continuous state is mentioned second. An analysis of other passages within the contemporary textbook literature shows a similar trend. Over time, it became more common for authors to switch the descriptions around: mentioning continuity as the principal trait and analogy as more secondary. This indicates how analogue computing's identity was shifting away from analogy. By 1970, continuous variables had become the definitive characteristic. However, just as Bush and Philbrick had classified analogue and digital in terms of use, other technologists began forming their own interpretation of the analogue–digital dichotomy. Based on the idea that analogue supported more speculative investigation, Douglas Hartree described the distinction in term of instruments and machines.[10] Similarly, for the British sci-

[8] Fifer'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.

[9] Fifer (1961) pp. 2–3.

[10] See Chap. 2, p. 47 note 85, below.

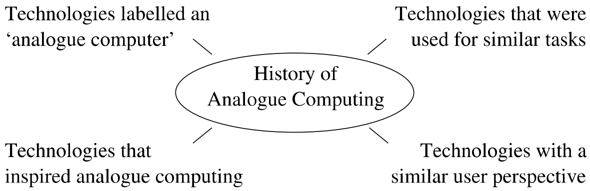

Fig. 1.1 Relevant themes to the history of analogue computing

entist Donald Mackay, the classification hinged on quantitative versus qualitative, analogue computing being a tool for qualitative investigation.[11]

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

Interestingly, the technical labels of 'analogue' and 'digital' first emerged in the 1940s to provide a handle on two emerging classes of computer technology. Over the following decades, the analogue–digital classification evolved to distinguish two types of computing. Other uses of this dichotomy: describing and classifying signals, transmission, and even clocks, developed from there. While classifications can guide the historian, they can also create barriers between the two themes, making it difficult to provide a synthetic account.

Because later definitions of analogue were absorbed into the historiography of analogue computing, there have been disagreements over how the history should be presented. For example, Campbell-Kelly and Aspray (1996) who defined analogue 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.'[12] This disagreement pivots on whether the history of analogue computing should be framed in terms of technical classification (continuity) or type of use (modelling). By focusing on the perspective of use,

[11]MacKay (1951) pp. 1.4–1.5.

[12]Campbell-Kelly and Aspray (1996) p. 60, Small (2001) pp. 6–8. Similarly, in introducing the analogue–digital classification, Historian 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).

we can attempt to avoid the dangers of 'back-projecting' modern understandings of the analogue–digital classification. As introduced in the next section, a modelling perspective will help present the relationship between the two classes of machine.

1.3 Analogue Computing as Modelling Technology

Whilst a diverse collection of technologies are considered part of the history of analogue computing, many early analogue 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 analogue computer must be situated within the history of modelling technology.[13]

When Campbell-Kelly and Aspray (1996) introduced analogue computing into their account of computer history, they did so with a context of modelling.[14] 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 analogue in terms of the continuity of variables, analogue computing was often described to non-technical audiences in terms of its use as a modelling technology. For example, when the *London Illustrated News* ran an article on TRIDAC, a large (analogue) 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 programme, which may include periods of straight flight, slow turns or violent, evasive manoeuvres.[15]

Describing analogue computing in terms of modelling and simulation emphasised its applications and was therefore common in analogue sales literature. For instance, EMI chose to market their commercial analogue (the EMIAC II) as the modern successor of scale models (see Fig. 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

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

[14] See Campbell-Kelly and Aspray (1996) pp. 60–63.

[15] Anon. (1954) p. 995.

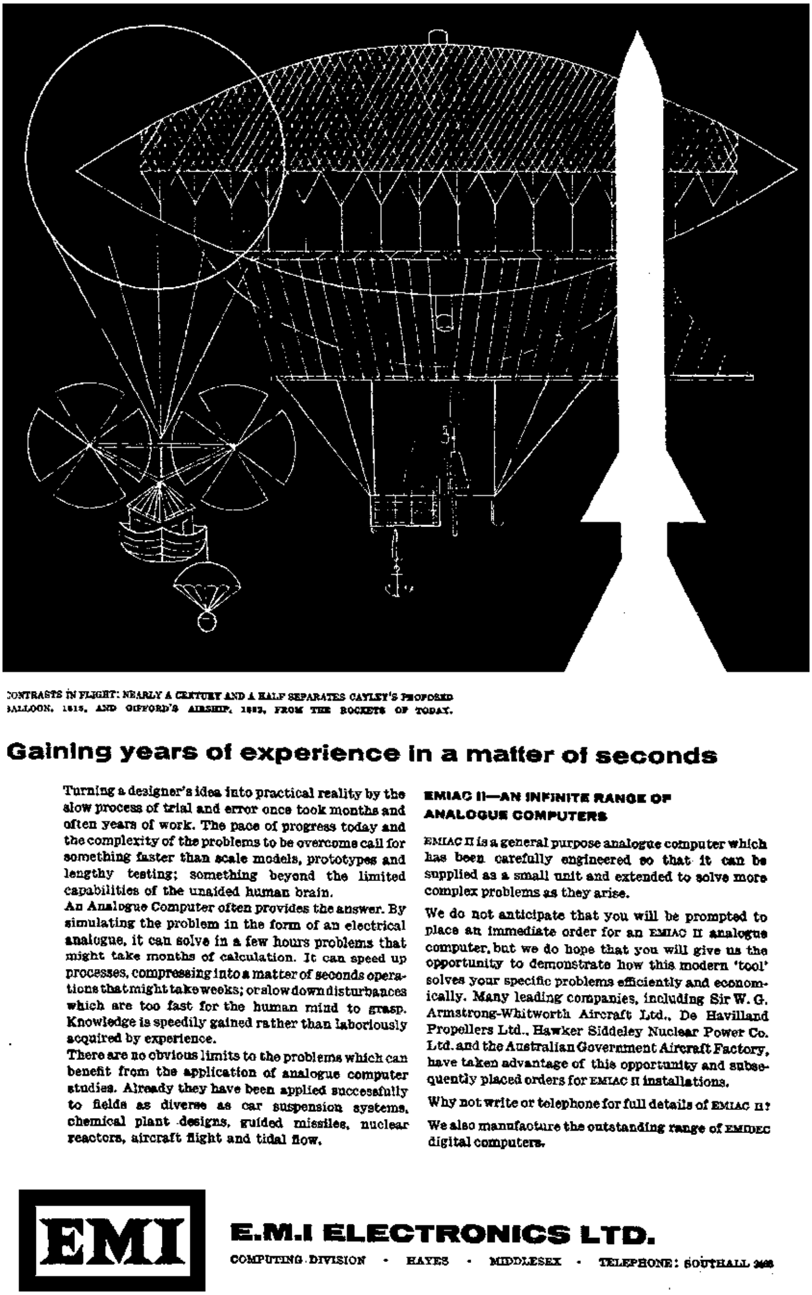

Fig. 1.2 An advert for the EMIAC from 1959. © EMI. Note the emphasis placed on modelling. This stresses the importance of seeing analogue machines as experimental environments and not simply as calculators. Here we read that the analogue computer was a tool where: 'knowledge is speedily gained rather than laboriously acquired'

> 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.[16]

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. To put analogue computing in context, this study 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. 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.[17]

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 analogue computing, David Mindell's *Between Human and Machine* suggests that alternative narratives of the computer have been overlooked. Instead of taking the view that analogue technology was primitive (while digital was progressive), Mindell recognises that the transition from analogue to digital was 'neither instant, obvious, nor complete'.[18] This highlights how themes other than information processing have contributed to the development of the computer.[19]

To understand the history of computer modelling requires an investigation of analogue computing. This book argues that there were communities within research establishments, industry, and academia, which all required technology to support a

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[16]EMI (1955–1965).

[17]Mahoney (2005) pp. 107–108.

[18]Mindell (2002) p. 10.

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

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 models such as scale models, then as mechanical or electrical analogues, and finally as software packages installed on digital computers. This book 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.

1.4 Structure of This Book

Building on previous investigations into the history of analogue computing, this work aims to develop connections with wider work on modelling. The book falls into two parts: Chaps. 2–4 investigate the development of the overarching themes of theory and identity, and Chaps. 5–8 explore the second theme of analogue application and practice. This combination is important for two reasons. First, it allows us to explore the linkages between concepts and communities—vital for understanding the evolution of analogue 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 analogue computers. By bringing modelling to the forefront, we see analogue computing in the light of its merits. We begin to understand how digital computing evolved to replace analogue 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 analogue computing meant for the people 'on the ground'. These were the people 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 analogue story forward were themselves shaped by its theory.

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

1.4.1 Part I: Modelling, Calculation and Analogy: The Themes of Analogue Computing

Chapters 2–4 address the main themes surrounding analogue 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. While previous scholarship has shown such technological shaping to be key, this book 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 'analogue identity', we draw on the importance of labels such as analogue and digital, concepts such as continuity and analogy, and 'use-themes' such as modelling and calculation.

As we explore the history of analogue computing, we will see that much of the conceptual framework provided in the secondary literature conflates what are really two separate themes of analogue computing: calculation and modelling. Chapter 2 reviews the history of analogue computing technology and gives an overview of the variety of analogue computers in history, exposing continuity and analogy as dual meanings of 'analogue'. In attempting to construct a chronology of analogue computing consistent with the two themes of continuity and analogy, Chap. 2 concludes that the history is best represented with separate time-lines. Through a three-strand chronology, a perspective of modelling technology is shown to be particularly applicable to understanding the history of direct analogue computers. It becomes clear that a dichotomy of 'equation-solving' versus 'modelling' is emergent from the sources.

Building on these multiple perspectives of use, Chap. 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 analogue computing the relationships between problem, machine and user were dynamic and less prescribed than typical data processing, equation solving, or calculating. Tracing the formation of this modelling culture, Chap. 4 discusses the emergence of the discipline of 'electrical analogy'. As discussed above, the definition of analogue computing is complex, and was in flux during the 1940s. Particularly interesting is the blending of the concepts of analogy and continuity which enrolled disparate technologies into computing. Within the technological frame of computing, analogue was associated with digital, both technologies being 'computers'. Initially, this enrollment was good for analogue technology. However, later in the history, this association turned sour. Analogue became the 'poor relation' of computing and was redefined to become a non-computational technology.

1.4.2 Part II: Analogue Computing in Use: A Selection of Contexts

While the early chapters discuss the overarching history and the themes relevant to the formation of analogue culture, this culture was strongly situated within the contexts of use. The rest of this book therefore investigates a number of those contexts. Each chapter narrates a particular story based in a different application area. Chapter 5 explores the use of analogue machines in British higher education; Chap. 6

discusses analogue modelling of oil reservoirs at BP; Chap. 7 discusses aeronautical use; and Chap. 8 considers a type of analogue 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 analogue. Following the idea of partial failure, each chapter highlights that defining the relative merits of analogue and digital was complex. Although analogue technology was replaced, its technical culture continued to grow and evolve.

Chapter 5 investigates the activities of British Universities and their use of analogue computing. As well as providing a history of analogue activity at a number of key institutions, funding issues are also discussed. The chapter undertakes a quantitative analysis of analogue use by looking at the research theses completed at British Universities during the period. This analysis demonstrates the wide application of 'ordinary' computing—the day-to-day application of stabilised technology rather than the innovation of new technology. Supporting the argument for multiple perspectives of use, this chapter describes how various applications of analogue (calculation, modelling, and control) follow different historical trajectories. Secondly, it explores the consequences of classification in the funding of analogue computing. Through looking at the funding of these machines, we see how the wider policy making climate initiated the decline of analogue.

Chapter 6 takes the idea of ordinary application further and explores why in 1961 the research division of BP, a world class petroleum company, would choose to install an analogue computer. This story discusses the use of electrolytic tanks and resistance networks for aquifer modelling. BP's analogue computer is an example of ordinary computing application. Because BP procured both an analogue and a digital computer at the same time, the chapter concludes that analogue–digital superiority was not an immediate concern for them. Instead of alternatives, these two classes of computer were complementary. This chapter confirms that historians of computing must look at normal, ordinary, usage in order to fully understand the technology's contemporary use.

Before an engineer can rely on a technology to assist with design work, it has to become 'trustworthy'. Considering the claim that analogue was intuitive to use and well-regarded amongst engineers, Chap. 7 examines their use in aeronautical design. Within this engineering community, analogue computing was understood to be a technology to model and experiment with, rather than to calculate with. It was the benefits of analogue computing as a modelling technology that were cited by those who preferred it to digital. In this chapter, the persistence of analogue computing is explored in terms of its reliability and trustworthiness, and how engineers belonged to the 'analogue generation'.

In the history of computing literature, meteorology is always presented as an area dominated by digital.[20] However, Chap. 8 shows that experimental and inexact techniques existed alongside the numerical/computational parts of this science. In fact,

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[20]William 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

we find that physical analogue models were in use, but were not generally called computers. While there were no analogue–digital tensions, the issue of numerical versus physical was of concern. Hence the labelling of technologies can mask 'non-computational' analogue use.

The four studies described in Chaps. 5–8 highlight the importance of so-called 'direct' analogue computers. While 'indirect' analogues modelled a mathematical system such as a set of differential equations (and could therefore be used to solve equations), 'direct' analogue computing did not rely on mathematical formulation. Instead, direct analogues modelled a physical system based in one medium with another physical system.[21] These technologies, typically resistance networks or electrolytic tanks, were used for modelling heat flow and other complex physical phenomena. Situating analogue computing within the wider history of modelling technologies identifies the connections between computers and other technologies such as electrolytic tanks, electrical models, and even wind tunnels.

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.

[21] See Bromley (1990) p. 157 and Small (2001) pp. 30–31. It 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.

Chapter 2
A Multi-Stranded Chronology of Analogue Computing

This chapter describes the origins and evolution of analogue computing.[1] However, it is important to emphasise that the history of modern analogue computing is inextricably linked with the history of modern digital computing. In fact, the phrase 'analogue computing' was only coined as a result of the invention of digital computers in the 1940s. In terms of the wider history of computing, the 1940s was a period of significant innovation and saw the unveiling of Howard Aiken's Harvard Mark I; the invention of an automatic electrical calculator by John Vincent Atanasoff; and the development of the electronic ENIAC.[2] Scientific culture was thirsty for the electronic mechanisation of mathematics, and it was from this inventive soup that, inspired by a need to contrast the old with the new, the technical labels of 'analogue' and 'digital' first emerged.

The first use of the word 'analogue' to describe a class of computer is attributed to Atanasoff, who, although a pioneer of digital technology, had previously used analogue 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 'analogue' and 'digital' to a whole range of problem solving technologies, enrolling them into a computing culture. Some of these technologies were already considered calculating machines, but for a number of technologies and ap-

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[1] This chapter is an expanded form of a previously published article (Care 2007a).

[2] Developed during wartime USA, the Harvard Mark I became operational in 1944 and was based on electro-mechanical components. However, the future for both analogue and digital computers would be found in the speed and flexibility of electrical and electronic components. Other important early work includes that of the German pioneer Konrad Zuse, and engineers within the British code breaking effort of World War II. In terms of future influence on computing technology, much of the significant innovation was American.

[3] Working at Iowa State College during the 1930s, Atanasoff had developed the Laplaciometer to help him solve problems based on Laplace's equations. It was therefore a tool for solving partial differential equations (Murphy and Atanasoff 1949).

C. Care, *Technology for Modelling,* History of Computing,
DOI 10.1007/978-1-84882-948-0_2,

proaches, it was only through association with analogue computing that they would become 'computational'.[4]

This chapter presents a chronology of analogue computing in which a distinction is drawn between two major strands of analogue computer: one supporting calculation, the other concerned with modelling. These two strands roughly correspond to a classification established by the technology's practitioners: namely, that of *indirect* and *direct* analogue computers. We will return to the indirect/direct distinction later in the chapter, but for now it is enough to acknowledge that the sheer existence of this classification justifies approaching the history from both themes. This chapter argues that it was not until the concept of an 'analogue computer' emerged that these two strands of the technology's history were unified (to form a third strand).[5]

2.1 Two Meanings of Analogue: The Tension Between Analogy and Continuity

Before we begin, it is important to clarify some terminology. In English, the word *analogue* has traditionally been used to convey likeness, similarity or correspondence. Like *analogy*, it derives from the Greek *analogon* for equalities of ratio or proportion.[6] During the twentieth century, the word developed a second technical meaning: one now commonly employed to describe electromagnetic waveforms. Rather than a discrete or digital signal, an analogue waveform is a continuous function (see Fig. 2.1). It is from this second meaning that the technical labels 'analogue television' and 'analogue radio' are derived, and as a result of this technical use, 'analogue' is now used to refer to continuity in general. For instance, popular usage of the analogue–digital dichotomy is found in the classification of clocks—analogue clocks employ a continuous representation of time (the rotation of the clock's hands)

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[4]The 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.

[5]As 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). We will see how the technologies that came to be known as analogue were a unification of both calculating and analysis tools.

[6]This 'similarity' is understood to be structural, concerning correspondences of form rather than content. See 'Analogue, *n.*, and *a.*', *The Oxford English Dictionary*, 2nd edn. 1989. OED online 2010, Oxford University Press, Accessed Feb. 2010, http://dictionary.oed.com/cgi/entry/50007887; 'analogon', *The Oxford English Dictionary*, 2nd edn. 1989. OED online 2010, Oxford University Press, Accessed Feb. 2010, http://dictionary.oed.com/cgi/entry/50007883; and 'analogy', *The Oxford English Dictionary*, 2nd edn. 1989. OED online 2010, Oxford University Press, Accessed Feb. 2010, http://dictionary.oed.com/cgi/entry/50007888.

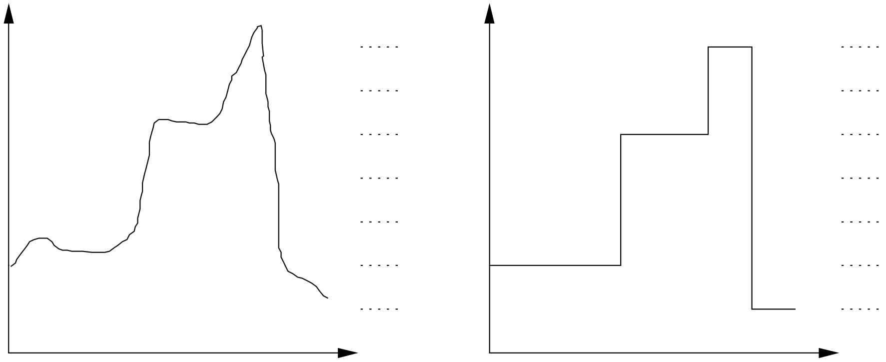

Fig. 2.1 An example of an analogue and digital signal varying over time. The signal on *the left* varies over a continuous range to the granularity imposed by physical properties. The signal on *the right* has been digitalised over a range of discrete values. Alongside analogy, continuity is a second meaning of analogue. 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

whereas digital ones use numeric digits. Additionally, recent advances in digital audio have resulted in digital acting as a key word for sound reproduction: analogue representing the crackly, out-moded, and less desirable technologies of vinyl records and tape cassettes.[7]

If the word *analogue* has two meanings, analogue computing can be understood in terms of them both. Firstly, analogue computers rely on the construction of a suitable analogy (or correspondence) between two physical systems; secondly, analogue computers use an internal representation that is continuous.[8] That analogue computing can be interpreted through both meanings is not simply a convenient coincidence. Certain analogue computers were originally referred to as 'analogy machines' and the association of the word with continuity arose through the comparison of these machines with their competitor technology, the digital computer. The double meaning exists as a direct result of analogue computing.

Shaped by usage, the word 'analogue' evolved to become synonymous with continuity, establishing a term that was subsequently exported to other technical cultures such as signal processing and control engineering. In turn, analogue became a technical label in the consumer culture of audio and video technologies. It could be argued that this is the most significant cultural legacy of analogue computing.

[7]Many 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. A few decades ago, 'broadband' was a specific 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.

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

Had the technology not been compared with digital machines, common language would have not received the key word ‘analogue’. Essentially, analogue computing is the *raison d’être* of the analogue–digital classification common in modern technical rhetoric. If analogue computing had not been so-called, we would probably be replacing our out-moded ‘continuous’ radios and televisions in favour of new ‘discrete’ versions.[9]

2.2 Towards a Chronology of Analogue Computing

The conflation of the two meanings of analogue, while obvious in the technology’s contemporary context, has led to confusion within its historiography.[10] Although the blending of the concepts of analogy and continuity was central to the development of analogue computing, an analysis that can temporarily disassociate them will offer clarity on the history of analogue computing.

Any reader familiar with the history of technology will know that technological evolution is rarely a straightforward sequence of machines and ideas. The history of analogue computing is no exception and appears to be the consequence of a complex and evolving relationship between two technological strands: continuous calculating devices (the ‘equation solvers’), and the technologies developed for modelling. To capture this, the remainder of this chapter is structured into three thematic time-lines. The first (Sect. 2.3) describes the invention of *continuous* calculating aids—analogue devices well known to the history of computing.[11] The second time-line (Sect. 2.4) focuses on the perspective of modelling and analogy-making technologies such as models of power networks or electronic alternatives to wind tunnels. Finally, a third time-line (Sect. 2.5) 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 analogue computer was enrolled into the domain of computing technology, paving the way for the eventual migration of analogue/digital rhetoric into other disciplines such as communications and control engineering.[12] The relationships between these three time-lines is illustrated in Fig. 2.2.

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[9]The 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 2010, Oxford University Press, Accessed Feb. 2010, http://dictionary.oed.com/cgi/entry/50007887.

[10]See the debate over the identity of analogue computing in James Small’s critique of Campbell-Kelly and Aspray (1996) as described in Sect. 1.2, p. 9, above.

[11]These 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).

[12]Control systems will not be considered in detail in this book 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 analogue (particularly the gun directors and other embedded computation).

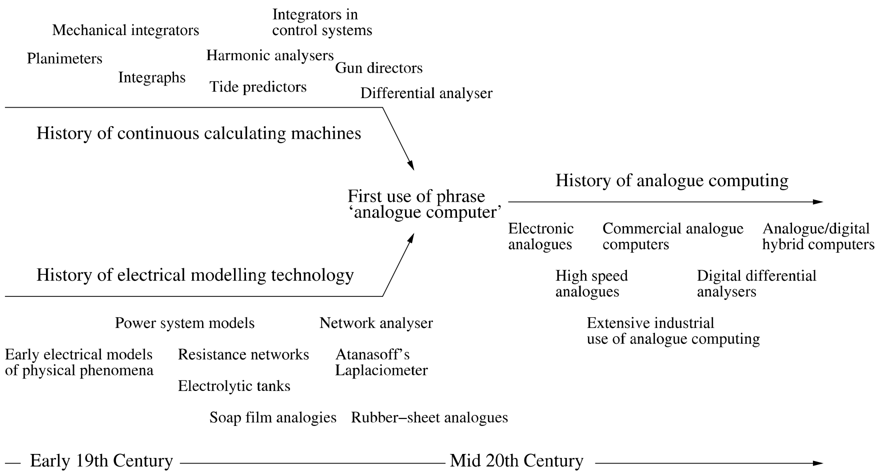

Fig. 2.2 The three strands of analogue chronology. This diagram provides a rough overview of the history of analogue computing. This rest of this chapter provides the detail of this three-stranded time line. Section 2.3 addresses the history of continuous calculating machines; Sect. 2.4 discusses the history of electrical modelling; and finally Sect. 2.5 covers the blending of these two themes into one common history: the history of analogue computing. Arranging the history this way helps make sense of the different ways that analogue computing has been used

Table 2.1 Common dichotomies in the history of analogue computing. Each refers to a different kind of distinction, but when applied to analogue computing technologies roughly maps to previous use of the direct–indirect distinction

Theme	Dichotomy
Application oriented	Calculation/modelling
User perspective	Equation solvers/simulators
Technical representations	Continuous calculators/electrical analogies
Role of mathematics	Indirect analogues/direct analogues

As already discussed, the division into three time-lines is an attempt to organise the variety of devices that we now call 'analogue' while remaining faithful to the distinctions emergent from the contemporary source material. 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 (see Table 2.1). 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.

2.3 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 mathematical tools such as Napier's bones and the slide rule. Using material culture to embody mathematical theory, these mechanisations encoded particular mathematical operations, equations, or behaviours, into physical artefacts. These inventions became known collectively as calculating machines. It is important to note that amongst these early devices, there was no explicit distinction between discrete and continuous representations of quantity.

Some mathematical operations are easier to mechanise than others. For instance, mechanical addition is possible with a differential gear, a mechanism that has been widely known since at least the seventeenth century. However, producing a mechanisation of higher mathematical operations such as differentiation and integration remained unsolved until the early nineteenth century. As it turned out, mechanical embodiments of the calculus were far more straightforward to engineer for those technologies that were later labelled 'analogue', hence it was during this period that a continuous-discrete dichotomy first emerged.[13]

Following the analytical scheme of this chapter, a more complete history of calculating machines could include an additional time-line focusing on non-continuous calculating devices such as mechanical stepped-drum calculators, key-driven Comptometers, and other late-Victorian calculating aids. However, since our story is about the origins of analogue computing, this section focuses on continuous calculating machines, and in particular, the mechanical integrator and its technical predecessor, the planimeter.

2.3.1 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

[13]On 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 analogue 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).

simple but conceptually complex instrument that was used to evaluate area.[14] 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 phrase ‘continuous calculating machine’.

The history of science is scattered with examples of parallel invention, and the planimeter is an excellent example of many inventors converging on the same idea. 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.[15] 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: during the 1850s, one writer estimated that in Europe alone, there were over six billion land areas requiring annual evaluation.[16] Another major application during the industrial revolution was calculating the area of steam engine indicator diagrams.

2.3.1.1 Hermann, Gonnella, Oppikofer: The Various Inventors of the Planimeter

Although many early planimeters were invented independently, it is generally accepted that the first planimeter mechanism was 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

[14]Croarken (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).

[15]The most popular planimeter to be manufactured was the Amsler polar planimeter, invented in 1854 and selling over 12,000 copies before the early 1890s (see Fig. 2.3). 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.

[16]Bauenfeind (writing in 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).

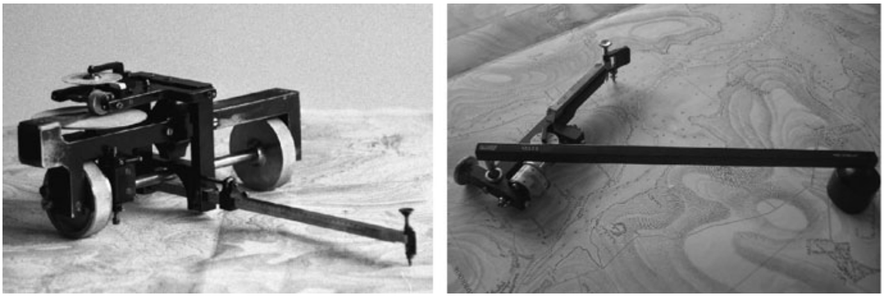

Fig. 2.3 A rolling disc polar planimeter (*left*) and a compensating polar planimeter (*right*). Images © Carina Care 2004

exists (see Fig. 2.4). 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 (see Fig. 2.5) 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 being dependent on both the rotational speed of the cone and the displacement of the 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.[17] Gonnella was also the first inventor to write and 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.[18] As this planimeter also employed a cone in the variable gear, it is unclear to what extent Oppikofer's design was an original contribution.[19] Although the early devices were based around a cone and disk variable gear, the mechanical integrators used in later calculating machines employed a wheel and disk. Despite the idea of using such a mechanism also being 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

[17]The 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.

[18]Bromley (1990) p. 167, Fischer (1995) p. 123, de Morin (1913) pp. 56–59.

[19]Although 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).

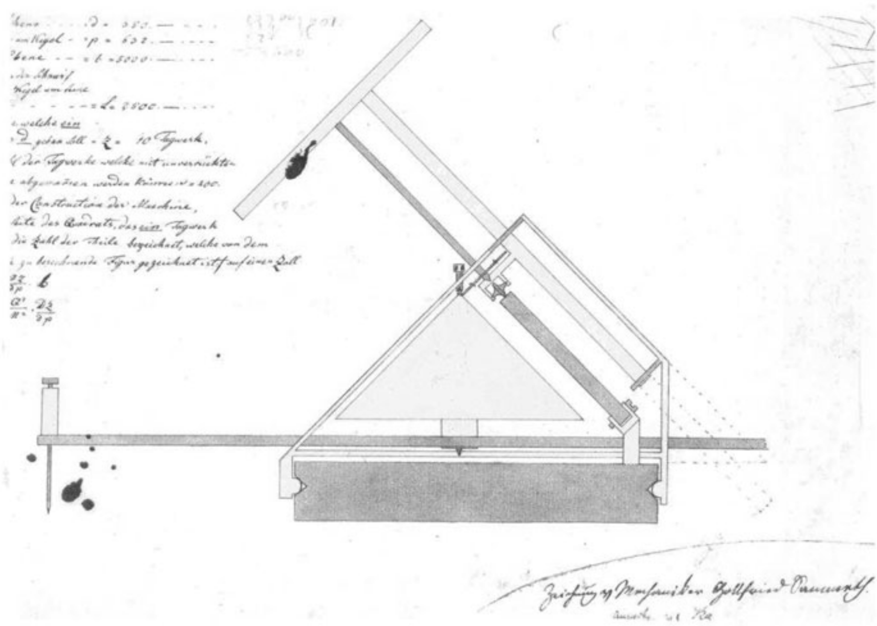

Fig. 2.4 An early drawing of the Hermann planimeter. Source: Bauenfeind papers, Deutsches Museum

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.[20]

Other scientists and instrument makers subsequently developed planimeters. Some of these were also independent innovations such as the 'platometer' devised around 1850 by the Scottish engineer John Sang which was also exhibited at the Great Exhibition.[21] Another major innovation in planimeter design came with Amsler's polar planimeter. However, these devices, although important in the history of planimeters, were not developed into mechanical integrator components used in ana-

[20] Royal Commission (1851) vol. III, p. 1272, item 84, Royal Commission (1852) pp. 303–304, col. 2.

[21] See 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).

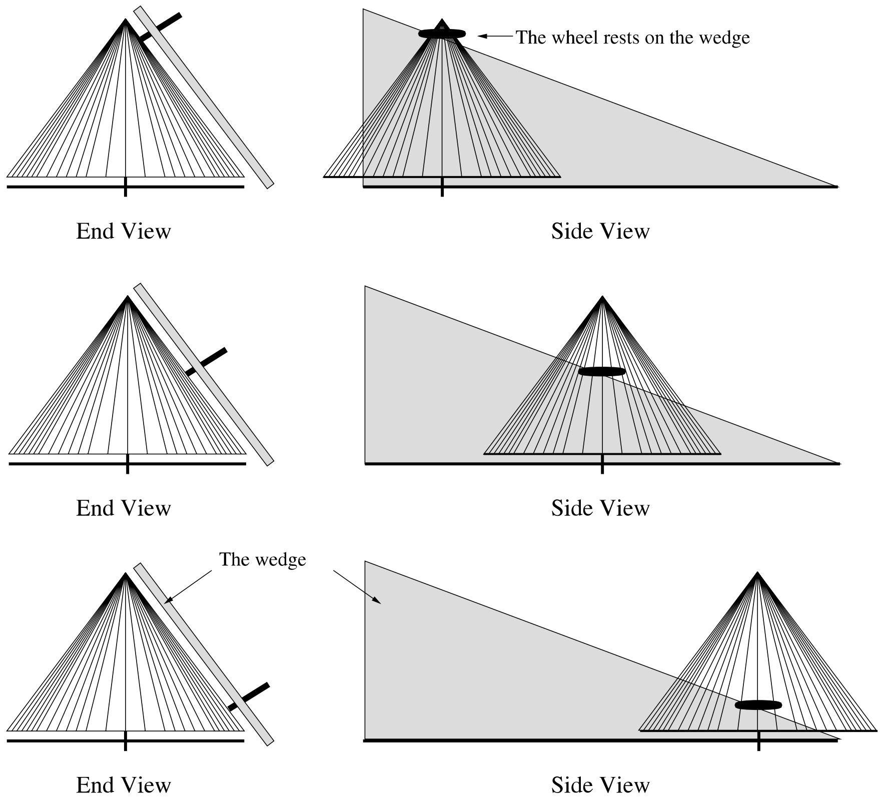

Fig. 2.5 A modern of the variable gear of the Hermann planimeter. The illustration shows how a wedge was used to guide the wheel up and down the edge of the cone as the mechanism slid along its track

logue 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.

2.3.2 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 admira-

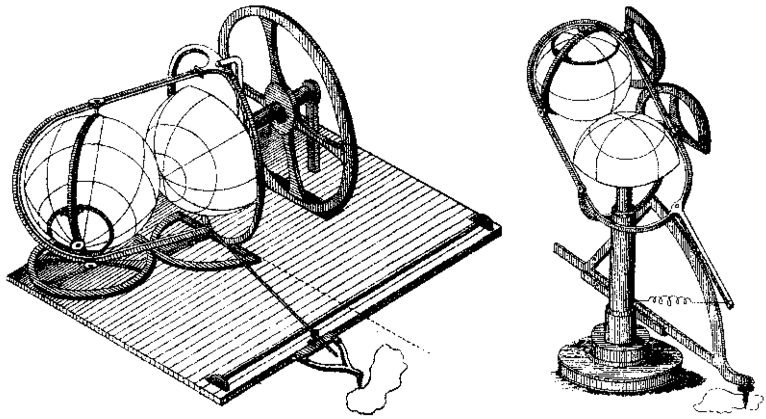

Fig. 2.6 Maxwell proposed two planimeter designs based around his pure-rolling sphere-on-hemisphere mechanism. One (*left*) corresponded to integration over Cartesian coordinates and the other (*right*) to polar coordinates. Source: Maxwell (1855b). Reproduced with the permission of Cambridge University Press

tion.' This impetus came from Sang's platometer which employed a cone and wheel mechanism designed to measure areas on maps and other engineering drawings.[22]

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 (see Fig. 2.6). 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.[23]

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.[24] 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

[22]Maxwell (1855a) p. 277. It is claimed that apart from Gonnella'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).

[23]Maxwell (1855d).

[24]Maxwell (1855e), Campbell and Garnett (1882) pp. 114–115. 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).

to eliminate slip.[25] Although a working example of Maxwell's design 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 (see Fig. 2.7) is an important chronological landmark, marking the beginning of integrator-based analogue computers.[26] The use of the word 'integrator' 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 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.[27] 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.[28] The following 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).[29]

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 har-

[25] When James Thomson simplified the design and introduced some slipping, although the accuracy was acceptable, Maxwell wrote to him and suggested various strategies to return to rolling. See Thomson (1876a), Maxwell (1879).

[26] Earlier 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 edn. 1989. OED online 2010, Oxford University Press, Accessed Feb. 2010, http://dictionary.oed.com/cgi/entry/50118577.

[27] Thompson (1910) vol. II, pp. v, vi, 730, and 745.

[28] Between 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 Government, investigated the mathematics of tides.

[29] Thompson (1910), pp. 1247–1254, British Association (1876) pp. 23 and 253, Thomson (1875) p. 388.

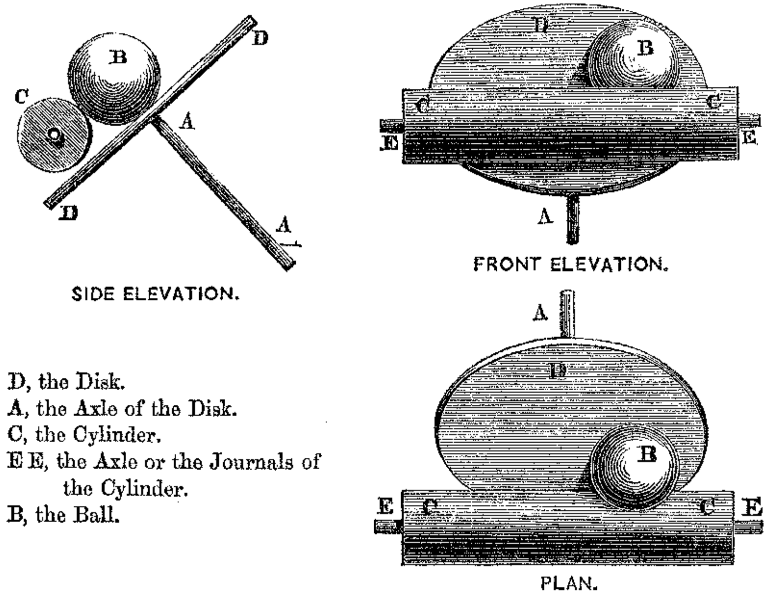

Fig. 2.7 The Thomson 'Integrator' employed a wheel and sphere mechanism. It is similar to the Wetli wheel-and-disk mechanism but uses some of the enhancements of pure rolling that Maxwell argued were so important. Source: Thomson (1876a)

monic base data, Kelvin desired to automatically generate this data. His 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.'[30] 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.'[31]

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.[32] 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

[30]Thomson (1876b) p. 266.

[31]Thomson (1876b) p. 266.

[32]These 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.

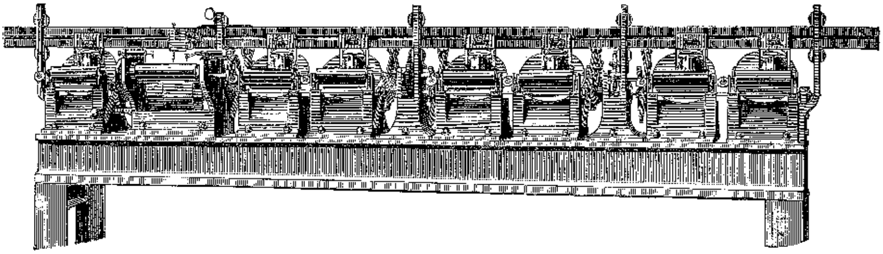

Fig. 2.8 Line drawing of the Kelvin harmonic analyser. Source: Scott and Curtis (1886)

arbitrary order.[33] Kelvin's final paper concluded with a powerful 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.[34]

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'.[35] The harmonic analyser (see Fig. 2.8) was used to derive the composite harmonics of tidal data, and also to solve equations for the Meteorological Office.[36] As a technology, it ushered in a new genre of calculating instrument: the continuous calculating machine.[37]

[33]Thomson (1876a, 1876c, 1876d).

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

[35]Thomson (1882) p. 280.

[36]After 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).

[37]Special purpose analogue 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.

2.3.3 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 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.[38]

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 'analogue computer', was coined by those making technical distinctions.[39] 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.

2.3.3.1 1885: H.S. Hele-Shaw and H.P. Babbage: An Early Analogue–Digital Debate

A major part of the history of analogue computing are the debates that analogue users and inventors had with their digital counterparts. Even before the two categories of computer were firmly defined, people posed questions and had discussions about what the 'best' approaches to mechanising calculation might be. At a meeting of the Physical Society of London in April 1885, we can find a particularly interesting example of such a debate between two well-known characters in the history of computing. On the digital side, we find Henry Prevost Babbage, the youngest son of Charles Babbage.[40] Arguing for analogue (then called 'continuous') is Professor Henry Selby Hele-Shaw, an eminent engineer and inventor of a number of analogue computing mechanisms.

Then working at the Royal School of Mines (Now part of Imperial College, London), Hele-Shaw had advanced the design of integrator mechanisms and understood

[38] Aspray (1990c) pp. 51–54.

[39] At this time 'analogue' would have referred solely to analogy.

[40] Despite his father's pioneering work on computing, Henry's interest in computing came later in life. Henry 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, 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. Henry died in January 1918, aged 93. See Swade (2004), Cohen (1988).

the distinction between such devices and the numerical calculating machines available for basic arithmetical tasks. At this meeting of the Physical Society, he was presenting a paper that provided a comprehensive review of all the various classes of mechanical integrator. While his paper is an interesting source for understanding the various technologies available for mechanising integration, it was in the discussion of that paper (transcribed in the society's *Proceedings*) where our 'debate' occurred. Henry Babbage's comments, directed towards Hele-Shaw, are perhaps the earliest example of such a debate.[41]

> Major-General H.P. Babbage remarked 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 proved 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.[42]

Was Henry Babbage correct to criticise Hele-Shaw's view of continuous calculators? In many ways, Babbage 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 analogue proponents throughout the following century.

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[41] Of 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-lines blended together.

[42] Shaw (1885) pp. 163–164.

2.3.4 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).

2.3.4.1 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 describe 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.[43] 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 (see Fig. 2.9). 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.

[43] Campbell and Goolden (1884) p. 147.

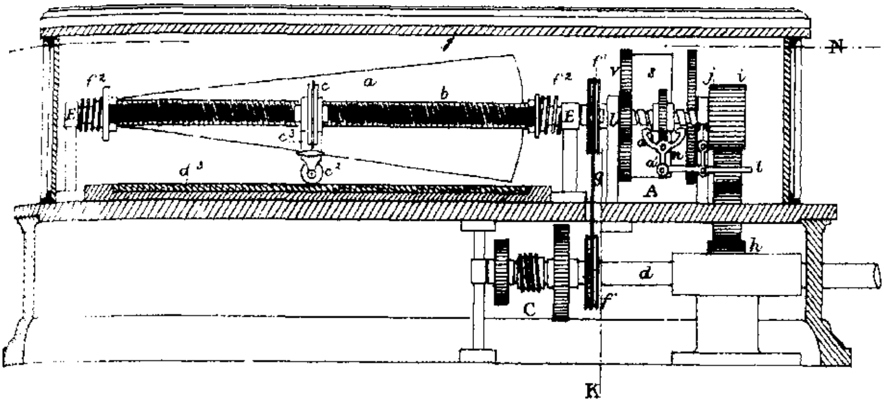

Fig. 2.9 Side elevation of the 'Blythswood Speed Indicator', the cone is clearly visible, the wheel (viewed here sideways-on) is halfway along its shaft. Source: Campbell and Goolden (1884). Reprinted with permission of The Institute of Physics

The Blythswood indicator is an early example of embedded analogue computing for control systems.

2.3.4.2 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 superior guns or the fastest ships, naval engagement also demanded advanced computing methods.[44]

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. The pre-calculated solution was to tabulate the gun settings for a pre-defined range of important parameters such as air speed, direction or speed of target. The alternative was to build a real-time system whose mechanism reflected the actual relationships between different variables in the problem domain and established the correct gun settings. These were known as fire control systems.[45] One of the earliest fire control systems was designed for

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

[45]Computation 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

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.[46]

2.3.4.3 1915: Technology Transfer: Elmer Sperry, Hannibal Ford and Fire Control in the US Navy

Despite Pollen's invention, fire control would initially find a more natural home on American warships. The principal inventor of the analogue 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.[47]

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. 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 Fig. 2.10).[48]

2.3.5 1920–1946: The 'Heyday' of Analogue Computing?

During the inter-war years, application of mechanical analogue computers flourished and became an important part of the warfare technologies employed in World

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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.

[46] See Pollen and Isherwood (1911a, 1911b), 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, who 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.

[47] Mindell (2002) pp. 24–25.

[48] Ford (1919/1916a), Clymer (1993) pp. 24–25, and Mindell (2002) pp. 37–39.

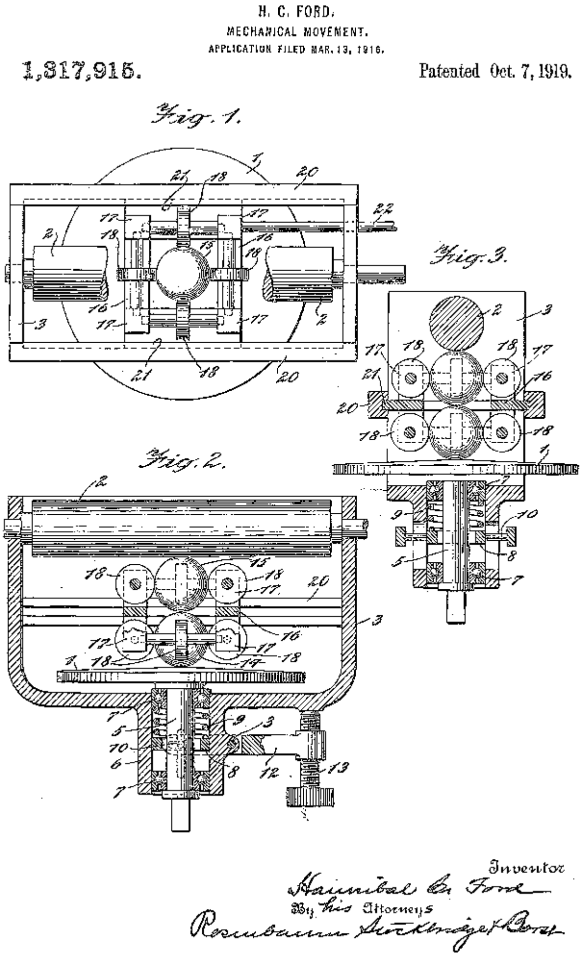

Fig. 2.10 Images from Hannibal Ford's patent for an integrator. The disk and cylinder inherited from the Thomson integrator are clearly visible. Source: Ford (1919/1916a). Ford's integrator employed a spring to compresses the disk on to a double-sphere mechanism, delivering maximum torque, an invention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

War II. As a consequence, historians have christened this pre-1946 period a 'heyday' of analogue computing.[49] During this period there was simply no digital competition, thus analogue 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 World War II as 'analog's finest hour'.[50]

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[49]As exemplified by Campbell-Kelly and Aspray (1996), this was based on the observation that many archetypal analogue 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 analogue computers. However, labelling this period a 'heyday' does not have to imply that there was no successful post-war story.

[50]Mindell (2002) p. 231.

2.3.5.1 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 and Kelvin lacked the required torque amplifier. The torque amplifier used in the differential analyser was developed by Niemann at the Bethlehem Steel Corporation.[51]

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 adviser to President Roosevelt.[52] Bush's involvement with analogue computing began during his Masters degree when he developed the profile tracer, an instrument which, when pushed along, used a mechanical integrator to record changes in ground level. 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.[53]

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 (see Fig. 2.11).[54] The differential analyser was an exceedingly popular instrument and many copies were made and installed in research 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.[55]

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[51] The 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, pp. 665–669, and Mindell (2002) pp. 158–159.

[52] There are many correspondences between Bush and Kelvin. Both were successful scientists and technologists. Each 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).

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

[54] An accessible introduction to the differential analyser (with diagrams) is given by Bromley (1990). A number of differential analysers were constructed out of Meccano (See Chap. 5, p. 99) and had reasonable accuracy.

[55] See Owens (1996), Mindell (2002) pp. 170–173.

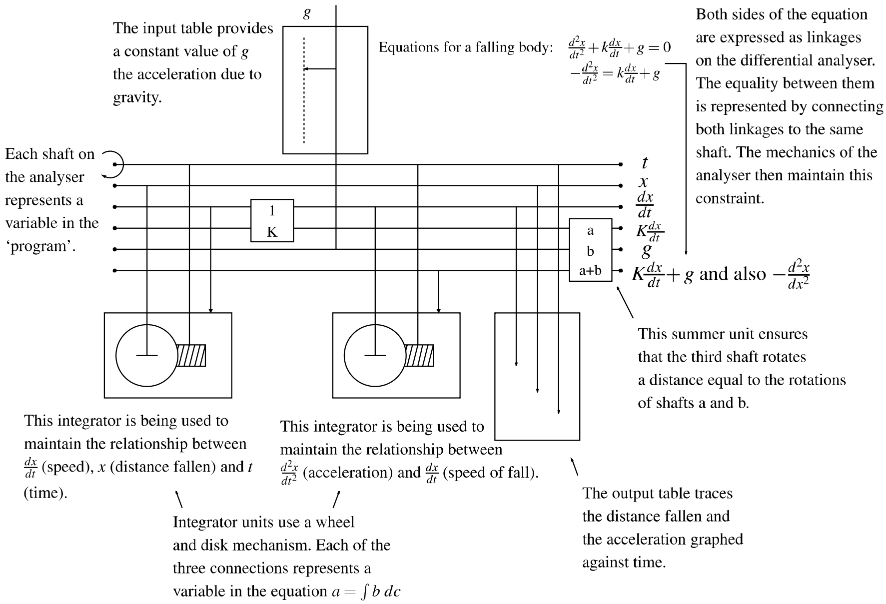

Fig. 2.11 A 'program' for the differential analyser of a free-fall problem. Each linkage between shafts corresponded to a different mathematical operator in the original equations. Based on an example given in Bush (1931) p. 457

As an icon of mathematical mechanisation, the differential analyser became a focal point in the formation of early computing culture. In 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.[56]

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'.[57] His belief was that the machine could provide significant cognitive support for mathematical work and he fully expected this 'instrumental analysis' to become a major approach 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 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.

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[56] See Williams (1954) p. 1, Care (2007b).

[57] Bush (1936) p. 649.

> 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.[58]

On reflection, 'differential analyser' was an interesting name to choose for this machine, and a number of other prominent members of the computing community questioned this choice of terminology. For instance, In January 1938, Douglas Rayner Hartree gave a talk to the Mathematical Association. He argued that the name of the differential analyser was, as he wrote, 'scarcely appropriate as the machine neither differentiates nor analyses, but, much more nearly, carries out the inverse of each of these operations.'[59] Similarly Hollingdale and Toothill (1970) suggested that a better name might have been 'integrating synthesizer'. In describing how the machine was used they noted that mathematical expressions were built up 'term by term' and that this process was 'hardly a process of analysis'.[60] Thus we can see that when thinking about the nature of computing, the distinction between analysis and synthesis was an important contrast to make. George Philbrick, another pioneer of analogue computing, also observed that not all computing was analysis, advocating synthesis as part of his 'lightning empiricism'.[61]

The differential analyser is a good place to complete this time line. We have seen how the demands for calculation inspired the creation of a number of analogue devices such as planimeters and integrators. These devices were then aggregated into larger systems for equation solving, such as the differential analyser. However, not all analogue devices were used to solve equations. The following time line describes those used for modelling: machines where *synthesis*, not analysis, was the central concern.

2.4 Second Thematic Time-Line—From Analogy to Computation: the Development of Electrical Modelling

As previously described, there are two main aspects to analogue computing: continuous representation and physical analogy. In the last section, the history of the mechanical integrator gave us a story of the continuous calculating machine. In this

[58] Bush (1970), p. 262.

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

[60] Hollingdale and Toothill (1970) pp. 79–80.

[61] See Sect. 4.3.1, p. 86, below.

section, we turn to the tradition of analogue computing that emphasises the construction of analogies.

In a sense, analogue 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 into sophisticated, general purpose tools.

2.4.1 1845–1920: The Development of Analogy Methods

During the nineteenth century, model construction embraced the new medium of electricity. 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 also the history of ongoing attempts to manage an electrical (and later electronic) modelling medium.

In the context of direct analogue computing, this modelling medium took two forms: analogues were either based on circuit models, of which the network analyser became an archetype; or alternatively, an analogue was established by exploiting the physical shapes and properties of a conducting medium such as conducting paper or electrolytic tanks.[62] Electrolytic tanks offered a continuous conductive medium while resistance networks had a necessarily discrete representation of the flow space.[63] Together, these techniques became grouped under the umbrella concept of 'electrical analogy'. Analogue models were first referred to as 'electrical analogies', and then later as 'electrical analogues'. Gradually, the experimentalist culture of the laboratory was replaced by more generic technologies, laying the foundations for approaches based on physical analogy to become *computing* technology.

2.4.1.1 Tracing Field Lines, Field Analogies and Electrolytic Tanks

A whole class of analogue computing was dedicated to the modelling of field potentials. These analogues were typically used for solving problems that would otherwise have required the solution of partial differential equations. They employed

[62] As well as tanks and networks, other novel media were employed, for instance the Hydrocal, a research analogue developed at the University of Florida around 1950, was based on pipes and 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 analogue computers, the transition took longer because a suitable and trustworthy digital representation had to be established.

[63] Note that this starts to frustrate certain clear-cut definitions of analogue computing. Contemporary actors were using the labels 'discrete analogue' and 'continuous analogue.'

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 phenomenon into a visual diagram and allowed scientists to begin exploring the analogy between fluid flow and electrical fields.[64]

Electrolytic tanks were the logical extension of paper-based field plots. 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 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.[65] Initially part of the material culture of experimental physics, electrolytic tanks would later become an important technology of analogue 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 an alternating electrical current to the fixed electrodes established an electrical field which could be explored with the mobile electrodes (see Fig. 2.12). 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).[66] In this way gradient lines of an electrical field could be mapped.

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[64]Small (2001) p. 34. As well as conductive electrolyte, conductive 'Teledeltos' paper was also used extensively during the 1950s and 1960s.

[65]Adams 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, 1915), G.C.F. (1915), Anon. (1897a, 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.

[66]See Adams (1876).

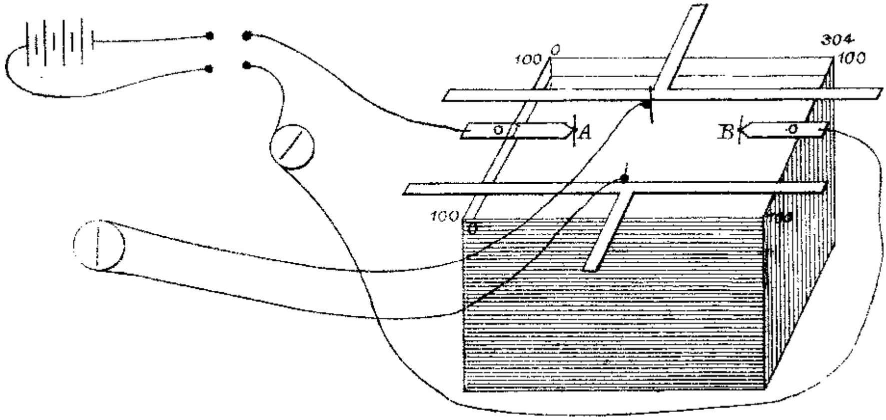

Fig. 2.12 A diagram of Adams' electrolytic tank from his original paper. The fixed electrodes are marked A and B, the mobile electrodes are connected to the T-shaped handles. Source: Adams (1876). Reproduced courtesy of the Royal Society

2.4.1.2 Miniature Power Networks and Resistor-Capacitor Models

Another important technology was electrical network models, also originating in the nineteenth century. For instance, in the 1880s Thomas Edison, the inventor of the light bulb, employed a research assistant to build scale models of power networks. Initially one-off models, over a number of years electrical networks evolved from being special purpose laboratory experiments into more general purpose set-ups. Subsequently, these electrical analogues were replaced by programmable analogue computers, before a final transition to programmable digital computers was made during the 1960s and 1970s.

2.4.2 1920–1946: Pre-digital Analogue 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 analogue methods in engineering.[67] It was around this time that analogue culture was beginning to stabilise, allowing the discipline of electrical analogy to become enclosed and established. As a result, electrical network analogues became part of the literature of computing.[68] The his-

[67]See, for instance, Nickle (1925) or Karplus and Soroka (1959).

[68]This 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

tory of the enclosure and stabilisation of the analogue discipline will be covered in Chap. 4.

The following sections outline some major landmarks in analogue modelling between 1920 and 1950, including: the development of electrical networks, electrolytic tanks in France, the modelling culture associated with high-speed analogue circuits, and the electrical modelling of oil reservoirs.

2.4.2.1 1924: The Origins of the MIT Network Analyser

Resistance network analogue 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.[69] 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. It is clear that contemporary users saw this technology more as a modelling tool than equation solver. For example, Bush described the network analyser as an instrument in which whole equations mapped to a particular set-up. By contrast, he understood that the differential analyser established analogies between the machine and individual components of a differential equation.[70]

Resistor-capacitor circuits could also be harnessed to directly solve mathematical equations. For instance, during the early 1930s, the Cambridge scientist Rawlin 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 in 1933.[71]

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number of articles classified under ‘computer devices and techniques’ grew to encompass both electrical networks and more conventional analogue 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 circuits’ that existed in 1947, being either reduced in size, or removed by the early 1950s.

[69] This 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.

[70] See Bush (1936).

[71] A 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).

Because it modelled mathematical equations, the Mallock machine is a fine example of the kind of analogue 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.[72] Vannevar Bush was impressed with the technique of using transformers, and used it as a starting point for further work in circuit models.[73] 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 analogue computing. This blurring of the two types of analogue computation was typical of Bush's approach to computing. At MIT the two perspectives of analysis and synthesis were managed within one research program.[74] We will return to this 'blurring' in the third thematic time-line, but first we need to consider other important analogy-making technologies.

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 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 become blended in 'analogue computing'. The two types of analyser represented different activities—two perspectives of use—sub-dividing the analogue computing class. Small described them as competitive technologies that 'maintained distinct lineages, but nevertheless shared a similar conclusion; their displacement by electronic digital computers.'[75]

2.4.2.2 1932: Le Laboratoire des Analogies Electriques: Electrolytic Tanks in France

So far we have mainly reviewed the Anglo-American story, however, there was significant parallel activity in other countries. One particularly interesting example is the work of the French mathematician Joseph Pérès (1890–1962) who became

[72] The 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.

[73] See Bush (1934).

[74] Mindell (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, Akera (2007) pp. 31–32, Owens (1986), Wildes and Lindgren (1985) pp. 86–87.

[75] Small (2001) p. 40.

well-known for his use of electrolytic tanks to model physical systems.[76] In 1921 Pérès had been appointed Professor of Rational and Applied Mechanics at Marseilles where he was inspired by the analogue modelling of his colleague J. Valensi. Valensi had been working on a fluid dynamic problem by employing an analogy between streamlines of fluid flow and potentials in an electrical field.[77]

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, along 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 number of aircraft manufacturers until 1940 when the outbreak of war in Europe prompted the laboratory to be dispersed and the remaining equipment destroyed.[78]

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

2.4.2.3 1935: George Philbrick and the Polyphemus: Development of Electronic Modelling at Foxboro

Another type of analogue technology arose from the electronic modelling of control systems. This lead to the popular class of machine referred to as the 'General Purpose Analogue Computer' (or GPAC). The GPAC was essentially an electronic version of the differential analyser.

Many of the pioneers of these high speed analogue computers had previously undertaken research in control systems analysis or similar fields. One such character was George Philbrick (1913–1974), a Harvard-educated engineer.[79] Working

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

[77] In 1924, the same year that Valensi used an electrical analogue 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).

[78] Pérès (1938), Mounier-Kuhn (1989) p. 257.

[79] Mindell (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.

at the Foxboro Corporation, Philbrick developed the Automatic Control Analyzer (ACA) simulator (nicknamed 'Polyphemus'), an early electronic computer.[80] Like many prominent control engineers, Philbrick worked for the US government as a fire control researcher during World War II. Working within Division 7 of the National Defense Research Council (NDRC), he met several, later eminent, engineers who were involved in the early seminal work on control electronics and servomechanisms.[81] Once his wartime research was completed, Philbrick had intended to enrol at MIT as a graduate student and develop a high-speed analogue 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 and later became a major manufacturer of analogue computers.[82] Philbrick's approach to analogue computing is discussed in Chap. 4.

2.4.2.4 1942: William A. Bruce and the Modelling of Oil Reservoirs

An interesting example of analogue computing as a modelling medium is the application of electrolytic tanks and resistive networks to the modelling of oil reservoirs. This application dates 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 analogue 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.[83]

He worked for Foxboro between 1936 and 1942, under the eminent control engineer Clesson E. Mason. Mason was awarded the Rufus Oldenburger Medal for his work on automatic control in 1973. See Paynter (1975) and Anon. (2005b).

[80] Similar activities were going on in other engineering contexts. In 1939 Helmut Hoelzer was working on early analogue computing as part of German missile research, and in Britain a team developing radar crew trainers at the Telecommunications Research Establishment (TRE) constructed an analogue simulator using electro-mechanical integrators, which they called 'the velodyne'. The TRE was central in laying the foundations of post-war analogue 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 analogue culture. See Small (2001) pp. 66–67, 69–71, McLeod (1968) p. 15.

[81] See Mindell (2002) pp. 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.

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

[83] Peaceman (1990) pp. 106–108, Bruce (1947/1943).

Throughout the following two decades, large numbers of patents for reservoir analysers were granted. Initially, the inventors made no reference to analogue, analogy or computing. Throughout his 1945 patent application, Bruce described his circuits as an 'electrical counterpart of a reservoir'. However, later reservoir analysers would be described as 'electrical analogies' and thus become part of the history of analogue computing. Their story is told in Chap. 6.

2.5 Third Thematic Time-Line—Analogue Computing and the Entwining of Calculation and Modelling

The previous sections described the major technologies considered important to the history of analogue computing. However, it was only after the emergence of the digital computer that it became necessary to assemble these various technologies under the umbrella term of 'analogue computing'. In the formation of an analogue 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.

2.5.1 1940: The Emergence of Analogue Computing as a Technical Label and Class of Machine

According to the *Oxford English Dictionary* the earliest use of the word 'analogue' to describe a class of computers occurs in a 1946 article authored by Douglas Hartree.[84] Published in *Nature*, the article stated that the classification was established on the other side of the Atlantic.[85] It is assumed that Hartree was introduced to the analogue–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 analogue 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

[84] 'Analogue, *n.*, and *a.*', *The Oxford English Dictionary*, 2nd edn. 1989. OED online 2010, Oxford University Press, Accessed Feb. 2010, http://dictionary.oed.com/cgi/entry/50007887.

[85] Hartree wrote that 'the American usage is analogue and digital machines', (Hartree 1946, p. 500). In fact, Hartree actually preferred to use 'calculating machine' for digital and 'calculating instrument' for analogue, 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.

identified a paper describing a digital computing technique (Atanasoff 1940) as the earliest record of his usage.[86] In this paper he wrote that 'he was aware of the possibility of using a mechanical or electrical analogue but discarded this method, as being too inaccurate and cumbersome.'[87]

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 analogue 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 analogue 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.[88] 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 analogue 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 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.[89]

For Mauchly and Atanasoff, the technology they named 'analog' was based on physical analogy. Hence, an analogue was a machine or set-up which maintained a correspondence or analogy between two physical systems. The continuous nature of the machine was coincidental. A similar emphasis was made by Douglas Hartree who considered measurement to be a central aspect of his analogue *instruments*, the technology that operated by '...translating numbers into physical quantities of

[86] Atanasoff (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'.

[87] Atanasoff (1940) p. 316.

[88] Mauchly (1984) pp. 125–126.

[89] Mauchly (1941)—this usage was attributed to Atanasoff. While Mauchly made no direct reference in these notes to the relationship between analogue 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.

which the numbers are the measures... finally measuring some physical quantity to give the result.'[90] Even forty years on, Atanasoff retained an emphasis on measurement rather than continuity: 'In analog computers...', he writes, 'a number is represented by a physical quantity in the machine as measured by some system of units'.[91]

2.5.2 *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 analogue, some digital.

One of the major technical benefits of the wartime research was the improvement in electronics. During the years after 1945, analog computers were constructed using electronic components, the mechanical integrators being replaced with capacitor charging circuits. The replacement of the mechanical with electronic was not immediate. The 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.[92] High speed components facilitated a new type of analogue 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.'[93]

2.5.2.1 The Development of Electronic Differential Analysers

Now unified under 'analogue computing', analogues came to be classified as either direct or indirect. The indirect analogues were essentially the developments of the

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[90] Hartree (1947) pp. 7–8. Hartree did refer to continuous data, but not as a defining feature of analogue 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).

[91] 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 analogue computing manipulates measures that represent numbers. Atanasoff's use of *direct* should not be confused with the two categories of analogue computers—direct and indirect—that came later.

[92] Small (2001) pp. 54–56.

[93] EMI (1955–1965).

equation solving tradition. 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 analogue computer was developed by Macnee (1949). Similarly research machines were developed in various universities and research establishments. In America most post-war analogue computing was organised by the Office of Naval Research (ONR), which organised a number of large projects and symposia. In the UK, most of the early research was undertaken in relation to aeronautics, the large TRIDAC machine becoming operational in 1954.[94]

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 Chap. 7), resistance analogues used in hydrology and ground water research (see Chaps. 5 and 6), and modelling electric transmission networks.

2.5.2.2 Early Digital Computers as the Evolution of Analogue Architectures

Although digital computers are a distinct technology from analogue, it is possible to see many of the early digital machines as the evolution of an analogue architecture. Indeed, if the distinction between analogue and digital only emerged *after* the development of digital computing, it makes sense that the earliest machines might expose a closer relationship between the two.

Earlier we referred to ENIAC, arguably the first programmable electronic digital computer.[95] 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. A major application of analogue computers was mechanising the calculus and the ENIAC was intended to solve those problems. Essentially, this machine was the digital replacement of the differential analyser. An insightful quote from the ENIAC patent (submitted in 1947) shows that making an analogue 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. Although existing continuous variable

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[94] Small (2001) pp. 181–182.

[95] ENIAC 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.

> machines such as the differential analyser and the AC network analyser are exceedingly rapid, the class of problems which they can solve is limited.[96]

As can be seen from the quote, the 1940s was the period when the concept of the analogue 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.[97] Furthermore, 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 analogue 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 analogue—the Laplaciometer—led Atanasoff to his different approach to building a digital computer.[98]

2.5.2.3 Analogue Techniques on Digital Hardware: The Digital Differential Analyser

While the ENIAC was partly inspired by the analogue computers that preceded it, another technical evolution based on analogue concepts was the Digital Differential Analyser (or DDA). The principle behind the DDA was that the analogue integrators could be replaced by software integrators 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 virtual summers, integrators, and other analogue components, just as on a differential analyser or GPAC. In this sense, the DDA was an attempt to separate the analogue approach from the analogue technology.

One example of a DDA is the MADDIDA computer constructed by engineers at Northrop aircraft.[99] 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

[96] Eckert and Mauchly (1964/1947) col. 3.

[97] Brainerd (1976) p. 483.

[98] Burks (2002).

[99] Northrop 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).

perform celestial navigation functions. The Snark was 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.[100] 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 analogue differential analyser.[101] 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.[102] 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.[103]

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 Ordinance Laboratory.[104] 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.[105] In Britain, DDAs were referred to as 'incremental computers' and over the following decade, they became a popular technology for computation on board aircraft. 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 claimed that the technology was sufficiently advanced for DDAs to be 'adequate for most airborne applications'. However, when compared to traditional analogue computers, they still had 'a speed disadvantage' when used for simulation work.[106]

In an article about the history of the MADDIDA, Spicer (2000) described it as a 'bridge between worlds'. The concept of the digital differential analyser crossed the boundary between analogue and digital. Here was a digital machine that employed

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

[101] Ironically, the MADDIDA was still too large for use in the Snark, so the final guidance system was fully analogue.

[102] Eckdahl et al. (2003), Tropp (1987) pp. 266, 357.

[103] Anon. (1951a). For a technical overview of the DDA, see Donan (1952), Sprague (1952).

[104] Meissner (1954) pp. 134, 137.

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

[106] Rowley (1960) p. 9. The computer being described had been developed by AV Roe and Co. at their Chertsey research laboratories. The computer was primarily developed to manage on board navigation and also simple simulations.

the benefits of numerical representation, and yet organised its computing like a differential analyser. For many contemporary engineers, blending of analogue and digital approaches appeared to be the logical direction in which the technology would develop. Commenting on the history of DDAs, Maurice Wilkes wrote that machines like the MADDIDA were 'on an impressively small scale' when compared with the digital alternatives of the day.[107] However, general purpose digital computers eventually became small enough to compete without having to sacrifice generality.

2.5.3 1950–1965: The Commercialisation of the Analogue Computer, and the Invention of Hybrid Computing

During the years after 1950, the analogue 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 analogue manufacturers eventually dominating the market, both in America and Europe. Electronic analogue computers were typically used for three major applications: solving differential equations, modelling complex systems, and simulating control systems. In Chap. 5 we will return to these three types of application. The history of analogue computing in British academia followed different trajectories for each type of use.[108]

The demise of the analogue computer was a gradual process and the technology went through one more stage of innovation before disappearing. This was the development of hybrid computing. Although the DDA was a form of hybrid, there were various other types. These ranged from conventional analogues whose patchboard and control circuits were managed by a digital computer, through to computers where analogue-to-digital converters were installed to allow analogue variables to be stored in memory and manipulated by a digital computer. The analogue 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.

However, during the 1960s most analogue 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'.[109] The qualities of new digital software laid analogue's traditional advantages of speed, cost, and ease of use, to one side. As one commentator put it:

[107] Wilkes (2000) p. 538.

[108] For Small, the commercialisation of analogue computers began in America in 1948 and in Britain in 1953. See Small (2001) p. 179.

[109] Newell (1983) p. 196.

> 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.[110]

Despite the demise of analogue computers, there was a continuation of analogue culture. In a similar vein to the DDA projects, the next stage of evolution was the simulation of analogue computers, not with digital hardware (as with the DDA), but with software. Various simulation languages were proposed, allowing the users of analogue computing to transfer their programming knowledge from the old technology to the new. It is tempting to frame the transition from analogue 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 analogue computers were not immediately decommissioned, highlights that a mixture of both analogue and digital computers were 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 analogue 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'.[111] The future was digital, but the ideas, techniques and language of analogue would persist. Even today, engineering modelling and simulation practice still uses the language of integrators, summers and other analogue computing components. This is best exemplified in the graphical interface to the popular MATLAB Simulink.[112]

2.6 Conclusions

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

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[110] Holst (2000) p. 59.

[111] ACM (1968) p. 159. The development of analogue simulation languages is discussed further in Sect. 4.4.1, p. 90, below.

[112] Atherton (2005) p. 67, Bissell (2004) pp. 7–8.

Through investigating analogue's identity, it becomes evident that there were two key aspects to analogue computers: the use of continuous representation (reflecting the modern analogue/digital classification), and the application of *analogy* (visible in the etymology of the word 'analogue'). While clearly interrelated, these two aspects of continuity and analogy belong to two separate (albeit closely interrelated) histories of technology. Each of these histories became entwined when computer pioneers began to refer to the concept of an 'analogue computer' in the 1940s. Although the dual-meaning of analogue is implicit in previous accounts, authors have tended to mix their discussions of continuity and analogy. In this chapter, the history of analogue computing was structured around this dual-meaning. It was only once analogous modelling and continuous calculation were enrolled into the discourse of computing, that firstly, they became recognised as two different approaches of the same 'whole'; and secondly, that the need arose to name this 'whole'. This convergence appears to have begun during the 1930s, and came to fruition during the early 1940s.

Previous research on the history of analogue computing has tended to focus on those artefacts that are more easily understood within a trajectory of information processing. Often this is adequate, as analogue computing is described to provide a background context for the history of early digital computers and their invention. However, focusing solely on this part of the history emphasises analogue as a precursor to digital, but not as an alternative. This resulted in a number of scholars attempting to revisit the post-war analogue history, questioning why analogue 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 analogue computing.[113] While the history of the equation solvers is quite well understood, there has been less research into those technologies described in the second time-line. The technologies that came to be classified direct analogues were novel computing tools which provided visual experimental modelling environments. These were not just used for information processing, but also for *modelling*.

Having looked in detail at the history of analogue devices of the first time-line, we can now move on from the stories of differential analysers, planimeters, and integrators—the analogue equation solvers. The rest of this book 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, analogue modelling techniques. In Chap. 3, we turn our attention to how a history of computing can account for the computer as a modelling machine. Later, Chap. 4 returns to the relationship between electrical analogy and analogue computing, exploring how analogue culture emerged. Finally, the second half of this book investigates a number of specific contexts where analogue computing was used as a modelling technology.

[113] Small (2001).

Chapter 3
Modelling Technology and the History of Analogue Computing

As discussed in Chapter 2, the concept of an 'analogue computer' did not exist before the mid-twentieth century. The phrase was coined to describe a class of computing technology whose popularity had gathered momentum during the 1930s. However, although these technologies were new, what the pioneers of analogue computing were doing in the early twentieth century was not entirely new. These pioneers were, themselves, following a tradition of modelling that has a long heritage in the history of science. What *was* innovative was the evolution of their tools. As computational technology became more and more capable, various specific modelling techniques were replaced by more generic computing techniques. The invention and application of computer technology enabled the creation of new environments for modelling.

Chapter 2 demonstrated how the history of analogue computing can be presented in terms of both calculation and modelling. Through considering the computer as a modelling machine, this chapter will investigate the wider modelling culture surrounding analogue computing. In a recent introduction to a series of articles on the history of analogue computing, historian James Nyce wrote that 'the digital paradigm is now so pervasive that challenges to it are also framed (and won) in its terms'.[1] Essentially, the bias and perspective of current computing culture heightens the difficulty of understanding analogue computing in context. In particular, the precise definition of analogue computing, as understood by its contemporary users, is subtly different from the modern perspective. This chapter argues that this variance can be explained in terms of modelling.

Modelling is a major use of computer technology that until recently had received little attention from historians of computing. For many uses of computing, it is not necessary to consider the computer as a modelling technology, but rather as a calculator or information processor. However, any analysis of analogue computing must be situated within a history of computing informed by both information processing and modelling. While analogue computers were not solely used for modelling, a historiography of models and modelling provides a coherent view of the history.

[1] Nyce (1996) p. 3.

C. Care, *Technology for Modelling,* History of Computing,
DOI 10.1007/978-1-84882-948-0_3,

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 analogue computing and discusses the wider relationship between computing and modelling. It then returns to discussing how the theme of modelling fits within the history of analogue computing.

3.1 Modelling: A Variety of Definitions and Associations

With the benefit of hindsight, it is not difficult to find examples that illustrate the significance of the computer as a modelling medium. 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 a key application. 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]

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 experimental the modelling. With modern computers, technology now provides virtual environments, re-defining the boundaries of what it is possible to create. Computers support the management of an inherently flexible and vast medium of electronic state. Through enabling 'creating' and 'making' with electronic 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 'analogue', 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, a model could be 'almost anything from a naked blond to a quadratic equation'.[3]

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[2]A 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 (Bialynicki-Birula and Bialynicka-Birula 2004). The development of computational science and the centrality of models and simulations are considered at length by Humphreys (2004) Chaps. 3–4, Hartmann (1996), and Galison (1997) Chap. 8. From a historical perspective Yood (2005) gives an account of the development of computational science at the American Argonne National Laboratory.

[3]Goodman (1969) p. 171, McCarty (2004) p. 257.

It is beyond the scope of this book to discuss the exact nature and meaning of models and modelling. For our purposes, it is sufficient to acknowledge that these concepts have multiple meanings, and that we must therefore exercise caution when interpreting historical descriptions of the technology's use. Rather than developing a precise definition of modelling, it is helpful to consider how positioning the computer as a modelling technology differs from other themes in the history of computing.

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

[4]Recent 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 Charles Babbage and the development of the Harvard Mark I nearly a century later.

[5]Campbell-Kelly (2002).

[6]The issue of not back-projecting modern definitions of computing is a real challenge for the history of computing. In a recent book review, Kidwell (2006) discusses this issue. She writes that

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 production line 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 now extensive literature, these two types of use are central in understanding the development of business computing and the commercialisation of the digital computer.

However, analogue computing does not fit well within this historiographical tradition. For its users, the analogue computer was more like a scientific instrument, an experimental tool that guided their reasoning. Throughout the development of analogue technology its users were motivated by a desire to model and understand the world. This difference becomes significant when analogue technology is considered as a precursor to digital computing. When historians emphasise data processing, nineteenth century analogue machines are portrayed as a technological dead end—what L.J. Comrie called a 'dark age' of digital computing.[8] Echoing our earlier quotation from James Nyce, historian Aristotle Tympas has commented how changing perceptions of computational identity have lead to the 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 analogue history (namely, those belonging to the first thematic time-line of Chap. 2). In terms of pure information processing, studying post-1940s analogue technology seemed irrelevant.[10] This supplied the fuel for

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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).

[7]These industrial metaphors extend back to Charles 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 Cadestre 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.

[8]See 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.

[9]Tympas (2003) pp. 76–77.

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

those scholars who during the 1990s were to re-address the history of analogue computing. 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, and culture.

Within a narrative of modelling, the history of analogue computing is far broader than the chronology of those machines that were described as 'analogue computers'. It is a much bigger story encompassing the history of both calculating and modelling devices. Therefore, alongside information processing, we should consider a second, more user-intimate, mode of computing (see Fig. 3.1). As well as providing a means for manipulating and presenting information; computing technology can, and has, been used to *generate* knowledge. In other words, users can approach the computer as a means to discover new knowledge, an activity of information generation rather than information processing, an activity of 'modelling'.[11]

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 analogue computing and its related technologies. In contrast to basing definitions on the continuous representation, using modelling as the meta-narrative for analogue computing encourages consideration of the technology's users. Those who worked with analogue 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. Through exploring perspectives of use, this analysis provides a clearer picture of the development of analogue computing than the idea of 'alternatives' proposed by Small (2001).[12] The following sections consider the philosophical and historical arguments for this perspective.

3.3 Support for Thinking of the Computer as a Modelling Medium

The invention of computer technology was not an isolated invention, but rather a sequence of events situated in a much broader history. Essentially, the computer is a composite technology, a point of convergence of various types of special purpose mechanisation. It is now common for histories of computing to be based around

[11] There is clearly an important philosophical distinction between knowledge and information that is beyond the scope of this book. 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. Computers 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.

[12] As discussed in Sect. 1.1, p. 6, above.

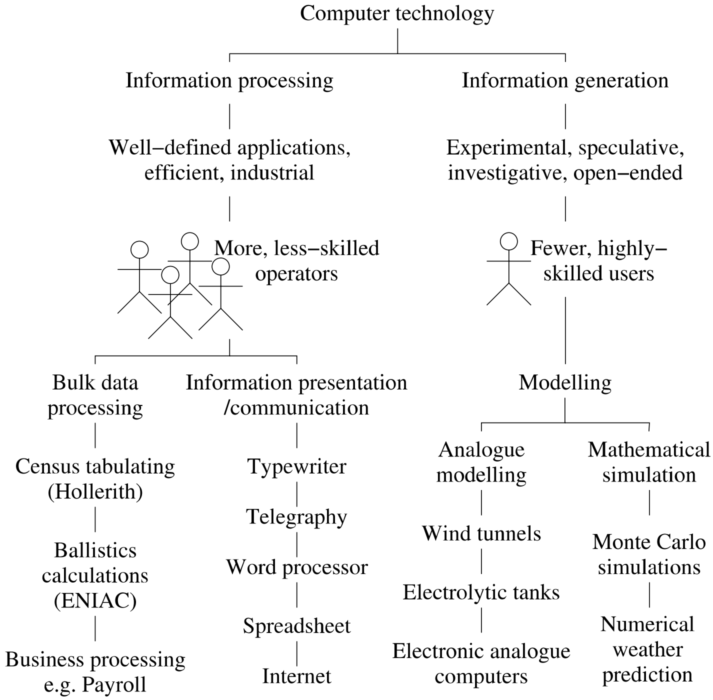

Fig. 3.1 Information *processing* and information *generation* represent two fundamentally different approaches to computing. Computer history needs to account for both

this kind of convergence, 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.[13] 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 with each application 'introduced' to the historiography of computing, a new set of technologies become part of its history. 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 sep-

[13]Two popular histories that follow this general pattern are Campbell-Kelly and Aspray (1996) and Essinger (2004). Critiques 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.

arate practices of forecasting, observation, and theoretical modelling.[14] 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. 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. The computer has essentially unified a plurality of applications.[15] Obvious examples are communication, 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'.[16] Informed by the idea of the computer being a composite technology, analogue 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.[17] Some justification for framing computing as modelling has already been given in Chap. 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, and these are discussed the following sections. Before returning to the primary sources (and the practice of analogue computing), it is helpful to consider these theoretical perspectives.

3.3.1 Theoretical Support for a Modelling Perspective

With relation to modern computing, philosophical support for this 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'. He concludes that to understand computers purely as 'knowledge jukeboxes' misses their greater potential as modelling tool. He argues that computers should also be considered 'modelling machines'.[18]

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[14] See Sect. 8.1, p. 159, below.

[15] See Galison (1997), Chap. 8.

[16] See Humphreys (2004).

[17] A 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), Chap. 8.

[18] McCarty (2005) p. 27.

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.[19] 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 a ‘mimetic function’ of aspects of the world, and are often identified by their ‘realist mode of description’.[20] 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.[21]

It is from these references to instruments and simulations that links between modern computing and analogue computing begin to emerge. A number of philosophers of science have considered the relationship between analogue computers and scientific models—analogue computers being positioned on the intersection of models and instruments.[22] 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.[23]

Besides the fact that both orreries and pendulums have been associated with analogue devices,[24] as an instrument, analogue computers correspond with two of Van

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

[20] Hughes (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 Rohrlich 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.

[21] Numerous 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.

[22] See Hesse (1963) and Morgan and Morrison (1999b). Recall how Douglas Hartree used ‘calculating instrument’ and ‘calculating machine’ to distinguish between ‘analogue’ and ‘digital’. See Sect. 2.5.1, p. 47, above.

[23] Van Helden and Hankins (1994) p. 4.

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

Helden and Hankins' categories. Firstly, in many applications of analogue computing, users created computational artefacts that were 'models or analogies to nature'; secondly, just as the air-pump provided a new environment from which to explore phenomena, so the analogue computer provided a new environment through which to think about and construct models of certain physical systems. In an article describing an all-electronic differential analyser, A.B. Macnee wrote that he expected the 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.'[25] In addition, analogue computers were always 'the means of visual or graphic display'. Able to support dynamic models, analogues were able to support interactive visualisation long before their digital counterparts. As a consequence, analogue computing researchers often developed expertise in visualisation technology. For instance, it was in the context of analogue computing research that Donald MacKay described an early form of three-dimensional display.[26] Although he started his career developing analogue computing, he later moved into neuroscience research and used his analogue skills to develop novel display apparatus.

As an instrument, the analogue 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.[27] Every calculation on an analogue computer can be considered an experiment with the computing mechanism, 'playing through' a sequence of actions analogous to a physical experiment. With analogue computing, the human operator was often guided towards the solution of the equations that they were interested in. Computation was the result of an ongoing interaction. Essentially, the analogue 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, analogue models faithfully represented reality. As a contemporary text book describes:

> 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.[28]

Of course, it is not just analogue 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

[25] Macnee (1949) p. 1315.

[26] MacKay (1949). Mackay's work is discussed further in Sect. 5.4, p. 111, below.

[27] See Chap. 6, below.

[28] Fifer (1961) vol. I, pp. 2–3.

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.[29]

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.[30] In essence, the modeller invests in a particular modelling paradigm to the point that the representation becomes a significant shaping-factor in their own natural outlook. For those who used analogue computers, analogues appeared the 'best' way. Whether by analogue 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 analogue computing, many users found the models they created to be inherently more flexible and trustworthy than those created on digital machines.[31] 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 analogue 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.

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[29]Galison (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.

[30]She 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'.

[31]Many such concerns related to familiarity, an issue explored with reference to aeronautical engineering in Chap. 7.

> 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.[32]

Individual experiment with the analogue 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 analogue computer can assist with 'gaining knowledge of the economy through the mind's eye'. Once a user was satisfied that the analogue's properties corresponded to their experience of the world, experiences of the referent and the analogue began to merge.[33]

3.3.2 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.[34] 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-interpreted 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

[32]Karplus 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).

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

[34]Rheingold (2000).

> or batch processing. You would want modeling—an exotic new use for computers that the aircraft designers were then pioneering.[35]

Note that modelling is Rheingold's choice of word, and this language highlights how different the modelling application must have appeared. Other commentaries note this distinction. For instance, in their history of computing Campbell-Kelly and Aspray suggest that interactive computing, time-sharing, and the personal computer belonged to a distinct strand of computer history: a strand notably different from batch processing systems.[36] When we consider the use and application of the modern personal computer, it becomes clear that the modern culture of computing has a far greater affinity to this modelling culture than to that of bulk data processing.

Further support for a modelling perspective is found in the work of David Mindell. In *Between Human and Machine*, he describes the development of cybernetics in terms of the history of control systems and analogue computing.[37] Moving away from data processing, Mindell's analysis emphasises 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.'[38] 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, rearing their heads as two distinct technologies: the network analyser (modelling), and the differential analyser (equation solving).[39]

Mindell's work is an important reminder that alternative narratives of computer history offer new insights into the limitations of current understanding.[40] He suggests 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, machine representation, . . . , the importance of training, the evolution of user interfaces, the creation of the human operator.[41]

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[35]Rheingold (2000) p. 135. © MIT Press. Reprinted with permission.

[36]See Campbell-Kelly and Aspray (1996) p. 185.

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

[38]Mindell (2002) p. 10.

[39]These 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, 1936).

[40]Mindell (2002) p. 10, Owens (2003) p. 843.

[41]Mindell (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 Sect. 1.3, p. 12, above.

The modelling focus emphasised in this book 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 analogue computing enabled rich mappings between machine representation and the world. Mindell described how engineers like Harold Hazen saw analogue 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.[42]

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, analogue 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 analogue computing in terms of alternatives.[43] By shifting the perspective from information processing to a narrative that incorporates modelling, we start to see the true benefits and deficiencies of analogue technology as it was understood in context.

3.4 Analogue Computing as a Technology of Modelling

Many computing applications belong to a family of modelling technology, and it is clear that analogue 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 analogue computing. Looking back, the centrality of modelling as an application of analogue is clear. However, what did analogue users understand by modelling and simulation?

In his account of George Philbrick's ACA[44] simulator, Holst (1982) claims that the terms 'modelling' and 'simulation' as used by Philbrick were relatively new. In particular, he suggests that the association of the word 'model' with electronic artefacts was a new technical concept.[45] While Holst's etymology might not be

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[42] Mindell (2002) p. 163.

[43] See Small (1994, 2001).

[44] See Sect. 2.4.2.3, p. 46, above.

[45] Holst 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

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.[46]

This idea of incompleteness resonates with the idea of computer-based experimentation. Computers were not just for well thought out activities, 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 analogue computers could be understood in terms of two kinds of electronic model: 'analyzers' and 'synthesizers'.[47] Over a number of years he came to realise that his use of analogue 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.[48]

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 book on computing published in 1970, Stuart Hollingdale and Geoffrey Toothill described computing as being either 'equation solving' or 'simulation'. Simulations involved an analogue computer and were a study where 'there is no need for mathematical manipulation… quantities having a direct physical interpretation.' Both of these authors had extensively used both types of computer. Interestingly, they

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 2010, Oxford University Press, Accessed 1st October 2006, http://dictionary.oed.com/cgi/entry/00313038.

[46]Holst (1982) p. 144 © 1982 IEEE.

[47]Many 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.

[48]Philbrick (1972b) p. 108.

describe a number of concerns regarding the use of the (digital) equation solvers. These were that this class of computer required greater human effort, and that when employing an equation solving approach: there were risks of 'introducing unwarranted assumptions' or, perhaps worse, 'overlooking important secondary aspects of the system'. So we see that even in 1970, digital methods were not always seen to be as reliable or trustworthy as the results derived from an analogue model.[49]

In offering tools for both modelling and calculation, analogue computers brought analysis and synthesis together. This is the 'philosophical' version of the technological story proposed in Chap. 2. There we saw a technical entwinement of two types of machine to establish 'analogue' 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.

3.5 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.

Analogue 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 analogue, 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 analogue computers. When Rheingold described modelling as an 'exotic new use', what was 'exotic' was the application of digital computing in this domain.[50] To 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

[49] See Hollingdale and Toothill (1970) pp. 80–81.

[50] One 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 analogue electrolytic tanks. The application of digital computing to replace these techniques was certainly a novel use of technology.

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 process began quite early on, analogue continued to be used in certain applications. For basic calculation tasks, the digital computer quickly overtook the analogue. 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 faster at equation solving, well-suited to data processing and possible to time-share. However, it was not always the tool of choice for modelling and in certain respects analogue was superior. Digitalisation progressed, partly due to digital's superiority in key application domains and also due to the perception that where it was deficient, it would soon catch up. Part II of this book will discuss what happened during that catch up.

Chapter 4
Origins of Analogue: Conceptual Association and Entanglement

Analogue computing derives its name from 'analogy' and before the phrase 'analogue computing' was first coined, the pre-existing technologies were called 'electrical analogies' or 'electrical analogues'. Previous chapters have discussed how the concept of an 'analogue computer' was born around 1940 with the merging of two themes: continuous computing (a theme of calculating and processing), and electrical analogy (a theme of modelling). However, we have not considered what we mean by 'electrical analogy' or where this terminology came from. While Chap. 2 focused on machines and the development of technology, the following pages will explore the development of analogue ideas and practice, investigating when it became commonplace for scientists and engineers to model real-world situations as electrical systems. This chapter is about the history of a concept: the concept of 'electrical analogy'. We will see how, as the use of successive types of analogy became established practice, a discipline of analogue computing began to form.

When discussing the evolution of this modelling culture, it is helpful to remember that the analogy between physical systems and electrical systems is a two way relationship: either can mimic the other. However, when this analogy is used as a modelling technique, the analogy generally has a direction. One side of the analogy is the *referent*—the system under study—and the other is the model or representation of that referent. The referent is the unknown domain, and the model is the known. The history of science provides examples of both directions: physical models of electrical systems and electrical models of physical systems.

This chapter proposes that the history of analogue computing evolved through a number of stages of use. The story begins in the late nineteenth century with the popular use of mechanical analogies to model electrical referents. This use, which we shall call the 'forward analogy', inspired a second type of analogy: the use of electrical analogies to model mechanical systems (establishing a 'reverse analogy'). During the early decades of the twentieth century, this process of modelling by electrical analogy gained widespread acceptance. As a result, it became common to describe a model based on electrical analogy as an 'electrical analogue'. The final stage of evolution was the alignment of the practice of electrical analogy with the emerging technology of computing. This saw a shift in jargon: the name 'analogue

C. Care, *Technology for Modelling,* History of Computing,
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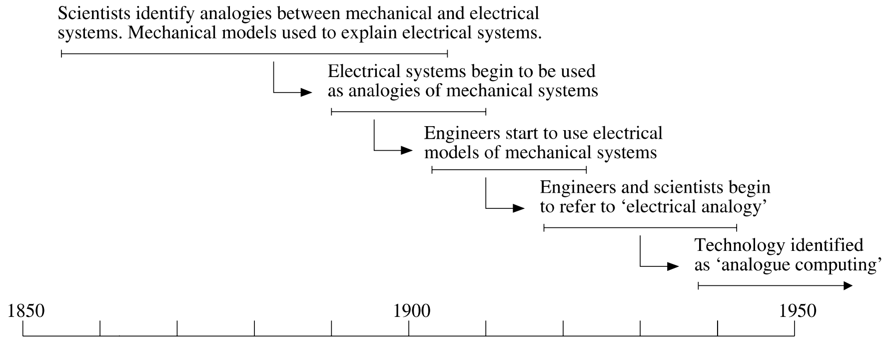

Fig. 4.1 Successive stages in the evolution of electrical analogy. This rough time line shows how different terminology and concepts stabilised

computer' replacing 'electrical analogue'. These stages provide a rough framework for explaining how there came to be an 'analogue' class of technology that was distinct from digital. Illustrated in Fig. 4.1, they show how the non-computational methodology of electrical analogy became *enrolled* into computing culture.

Once enrolled into the discourse of computing, the discipline of 'analogue computing' began to stabilise. As a result of this new-found stability, textbooks started to be published on analogue computing, analogue computing was incorporated into the syllabus of university courses, companies marketed analogue computers, and user groups began to form. However, the stability was short lived. Within a couple of decades, many applications of analogue computing had begun to dry up, giving way to the 'superior' technology of digital. However, although digital became the dominant technology, it was not always perceived as superior in every respect. For applications that did not immediately shift to digital, the technology began to be redefined. These applications once again became non-computational experimental set-ups, effectively dis-enrolling their users from the wider computing community.

4.1 The Establishment of 'Forward Analogy': Historical Influences from Electrical Theory

Before we can discuss the history of electrical analogy and its role in the history of analogue computing, we need to understand the modelling culture that preceded it. The use of models and analogies in science has a long and interesting history. For nineteenth century scientists (or natural philosophers, as they were then called), the modelling technique of analogy-making had a well established scientific pedigree. Central to this heritage was the development of so-called 'mechanical models', mental constructions that were popular in nineteenth century British physics. Lord Kelvin, for instance, was famous for having put great value in the use of models for developing scientific theories. Mary Hesse was one of the first modern philosophers to seriously investigate the history of scientific models. She notes how Kelvin had employed the ideas of heat flow, an established theory, to model the field theory of electrostatics. The key role of mechanical analogies was to explain the unknown in terms of the known. Other examples include the billiard-ball models of gases, and the 'model of gravitating particles' which was 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.'[1]

As an example of this 'culture of analogy', the following quotations from Kelvin's *Lectures on Molecular Dynamics*[2] 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:[3]

> 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 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.[4]

> 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.[5]

Throughout the late nineteenth century, the analogy drawn between an (unknown) electrical system and a (better known) mechanical system was a common way to explain electrical theory. Moving into the early decades of the twentieth century, these analogies were central in engineering education. Much was written on

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[1]Hesse (1970) pp. 22–23. For the wider story of scientific models, Hesse (1963) gives a full account of the use of analogies and models in the history of science.

[2]The 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).

[3]Equating 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) pp. 71–72.

[4]William Thomson, *The Baltimore Lectures*, Lecture 11 (Thomson 1884, p. 111).

[5]William Thomson, *The Baltimore Lectures*, Lecture 20 (Thomson 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 analogue computing the conceptual heritage of what they were doing. This was true for researchers working on electrolytic tanks.

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 principles'. This series ran for 19 weeks and covered a whole range of set-ups from simple analogues of current flow to models of electrical capacitance and resonance.[6]

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 the new kind of analogy: reversing the familiar relationship between electrical and mechanical systems, and applying electrical systems to aid the investigation of mechanical systems.

4.2 Modelling with Electricity: Early Use of a Reverse Analogy

If we consider the kind of analogies that underpin both the practice and heritage of analogue computing, we must focus on a turning point that came about around the turn of the century. This turning point hinged on the idea of using electrical state to model aspects of the world.

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, something that developed significantly around 1900. For example, in the eleventh edition of the *Encyclopaedia Britannica* (published 1911), Ludwig Boltzman[7] referred to this 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.[8]

Although such analogies were already familiar to scientists, it was not until around 1920 that engineers began to make clear reference to the reverse analogy as part of their analytical tool kit. It was within the context of engineering practice that applications of electrical analogy became established and stabilised.

Many of the analogue computers that had the largest impact on the history of computing originated in the United States. It is therefore important to consider how

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[6] Anon. (1926).

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

[8] Boltzmann (1911) p. 640.

the use of electrical analogies developed within the American scientific scene. To get a handle on the scientific mood of early twentieth century America, a useful source is the pages of the *Journal of the Franklin Institute*, a journal that published developments in applied science and engineering. By analysing the scientific papers published in this journal, we can take a cross-section through the scientific mood of those early decades of the twentieth century.

In terms of the use and application of electrical analogies, one noteworthy paper is a 1908 article by Edwin Northrup, an American physicist and inventor of electrical instruments.[9] Mirroring contemporary usage of models, Northrup's analogies were more educational than computational.

Northrup's discussion of electrical 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 '$\Omega =$ *Mass of Particle*')[10] and tabulated the mappings of different analogies. 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 household'.

> [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.[11]

Just like Kelvin, Northrup's principal use of analogies was to use the known phenomena to illustrate and model 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.

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[9] A 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 D.Sc. See Northrup (1895), Amherst College (1951) p. 73, Northrup (1912) preface, IEEE (2007), Northrup (1937).

[10] Northrup (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.

[11] Northrup (1908) pp. 2–3.

4.2.1 Clifford Nickle and Vannevar Bush: Modelling with the Reverse Analogy

The early uptake of electrical analogy as a modelling medium came from American engineers. Perhaps this explains why analogue computing became such an important tool for this community. Salient amongst the famous engineers of this period is Vannevar Bush, from whose research programmes the network analyser and differential analyser—both archetypal analogue computers—would emerge. As a student, Bush attended Tuft's college, a school that placed particular importance on graphical representation and inexact methods, rather than solely on abstract mathematical ones.[12] 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 mechanised computing, or 'instrumental analysis' as he called it. This blend of the empirical and mathematical was embedded into the research culture he directed at MIT.

Around 1920, the analogue culture began to crystallise and Bush was at the centre of this. Before he went to MIT, he published an early example of his approach in an investigation on gimbal stabilisation. His technique used an electrical system whose formulae were, for Bush, '…much more convenient' than those for the mechanical problem. The published paper included equivalence tables like those used by Northrup, and presented analogies with a mixture of diagrams and text.[13] 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.[14]

4.2.2 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.[15] Within General

[12]Small (2001) p. 40.

[13]In his analysis, Bush derived his analogies 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.

[14]See Nickle (1925).

[15]Bewley (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

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 generalisations 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...
>
> [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.[16]

As part of this experimentalist culture, Nickle employed a variety of problem solving techniques and understood their limitations. In particular, he argued that existing graphical approaches for solving the complex mathematics of power systems were reaching their limits.[17] 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.'[18] This seminal work presented an extensive set of example 'equivalence circuits', each modelling the different common classes of system. With these examples, Nickle was making the clear claim that electrical analogies could be used as a generic problem solving tool.[19] Following traditions in earlier work by Bush, his contribution was to claim that an analogy was 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'.[20]

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 formative period for modern engineering. In general, the discipline was becoming more and more quantitative. Within this climate,

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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).

[16] Bewley (1963) cited in Owen (1999) p. 12.

[17] He cites Bush and Booth (1925) as an example.

[18] Nickle (1925) p. 854.

[19] See 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 Bush or Pérès (1938) confirm its significance.

[20] Nickle (1925) p. 844.

Nickle's publication carved out a space for analogue methods and, within a few years, the key-phrase 'electrical analogue' would emerge. An embryonic form of analogue computing, Nickle's work shows how engineers were starting to use electrical circuits as a generic modelling medium. This approach was quickly adopted, and during the 1930s the use of electrical analogies became abundant in many areas of engineering research and the terminology of 'electrical analogy' began to expand into new domains.

One example of the expansion of analogy methods can be found in the field of sound and vibration research. Within this domain, the use of electrical models was well established, but these methods were rarely referred to with common language. However, 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 writer claimed that the design of the gramophone 'owe[d] much to the theory derived from analogies between mechanical and electrical systems'.[21] 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.[22]

We can see that the terminology of '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 evolved from scattered research pursuits into an enclosed discipline. Perhaps the best example of this stabilisation was the name chosen for the research laboratory established by Pérès and Malavard in 1932. Based within the University of Paris, they named their new department *Le Laboratoire des Analogies Electriques*.[23] Engineers could now refer to an 'electrical analogy' as a concrete technique of investigation. For example, in 1939, a researcher submitted an M.Sc. thesis in engineering to the University of London entitled: *A method of finding frequencies of torsional vibration using an electrical analogy*. His thesis was a collection of various investigations using analogous circuits.[24]

By the late 1930s, the use of electrical models to represent physical systems was well established. This initiated the process which would lead to the formation of 'analogue computing' around 1940. As enclosure progressed, the discipline gathered momentum, actively enrolling scattered disparate research programmes into the discipline of electrical analogy.

[21] See Whitaker (1928) p. 41.

[22] Oliver (1930) p. 318.

[23] Malavard (1947) p. 247. See Sect. 2.4.2.2, p. 44, above.

[24] Bailey (1939).

4.2.3 Stabilising the Field: Bush's Classification Schemes and Their Enrolling Function

While pioneers such as Nickle had established the use of analogy as a generic problem solving tool, it was Vannevar Bush who really started to make the connections that would result in these techniques becoming associated with computing technology. Working at MIT, Bush had built the differential analyser, but he was also enthusiastic about developing models based on electrical analogy. Historian Atsushi Akera notes how Bush had realised that after the success of the differential analyser, computing machines could become research programmes in their own right. As a result, both electrical analogy and equation-solving became part of this new discipline.[25] Through several high profile publications during the 1930s, Bush began describing electrical analogy as a tool for generic problem solving. It was in these papers that Bush heralded Nickle's work as seminal.

By 1934, Bush was articulating a clear idea of electrical analogy. Although he did not use the phrase 'computing', he explained that there were three 'principal methods' to approaching problem solving: mathematical investigation, physical modelling (he gave the example of a shaking table); and thirdly 'an analogous electrical circuit.'[26] 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 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.[27]

The following year, Bush was invited to deliver the American Mathematical Society's Josiah William Gibbs Lecture. A prestigious annual lecture (the previous one had been given by Albert Einstein), the focus of the event was always on the applications of mathematics.[28] In his lecture, Bush explored the idea of what he called 'instrumental analysis'. Although he did not use the phrase 'computing', he was effectively defining a taxonomy of computational aids. His categories (see Fig. 4.2)

[25] See Akera (2007) pp. 30–33.

[26] See Bush (1934) p. 289–291.

[27] Bush (1935) p. 6.

[28] Anon. (2007).

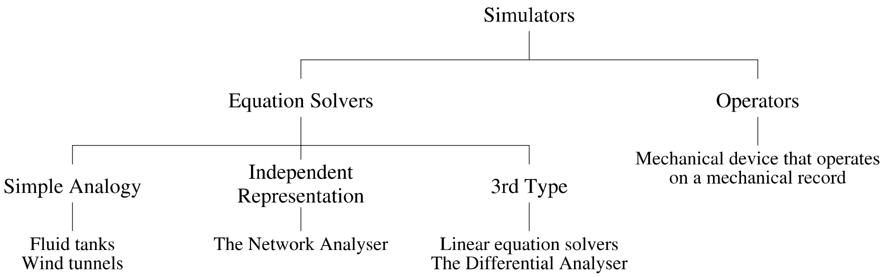

Fig. 4.2 Bush's classification of 'instrumental analysis'. The closest mapping to digital computers are Bush's operators. These were information processing machines that stored data on mechanical records such as punched cards. Within his equation solving class Bush identified that either a very direct analogy was employed—such as a scale model in a wind tunnel—or, alternatively, that an analogy based on a completely different type of media be used. His 'independent representation' class therefore maps closely to direct analogue computing. The third type of equation solver (which Bush did not actually name) used the most abstract analogies and covered what would later become known as indirect analogues: machines that facilitated the solution of an equation. When Bush was writing, there were no digital machines available for equation solving. What he is essentially describing is a separation of calculation and modelling technologies from the information processing machines

give us a real insight into how a pioneer of computing perceived the structure of the discipline.[29] Bush's taxonomy was based on analogy rather than continuity. However for the American physicist John Atanasoff, these two facets of analogue became entwined and conflated.[30] 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 pursuing the development of generic analogues. For instance, Myron Pawley, a faculty member of the Colorado School of Mines, aimed to establish generic analogies. His work suggested a notation for representing the analogies between generic systems of mechanical components and networks of electrical components. Behind 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.[31]

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[29] See Bush (1936).

[30] Recall that in 1941, Mauchly would attribute his analogue-impulse distinction of computer technology to Atanasoff. Following Atanasoff's classification, Mauchly concluded that an analogue 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).

[31] See Pawley (1937).

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 published in the late-1940s described a resistance-network model not as an analogue or analogy but instead as an 'electrical equivalent.'[32] 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 triggered a re-labelling of the older technologies. As described in Chap. 2, it was in the context of the ENIAC's unveiling in 1946 that Douglas Hartree would first refer to analogue and digital (Hartree 1946, p. 500). With the subsequent completion of the EDSAC in 1947, the EDVAC in 1949, and the publication of early monographs, the analogue–digital classification became foundational terminology.[33]

4.2.4 Positive Association with Computing and Computational Rhetoric

The adoption of the label 'analogue computing' created a technical class into which other technologies could be enrolled. One example of this is the Bruce reservoir analyser (described in Chap. 6). When William A. Bruce, an American physicist, first developed this analyser in 1943, he described it as an 'electrical counterpart'.[34] It was only after successive analysers had been invented and associated with analogue computing that the Bruce analyser was labelled an electrical analogue and later an analogue computer.[35] A history of petroleum engineering written in 1961 described the Bruce analyser as an analogue 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, analogue computing projects benefited from being part of the 'computer age'. For a number of reasons, ranging from funding to marketing issues, a whole variety of devices started to be labelled 'computers'. As a result, there are a number of technologies that are analogue by association rather than through being inherently analogue. Two such 'analogue oddities' are the Phillips machine and the Jerie computer.

[32] Hughes and Wilson (1947), p. 103.

[33] See Hartree (1947, 1949), Murray (1948).

[34] See Bruce (1947/1943) col. 2.

[35] Patents for subsequent analysers described the technology as an electrical analogue—see Aronofsky (1958/1951), Loofbourrow et al. (1957/1952). By the 1950s reservoir analysers were routinely being classed as analogue computers (Montague et al. 1956, p. 12). When Birks, a BP reservoir engineer, summarised the development of reservoir analysers he introduced them as analogue computers. See Sect. 6.2, p. 132, below.

These technologies were quite different from other mainstream analogue 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 analogue computing can seem a little loose. However, both were identified by contemporary actors as analogue computers, so these devices are analogue by association.

Like many of the analogue 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.[36] 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. Although it is frequently cited as an analogue computer, recent scholarship has questioned whether this is really a computer in a general sense. But since the machine was understood as a 'computer' in context, it should be considered part of computer history. The real purpose of this invention was to produce an illustrative model of Keynesian economics. This is a clear example of computing being broader than purely calculation.[37]

Another illustration of the broad spread of technology that became labelled a 'computer' is an analogue device developed for photogrammetry 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 '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 Fig. 4.3) was patented by the ITC and was marketed and manufactured with reasonable success.[38]

4.3 Formation of an Analogue User Culture

So far we have described the evolution of analogue computing's surrounding culture. Initially, there was no core identity surrounding the devices which later became members of analogue computing's technological frame. There was a disparate group of calculation and modelling devices, and the two identities of analogy and continuity co-existed. In his theory of invention, historian Wiebe Bijker noted that

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[36] Phillips (2000), Morgan and Boumans (2004), and Hally (2005) pp. 185–205.

[37] 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).

[38] Jerie (1957–1958, 1960/1958, 1965/1960), ITC News (2001).

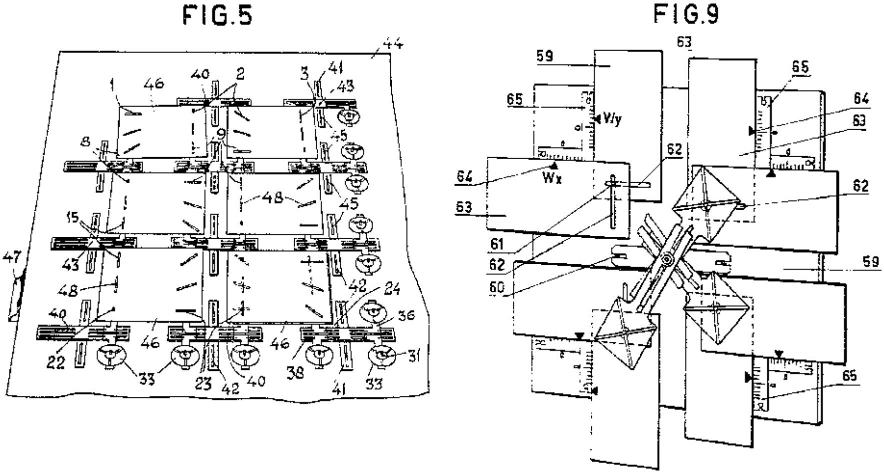

Fig. 4.3 Illustrations of the Jerie Analogue Computer. Source: Jerie (1960/1958). The Jerie computer used a mechanical design in which the unknowns of the equations were represented by elastic links between plates (see also Jerie 1965/1960). The various aerial photographs were transferred on to overlapping 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

innovation in this type of situation is often ‘radical redefinition’ (anything is open to change because there is no central identity restricting classification).[39]

In the period between 1910 and 1930 we see that the variety of approaches began to cluster together. This period began 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 analogue faced little competition.[40]

However, with the emergence of digital technologies, there became a need to identify analogue computing as something distinct and different from the rest of the field. Thus, around 1940, a period of analogue and digital computing was established. In this phase, there emerged two types of computing, each with various merits that (in a certain sense) were portrayed as competing technological solutions. This third phase explains why historians often choose to frame the history of post-war analogue computing with the controversies between analogue and digital. It is all to easy, with hindsight, to talk about digital being the obvious successor to analogue technology. 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 analogue’s identity.

[39]Bijker (1992).

[40]Mindell (2002) p. 231.

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 analogue computers started to be manufactured commercially, creating a new community of analogue users.[41] To understand what this analogue culture looked like, textbooks and technical newsletters offer some interesting insights. One interesting user community existed around GAP/R and their trade publication *The Lightning Empiricist* (published aperiodically between 1952 and 1971).

4.3.1 George Philbrick and Lightning Empiricism: An Exemplar of Analogue 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 'Analogs Yesterday, Today and Tomorrow or: Metaphors of the Continuum', was originally published in a trade journal named *The Lightning Empiricist*.[42] 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'.[43] This sentiment is echoed in other writings.[44]

Philbrick's technical career had its origins in the simulation and control culture of the Foxboro Corporation where he had simulated mathematically complex systems

[41] A useful indicator of the developing analogue culture is the emergence of textbooks which began to appear around 1950. Popular early texts on analogue computing included Korn and Korn (1956), Johnson (1956), and Soroka (1956). Michael E. Fisher, an analogue 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 analogue 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 analogue 'program' could be easily transferred between different types of machine.

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

[43] Williams (1994) p. 1.

[44] Holst (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. 2002). 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/.

with causal feedback loops. This background meant that Philbrick was an advocate of high-speed analogue 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'.[45]

Perhaps most significant were Philbrick's (often rhetorical) writings describing his perspective on the relationship between modelling, computing, and simulation. Philbrick and his colleagues coined the term *Lightning Empiricism* to convey the rapid experimental 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'.[46] The first issue was dated June 1952 and distributed free of charged 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).[47]

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.[48]

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 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

[45]Philbrick 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 analogue 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).

[46]Frontmatter. *The Lightning Empiricist*, 1(1), 1952.

[47]Anon. (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.

[48]Philbrick (1969) p. 24.

> 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.[49]

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.[50]

> ...the point is that models and analog procedures generally can add inspiration 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.[51]

Just as Bush's writing shows the importance of the modelling culture within 1930s engineering, Philbrick's essays provide a handle on analogue 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 analogue 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'.[52]

> 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*

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[49] Philbrick (1963).

[50] Philbrick (1969) p. 24.

[51] Philbrick (1969) p. 22.

[52] *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, 1963c).

> things may be permitted to be. Rather than being flippant, as this last remark may 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.[53]

Through these publications we can trace an ongoing analogue rhetoric comparing the beautiful, sophisticated and elegant analogue 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 analogue 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 analogue use, but also the surrounding technical culture.

4.4 Simulation Culture and the Transition to Digital

We have seen how once analogue computing had become established, communities and user groups began to cluster its use and application. One of the more influential of these was the community established by John McLeod. In 1952 McLeod formed the 'Simulation Councils' and with his wife began publishing a monthly newsletter. The newsletter became popular amongst the developing discipline of simulation. The original members of this community were engineers who were using both analogue and digital computers to undertake iterative experimentation and modelling. After a number of years, the newsletter evolved into a regular section of the journal *Instruments and Automation*, and the original name—Simulation Councils Inc.—was re-branded as the Society for Computer Simulations International (CSCI). In turn, CSCI began publishing the respected journal *Simulation*. If McLeod is to be thought of as a founding father of the discipline of simulation, then he should also be considered an important pioneer in the history of computing application.

The Simulation Councils were an application driven community. When first established the members chose the name 'simulation' in order to disassociate the community from one particular technology. Throughout their early newsletters, the community clearly viewed both analogue and digital as complementary tools. Different computers were suited to different modelling situations. 'If you have a choice, use the best tool for the job; if you have no choice, use what you can—but simulate!' wrote McLeod in 1968.[54]

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[53] Philbrick (1969) p. 16.

[54] McLeod (1968) p. 8.

The community explored a vast territory of model construction, mapping out different applications and the techniques most suited to them. Because simulation was an activity rather than a technology, they were quick to try out newer, digital, techniques when appropriate. One of the important developments was the introduction of analogue-simulation software, programming languages that offered an analogue quality, or allowed programmers to think in an analogue way. This tradition can still be seen in the two modern practices of discrete event simulation and continuous simulation. Although digital, many of the approaches behind simulation languages were inspired by the practices of analogue computing.

4.4.1 Digital Languages for Simulating Analogue Computing

The realisation that digital would eventually out-perform analogue was widely accepted from the early 1950s. However, it was not always very clear what form the digital computer would take: the kind of machinery, its size and mode of operation, its design, its interface and its programming language. The users of computing wanted to blend the different benefits of analogue and digital computing. Some of these users turned to hybrid technology, building machines that combined both types of hardware. Others turned to digital computers but tried to recreate analogue qualities.

One such development was the invention of analogue simulation programs.[55] These ran on a digital computer, but provided an analogue interface where problems could be managed using the functional blocks, integrators, summers and scalers familiar to other analogue computer users. For two contemporary commentators, this kind of program was in this same tradition as FORTRAN and ALGOL since these were all part of 'a host of problem-oriented languages for specific applications.'[56] These were languages that allowed an engineer to program in a 'computer language closely allied to the language of his own field.'[57] The first published program of this kind was presented in a paper at the 1955 Western Joint Computer Conference, by Dr. R.G. Selfridge, a researcher at the US Naval Ordnance Test Station (USNOTS) at Inyokern, California. At the station Selfridge had access to a REAC (Reeves Electronic Analog Computer) and an IBM 701. The motivation behind creating the software was to enable problems designed for the REAC to be run on the 701, enabling both greater accuracy and also the solution of more complex problems. The underpinning integrating algorithm was Simpson's Rule. Although this implementation was still relatively unsophisticated, Selfridge concluded his 1955 paper with the statement that 'many of the problems run at present [on an analogue] could be transferred, with advantage, to digital computers.'[58]

[55]The inclusion of these languages in the ACM computing curriculum was discussed in Sect. 2.5.3, p. 54, above.

[56]Brennan and Linebarger (1964).

[57]Brennan and Linebarger (1964).

[58]Selfridge (1955).

The next published development originated from work at the California Institute of Technology's Jet Propulsion Laboratory. This system was named DEPI—an acronym for Differential Equations Pseudo-code Interpreter—and was developed by H. Fred Lesh. Lesh's approach was driven by a different motivation to Selfridge's work. Reflecting on the early developments of analogue languages, Brennan and Linebarger (1964) noted that while Selfridge had been motivated by the 'inadequacy of his analog facility for large problems', Lesh was more interested in giving digital computing an analogue feel. Wanting to simplify the 'then burgeoning' complexities of writing digital programs, DEPI allowed its user to program using the standard components of analogue computing.[59]

Although DEPI introduced a computational overhead that resulted in prolonged run-times, it did provide a tool that was easier to program. Brennan and Linebarger stated that 'a real saving resulted from its programming ease and operational flexibility.'[60] Because these programs were essentially modelling an analogue computer on digital hardware, there were many choices to be made surrounding the extent to which realism was maintained. For example, in the ASTRAL translator—developed by Convair Astronautics in 1958—analogue computer problems were translated to digital code that mimicked the hardware of a specific computer. This machine was Electronic Associates' PACE analogue computer, and in this software, the mapping was so close that even the negated outputs of individual components were preserved.[61]

Table 4.1 show some of the digital simulations based on analogue components. Of these, MIDAS is a particularly interesting example because it became a successful engineering tool for the aviation industry. The language was developed during three successive developments: the original version (MIDAS I) was developed by the Wright Patterson corporation and MIDAS II by North American Aviation. Both of these versions provided an interactive interpreter for analogue modelling. The final evolution—MIDAS III—developed by Convair, saw the technology become a 'pre-compiler', generating FORTRAN code from MIDAS input. This improved speed but the loss of an interactive interface meant that the tool became further removed from its analogue heritage.

4.5 Dis-enrollment of Analogue Computing and the Redefinition of Analogue Culture

The previous pages have described how analogue computing culture developed around the evolving concepts and practices of electrical analogy. This then led to the existence of two computing cultures, one analogue and one digital, and rhetorical

[59]Brennan and Linebarger (1964) p. 248.

[60]Brennan and Linebarger (1964) p. 248.

[61]On an electronic analogue computer, the output of an integrator or summer was negated as a consequence of the circuits employed to perform integration.

Table 4.1 Digital simulation languages using analogue techniques. These systems allowed problems to be specified using the common building blocks of analogue computing (integrators, summers and multipliers) even though the solutions were derived by numerical methods

Date	System/Inventor	Institution
1955	Selfridge's program for an IBM 701	US Naval Ordnance Test Station
1957	DEPI (Digital Equations Pseudo-code Interpreter)	California Institute of Technology
1958	ASTRAL (Analog Schematic Translator to Algebraic Language)	Convair Astronautics
1959	DEPI 4	
1961	DYSAC (Digitally Simulated Analog Computer)	
1962	PARTNER (Proof of Analog Results Through a Numerical Equivalent Routine)	Honeywell, Aeronautical Division
1962	DAS (Digital Analog Simulator)	Martin Company
1963	JANIS	Bell Telephone Laboratories
1963	MIDAS (Modified Integration Digital Analog Simulator)	Wright-Patterson Air Force Base
1964	PACTOLUS simulator for the IBM 1620	IBM Research Laboratory, San Jose

battles between the two. This is a story of social construction. However, to explain what happened afterwards is to account for the social *deconstruction* of analogue computing: its dis-enrollment. As is well documented by history of computing literature, between 1950 and 1960 digital became the dominant technology. As a result analogue culture began to be dis-enrolled.

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

The translation into electrical engineering created new sub-disciplines of 'analogue electronics' and 'analogue control' and analogue 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.[62] These were later independently enrolled into the digital computing frame.

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

This chapter emphasised that analogue computing is broader than its technology, theory, or practice. Development of technology and theories about that technology do not develop in a vacuum. Instead they 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 analogue 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 the 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.[63] On the desk sits an oscilloscope, and alongside sits a label, jokingly bearing the words 'Analog CAD', a pun implying that the technology is the analogue equivalent of modern Computer Aided Design (CAD) software. The tinkering spirit, the hands on 'engineering feel', and the rhetoric of the 1950s analogue culture still exist today: the difference is that the discipline has been redefined. No longer computational, the modelling culture of analogue computing evolved into the design culture of analogue electronics.

[62] An example is the application of electrical analogues to hydroscience. During the 1960s, modelling ground water systems was a well-known application of resistance networks and other electrical circuits. Analogue techniques continued to be significant modelling tools in this domain, but their users stopped referring to these set-ups as 'computers'. A technology that had previously been computational had returned to being a physical model. See Prickett (1975) for examples of non-computational analogue computing—what he calls 'electrical models'.

[63] See the cover images of Williams (1994).

Part II
Analogue Computing in Use: A Selection of Contexts

Chapter 5
Analogue Computers in British Higher Education

The previous chapters have argued that in order to fully understand analogue computing, we must consider the different ways that the technology has been used. In particular, the history of analogue computing must account for the computer as both a calculation and modelling tool. This chapter discusses the history of analogue computing within the context of British higher education. Through this case study we see how analogue computing was used for a whole variety of applications and how each of these modes of use has its own history. In terms of the relationship between analogue and digital, this chapter also investigates how analogue computers were funded. We will see that users of analogue computers had to compete with those of digital for grants from the same funding sources. We will also discuss the implications that technological classification had on the funding of these machines.

The British education sector covers a broad range of institutions. During the 1950s and 1960s, the major users of analogue computing included both the traditional universities and also the colleges of advanced technology. Broadly speaking, scientific analogue computing research was the domain of the universities, whereas the research and teaching undertaken by the technical colleges was more aligned to industry. For example, at the Bristol College of Science and Technology (subsequently the University of Bath), the analogue computing laboratory had strong links with Rolls-Royce and ran an annual summer school to educate their new trainee engineers in analogue computing.

Much like the history of digital computing in higher education, analogue use falls into two periods: firstly a prototyping phase where analogue computers were developed in-house, followed by a second phase of commercialisation where analogues (now products rather than prototypes) were manufactured and sold to university departments. In his description of analogue computing at Manchester between 1956 and 1962, Derek Atherton recalls that the research machine, occupying 'around 400 square feet' of floor space, was developed in-house with a custom design even at component level. According to Atherton, this was mainly due to a lack of cheap commercial parts. The cheapest available amplifier (manufactured by GAP/R) cost

C. Care, *Technology for Modelling,* History of Computing,
DOI 10.1007/978-1-84882-948-0_5,

four times more than their own and 'was technically inferior'.[1] In-house development was standard practice for the first generation of electronic analogue computers built during the 1950s. However, by 1960, universities had begun to purchase their computers from a manufacturer. With this shift, analogue research focused less on innovating hardware and turned its attention towards developing techniques and applications for the commercial analogues.[2] Generally, university requirements were on a lower scale to industry, with computers being used to illustrate the principles of analogue modelling rather than simulating complex systems. Popular educational manufacturers were Solartron, EMI, and EAL, and a number of these companies also released smaller machines for classroom use.[3]

As well as a history of analogue innovation, there is an important story of analogue computing being used as a research tool in many institutions. The story of analogue computing presented by previous scholarship in the history of British computing hinges on the pre-war differential analysers at Manchester and Cambridge: machines that were replaced by early digital machines. However, analogue computing was widely used after 1950. As an indication of its popularity, Fig. 5.1 shows the growth of research projects using analogue computing between 1940 and 1979. We can see that there was significant activity in analogue use well into the 1970s. Figure 5.2 shows the top 10 institutions contributing to these statistics. When discussing the demise of analogue computing, it is key not to forget the ordinary, everyday use of this technology. Furthermore, many of the researchers used analogue technology to solve specific problems. As digital computers replaced analogue, many members of academic staff translated their skills in the language of the newer technology: analogue modelling expertise evolved into (digital) simulation skills. It is crucial for history to identify these common strands of 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 analogue devices during the 1930s.[4] As a result, most of the successful analogue installations were technologies 'imported' from American research.

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[1] Atherton (2005) p. 66.

[2] This pattern of use can be seen across the history of analogue computing. Small (2001) shows how companies and institutions progressed through three categories. These were 'developer/users', who constructed analogue 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 (p. 205).

[3] For instance, Solartron launched its 'Analogue Tutor' in 1957, EMI produced an educational version of the EMIAC II in 1965, and during the same period, a desktop version of the KAI PACE computer was marketed. See EMI (1965a) p. 9, Small (2001) pp. 189 and 202. The popularity of Solartron and EMI was due to the Ministry of Technology's 'buy British' policy (see p. 118, 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).

[4] Historian Mary Croarken notes that analogue 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 technology for

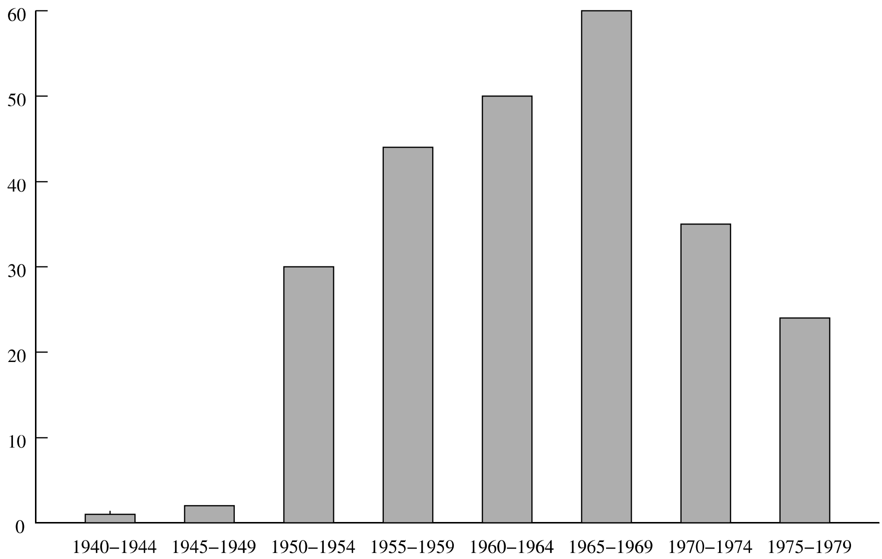

Fig. 5.1 Number of analogue research theses by year, 1940–1979. These include research into analogue hardware, applications, and also hybrid research. Data from before 1950 is sparse because it was only after 1946 that 'analogue computer' became common terminology. The graph concludes with 1979 as only 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)

One person who brought these computing concepts back to Britain was the Manchester applied mathematician Douglas Hartree. Hartree had, in a 1933 visit to MIT, used Bush's differential analyser as a research aid.[5] 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'), they developed a machine that had reasonable accuracy. In the following years, Hartree encouraged other academics to develop Meccano analysers[6] and the success of these home-grown calculating

its own sake. An exception to this was the electrical analogue devised by Mallock which inspired the later work on transformer analogues. See Sect. 2.4.2.1, p. 43, above.

[5]Croarken (1990) pp. 47–48 and 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 analogue–digital classification. See Sect. 2.5.1, p. 47, above.

[6]In 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 and 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

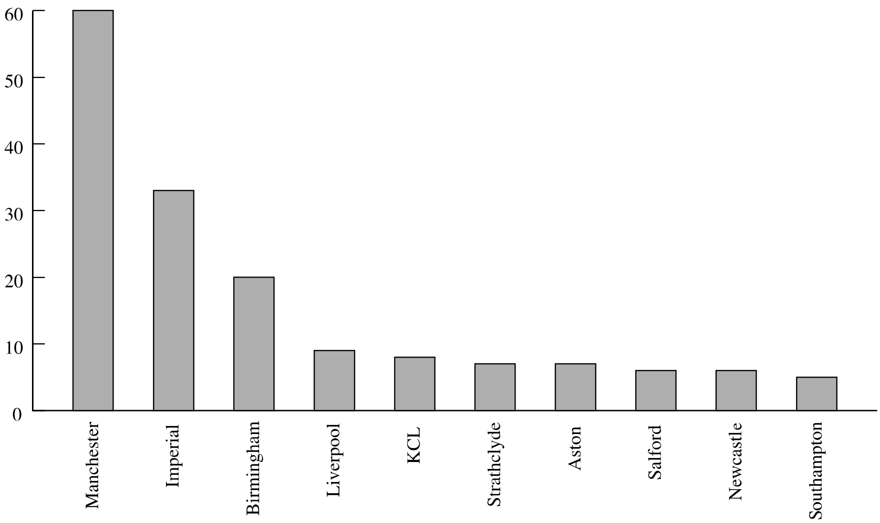

Fig. 5.2 Number of analogue research theses by institution, 1940–1979. (UMIST and Manchester are combined.) This chapter looks in depth at Manchester, Imperial, Birmingham, and King's College, London. These include research into analogue hardware, applications, and also hybrid research. These statistics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

machines motivated the manufacture and installation of full size copies at Manchester, Cambridge, and the National Physical Laboratory (NPL).[7] Interestingly, the same establishments would later become the three pioneering centres of the UK's development in stored program digital computers, initiating the replacement of analogue's use for calculation or equation solving.[8]

While applications for analogue 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 analogue computing within the Engineering Department at the University of Manchester, a department whose research programme in control systems would employ the analogue technology for many subsequent years. Because of this range of applications, the history of analogue computing in universities is really a history of three major themes: calculation, modelling, and control.

Belfast. See Robinson (2005) pp. 78–80, Croarken (1990) p. 51, Croarken (1992) p. 10, Bromley (1990) p. 184, Wood (1942) pp. 71–73.

[7]The 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.

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

5.1 Calculation, Modelling, or Control: Three Different Uses, Three Different Histories

University use of analogue computing was interdisciplinary, as the technology supported a whole spectrum of applications. An investigation of the abstracts of British theses published between 1950 and 1980 shows that there were at least 200 theses that made use of analogue techniques. Of these theses, 40% belonged to disciplines other than computing.[9] Applications of analogue computing ranged from studies in experimental psychology through to investigations by mechanical engineers. When grouped and classified, it becomes clear that these applications fall into three major categories. These themes of use are: calculation, modelling, and control. Calculation here refers to equation solving, and modelling to use of computers to build set-ups that modelled dynamic systems. Although closely related to modelling, the use of analogue computing for control relates more to the design and simulation of analogue controllers. In terms of the three-stranded chronology proposed in Chap. 2, applications in modelling and control were included within the second thematic strand. To take a well-known example of university computing: a *calculation* use of analogue computing corresponds to Douglas Hartree's activity during the early 1940s. Hartree made extensive use of differential analysers to solve the equations specific to his work as a physicist. Hartree represents the kind of user who had specific equation-driven problems to solve, and thus when digital computers became available, jumped on to the bandwagon of these 'even better' calculators.[10] Alternatively, a modelling use relates to the explorative modelling that technologists such as George Philbrick had advocated. Developing a complex, dynamic system—perhaps with a visual interface—was an application particularly suited to analogue. Thirdly, certain analogue computing components were used to simulate control systems.[11] These three uses actually represent different engineering practices and although there is a close relationship between the technologies of analogue modelling and control, the people engaged with these technologies belonged to quite different communities.

University applications of analogue computing can be clearly categorised into this threefold scheme of use. Furthermore, when viewed historically, each of these strands of use had its own trajectory and 'heyday' (as demonstrated by Fig. 5.3 and Fig. 5.4). For instance, applications in calculation dried up before those in modelling or simulation. However, most scholarship in the history of analogue computing has related to the use of analogue computing in calculation. This explains why the majority of previous narratives focus on the very early users of analogue computing such as Manchester or Cambridge. Because the Manchester Baby and the EDSAC

[9]Determined from analysis of data from the *Index to Theses* (Theses 2007). Prior to 1950, it is difficult to identify applications of analogue computing due to a lack of stabilised terminology.

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

[11]This book only touches on control systems, the interested reader is directed towards Mindell (2002) or Bennett (1979).

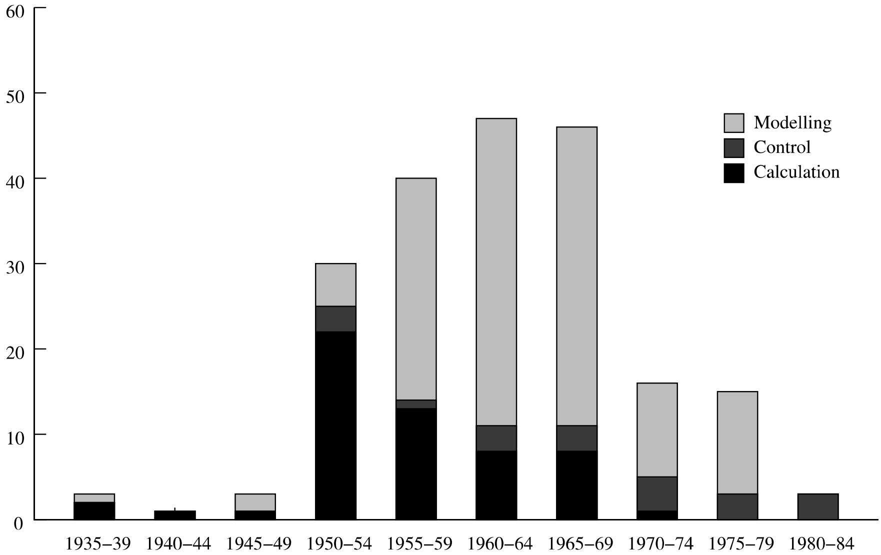

Fig. 5.3 British theses sub-divided by type of application. The graph clearly identifies a different 'heyday' for each type of application. Analogues for calculation were being replaced in the late 1960s, while there was significant application of analogues for modelling lasting into the late 1970s.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

machines led a rapid decline in the role of analogue 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 analogue controllers, and continued to install and maintain analogue (and later hybrid) computers for many subsequent years.[12]

While the differential analysers installed at Cambridge and Manchester remain the principal landmarks of analogue calculation, the post World War II developments of analogue computing are the landmarks of analogue modelling and control. Of the three uses, control appears to have been the most resistant to digitalisation. Analogue control systems were still in frequent use during in the 1970s.[13] Furthermore, even after the introduction of digital controllers, it was common for a controller's test rig to be an analogue computer model. The following sections outline the history of analogue computing as used for simulation and modelling at a number of key institutions. The most significant institutions were the two universities in Manchester, and Imperial College in London. Also of interest is King's College,

[12] Small 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).

[13] See, for instance, Bonnor (1997).

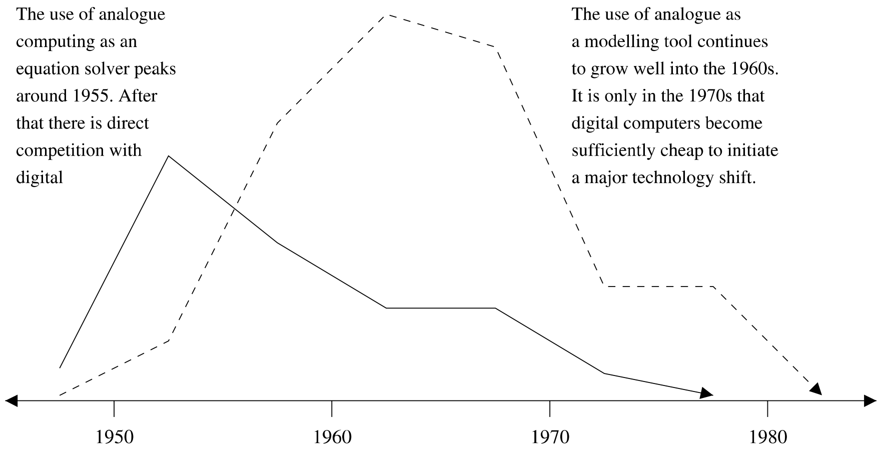

Fig. 5.4 The different historical trajectories of analogue calculation and analogue modelling based on the number of research theses to employ a particular type of use. The number of applications for calculation or equation solving is shown by the *solid line* and clearly peaks in the early 1950s before steadily declining over the following decades. When historians describe analogue computing as the precursor to digital this is the type of use they are referring to. However, the applications of analogue computing as a *modelling* tool (*dashed line*) follow quite a different trajectory. Initially there were few research projects creating analogue models, but this rose to a peak in the mid 1960s. This rise probably indicates that prior to 1950, this kind of use was not always understood to be *computing* and so any research activity was not enrolled into analogue culture. The decline after 1965 indicates the gradual replacement of analogue modelling with digital modelling. Both series show that the replacement of analogue applications with other technologies was a gradual process

London, which had a slightly smaller, but more focused research programme developing high-speed computing. Representing the perspective of a technical college, Sect. 5.6 discusses analogue use at the Bristol College of Science and Technology and highlights the importance of analogue teaching.

5.2 Analogue Research at Manchester: Networks, Tanks, and Hybrid Computing

Today, the University of Manchester is the largest UK university. The present institution was created as a result of a 2004 merger between the Victoria University of Manchester and the University of Manchester Institute of Science and Technology (or UMIST).[14] The engineers of the Victoria University are well-known in the history of computing. It was here, within the Department of Electrical Engineering,

[14]These 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).

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 analogue research. Compared to the Victoria University, UMIST (then called the Manchester College of Science and Technology) had a slightly more industrial focus, and analogue computers were in wide use. On the other hand, engineers at the Victoria University, already pioneers of digital calculation, were mainly using analogue computing for control engineering problems.[15]

At the College of Science and Technology, students were using analogue for a much broader range of problems. Their use covered all three themes: calculation, modelling, and control.[16] The major research focus was, however, the development of network analysers for simulation and modelling. Under the supervision of Eric Bradshaw and Colin Adamson, a number of projects investigated their application and developed bespoke hardware to extend them.[17] During the late 1950s, the department also developed transformer network analogues, machines similar to network analysers but utilising AC transformer windings to represent quantities.[18] Researchers were also developing electrolytic tanks. Within the Department of Mechanical Engineering, J.K. Royle and H. Naylor used them to investigate fluid flow in pipes.[19] 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. By 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) that reflected the real-time potentials in the tank. In the field mapper developed by Burtt under the supervision of J. Willis (in 1954), the display was

[15] At the Victoria University, the principal technology was general purpose (and so indirect) analogues. 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, even this should be understood as an example of normal application, rather than the development of generic analogue computing. See Potts (1953).

[16] For 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).

[17] See 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 (pp. iv–v). Prof. Bradshaw was an important character within the Electrical Engineering community. He had received a Ph.D. from the University of Glasgow, and was the founding editor of the *Bulletin of Electrical Engineering Education*. See Hartley (1998).

[18] In 1958 Salah El-Sobki, an Egyptian graduate student, submitted a Ph.D. thesis describing improvements and applications of a 'transformer analogue' computer. Inspired by the Mallock Machine, these transformer analogues were based on a generic analogue 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.

[19] See Naylor (1956).

updated 25 times a second.[20] The series of research projects undertaken within this context confirm that analogue 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 analogue–digital converters.[21] As well as investigating hybrid computing, the 1960s saw many researchers make the transition into new domains such as digital simulation. For instance, the lecturer Michael G. Hartley, who had previously taught analogue computing (and published *An introduction to electronic analogue computers*) would later supervise academic research into digital road traffic simulation.[22] This is indicative of how analogue computing culture evolved into the digital world. By redefining analogue computing expertise into simulation expertise, there was a continuity of practice.

5.3 Analogue 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.[23] Like Manchester, a particular research interest was the development of transformer analogues, research that resulted in a simpler design which was later manufactured commercially.[24] Alongside this work, A.J. Boothroyd and Edward Colin Cherry were developing electrolytic tanks, and using them to model electrical circuits.[25]

Jackson left Imperial in 1953 but research in analogue computing continued.[26] Many of the later studies involved some application of digital computing. For example Blackman (1957) developed an early hybrid computer in which an analogue

[20]See Burtt (1954), Burtt and Willis (1957).

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

[22]Hartley (1965), Saleeb (1964, 1967).

[23]This resulted in a number of Ph.D.s: Jackson supervised Abou-Hussein (1950), Boothroyd (1951), and Ismail (1955). Humphrey Davies, then a reader in this department, was also involved in this research and supervised Faragalla (1954).

[24]In 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.

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

[26]Jackson 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 where he worked for the rest of his life. See Brown (2004).

resistance network was combined with a digital computer. The digital circuits provided the storage and automated capture of analogue quantities while also facilitating the extraction of logarithms. Other studies were more comparative, for instance, one Ph.D. student investigated the relative merits between numerical methods, graphical approaches and electrolytic tanks for solving physical problems.[27] Network analysers continued to be researched as tools for modelling power system stability. In the early 1960s, the Department of Electrical Engineering collaborated with the Central Electricity Generating Board (CEGB) to investigate grid stability problems, Ph.D. researchers being jointly funded by the DSIR and the CEGB.[28] A table of Imperial theses is given in Table 5.1.

5.4 King's College London: Analogue Computing at 'Ultra-High Speed'

Analogue research at the University of London's King's College (see Table 5.2) was not on such a grand scale as at Manchester or Imperial, but is interesting because it focused on high speed analogue computing. Of particular significance was the research initiated by Donald MacKay (1922–1987) in the departments of Physics and Electrical Engineering.[29] MacKay had joined the physics Wheatstone Laboratory during the late 1940s and started building high speed analogue computers. MacKay spent the war years working on radar within the Admiralty Signals Establishment. It was during this wartime work that he became interested in computing circuits, particularly from their use in gun directors.[30]

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'. Combining both a deep understanding of information theory with a passion for physical experimentation, MacKay had the perfect background for analogue computing. For MacKay, the desire to maximise the information-theoretic capacity of a computer and also construct an experimental environment, led, quite naturally, to develop high speed analogue computing.[31] At the time, most analogue computers did not operate at

[27] See Kovattana (1961).

[28] See Short (1965), front-matter. In his study of network analysers, Short considered both analogue 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).

[29] King'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).

[30] See Anon. (1987), Hale (1945).

[31] MacKay (1950) p. 289.

Table 5.1 Analogue research dissertations at Imperial 1950–1979

Year	Researcher	Degree	Department	Supervisor	Technology
1950	M.S.M. Abou-Hussein	Ph.D.	Elect. Eng.	Willis Jackson	Resistance network
	An A.C. network analyser using transformers.				
1950	R. Makar	M.Sc.	Elect. Eng.	E. Colin Cherry	Electrolytic tank
	The use of an electrolytic tank in circuit analysis and synthesis.				
1951	A.R. Boothroyd	Ph.D.	Elect. Eng.	Willis Jackson	Electrolytic tank
	The electrolytic tank as an aid to electric network design and its application to filter synthesis.				
1952	J.N. Holmes	M.Sc.	Elect. Eng.	–	–
	The design and use of a correlation function computer for the analysis of speech waveforms.				
1952	S.L. Chen	M.Sc.	Elect. Eng.	–	–
	An harmonic analyser for non-linear circuit analysis.				
1952	J.H. Westcott	Ph.D.	Elect. Eng.	–	Resistance network
	The synthesis of electrical networks with particular reference to servo-mechanisms.				
1953	S.K. Ip	M.Sc.	Elect. Eng.	E. Colin Cherry	Electrolytic tank
	An electrolytic tank as an analogue computing machine for factorising high degree polynomials.				
1953	D. O'Kelly	M.Sc.	Elect. Eng.	–	Resistance network
	The development and application of a transformer analogue network analyser.				
1955	M.K.E. Ismail	Ph.D.	Elect. Eng.	Willis Jackson	Resistance network
	Development of the transformer analogue analyser and its application to electrical machines.				
1955	F.F. Faragalla	Ph.D.	Elect. Eng.	Humphrey Davies	Resistance network
	A synchronous machine analogue and its application to power system dynamical analysis.				
1956	C.P. Kuriakose	Ph.D.	Elect. Eng.	–	Resistance network
	Stability investigations with dynamic network analysers.				
1957	N.G. Davies	M.Sc.	Elect. Eng.	–	Resistance network
	A low frequency analogue multiplier.				
1957	P.F. Blackman	Ph.D.	Elect. Eng.	J.A. Westcott	Hybrid
	A computer combining analogue and digital principles to investigate network functions...				
1958	A.A. El-Shirbini	Ph.D.	Mech. Eng.	–	–
	Study of turbulent flames by electric analogue.				
1958	S. Saha	Ph.D.	Geophysics	–	–
	An experimental investigation of analogue methods for computing gravity and magnetic effects.				
1959	W.R. Atkins	M.Sc.	Elect. Eng.	–	–
	Pulse width modulation and analogue multiplication with transistor circuits.				
1960	T. Kovattana	Ph.D.	Elect. Eng.	J.R. Barker	Resistance network
	Networks of non-linear resistors and their application as analogues...				

Table 5.1 (Continued)

Year	Researcher	Degree	Department	Supervisor	Technology
1960	S. Rudzinski	M.Sc.	Elect. Eng.	–	–
	The analogue representation of the two-axis commutator machine.				
1961	A.A.K. El-Bahadli	Ph.D.	Mech. Eng.	–	–
	The electric analogue for turbulent flame studies: an investigation of its validity.				
1961	C. Lemyre	Ph.D.	Elect. Eng.	–	–
	Study by analogue means of base charge properties of junction transistors…				
1961	C.J. Bland	Ph.D.	Physics	–	–
	An analogue computer for the investigation of the trajectories of cosmic ray particles…				
1962	W.F. Fincham	Ph.D.	Elect. Eng.	–	–
	A study of the mechanism regulating the composition of the human blood…				
1963	N.H. Gillon	M.Sc.	Elect. Eng.	–	Resistance network
	An RC analogue for eddy current problems.				
1964	B.P. Apaydin	Ph.D.	Elect. Eng.	–	–
	Study and analogue simulation of the dynamic behaviour of transistors for small signals.				
1964	D.N. Davies	M.Sc.	Elect. Eng.	–	–
	Approximately optimal control of a non-linear system by means of an analogue computer.				
1964	P.C. Hedgecock	Ph.D.	Physics	–	–
	An analogue computer study of cosmic ray threshold rigidities.				
1965	R.E. Parking	Ph.D.	Elect. Eng.	–	Resistance network
	An investigation of the transmission properties of distributed resistance-capacitance networks.				
1965	M.J. Short	Ph.D.	Elect. Eng.	D.G.O. Morris	Resistance network
	The conjoint use of a network analyser and analogue computer…				
1966	D.P. Deziel	Ph.D.	Business	–	–
	Applications of analogue computers in operational research.				
1976	C.B. Giles	Ph.D.	Elect. Eng.	–	Hybrid
	The development of a hybrid simulator for power system control investigations.				
1977	N.L. Shore	Ph.D.	Elect. Eng.	–	Hybrid
	Hybrid computer simulation and on-line digital computer control of D.C. link.				
1978	A. Nava-Segura	Ph.D.	Elect. Eng.	–	Hybrid
	Hybrid computer simulation of HVDC systems.				

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.[32] Describing the flexible parameter variation offered by rep-op, one of MacKay's research students later wrote that MacKay's computer provided an

[32]See Sect. 2.5.2, p. 49. Fisher wrote that before he began his Ph.D. 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; the other was a high speed machine that had been invented across the

Table 5.2 Key analogue research dissertations at King's College, London

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

ideal environment for solving 'trial-and-error problems' or investigating the effects of 'continuous parameter changes'.[33]

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 analogue research at King's.[34] 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 Ph.D., MacKay had collaborated with E.M. Deeley, another physics research student who was awarded his doctorate in 1950.[35] Their research focused on computing units for function storage and mul-

Atlantic by Macnee (1949). An earlier consideration of repetitive computing elements for control systems modelling, describing the wartime work, is given by Williams and Ritson (1949).

[33]Fisher (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).

[34]Anon. (1987). The computer is detailed in MacKay (1951, 1955).

[35]MacKay 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 had become a full-time academic within the Department of Electrical Engineering. See Deeley (1955) p. 263, Harris (1963), introduction, Okon (1966), introduction.

tiplication, employing 'Williams tubes'.[36] 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 generator. 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. The invention of a device of this type was clearly topical. A similar function generator had already been 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.[37] The function generator and memory unit for MacKay's analogue computer went through several subsequent developments, being further refined by his first graduate student G.D. Bergman who submitted his Ph.D. in 1955.[38]

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 analogues could aid the theoretical physicist.[39] Shortly after completing his Ph.D., 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.[40] While MacKay's interest in high speed analogue 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.[41] This did not, however, immediately terminate his involvement with analogue computing, nor his collaboration with Fisher. In 1962, they co-authored *Analogue computing at ultra-high speed*, a work combining their respective theses.[42] Despite his shifting research interests, MacKay's early innovations in com-

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

[37] MacKay (1951) p. 10.02, 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.

[38] See Bergman (1955) p. 1.1.

[39] Fisher (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).

[40] A year later, he moved across the Atlantic to Cornell University. At Cornell he became Professor of Mathematics and Chemistry. He was elected FRS in 1971. (Anon. 1962c, 1965, 1971; Fisher 2007; Royal Society 2006.)

[41] Now renamed the 'MacKay Institute of Communication and Neuroscience' in his honour.

[42] See MacKay and Fisher (1962).

puting 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'. It was through developing the analogue computer that MacKay developed early three-dimensional projective displays which used coordinate mapping to create a three-dimensional effect.[43]

Much of the analogue research undertaken at universities during the 1950s had focused on developing actual hardware. Projects developed their own analogue computers, their own curve followers, and their own integrator circuits. However, by 1960, analogue research had shifted towards applying the established technology to scientific modelling and engineering design. Analogue computing would no longer be technologically innovative, but rather a more ordinary research tool. By the 1960s research into analogue 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 began to focus on techniques and application. Analogue computing at King's College was a blend of both innovative development and normal application. We have seen how Deeley, Mackay and Fisher all developed both hardware and techniques. However, elsewhere the technology was also being employed in normal usage. For instance, within King's Civil Engineering Department, analogue computing was applied to problems such as investigating stresses and strains in concrete, or studying soil seepage and groundwater flow. One of the researchers was John W. Bray who, in 1950, explored a variety of analogue models including electrolytic tanks which he found inferior to resistance networks. In 1958, under the supervision of Nash (a reader in Civil Engineering), research student Gordon Brooke completed a masters dissertation on investigating soil seepage using an electrolytic tank.[44] These examples were not innovative developments of technology, but were research studies exploring the technology's potential application.

5.5 Analogue Computing at Birmingham

A major location for research *using* analogue computing were the departments of Electrical Engineering and Civil Engineering at the University of Birmingham.[45] Table 5.3 details the dissertations from this institution. Within the Department of Electrical Engineering, the application of analogue computing techniques was directed by Professor A. Tustin, who throughout the 1950s supervised research stu-

[43] See Anon. (1987), MacKay (1949).

[44] Bray (1950), Brooke (1950).

[45] Analogue techniques were also applied to mechanical engineering research. For instance, around 1950 a number of students undertook research projects investigating analogue 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 they still referenced texts within the analogue computing literature.

Table 5.3 Analogue research dissertations at Birmingham

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

dents in control engineering and electrical system design.[46] During the second half of the decade, the department's technicians built a rep-op machine to support the re-

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

search of Cecil J. Pengilley, a Ph.D. student who was modelling the characteristics of electrical systems. The high speed analogue 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.[47] Analogue research within this department came to an end around 1960.

Within the Department of Civil Engineering, a research programme evolved that would favour analogue computers based on resistance networks and would apply them to various aspects of civil and aeronautical engineering. The programme was mobilised by Professor S.C. Redshaw, and investigated the applications of resistance network analogues to solving engineering problems such as heat flow, structural stability and aerodynamics. Chapter 7 will show that there were two major approaches to solving problems relating to fluid flow in aeronautics: tanks or networks. The Birmingham department favoured networks. Redshaw was a major contributor to the development of resistance network analogues. During the Second World War he had worked with Bolton Aircraft developing electrical analogue techniques for aircraft design, and held a patent for the improved network analyser he invented.[48] Over the following two decades, the group made numerous studies in electrical analogue 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 Ph.D. in 1960.[49] After receiving his Ph.D., Rushton became a full-time member of academic staff, eventually rising to Professor of civil engineering.[50] 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 Chap. 7).[51] This work

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[47]Pengilley (1957) p. 58.

[48]One 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).

[49]Rushton (1960). A number of Redshaw's research students (Anne Copson, Kenneth Rushton, and H. Ward) were applying networks and other electrical analogues 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 the 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).

[50]Rushton received a D.Sc. for his collected papers in 1971 (Rushton 1970).

[51]Rushton (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.

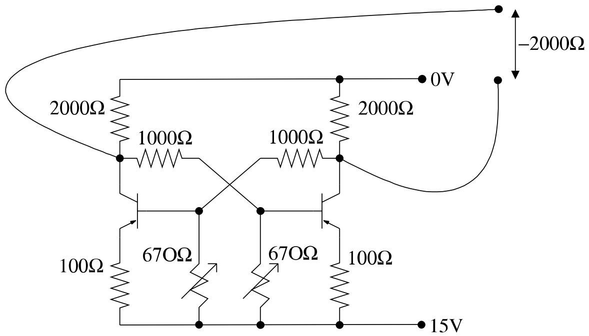

Fig. 5.5 The negative resistance circuit employed by Rushton in his investigations into elasticity. The component values shown correspond to a 'virtual' negative resistance of −2000 Ω. Based on an example in Redshaw and Rushton (1961a)

made extensive use of 'negative resistances'. In an electrical circuit, electrical resistance determines the electrical current. Rushton's 'negative resistance' circuit (see Fig. 5.5) induced a current in the opposite direction, hence giving the impression of a negative resistance. 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. Using these negative resistances simplified problems that had previously required a combined resistor-capacitor or resistor-inductor network. Instead, these problems could be modelled using a 'pure' resistor network of virtual resistances, some positive, some negative.

In Rushton's initial years as a lecturer, his main responsibility was to manage the analogue laboratory, and in this capacity he took an active role in assisting Redshaw's later students, and subsequently supervised many of his own.[52] From these investigations, Rushton applied the techniques developed from elasticity research to flow problems. His work spanned both airflow (investigating the wall interference in wind tunnels), and water flow (studying groundwater flow and 'multi-well dewatering systems').[53] In the following years, Rushton and Redshaw co-authored a number papers and, subsequently, a book on hydraulic flow.[54]

[52]See Harnden (1966) p. 156, Rushton (1970) pp. 2–4. Rushton provided technical assistance to a number of Redshaw's research students. In particular, he worked with B.D. McManus on the investigation of pipe networks, and they undertook a design study on the water network of the Corporation of Coventry, proposing the analogue method as a simple and cost effective solution (McManus 1965, introduction). He also advised E.C. Chan with his research on analogue models of 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 analogue 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 analogue techniques in 1970. See Rushton (1970), item 30.

[53]Rushton (1967), Herbert and Rushton (1966), Rushton (1970) pp. 2–3.

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

5.6 Analogue Computing at the University of Bath: An Example of a Technical College

At the University of Bath analogue laboratory, which was established in the early 1960s (first as the Bristol College of Science and Technology, and then as the University of Bath), analogue computers were bought-in from industrial manufacturers. The laboratory's first batch of teaching machines were bought from Solartron. Later, a further set of machines were purchased from the Anglo-American firm Electronic Associates Limited.[55] Equipped with 12 teaching machines, Bath's analogue laboratory had responsibility for teaching analogue computing techniques to mathematics and engineering undergraduates. As a result of being situated within a mathematics department, they developed a different approach to teaching analogue computing. This is evident in the publication of their textbook on analogue *programming* which became one of the standard works for teaching analogue computing in Britain. Moving away from the traditional 'electrical engineering' presentation of analogue computing, their textbook contained fewer circuit diagrams. The textbook, entitled *Systematic analogue computer programming*, treated the analogue computer as a black box which could be programmed and used without excessive knowledge of the internal circuits. Previous textbooks had been written for the electrical engineering reader and contained pages of circuit diagrams and encouraged the user to think in terms of voltage and current. Complementing this 'black-box' approach to computing, the book also encouraged the use of Machine Units (MUs). Some analogue computers represented a number with 10 volts, others used 100V, and some machines had an entirely different scale. Working with machine units bought a degree of platform independence, enabling a set-up (or program) to be transferable from one machine to another.[56]

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

The work at Bath finally came to an end in the late 1970s. Anecdotally, this is said to have come about when a senior mathematics professor decreed: 'they look old, I will have none of them.' The staff then had to transfer into new disciplines. For example, Alan Charlesworth, their 'senior hybrid programmer', changed his research direction and developed expertise in relational databases. It was because of

[55]Electronic Associates produced the high quality PACE machines and became the dominant provider of commercial analogue and later hybrid computers. As well as manufacturing computers, EAL also ran a successful analogue computing centre at Burgess Hill. See Small (2001) pp. 201–202, Anon. (1956–1958).

[56]Charlesworth and Fletcher (1974).

the department's involvement with hybrid computers that analogue had been able to co-exist with digital for so long.[57]

5.7 The Flowers Report and the Funding of Analogue Computing

Through looking at a number of academic contexts, we have seen how the analogue applications of calculation, simulation, and control were disparate in activity but associated in name. This association meant that the subtle differences between analogue 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) notes 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 analogue to digital. It contained the recommendations of a committee chaired by Brian Flowers, a professor of physics at Manchester University, and set out guidelines for funding university computing. To quote Agar, it recommended 'at least one computer per university and a budget commitment over twice that imagined a year before.'[58] The Flowers committee was established in March 1965 at the request of Frank Cousins, the Minister of Technology. Their report records how they '...decided that the review should concentrate on general facilities for digital computing and should exclude consideration of analogue computers.'[59] In identifying the key needs for the following five years, it was perhaps appropriate that the committee had decided to focus on digital machines. However, in doing so, the policy makers failed to leave room for the users of analogue. As a consequence of increasing the funding of digital, analogues 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 to the civil servant Donald F.E. King. For King, analogue–digital issues were of everyday concern. One request causing difficulty was from the Bristol College of Science and Technology for an analogue 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.[60] With the Treasury allocating the funds to underwrite the extra investment proposed by Flowers, it became

[57]When interviewed, Alan Charlesworth recalled how the research team at Bath had once 'tuned' the circuits of an analogue 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 analogue and digital was helpful for experimenting with applications in computer audio or visualisation.

[58]Agar (1996) p. 642.

[59]HMSO (1966) para. 34.

[60]See UGC (1952–1953).

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 analogue, and a treasury wanting to centralise 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 analogue computers should be treated.[61] King was not clear 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 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.[62]

While King wanted to argue that analogue 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.'[63] 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 analogue and digital.[64] Black was, in Jackson's opinion, an 'anti-analogue computer man'[65], but in a written reply, he provided King with a fair account and an interesting taxonomy. Distinguishing between differential analysers and 'simulators', he emphasises the importance of analogue 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 electri-

[61] A decade previous, Willis Jackson had held the Chair of Electrical Engineering at Imperial and supervised analogue 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).

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

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

[64] Alongside Gordon Black, there were nine other members of the Flowers Committee. The committee was chaired by Prof. B.H. Flowers and the other members were: 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.

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

> cal quantities—things they can imagine and measure for the quantities they are thinking about.[66]

Black described how engineers and physicists fell into distinct analogue 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 analogue 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 analogue 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.[67]

Conscious of not wanting to set a precedent to fund analogue, 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, 'the machinery which is recommended in the Flowers report should be quite capable of dealing with the few research analogue applications.'[68] This was an optimistic view. King thanked Black for his assistance, and decided that analogue 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 to allocate analogue, hybrid and digital-differential analysers within the provision of 'normal equipment', but limited funding to British machines costing less than £10,000. Any analogue requests not following this 'buy British' policy or costing more than the threshold required further authorisation.[69] Bristol's application along with similar applications from Manchester and other technical colleges remained unresolved. In a memo dated January 1966, King wrote:

[66]Letter 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 analogue 'cannot and does not count. Rather it measures.'

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

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

[69]Letter 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 analogue, 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.

> 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.[70]

And finally, by late March 1966, about a year after the college's original application, a decision had been reached. Analogue computers were not to be considered as computers. Instead they were 'ordinary equipment'.

> …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.[71]

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 analogue–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, the Flowers Committee were a technical group with a bias towards digital machines. Not wanting to set precedents about analogue procurement, they placed analogue computing out of scope, describing small analogues as 'laboratory equipment' and large analogues as unnecessary. This acted in tension with university departments who wanted specific machines to pursue their research and teaching agendas. In terms of funding, the result of this pushing and pulling was the eventual 'separation' of analogue computing from mainstream computing. Analogue devices had previously been enrolled into a discourse of computing, and in riding this bandwagon had benefited from the association with digital. Analogue was now the poor relation of computing: the association had turned sour.

5.8 Conclusion

This chapter demonstrated that not only were analogue computers used for different applications, but the historical trajectories for each type of use was different. Thus analogue's role as a calculator or equation solver reduced 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 the argument that post 1950s analogue computing was downplayed, it proposes a different explanation of *why*. The major analogue use that remained

[70]Memorandum from D.F.E. King to E.M. Church, 11th January, 1966 (UGC 1952–1953).

[71]Letter from H.B. Jay (Department of Education and Science) to E.M. Church (UGC), 7th April 1966 (UGC 1952–1953).

significant were the modelling and simulation applications. This is a clear example of how these different interpretations of 'computing technology' have been shaped through different usage, and so need separate historiographical narratives.

A history of use covers not just the technologies, but also the people. In the accounts of the various institutions, one common thread is how people responded to digitalisation. We saw how many academics who had researched and taught analogue computing began to redefine their expertise. In the accounts of Imperial and Manchester, some analogue experts became simulation experts. Others moved into new fields. For instance, MacKay applied prior knowledge of information theory, analogue computing and control, in his neuroscience research, his analogue background allowing him to develop novel visualisation techniques. At Bath, Alan 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. As analogue computing began to be replaced, this department redefined itself. Mounier-Kuhn (1989) describes how Malavard responded to the decline in analogue computing by reorienting the focus of the research 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. Commenting on the history of LIMSI, historian Pierre Mounier-Kuhn wrote that since the laboratory's first trials of speech synthesis, it continued to be a leading research centre for 'computer graphics and speech recognition by computer'.[72]

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 analogue–digital classification, and the result was that only small teaching installations were procured. Had such funding initiatives been more open to analogue computing, the digital computer would still have become dominant, but we might have seen even greater use of hybrid computing along the way.[73]

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[72] Mounier-Kuhn (1989) p. 258.

[73] For 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 analogue and digital.

In summary, this chapter has highlighted the need for user-centric history based on multiple perspectives of use. In considering users it noted how analogue 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 analogue expertise into the digital world. In this story of redefinition, higher education provides an interesting window on the issue of analogue identity. 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, analogue became excluded from computer funding schemes. Gordon Black had referred to himself as a ‘digital type’. Now the ‘analogue type’ were rapidly redefining themselves to become *modelling* experts.

Chapter 6
Analogue 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, 1962[1]

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 analogue computer (or analyser) was installed to aid the work of BP's Exploration Research Division. As well as providing support to BP, this division undertook consultancy studies for other oil companies, and it was for this work that the reservoir analyser was most useful.

Earlier in this book, we discussed the electrolytic tank and its use as an analogue computer. In this chapter we will see the importance of these tanks to the modelling of oil reservoirs and also see how electrical networks were subsequently applied to the same problems. This application of analogue computing began in the 1930s when researchers working for large petroleum corporations began to develop electrical models to model the hydrodynamics of subterranean oil reservoirs.[3] The analogue computer installed at BP allowed reservoir engineers to simulate an oil field reservoir through the creation of an electrical model that could be studied in a

[1] Anon. (1962a) p. 20.

[2] BP installed an English Electric DEUCE in 1956 to perform refinery related calculations, but the machine was also extensively applied to solve Operational Research problems. See Bamberg (2000) pp. 398–399.

[3] The association between these electrical models and analogue computing was forged as the inventors of reservoir analysers began to patent their work. Many early inventors of these analysers did not refer to analogue computing. However, either their patent attorneys or the patent offices saw the connection. The patents are all classified as computing technology.

C. Care, *Technology for Modelling,* History of Computing,
DOI 10.1007/978-1-84882-948-0_6,

laboratory setting. Through exploring the effects that various oil production strategies had on the electrical model of the reservoir, the computer could be used to predict the optimum approach to extracting oil. The machine was manufactured by EMI Electronics Ltd to the custom specification of BP engineers. Once built, the computer was 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] Furthermore, for the engineers who prepared the specification of this machine, analogue 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 analogue computing. This chapter describes the history of the analogue reservoirs that inspired this machine, and then investigates the story of its procurement and design.

Despite their use of analogue computing, the engineers at BP did not actively engage with the analogue–digital debate. Located within an industrial setting, the engineers pursued analogue techniques because other oil companies were deriving useful results from them. The story of this analyser suggests that we should not simply portray analogue as a predecessor technology, or even as a pure alternative, to digital. At BP, analogue and digital were *complementary* technologies of computing.

6.1 Production Management and the Application of Analogue Computing

Any mining industry faces two major challenges: first, the discovery of a natural resource; second, its effective extraction. Undertaking a rather special form of mining, the petroleum industry has the additional challenge that their resource is not mineral ore, but subterranean oil and gas. It was through the need to model complex underground hydraulic that analogue computing technology was introduced to this context.

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 approaches to maximise oil production. The optimum strategy depends on an oilfield’s characteristics. Since badly made production decisions can render large volumes of crude oil unobtainable, predicting the long-term effects of a particular strategy is important. 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.[5] However, due to the

[4]BP Newsletter (1961b). Carter were a subsidiary of the Standard Oil Company.

[5]Carter (1961) notes that prior to the mid-1920s, there was no significant or organised production research with a long-term perspective. What did exist was ‘sporadic and unorganised’ and ‘primar-

mathematical complexities associated with this theory, reservoir engineers turned to analogue models—physical systems with behaviours analogous to the reservoir.[6] These systems were called 'reservoir analyzers'.

Most oil reservoirs are surrounded by porous water-bearing rocks known as an aquifer, and because these rocks exert hydraulic pressure on the reservoir, variations in aquifer pressure determine production rates. The main focus of the early reservoir analysers was predicting the pressure changes due to the effects of water influx.[7] As a dynamic modelling tool, reservoir analysers became an important technology to assist long term production management.

The first widely reported application of analogue 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.[8] Interestingly, although Carter did patent the analyser, they did not attempt to license the technology. Instead, they presented the invention as a benevolent contribution to the industry. Carter's corporate journal ran an article entitled *A Gift From Carter*, with the subtitle: *To Science and Industry, an Oil Pool Analyzer which forecasts the production future of an oil field in the interest of conservation.*[9]

6.1.1 Modelling Hydraulic Pressures with Electricity: William A. Bruce and the Carter Analyser

Reservoir analysers certainly began as an instrument of science rather than a tool of engineering. Bruce had trained as a physicist, receiving a Ph.D. from the University of Washington in 1938. His thesis topic was on X-Ray scattering studies of zinc crystals, and shortly after graduation he joined the research team at Carter.[10] In line

ily 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). This formalisation of production research offered significant improvements. 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).

[6] Carter (1961) pp. 1026 and 1097.

[7] See, for example, Craft and Hawkins (1959) p. 205.

[8] Earlier analogue models of reservoirs were developed during the 1930s. A history of Petroleum Engineering published in 1961 referred to the work of Wyckoff, Botse & 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.

[9] May 1946 issue of Carter Oil's newsletter *The Link*.

[10] Only three months passed between his last publication to acknowledge the University of Washington and the first to mention an affiliation to Carter. See Bruce (1938b), Jauncey and Bruce (1938) p. 163, Severinghaus (1939) p. 594.

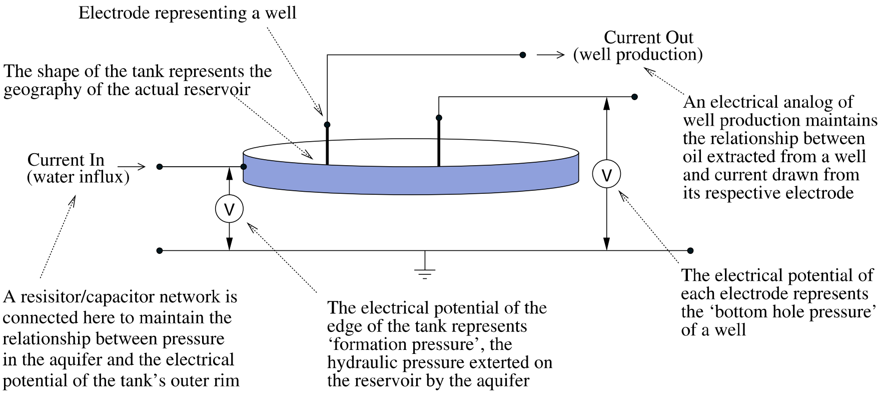

Fig. 6.1 The main features of the Bruce reservoir analyser, interpreted from his 1947 patent. The reservoir is modelled with an electrolytic tank, with electrodes representing wells. Current flow into the tank is controlled by a model of the aquifer. The flow of current out of a given electrode is proportional to the production flow of the corresponding well. 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

with his training as a materials physicist, Bruce was initially assigned to a project investigating the effects of arc welding on the 40ft cylindrical tubes used to encase oil wells.[11] However, during the following years, Bruce turned his attention away from materials research and began developing his reservoir analyser, modelling an oilfield's aquifer region using a network of electrical components. He recreated the hydraulic pressures in the aquifer and reservoir by representing water-influx and oil production with electrical current.

The analyser consisted of two sections, one an electrical analogue of the reservoir and the other a resistor-capacitor model of the aquifer. The reservoir was represented by a tank with a conductive edge containing a low conductivity electrolyte (see Fig. 6.1). By representing the water drive into a reservoir as a 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 measurements of reservoir data, usually drawn from observations over a minimum of two to three

[11] See Severinghaus (1939) p. 594, Bruce (1939) p. 578.

Table 6.1 The hydraulic-electrical analogies employed in the Bruce analyser

Actual reservoir (hydraulic)		Reservoir analyzer (electrical)
Hydraulic capacitance of aquifer	$\Longleftrightarrow$	Electrical capacitance in model
Hydraulic permeability of aquifer	$\Longleftrightarrow$	Electrical resistance in model
Aquifer pressure	$\Longleftrightarrow$	Electrical potential of tank's rim
Reservoir pressure	$\Longleftrightarrow$	Electrolyte potential
Well bottom-hole pressure	$\Longleftrightarrow$	Electrode potential
Oil produced from a well	$\Longleftrightarrow$	Current drawn from electrode

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 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. This process was 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.[12] A diagram from Bruce's analyser patent (reproduced as Fig. 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 analogue computer research, and by the mid-1950s reservoir analysers were in common use.[13] The patent records show that other significant players were the Sun Oil Company, the Texas Company and Union Oil. The main improvements made by these companies in their patents often related to usability, providing, for example, the facility to dynamically manipulate the model. Since BP engineers visited Sun Oil's research facility prior to specifying the design of their own analyser; the analysers developed at Sun Oil had a particular impact on the design of the BP machine.

6.1.2 Incorporating Repetitive Operation: The Reservoir Analysers Developed by the Sun Oil Company

The second major influence for the BP analogue computer was the series of analysers developed by Omar L. Patterson and other researchers based in Sun Oil's

[12]See Bruce (1947/1943, 1949/1945a, 1949/1945b).

[13]A contemporary paper (Odeh et al. 1956) commented on how the method had become 'an accepted procedure' (p. 200).

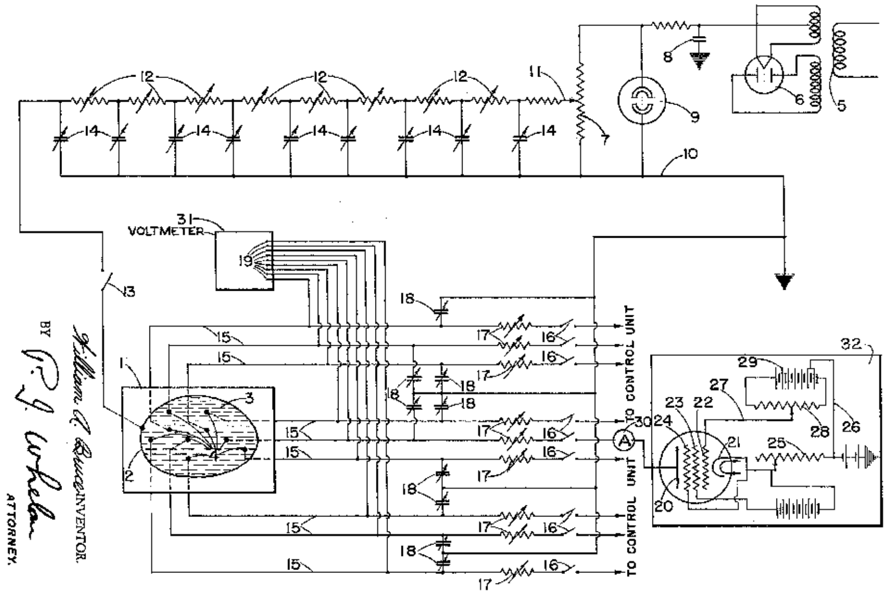

Fig. 6.2 The diagram of the Bruce analyser in the issued patent. The array of capacitors and resistors at the *top* of the diagram make up the electrical model of the aquifer and are connected to the edge of the electrolytic tank by closing switch *13*. The representation of the reservoir in the *bottom-right* of the drawing (labelled *1*) is drawn 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)

physical laboratory in Dallas.[14] One of the early innovations from this group was the incorporation of an analogue model of a reservoir's gas cap, another important feature of subterranean reservoirs.[15] These analysers were not just used for oil reservoirs but patented as generic analogue 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

[14]Between 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 analogue computation, two of the patents being entitled *Analog Computer or Analyzer* (Patterson 1955/1949, 1957/1950). Initially, Bruce had not made reference to analogue, 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 analogues, marking the beginning of their enrollment into the discipline of analogue computing.

[15]The gas cap analogue 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.

Jung identified the analyser described in Patterson's 1951 patent application as an early use of a non-inverting amplifier circuit.[16]

The Sun analysers differed from those of Carter Oil in their use of repetitive operation, a popular technique of mainstream analogue computing.[17] 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. Fifty years of oil production were represented by an analyser run-time of two milliseconds. While this allowed the historic matching to be completed on-line, the downside of the increased speed was that it became very difficult for a user to make measurements directly. Many general purpose rep-op computers solved this problem by using automatic recording circuits: often replacing user measurements and paper plots with the dynamic graphical output of an oscilloscope. In his analyser, Patterson used a technique that he called '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.[18] 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 lines and recording circuits for each individual electrode). One major benefit of Patterson's roaming probe set-up was that it became possible to investigate the pressure gradient between wells. 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 (see Fig. 6.3). 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.[19] Rep-op would be used in all subsequent analysers developed at Sun Oil.

Further developments in the Sun analysers also saw a 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 analogue models had all assumed that a reservoir could be accurately modelled as one single pool of oil; the Holt-Bryant study demanded the

[16] Patterson (1958/1951), Jung (2005) p. 782.

[17] See Sect. 2.5.2, p. 49.

[18] See Patterson (1955/1949) col. 2.

[19] Patterson (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, 1948), Lee and Herzog (1951/1949), Stelzer and Herzog (1954/1949, 1957/1951), Loofbourrow et al. (1957/1952), Stelzer (1961/1956).

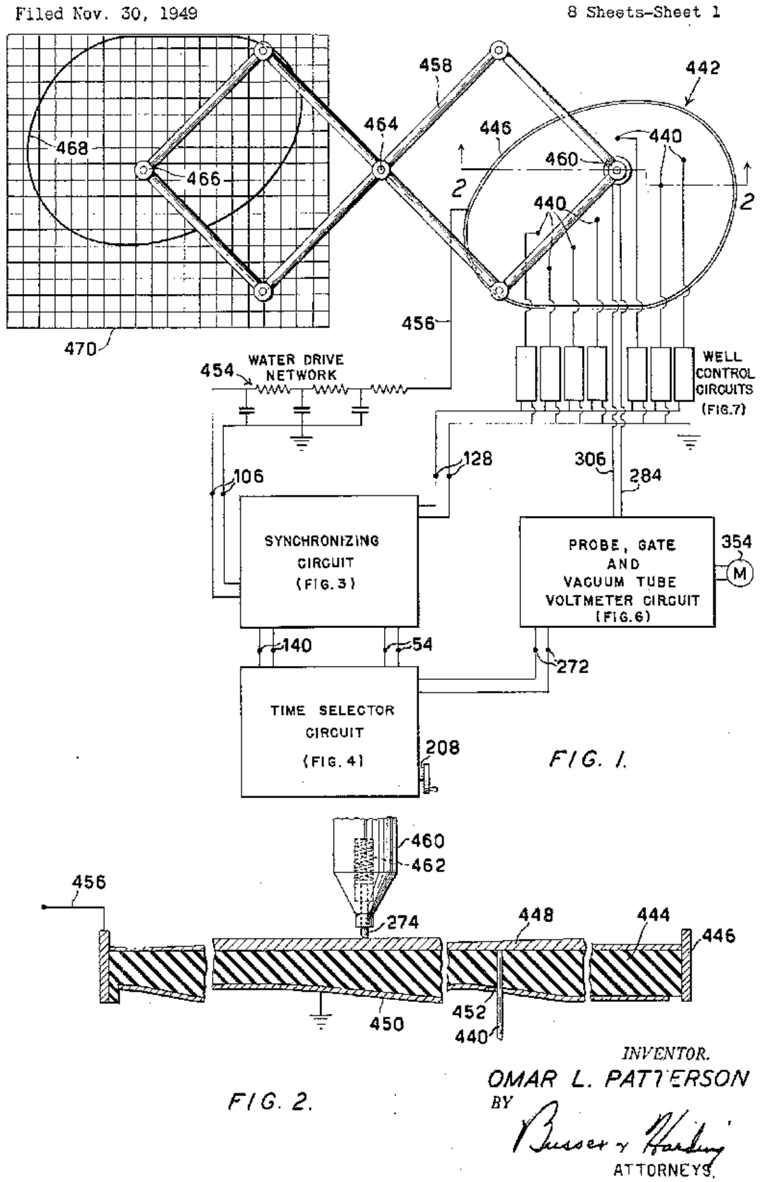

Fig. 6.3 Schematic diagram of an analyser designed by Omar Patterson of the Sun Oil Company. The pantograph mechanism connecting the paper plot and electrolytic model of the reservoir is clearly visible. *At the bottom* of the diagram is a side-on drawing of the solid reservoir model constructed from a non-conductive material covered by conducting paint. Source: Patterson (1955/1949)

invention of a 'multi-pool' analyser permitting the reservoir to be treated as three separate pools. This new type of analyser also incorporated extra analogue 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.[20] 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 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.'[21]

6.2 The Story of the BP Analogue 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.[22] 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.[23] 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', analogue computers that could 'predict future changes in reservoir pressure with production'.[24] Birks recorded that there were two main types of analyser in use, the 'Bruce or Carter analyser' and the 'Sun analyser'. In Birks' opinion, 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

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[20] See Patterson et al. (1956) p. 74. The Holt-Bryant reservoir was discovered in 1944 and was yielding oil by 1948.

[21] BP Exploration Research Minutes (1958) p. 2. See also p. 133, below.

[22] This 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 Fig. 6.4). BP's research program had originally begun in 1917, located in the basement of an old country house. By 1960 the operation had expanded into a large department occupying a nineteen 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).

[23] A chemist by training, Birks had obtained a Ph.D. for research into evaporation from the University of Leeds in 1949. See Birks and Bradley (1949).

[24] Birks (1956) p. 2.

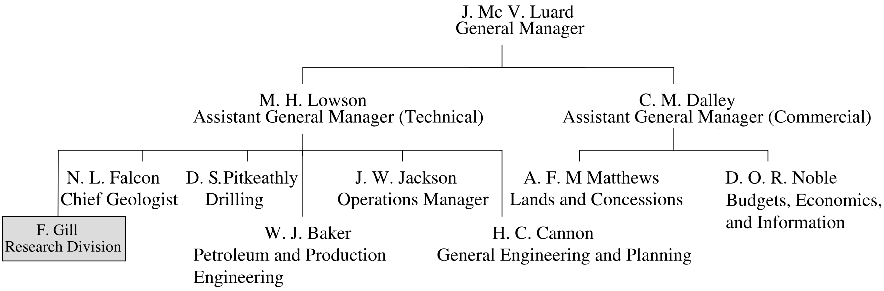

Fig. 6.4 The management structure of BP's Exploration Division. Highlighted is Mr F. Gill, the head of the division's research team based in Kirklington Hall and later Sunbury. The Exploration Research Advisory Committee provided communication between Gill's researchers and Lowson, their technical manager in London. The diagram shows how the research team related to other technical operations such as geology or drilling. Source: Based on information in Matthews (1962)

> 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 since it is much easier to use and gives a visual display of the pressure decline curve.[25]

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.[26] 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.[27] 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 analogue computer and provided a technical specification. Keep suggested that the original plan of purchasing one of the American analysers should be abandoned due to their designs not being 'flexible enough' for the group's consulting work.[28] 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

[25] Birks (1956) p. 2.

[26] BP Exploration Research Minutes (1958) p. 4.

[27] It 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.

[28] Keep (1958) p. 1.

and uses some excellent electronic techniques.'[29] 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. The minutes of the exploration committee record this decision:

> 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.[30]

6.2.1 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.[31] EMI Electronics, a subsidiary of the entertainment company *Electric and Musical Industries* (EMI), was formed around 1957 to bring together EMI's various interests in electronic goods.[32] EMI was a regular supplier of bespoke hardware to BP, and had recently completed a development contract for an instrument to investigate rock formations.[33] Since BP wanted to design the analogue computer within a similar business process, it made sense to use a company who they knew could produce a successful customised product.

EMI decided to develop the reservoir analyser around the technology of their commercial analogue computer, the EMIAC II. The name EMIAC was an acronym for *EMI Analogue Computer*. Similarly, EMI's range of digital computers were labelled EMIDEC. 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.[34] The EMIAC, like other analogue

[29] Keep (1958) p. 3.

[30] BP Exploration Research Minutes (1958) p. 2.

[31] BP Exploration Research Minutes (1958) p. 1.

[32] Anon. (1959a) p. 22, Hamilton (1997) p. 82. EMI were pioneers of a number of electronic products including medical scanners, computers, radar, and domestic television.

[33] EMI (1961) p. 8.

[34] EMIAC 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 (1959, 1962a, 1962b, 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.

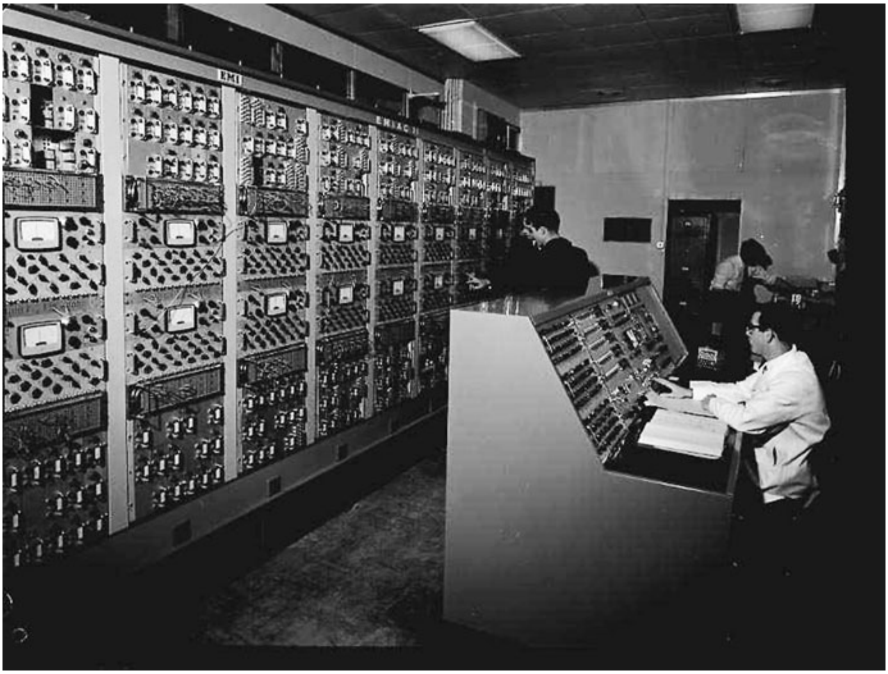

Fig. 6.5 The EMIAC II installed at Sunbury. EMI designed extra hardware specific to the reservoir modelling problem, most of which was built into the central console. The central console allowed the user to manage the timing circuits and the resistance networks which modelled the reservoir. The 18 EMIAC II modules (stacked two-high) are clearly visible in the nine racks in front of the console. The machine is most likely in the process of being re-programmed: in *the top left* of the photograph, one of the modules has had three of its C-Boxes removed. Source: BP Archive: reference EMIAC II 7331_1 © BP plc. Reproduced with permission

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.[35] To implement BP’s requirements, EMI assembled 18 EMIAC II rack mounted modules providing 324 C Box locations (see Fig. 6.5). EMI also developed some special purpose hardware to provide a network-analyser to model the reservoir’s aquifer.[36]

[35]For 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 analogue 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).

[36]Anon. (1963b) p. 151, EMI (1963a) p. 14.

Most of this hardware was built into a central control console (visible in Fig. 6.5) and was similar to another contemporary EMIAC customisation which provided a resistance network analogue for EMI's own Power Tube Division.[37]

6.3 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. In the team's own words:

> 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.[38]

Furthermore, during the five years between the identification of a need and EMI's delivery, analogue computing did not lose its applicability to reservoir engineering problems. In their 1963 annual report, BP heralded the analogue computer as a successful addition to their research establishment and despite there being only a few post-installation references to the computer's use, 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 existing assistant's work being 'mostly concerned with the computer.' This work 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.'[39] 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 contract (the budgeted price of the installation was £40,000) indicates that the analyser was indeed a successful purchase and that there was a healthy market for BP's consultancy services.

The BP archives do not record when the computer was decommissioned, but by 1975 most analogue computer applications and installations were disappearing

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[37]This machine consisted 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. See Harvey (1968).

[38]BP Exploration Research Minutes (1957) pp. 1–2.

[39]Gill (1963) p. 3.

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.[40] 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:

> 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.[41]

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.[42] If we assume that BP followed the rest of the industry in replacing analogue with digital, then the computer would have had a working life of between five and ten years, a reasonable lifetime for any computational tool.

6.4 BP and the Analogue–Digital Debate

In his history of analogue computing, Small (2001) refers to an 'analogue versus digital debate'. The BP story offers a chance to reconsider how end-users engaged with this debate. We can make two observations: firstly, at the local level, the BP engineers did not feel committed to a particular approach but procured analogue machines because they was 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 analogue computer; any installation of a technology bearing the name 'computer' was employed to advertise innovative practice at BP.

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[40] Peaceman 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.

[41] Peaceman (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).

[42] Compare Craft and Hawkins (1959) pp. 205–210, and Peaceman (1977) pp. 1–2.

6.4.1 Analogue–Digital Issues at the Local Level

In considering analogue–digital issues, both an application and research outlook can be identified.[43] 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 versus special-purpose technology. The general argument was that digital computing was a more appropriate technology choice 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 analogue computer as the central technology of Project Whirlwind. Whirlwind 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.[44] However, this again is an example drawn from the world of research rather than of application.[45] For those without the deep budgets of a defence contract, analogue computers were the tool of choice. BP's interest was not to develop computing technology. Rather, BP's need was for *normal* computer use.

An investigation of their decision making process indicates that 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 computor [sic] could not be used for these studies but later agreed with Dr Birks that there was a strong case for the analogue

[43] A 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, were among the first to articulate a clear distinction between analogue and digital. See Sect. 2.5.1, p. 47, 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.

[44] See Campbell-Kelly and Aspray (1996) pp. 143–145, Augarten (1985) p. 196.

[45] The 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 analogue computers had previously been used for. However, affordable digital alternatives to analogue computing were much slower in coming to everyday applications.

> approach, the studies being both awkward and time-consuming when carried out on the large digital computor which would be required.[46]

There was also concern amongst the committee that despite analogue 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'.[47] However, as 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.[48]

As engineers with an application perspective, the team understood the technology in terms of the business' needs. The language of the proposals did not presuppose that digital was better than analogue, neither did it represent a view that analogue was always more appropriate than digital. This is best illustrated by the fact that the proposal for the analogue computer also drew attention to the importance of acquiring access to a digital computer, and even suggested that the digital procurement should be given priority.[49] However, it is clear that such prioritisation was always grounded in the specific business application: the analogue 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 analogue would open new opportunities for consultancy in the long term and significantly extend the group's skills-base. Analogue 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 bespoke analogue machine based on the American techniques.

6.4.2 Analogue–Digital Issues at the Corporate Level

So at a local level, there was not excessive concern about whether a procurement should be analogue 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 analogue machines and this can be seen in the 1963 annual report where the

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[46] BP Exploration Research Minutes (1958) p. 3.

[47] BP 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.

[48] Docksey quoted in BP Exploration Research Minutes (1958) p. 3.

[49] The digital computer facilities were a priority because of the possibility of shared use with other teams, 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.

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.[50]

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. When you consider the vast difference in cost, it can seem odd that the annual report should mention both machines with seemingly equal prominence. Surely the digital procurement was vastly more prestigious? What we can interpret from this is that the installation of *any* kind of computer had publicity value. There was no embarrassment associated with installing an analogue 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. Furthermore, the fact it was called a 'computer' further helped strengthen the high-technology image that BP wanted to maintain.

6.5 Conclusion

The BP story offers a window on the use of analogue computing for industrial problems. We have seen that it was commercially viable in 1958 for a global company to invest in an analogue 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 analogue computer was an example of *normal* computing, and this explains why there was no need for BP to engage in the analogue–digital debate. Discussions around technical suitability were grounded in practical business benefits. Thus, analogue 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 analogue and digital were complementary rather than opposites. In explaining this, we have identified that BP had an application perspective rather than a research perspective. The reservoir analyser was employed as a normal tool and so there was no need for the BP engineers to engage with issues of classification and analogue–digital debate.

[50] '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).

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 analogue 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.[51] 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 the engineering culture that sought and used analogue computational assistance. In a sense, the importance of this installation to the history of computing is its normality. Returning to the BP context, the 'cog-in-the-machine' metaphor identifies more than just the status of the analogue 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 partly because of its specialised and mathematical, and also its long term nature.[52]

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 analogue computer was installed, the group achieved recognition by corporate level public relations, however, the analogue computer quickly became forgotten as its use slipped into the quiet and ordinary activities of the Iranian research contracts. When narrating the history of computing, it is all to easy to only discuss the innovative developments and forget that use of a technology persists long after a newer technique or machine has been invented. The exploration researchers had specific work to deliver and to do this, they relied on the special purpose technology of the analogue computer. Compared to the then innovative technology of digital computing, analogue was normal, ordinary, and used to get the job done.

[51] See 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).

[52] Gill (1963) p. 2.

Chapter 7
Analogue–Digital Decisions in British Aeronautical Research

Throughout the past two centuries, the science of flight has evolved into a large body of experimental and theoretical research. Like many other technical disciplines, aeronautics began as a experimental activity and later became more mathematical through the establishment of the engineering science of aerodynamics. This process of scientification can be seen in the development of the research methodologies of aeronautics. In an evolution from field experiments based on trial-and-error, towards laboratory-based approaches, a shift towards the laboratory setting motivated the invention of a whole series of standardised experimental environments. These modelling technologies included wind tunnels, direct and indirect analogues and, ultimately, the development of software packages for digital computers.[1]

The computer is central to the history of aviation technologies and this chapter focuses on the use of analogue computers in the design of aerodynamic structures.[2] In his history of electronic analogue computing, James Small states that it is 'difficult to overstate the influence' that aeronautics and guided weapons research had on the development of analogue technology.[3] Prior to 1950, analogues 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 analogues in this field, with the second investigating an analogue–digital debate which took place

[1] 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 analogue).

[2] The aerospace industry was a key agent in bringing computing out of the laboratory and into the wider world of industry. Ceruzzi explains that the aerospace industry was 'accustomed to complex machines that needed long break-in periods' and was 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 analogue computing.

[3] Small (2001) p. 57.

C. Care, *Technology for Modelling,* History of Computing,

DOI 10.1007/978-1-84882-948-0_7,

within the computation panel of the UK's Aeronautical Research Council (ARC), a government-supported advisory organisation.[4]

7.1 Analogue Computing for Aeronautics

Two major types of analogue computing were used in British aeronautics. Direct analogues 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) analogue computers were carried out by the Royal Aircraft Establishment (RAE) in Farnborough.[5] Between 1948 and 1954, RAE developed a series of indirect computers, culminating in TRIDAC. A large analogue occupying two purpose-built buildings, TRIDAC simulated the flight characteristics of guided weapons.[6]

Alongside indirect analogue computers based on summers, integrators, and other mathematical components, direct analogue 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 the wider history of modelling: encompassing analogues 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

[4]Founded 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.

[5]This was a consequence of the centralisation of guided weapons research at RAE in 1945. See Small (2001) pp. 180–181.

[6]Symbolising the climax of electro-mechanical analogue 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, 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 analogues. Installed at various aircraft manufacturers, commercial analogue computers were used for modelling guided weapons. For instance, a large EMIAC II analogue computer was installed in the factory of Armstrong Whitworth in Coventry to support their work on the Seaslug surface to air missile (EMI 1962b).

analogues and modern approaches such as digital finite element analysis.[7] Direct analogues 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 do not always appear to be compelling examples of computational technology. However, in terms of the problems they were solving, these technologies were the predecessors of modern computational modelling software. Electrical analogues 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 undertaken before wind tunnel tests.

7.1.1 Soap Film Models as Analogue Computers

One important, but unusual, example of a physical computational technology is the use of soap bubbles as analogue computers. In what might sound slightly eccentric, the physical behaviour of a soap film was used to solve complex problems. In terms of their role as a computational aid, contemporary technical discourse often described them as a computing tool and compared them to electrical tanks and networks. For instance, as Stanley Fifer's 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.[8]

This quotation clearly indicates a strong image of soap film analogies being an analogue computing technique. Fifer is not the only writer to have identified the technique as computational. For instance, Cyril Isenberg, who popularised the use of soap film in education, described them as an analogue 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.'[9]

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[7] Finite 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 analogues, this approach exploits the physical structure of a problem.

[8] Fifer (1961) pp. 770–771 (vol. 3).

[9] Isenberg (1976) p. 514. See also Isenberg (1975a, 1975b, 1992).

Evidence of the use of soap films in aeronautical research can be seen in the publications of the British 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. The results were determined by measuring distances on the film with a micrometer. The micrometer point could cause the film to burst, however this was usually prevented by limiting the size of the frame's 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.[12] 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 analogue.

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). Taylor and Griffith's work was 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 analogues 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, analogues 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

[10]The NACA was the forerunner organisation of NASA, the American space agency.

[11]See Batchelor (1996) p. 118, n1.

[12]Fifer (1961) p. 772.

[13]Busemann (1960) p. 194.

[14]See Taylor and Griffith (1917a, 1917b, 1918). 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 (DNB 2004).

[15]Rubbra (1964) p. 118.

[16]On 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).

> 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 analogue computing for aeronautics: the electrolytic tank.

7.1.2 The Electrolytic Tank as a Table-Top Wind Tunnel

The wind tunnel is probably the best known experimental environment for testing aerodynamic structures. 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 the high cost of use, research engineers began to use analogues to model airflow.[18] Through exploiting the analogy between electrical fields and airflow, electrolytic tanks offered an alternative experimental space.

As described in Chap. 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 war in Europe, a group of engineers met in the Library of the Royal Aeronautical Society

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[17] From a technical note by G.I. Taylor, appended to Southwell (1922) pp. 1–2.

[18] One 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).

[19] See Sect. 2.4.1.1, pp. 40–41.

[20] Mounier-Kuhn (1989) pp. 257–258.

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 team were actively promoting the use of electrolytic tanks as a generic problem solving tool, the majority of their work continued to be 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 Researches 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'. After some initial investigation, they constructed their own modified design, first operational during 1949. 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 of velocity in a wind tunnel. The method was only useful for studies of velocities below the speed of sound because the analogy ceases to hold at higher speeds.

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 (see Fig. 7.1). 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.[24] The effects of this change could then be seen immediately by re-investigating the model in

[21]This 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 analogue 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.

[22]Hargest (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.

[23]Hartshorn (1948) p. 1.

[24]Producing the accurate non-conductive model required special techniques. The approach taken at Saab was to create a mould using cross-sections.

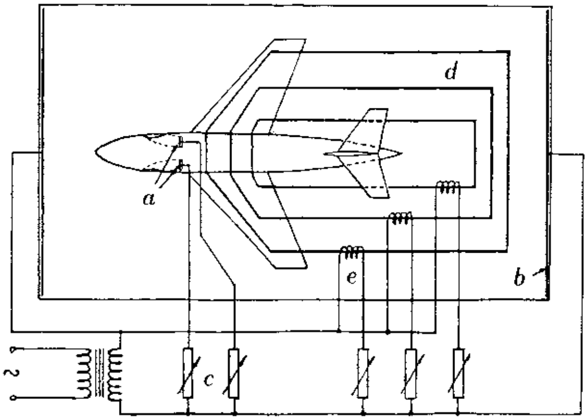

Fig. 7.1 Diagram of an aircraft model in the Saab electrolytic tank. The diagram shows the circuits added to model the aircraft's air intakes (labelled *a*), and the cyclic circuits (labelled *d*) for generating circulation around the wing. Source: Stenström (1949). © Saab. Reproduced with permission

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.[25]

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 design software now provides this experimental quality, but in 1950 it was direct analogues that provided interactive modelling.

7.2 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.[26] Guided weapons and a nuclear deterrent were to become the principal technologies to defend the British Isles, resulting in an expansion of military aerospace

[25] Stenström (1949) p. 21.

[26] Twigge (1993, 2002), Edgerton (1991, 2006), Nahum (2002).

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 engineers. As Brigadier Hinds of 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.'[27] 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.[28] They visited a number of the major companies and reported that 'appallingly crude methods of computing' were in use.[29] 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.[30]

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.'[31] It was these higher levels of expertise that were lacking in the British Industry.

[27] Brig. Hinds as quoted in Minutes of the 1st meeting of the ARC computation panel. See ARC (1952–1953), 21st November 1952, p. 2.

[28] Both 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 Ph.D. thesis entitled 'Stability and configuration of the wake behind a body moving through a fluid' in 1936. On leaving Imperial, he joined the aerodynamics research team at Farnborough where he remained throughout the wartime period. Goodwin remained at Cambridge and obtained a Ph.D. on: 'The quantum theory of surface phenomena' before joining the NPL. See Anon. (1932), Hollingdale and Toothill (1970), preface, Theses (2007).

[29] Goodwin as quoted in Minutes of the 1st meeting of the ARC computation panel. See ARC (1952–1953), Meeting 1, 21st November 1952, p. 2.

[30] Goodwin and Hollingdale (1952).

[31] Bollay (1947) pp. 106–107. Note the use of 'computer' to refer to a human computer.

As a consequence of these findings, the ARC decided to establish a 'Computation Panel'.[32] Chaired by S.C. Redshaw, an analogue computing expert from the University of Birmingham, the panel had a broad membership including the digital computer pioneers Maurice Wilkes and F.C. Williams.[33] Representing the government, was Brigadier G.H. Hinds, then the Director of Weapons Research for the Ministry of Supply.[34] Only half of the members were digital pioneers, the other half being either analogue experts or users of both technologies. Goodwin and Hollingdale were both members, each representing their respective establishments.[35]

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 the panel's early meetings their greatest concern was the lack of computer knowledge in industry, and they considered assembling an introductory handbook, and running short courses.[36] 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.[37]

The panel considered the whole range of computer technologies including direct analogues, indirect analogues, 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. During its seven years of existence, the panel indexed around 150 documents. Two major analogue 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 analogues for modelling aircraft flutter.

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[32]The panel was established in November 1952, was re-established as the computation *subcommittee* in February 1954, and was disbanded in late 1958. By 1958, the network of computing expertise was sufficiently established to warrant a more ad-hoc approach to discussing computing issues. See ARC (1954–1958), Meeting 21, 17th October 1958.

[33]Wilkes and Williams had led pioneering computer projects at the universities of Cambridge and Manchester respectively.

[34]Hinds 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 Ph.D.

[35]While Hinds and Wilkes were keen on digital, others in the group had a more open-minded view to analogue–digital issues and while there was an analogue–digital debate, there were no hostilities between the two camps.

[36]At Wilkes' suggestion, the panel decided to promote Hartree's *Calculating Instruments and Machines* and maintain a bibliography of relevant research papers.

[37]Although minuted, the statement is unattributed. ARC (1952–1953), Meeting 1, 21st November 1952, p. 2.

7.2.1 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. This was an important issue, because not only did the ARC have significant influence over the technologies used by research establishments and industry, their choices would ultimately impact on which university research programmes the Ministry of Supply would fund. 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.[38] Their conclusions were that there was need for both types of analogue:

> 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.[39]

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 one of the largest network analogue 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.[40]

The electrolytic tank was a unique computational medium and a digital competitor simply did not exist. 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 been involved in the actual computing process. Unlike a digital computer which

[38] Kuchemann and Redshaw (1954).

[39] ARC (1955).

[40] Fairthorne as quoted in Malavard (1947).

generated a solution, the electrolytic tank provided an environment for exploring solutions. This is captured in a report on aeronautical analogue 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 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.[41]

7.2.2 *Deciding Between Analogue and Digital: The Case of Flutter*

The discussion between types of analogue is interesting. However, the more pertinent question for engineers like those on the computational panel was how to decide between analogue 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.[42] Flutter was one of the key computational problems in the design of high-speed supersonic aircraft, and a complex problem for which analogue computing was commonly used.

Solving flutter equations was the major computational problem facing aircraft designers. Of all the calculations of aeronautical engineering, historian Paul Ceruzzi described flutter as 'the most urgent'.[43] He noted that theory had surpassed what could be computed easily by hand.[44] 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.'[45] 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 analogue computer application:

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[41] Hollingdale and Diprose (1953) p. 1.

[42] The 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. 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.

[43] Ceruzzi (1989) p. 33.

[44] It was flutter that encouraged Northrop to develop the MADDIDA digital differential analyser. Flutter also inspired the development of the IBM CPC computer. Ceruzzi described Northrop as a midwife of computer application. 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.

[45] Templeton (1955) p. 1.

> …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.'[46]

In this quotation, 'high speed computational aids' actually refer to analogue computing machines. RAE constructed two of these '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. While the digital technique proved viable, it 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.[47]

Solving a flutter problem was a three stage process. The first two steps were preparatory,[48] 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'.[49] The FS III which was in the planning stages in 1955, would work with twelve degrees of freedom.[50]

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.[51]

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

[46] Templeton (1955) p. 1.

[47] ARC (1952–1953), Meeting 2, 16th December 1952, p. 3.

[48] Firstly determining the 'normal modes of oscillation', and then calculating the structural and aerodynamic coefficients.

[49] Templeton (1955) p. 6.

[50] Alongside the modelling of the mathematical equations, RAE also developed smaller analogue 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 analogue computing process (Templeton 1955, pp. 4–8).

[51] ARC (1952–1953), Meeting 3, 23rd January 1953, p. 1.

flutter simulator should be used, while other 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. Together these two characters made a compelling case for the use of digital technology. As a digital computing pioneer, Wilkes was acutely aware of the benefits of 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 analogue was that it could be encapsulated into fairly inexpensive, well-targeted installations. For example, Redshaw saw the special-purpose nature of the flutter simulator as its main strength, thinking that a more generic machine 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.[52]

While pioneers like Wilkes could see the benefits of digital, the technical, engineering communities were resistive to change. This was most likely due to analogue 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.[53]

7.3 Thirty Year Persistence: The Shortcomings of Digitalisation

Despite a consensus early on within the panel that digital computers were the more general purpose and would become the technology of the future, analogue computing remained central to their discussions. A look at the papers circulated towards the end of the panel's existence show that developments in analogue computing were still commonplace in the mid to late 1950s. In the wider context, there was significant use of analogue 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 organising the use of a digital computer, users had a choice, either the aeronautical engineer could write the program himself, or it could be

[52] ARC (1952–1953), Meeting 2, 16th December 1952, p. 2.

[53] ARC (1952–1953), Meeting 2, 16th December 1952, p. 3.

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 required additional learning. 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 digital machines, 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 analogue computers—since the very nature of analogue 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. In 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 analogue for the experimental problems.[54] Engineers liked the idea of having their own machine with a real-time response. Digital computing would create a new culture of waiting for results.[55]

Another concern of the aeronautical engineers was the trustworthiness of digital software. Because engineers had framed their problems in terms of physical phenomena with analogue computing, there had previously been less need to worry about the verification of their models. This tension between the analogue 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 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. . .[56]

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

[54]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 analogue. 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 analogue and digital and emphasised their complementary roles. For instance, the authors note Hartree's involvement with the differential analyser and the ENIAC as 'an excellent early example in avoiding narrow specialisation on either analogue or digital computers' (Hollingdale and Toothill 1970, p. 80).

[55]This would be relieved by the introduction of time-sharing systems, minicomputers and later personal workstations. Perhaps this explains why engineers were not fully dis-enrolled from analogue culture until the 1970s.

[56]ARC (1952–1953), Meeting 3, 23rd January 1953, p. 3. Diprose was, at this time, employed by the RAE.

enough design work and were distracted by calculations. In 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 USA.' However, with respect to British engineering culture, the story was different and many engineers wanted to continue to manage the calculations themselves.[57]

Of course, the digital computer did eventually replace analogue techniques. To return to the story of Pérès and Malavard in Paris, their analogue facility evolved into a centre of hybrid computing, and later a centre of expertise for digital modelling. While the influence of analogue computing as a technology was fading out, it is important to realise that the analogue culture remained. The communities that had been specifically involved with digital computing were focusing on algorithm design, programming languages and machine hardware. Those involved in analogue and hybrid computing started to develop more exotic peripheral hardware involving sound, graphics and other analogue (continuous) electronics. This mirrors what we observed in Chap. 5.

7.4 Conclusion

In contributing to a history of use, this chapter emphasises how the preferences of contemporary actors shaped the history of this technology. Employing a modelling perspective helps show the rich story of analogue 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 analogue 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 analogue, modelling software had to provide the same levels of flexibility, interactivity and visualisation.

Within the ARC computation panel digital proponents 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. They also wanted to have their own machine that would not have to be shared. We saw how one engineer felt that employing a digital machine would make the tool 'not for exclusive use' and reduce 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 analogue 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. Earlier, Chap. 3 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

[57] Goodwin and Hollingdale (1952).

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 analogue computing within the aeronautical community. We have seen how engineers were concerned about the trustworthiness of digital representation, and that they liked having control of their own computing. Recall that Chap. 5 identified that analogue use could be classified into calculation, modelling, and control. Similarly, within the context of aeronautical engineering, equation solving tasks were the first to be digitalised. However, because of the need for digital methods to establish this trust, it was direct analogue computing (such as tanks and networks) that persisted the longest.

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 analogue computing were completely displaced, a whole generation after 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 analogue computing held their trust and supported their professional credibility. It took a generation for the credibility of digital to become fully established.

Chapter 8
The Analogue Dishpan: Physical Modelling Versus Numerical Calculation in Meteorology

The twentieth century saw major developments in the field of meteorology. Many of the major advancements were driven by the use of computers, the application of digital technology enabling complex numerical modelling. 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 analogue? Previous scholarship in the history of computing and meteorology rarely mentions analogue technology. Does this indicate that it was not used at all? This chapter takes a look at this application area and finds that where analogue devices were used, they were generally not electrical, and seldom referred to as computers. We will see how Lewis Fry Richardson—a pioneer of digital modelling—used physical modelling techniques to complement numerical processing. Following the story of the technique he proposed, we move on to discuss the work of Dave Fultz, a meteorology researcher who argued for the benefits of complementing mathematical study with experimental techniques.

Some readers may question whether the technology described in this chapter should be considered computational. Neither electronic nor mathematical, these examples can seem far removed from modern technology. However, these tools were providing alternatives to complex numerical modelling and are therefore part of the broader history of problem-solving and modelling. In previous chapters, this book has argued that historians should look for similarities of practice that transcend technical boundaries. These modelling technologies provide an important perspective on what came before modern computer models. The chapter concludes with a discussion of how these analogue set-ups relate to the history of computer simulation. Within the broader theme of modelling technology, this chapter is an opportunity to explore a context where analogue computing existed, but was not so called.

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[1] Dahan 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).

C. Care, *Technology for Modelling,* History of Computing,
DOI 10.1007/978-1-84882-948-0_8,

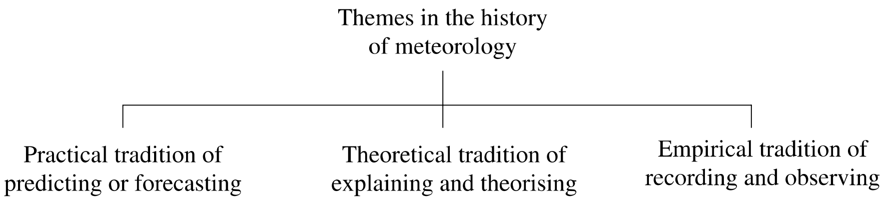

Fig. 8.1 Themes in the history of meteorology. Nebeker describes how the three separate traditions became unified into a single field during the twentieth century

8.1 Computation and the History of Meteorology

The major historical study of computational meteorology is Frederik Nebeker's *Calculating the weather*. In it, Nebeker stresses the centrality of the computer in the development of twentieth century meteorology.[2] Nebeker explains 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 (see Fig. 8.1).[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 describes as empirical and theoretical cannot be understated. Commenting on the history of American forecasting, Kristine Harper notes that most of the early American theorists never actually made a forecast, and that of those who did, few of their forecasts were made public.[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. Before pioneers like Lewis Fry 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. This required vast amounts of weather data to be tabulated and indexed, so that a forecaster could match the current

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[2]Historiographical consensus is that computational influences were 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).

[3]Nebeker (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.

[4]Harper (2003) p. 669.

weather and make predictions. In his book, Richardson presented this activity as highly inexact and unscientific.[5]

During the nineteenth century, computation had a minor role within meteorology. However during 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 analogue 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]

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 analogue. In particular, there was a physical modelling tradition in meteorology that bore resemblance to analogue computing, but was not labelled as such. It appears that for meteorological applications, analogue models were not enrolled into computing culture.[8]

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[5] See Richardson (1922b), preface.

[6] Agar 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.

[7] Agar (1997) p. 118.

[8] Edwards (2000) p. 248, Nebeker (1995) p. 181.

8.2 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 scientific laws.[9] As described below, Richardson is famous for proposing 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 techniques that still made use of the underlying physics. The methods of the so-called Bergen school became widely accepted during the 1930s and were used extensively until numerical prediction became the dominant approach to forecasting.

In terms of analogue computing, it appears that when analogue technology was used in early meteorological applications, it was employed 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 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 analogue computer to show the relationship between solar observations and weather.[12] Although analogue computers were employed as calculating aids in these examples, the historiography indicates that meteorology never became a major application area for electrical analogue technology.

8.3 Richardson's Forecast Factory and His Suggested Analogue 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* published in 1922, he outlined an

[9] Woolard (1922) p. 173.

[10] Bjerknes was called into practical forecasting work during the aftermath of war and therefore favoured those methods that would deliver results quickly. Hunt (1998).

[11] Shaw (1885) p. 164, Scott and Curtis (1886) pp. 382–383.

[12] Nebeker (1995) p. 168, Merzbach (1970) p. 12. See also Hess (1957), Gierasch (1982).

[13] Boulding (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.

approach that, as one historian put it, 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*. His original description of the forecast factory has been quoted in a number of histories of computing.[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 on how to mobilise the computation required to numerically model the Earth's weather. In a room built 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 was not suggesting this as a practical proposal, he had clearly given much thought to the practicalities of the problem. His description of the factory is reproduced below. Although fundamentally a human process, it is essentially a digital solution. However, as the final paragraph of the vision suggests, he also considered an alternative analogue set-up. Richardson writes:

> 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

[14] Lynch (2006) frontispiece.

[15] See Bailey (1993) pp. 77–78, Campbell-Kelly and Aspray (1996) pp. 54–57, Grier (2005) pp. 142–144, Williams (1999).

[16] Richardson 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).

> 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]

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] However, what is particularly interesting is the surprising reference to physical modelling. In the final paragraph, Richardson described a research and development laboratory constructing an analogue model. The actual analogy is not specified, but Richardson intended the behaviour of eddy currents in a spinning bowl to correspond to atmospheric flow patterns. Whether or not such a tool would be considered a *computer* is debatable. However, Richardson presents this set-up as a possible alternative to the 'myriad of [human] computers', and therefore, in some sense, as an alternative computing technology.

Throughout this book, we have taken a pragmatic approach to defining analogue computing. As a physical model conceived to replace conventional calculation, this rotating tank would be similar to many of the direct analogues already discussed. Furthermore, this kind of device did actually exist. Although not used for forecasting, the rotating bowl technique had a renaissance during the 1950s. Described as 'rotating dishpans', they were used to model atmospheric Coriolis forces caused by the rotation of the Earth. Modelling atmospheric flow with fluid flow, they provided a scaled experimental environment for laboratory experimentation.

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', highlighting that the relative merits between numerical and physical were not always clear cut. There appears to be two sides to Richardson's character: firstly Richardson the pioneer of the numerical method, the visionary of highly parallel digital computation; and secondly Richardson the quiet experimenter, working on a physical model. Being a celebrity character in the history of mathematical forecasting,

[17] Richardson (1922b) pp. 219–220.

[18] While the forecast factory was always described as a fantasy—'Richardson's dream' to quote Peter Lynch—the reality of human computing organisation based on factory economics was a reality. The *Oxford English Dictionary* records that the original usage of 'computer' refers to humans engaged in calculation or reckoning. There is now a significant body of 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).

[19] Richardson 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.

Richardson is usually portrayed as a pioneer of the mathematical method.[20] As such, it can seem unclear why he would have considered developing an analogue device.

As we will see below, Richardson did attempt to construct his spinning bowl while serving in the First World War. Using a basin of water on a rotating gramophone turntable, he constructed what he described as a 'working model' of the atmosphere.[21] Although he did not develop this initial experiment further, a copy of his research notes were passed on to the experimental meteorologist Dave Fultz of the University of Chicago, who was developing similar models of atmospheric motion.[22] We will return to the history of rotating fluid analogues 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'.

8.3.1 Richardson: Mathematician, Experimentalist, Quaker

To explore the tension between experimental and numerical approaches in Richardson's work, it is necessary to understand a little about his background. Richardson was born in 1881 in Newcastle-upon-Tyne, the seventh child of a Quaker family. He was well educated: first attending a Quaker school in York, followed by Durham College of Science in Newcastle, and subsequently King's College, Cambridge. After leaving Cambridge, Richardson entered a wilderness period, frequently moving between various teaching and research posts.[23] His 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.[24] During this period he undertook a variety of both practical and theoretical work.

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 their 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

[20] Richardson's whole career can be interpreted in terms of the application of mathematical modelling. This theme is clear in the recent review of his work by Hunt (1998). Nicholson (1999) noted that through all of his work ran the common theme of mathematical analysis and 'rigorous statistical methods' (p. 542).

[21] Ashford (1985) p. 71.

[22] We can assume that Fultz became aware of this early work from the description of the forecast factory. Oliver Ashford, Richardson's future biographer, supplied Fultz with a copy of Richardson's manuscript notes (Fultz et al. 1959, p. 4).

[23] He graduated in 1903 with first class honours in part I of the natural sciences tripos (Anon. 1903).

[24] 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 punctuated by many short-term contracts (p. 10).

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 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. For example, his Royal Society obituary describes how David Brunt, then a student at Aberystwyth and later an eminent meteorologist, recalled how he was always devising new instruments or techniques:

> ...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 experimentation 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

[25]His 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, Seigfried Sassoon, Robert Graves and other littérateurs wrote poems, autobiography and autobiographies disguised as novels; Richardson wrote equations' (p. 544).

[26]Examples include a technique to measure wind direction and speed by projecting spheres into the air, and various work on weather balloons.

[27]Hayes (2001) p. 10, Lynch (2006) p. 254, Ashford (1985), Anon. (1929, 1953), Gold (1953).

[28]Hayes (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).

[29]Sir David Brunt quoted in Gold (1954).

[30]Hunt (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)' (pp. xix–xx).

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]

We can therefore identify several factors that shaped Richardson's life and career. The prime factor was his passion for research in the mathematical sciences, and his particular interest in expressing complex systems with formulae. This is 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 interdisciplinary interest in research, we can begin to understand how both a physical analogue and mathematical computation could be considered part of the forecast factory.

8.3.2 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 Dif-*

[31] Herbert Morrell quoted in Ashford (1985) p. 57.

[32] Described by Ashford (1985) p. 113, and published as Richardson (1922a).

[33] Ashford 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. See Ashford (1985) p. 16.

[34] Richardson'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.

[35] Lynch (2006) describes how the idea of applying the numerical methods Richardson had devised in 1910 to meteorology had come to him gradually. The first record of a specific connection is in a letter to Pearson dated 1907, but Richardson's serious investigations on numerical forecasting began during his employment at Eskdalemuir.

ferences—to the Royal Society.[36] However, Richardson's desire to add a practical 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. Alongside these numerical studies he undertook many experiments investigating weather balloons, thermometers, and other instruments. Richardson was not a man to specialise, he maintained several different research careers throughout his working life. It is therefore not surprising that Richardson had multiple research agendas within meteorology.

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. 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.[37] Using the bowl he experimented, without success, with the effects of heating, mimicking the temperature variations on earth between the polar and equatorial regions. As his notes record:

> 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.[38]

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 Fig. 8.2) 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]

> 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

[36]The 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).

[37]Richardson (1916–1919).

[38]Richardson (1916–1919).

[39]Richardson (1916–1919). Also see Ashford (1985) p. 71.

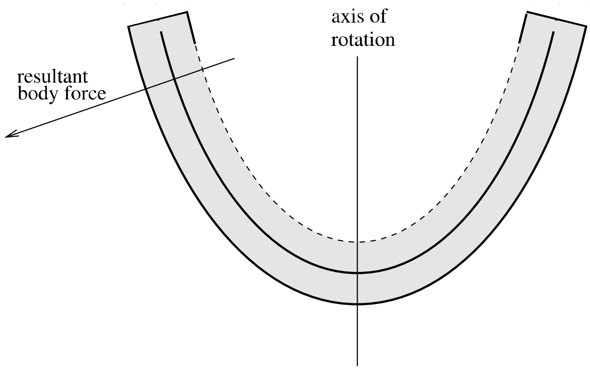

Fig. 8.2 A sketch of Richardson's double rotating bowl for modelling the atmospheric interactions between two hemispheres. One parabolic shell (*black curve*) is shown within another; the liquid (*shaded*) represented the atmosphere, and the inner shell, the earth's surface. Source: based on an original drawing amongst Richardson's papers in the special collections of The University Library, Cambridge (Richardson 1916–1919)

> 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.[40]

There is no evidence to suggest that Richardson ever extended his initial study. Certainly, the scope for further experiment was limited in France,[41] and by the time he returned to England, the two major topics on his mind were the completion of his book, and the design of weather balloons.[42] For Richardson, the dishpan experiment would not become a serious avenue of his meteorological research.

As discussed above, the expectation might be that as a pioneer of numerical weather prediction, Richardson's own activities would be firmly in the digital camp. His reference to analogue computing therefore appears an oddity. It is, however, possible to account for Richardson's involvement in terms of the major driving forces in his career: practical experiment and mathematical modelling. 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, 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 it very natu-

[40] Richardson (1916–1919).

[41] Ashford (1985) noted that '[t]he facilities available in France were obviously inadequate for Richardson himself to follow up these ideas.' (p. 71).

[42] In 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.

ral to be an experimentalist.[43] Considering Richardson's empirical background, we can conclude that it was not unusual that he should have considered analogue modelling. Working before the unification that Nebeker described, both analogue and digital approaches had credibility.

Actually, Richardson was not the only person to try to create a model of atmospheric motion. 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.[44] It was only after 1940 that the models could be measured to derive quantitative data; early models were purely qualitative.[45] Between Vettin's investigations and the 1940s, several passing (and seemingly independent) references are made to these 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 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.[46]

After 1900, various sources record meteorologists constructing spinning-bowl models. Writing in 1902, Bigelow indicated that he had seen a rotating experiment

[43]The 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.

[44]Fultz et al. (1959) p. 4.

[45]Fultz et al. (1959) notes 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).

[46]James Thomson 1892, as cited in Fultz et al. (1959) p. 4.

and in 1907 Cleveland Abbe also described their use. In addition to Richardson's experiment in 1918, a similar investigation was undertaken by Felix M. Exner in the 1920s. Exner's pan was one metre in diameter and 15 cm deep. To model the temperature difference, the perimeter of the pan was heated by a ring of gas flames and the centre of the tank was cooled. He used a block of ice as a cold source, and froze ink into that ice in order to trace the movement of cold water. Exner's tank had a period of rotation between three and seven seconds. In 1929, Carl Rossby at the United States 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 between three and four times a minute. Another similar experimental environment was Prandtl's rotating room (Karrussell), a three metre diameter space in which experiments were conducted. Prandtl was also reported as having attempted a dishpan experiment in a rotating room but the behaviour was deemed 'too irregular and ill-defined'.[47] He emphasised the importance of both experimental and theoretical research, and helped establish practical laboratories for investigating aerodynamics.[48]

Earlier in this book, we noted that physical modelling often became redefined into analogue computing. By 1950, the culture of the fast developing computational science of meteorology meant that an analogue computer was not credible in this setting. However, as an experimental approach, analogue models did have credibility. 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 analogue models were not an *alternative* to computational meteorology. However, they still provided useful results. Within meteorological science, these devices did not represent an analogue computing tradition, but they did represent an experimental tradition.

8.4 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 indicate the avenues of further study and research.'[49] Divided into 24 categories, its coverage ranged from discussions of the physical properties and dynamics of the atmosphere—such as atmospheric electricity, cloud physics, and atmospheric

[47] Fultz et al. (1959) p. 5.

[48] See Busemann (1960) p. 197.

[49] Malone (1951) p. v. The project was directed by a committee of seven prominent meteorologists and chaired by H.G. Houghton.

dynamics—through to meteorological optics and climatology. Practical issues were also 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’. The remaining articles discuss other modelling techniques in meteorological research and cloud formation, and were written by the American engineer Hunter Rouse and the British meteorologist Sir David Brunt.[50] 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.’[51] 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.[52]

According to Edward Lorenz, Fultz was the first to develop a physical atmospheric model that was able to ‘bear fruit’.[53] The main inspiration for Fultz’s dishpan experiments was the work of Carl Gustaf Rossby, who had already prototyped some basic models at the United States Weather Bureau. Rossby was of Swedish birth and had originally studied in Europe under Bjerknes. He moved to the US in the 1920s, and held a number of research positions at both the US Weather Bureau and the Woods Hole Oceanographic Institution. In 1940 Rossby moved to the University of Chicago where he became a founding member of their Department of Meteorology. Fultz was one of his students and received his Ph.D. in 1947.[54]

Within his Chicago laboratory, Fultz 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 (see Fig. 8.4). Just as Richardson had suggested in 1918, Fultz collected data with a camera that rotated

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[50] Rouse (1951), Brunt (1951). Rouse was extensively involved in the use of analogue 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. See Agar (1996).

[51] Fultz (1951) p. 1235.

[52] Fultz (1951) p. 1235. © American Meteorological Society. Reprinted with permission.

[53] Lorenz (1995) 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).

[54] Fultz’s Ph.D. thesis was entitled *Upper-air trajectories and weather forecasting*. Clearly a practical experimenter, included in his thesis is a card slide rule for deriving vorticity trajectories.

Fig. 8.3 Dave Fultz in a laboratory setting. © University of Chicago News Office, reprinted with permission

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.[55] Work began on first the Chicago dishpan in December 1946. Also similar to Richardson's design, the apparatus consisted of two hemispherical shells, one inside the other.[56] Over the following decade Fultz used his dishpans to undertake various investigations. He was still publishing papers on their use in 1959.

Fultz was not the only person Rossby had encouraged to develop experimental dishpans. During the early 1940s Rossby approached Athelstan Spilhaus to join a project at Woods Hole to build a rotating dishpan. The pan he built had a diameter of six feet. However, Spilhaus did not share Rossby's passion for visualisation. In an oral history interview, Spilhaus recalled that the experiment had provided a successful visual model, but that in his opinion, did not yield any new results. In 1942 he joined the war effort and left Woods Hole.[57] Von Arx carried on the dishpan research and later constructed an even larger pan with a diameter of eight feet that was able to reproduce more interesting phenomena such as cold and warm fronts. In the following years this large dishpan was used for a number of research projects, and was in use well into the 1960s.[58] In 1962, Marvin White made use of the apparatus to model solar activity. White writes how he had noticed that Fultz's images looked very much like photographs of the surface of the sun, and used the dishpan to model circulation in the solar atmosphere.[59]

For meteorologists like Fultz, experimental culture was a vital complement to the development of mathematical theory. 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.[60]

Although the dishpan experiments represent a physical rather than mathematical tradition, they were nonetheless important for knowledge discovery. Through his experiments Fultz was able to discover interesting chaotic properties in atmospheric flow. His view was that in the study of large-scale geophysical and meteorological systems, experiment was complementary to mathematics. He argued that the discipline would be revitalised by a combination of experiment, theory, and observation.[61]

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[55] Lorenz (1995), p. 92, University of Chicago (2002).

[56] The hemispheres were Pyrex flasks sized 5 litres and 3 litres. See Fultz (1949).

[57] AIP (1989).

[58] Faller (1956).

[59] White (1968).

[60] Tom Spence quoted in University of Chicago (2002) © University of Chicago News Office, reprinted with permission.

[61] Fultz (1961) p. 2.

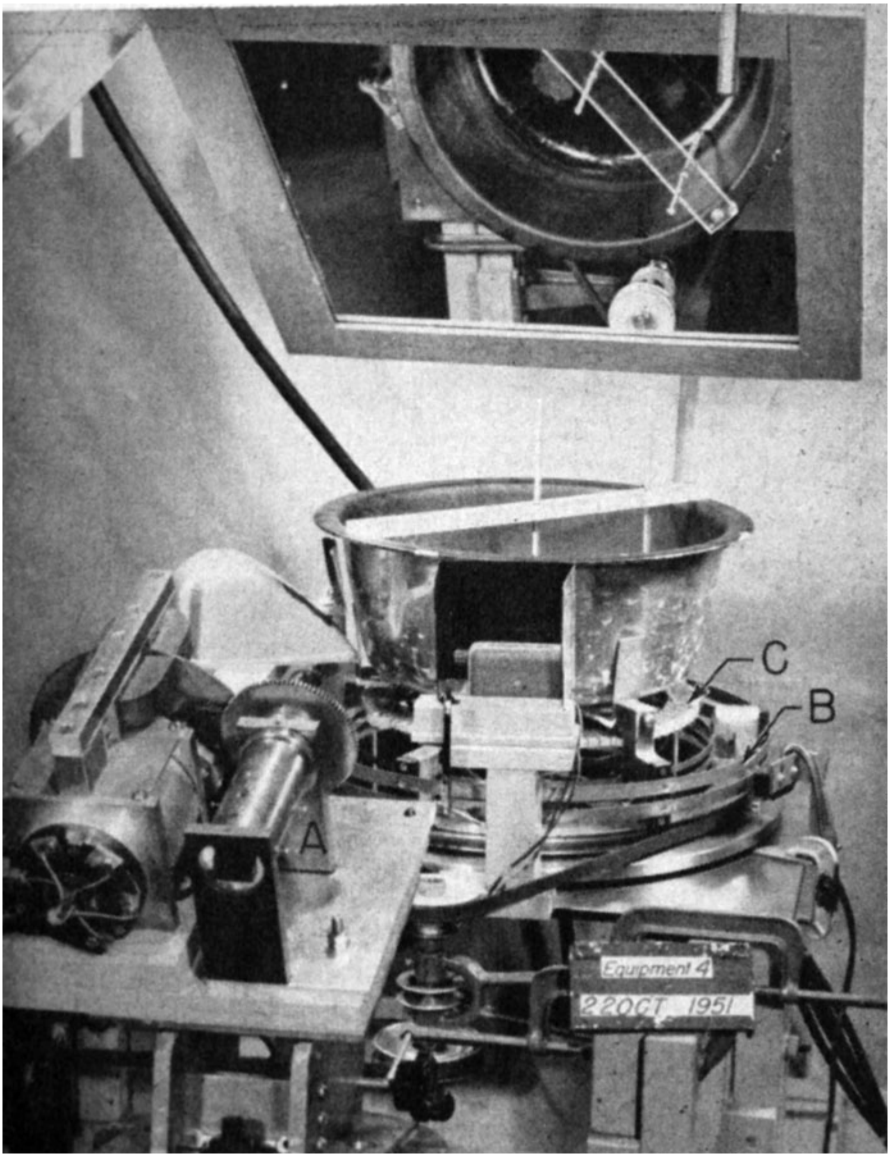

Fig. 8.4 Fultz's dishpan apparatus. In the centre of the image is the rotating metal bowl filled with water. Above the bowl is a mirror to reflect the view from above, and in the foreground is a camera directed at this mirror to capture the changes in flow. Source: Fultz et al. (1959) p. 6. © American Meteorological Society. Reprinted with permission

8.5 Conclusion

Apart from brief analogue 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.

When dishpans became a serious research activity they were not portrayed as computing aids, but rather as modelling tools for investigating atmospheric theory. For Richardson, these were clearly interrelated. Hence Richardson's comment 'but so far the arithmetic proves the better way'. This emphasises that physical modelling and mathematical calculation were alternative approaches for problem solving. This chapter has shown that within meteorology the physical analogues and experimental culture that elsewhere were enrolled into a discourse of analogue computing were separate. Not part of *computing* culture, 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 impact of theoretical classifications in shaping history. In previous work on the history of computing, meteorology is perceived as a stronghold of digital application. Through looking at the practices, we see that the boundaries between computational and non-computational differ from context to context.

This chapter is not the first study to associate the dishpan experiments with the history of analogue computing. It is interesting that in a recent study into the Phillips Machine, Vines (2000) identified correspondences between the Phillips Machine and Fultz's dishpans. Earlier in this book, we discussed how the Phillips Machine was not really a computer in a conventional sense, but that its primary quality was as a tool for visualising and reasoning about a complex system.[62] For Vines, the Fultz dishpan and the Phillips Machine supported the same kind of modelling. Models of this kind are always a major simplification of the actual complex process. However, Vines argues that, despite its simplicity, the machine 'provoked' a deeper insight into economics that fuelled Bill Phillips' later work.[63] Writing about Fultz's dishpan, he wrote:

> Reading about Fultz's inspired dish we can immediately see how it might be a strong guide to intuition for meteorologists. The insight which it provokes works by analogy. Nobody would claim that the dish 'was the weather' or that it provided a substitute for a mathematical model of the weather. But the insight is nonetheless powerful: the dish helps the observer see how such a model might be constructed.[64]

Whether this type of modelling environment should form part of the history of analogue computing (or the wider history of computing) could be argued either way. However, there is no doubt that if Dave Fultz or Bill Phillips were trying to build their models today, they would probably be directed toward a software package installed on their desktop computer. Despite the power of physical modelling, the

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[62] See Sect. 4.2.4, p. 83, above.

[63] Vines (2000) p. 58.

[64] Vines (2000) p. 41.

sophistication and confidence surrounding scientific software encourages modern scientists to create computer models and simulation. Both Fultz and Phillips built their models around 1950, at a time when digital computers were not as sophisticated, and the visual interactive quality of this type of experimentation had a more natural home with physical models and analogies. Within some fields, this practice of analogy-making was associated with computing, in other fields, it was not. However, regardless of their contemporary classification, these tools shared the same future: a future where physical models would be replaced by digital computing and software modelling. Whether or not they were computers, the dishpan models are certainly part of the history of pre-computational modelling.

Chapter 9
Conclusion

This study opened with two main observations of analogue computing. The first related to technological classification and the complexity of defining 'analogue computing'. The second noted that the major use of analogue computers was for modelling, indicating that the technology should be situated within a wider history of modelling technology. The first was an observation about analogue identity, the second was a more practical observation regarding analogue use.

Inspired by the first observation, the early chapters of this book investigated the theory and identity of analogue computing, discussing the origin of its classification and the evolution of its culture. Today, the analogue–digital classification is widespread: it is commonly used to distinguish between different media formats for music, and for different broadcast technologies (such as digital radio and television). Much of this use of analogue–digital has evolved from the technical use of the terminology in electronic and signal processing engineering. However, investigation into the analogue–digital classification showed that the labels 'analogue' and 'digital' originated in the classification of computational technology.

When originally used to classify computing technology, the word 'analogue' was chosen because it is derived from *analogy*. To fully understand analogue computing, the two key themes of continuity and analogy must be held in tension. Following these two conceptual themes, Chap. 2 demonstrated that two perspectives of use—equation solving and modelling—emerged from different types of analogue. In this chapter we saw that the historical sources fully support this distinction, and that when describing the pre-1940 history of analogue computing, it makes sense to narrate the history as two separate chronologies. The term 'analogue computing' brought these two themes together: creating a computational technology that could be used for both direct and indirect modelling. Direct analogues modelled actual physical relationships, whereas indirect analogues supported the solution of equations.

In identifying the two parallel histories of equation solving and modelling, it became clear that most scholarship had considered analogue computing as a calculating machine. Hence there was far less coverage of early analogues (often called 'electrical analogies') such as electrolytic tanks and resistance networks. Within

C. Care, *Technology for Modelling,* History of Computing,
DOI 10.1007/978-1-84882-948-0_9, © Springer-Verlag London Limited 2010

the theme of information processing, direct analogues (being special purpose devices) can appear insignificant. However, the meta-narrative of modelling developed in Chap. 3 helps explain why users often needed this technology. We can see that analogue computing fits within a historiography of modelling. When used as a modelling machine, analogue computing technology was not just an information processor, it was also acting as an information *generator*. When engineers argued for the merits of analogue computing, they were usually arguing for a machine that they could model and think with.

An important period in the history of analogue modelling is the use of electrical analogies during the early twentieth century. Tracing the formation of the culture of electrical analogy during the 1920s, Chap. 4 demonstrated that direct analogues 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 analogue computing and its use as a modelling technology, the second half of the book 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 analogue oil reservoir simulator. These studies explored the role of analogue–digital classifications in procurement decisions, and drew a distinction between ‘normal’ and ‘innovative’ computing. Chapters 7 and 8 discussed the relative merits of analogue and digital, identifying the qualities that made analogue 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 analogue historiography by focusing on modelling (the application), rather than analogue (the technology). They discuss the broader technologies that existed before electronic analogue 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. Analogue classifications shaped the formation of user communities as well as informing analogue–digital decisions over procurement and funding. In terms of use, different analogue applications followed different historical trajectories, and each application domain fuelled discussions of the technology’s suitability and applicability.

9.1 Three Principal Conclusions

The conclusions of this book 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 analogue community; and third, that where analogue–digital debates existed, concerns of analogue users related to their specific requirements rather than to the technology's merits. These debates were based on concrete use, not abstract theory.

9.1.1 Multiple Perspectives of Use Informing Multiple Historical Trajectories

One of the major findings of this study has been to acknowledge the importance of multiple perspectives of use in the history of computing. In Chap. 2 we observed that analogue computing could be separated into the two themes of calculation and modelling. Distinguishing between these two themes also helped clarify the was shown to assist with confusing definitions over the scope of 'analogue computing', one example being the disagreement over analogue identity being continuity or analogy.[1] Addressing both themes in parallel not only respects the distinction made in the original source material, but it also avoids history having to rely on watertight definitions of analogue computing in order to define its scope.

In Chap. 3 it was argued that analogue computing should be interpreted within a context of 'computer as modelling machine'. Furthermore, Chap. 5 suggested that the three main applications of analogue computing were calculating, modelling, and control—digitalisation occurring in separate stages for each application type. Analogue use for calculating and equation solving was replaced first, then analogue computing for modelling and simulation, and finally analogue components for control systems.

Multiple perspectives of use help explain the persistence of analogue computing. For instance, the BP computer could be perceived as a 'backward technology' 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 analogue in normal use. An example of normal computing, analogue computing was a popular tool that many users did not need to displace. Thus although digital might have been superior, analogue was still in use due to cost, simplicity, and general user expectations. Technological advancement from analogue to digital computing covers a significant period, and this was partly because digital techniques had to be individually developed and popularised for each application domain.

As shown in Chap. 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

[1] As exemplified in Small (2001)'s critique of Campbell-Kelly and Aspray (1996) (see Sect. 1.2 p. 9, above).

introduced in Part I, Part II of this book demonstrated how user culture shaped the theory and classification of analogue computing.

9.1.2 Classifications and Social Associations in the Construction and Deconstruction of Analogue Culture

If multiple perspectives of use (the practice) were shown to have shaped the theory, this book has also demonstrated that the theory and associations derived from technical classifications also shaped analogue use.

The history of analogue computing is a complex web of multiple histories of use. Thinking about associations, keywords and classifications provides a framework for demonstrating how analogue culture was enrolled into (and subsequently dis-enrolled from) computer discourse. The enrollment of 'electrical analogies' into the discourse of computing created theoretical associations between technologies. In turn, these associations subsequently guided how the users of analogue technology approached and perceived their tools. In Chap. 4 we saw how positive association permitted the enrollment of devices like the Phillips machine and the Jerie analogue into the technological frame of computing. We saw how analogue culture evolved around the developing associations between technologies, concepts, and use. This process of users and technologies being enrolled and dis-enrolled in and out of analogue culture has left a legacy of inconsistent definition. This mirrors Mindell's observation that the pathway from analogue to digital was 'neither instant, obvious, nor complete'.[2]

In Part II, we saw how this analogue 'identity' shaped various contexts. Within the technical culture at BP, analogue technology had a positive association with computing. Both digital and analogue technologies were 'computers' and therefore innovative technology. As such they had publicity value, and their installation was announced in annual reports and press releases. In contrast, a look at the field of meteorology in Chap. 8 showed that a domain dominated by digital did use direct analogues, but that these devices were not classed as computers. At BP, analogue and digital computers were both part of a coherent modelling tool-set. Within meteorology, analogue set-ups were not computational tools.

So in some contexts, analogue and digital were both computers and the analogue technology benefited from this positive association. However in Chap. 5, we observed that the ultimate consequence of this classification was that analogue's relationship with computing would turn sour. Within the university setting, early use analogue computing had flourished through its positive association with digital. But the positive association gradually became negative. Over time, digital became the preferred form of 'computer'. As a direct result, it became difficult to fund analogue technology as *computers*. Despite universities wanting to procure them, government

[2] Mindell (2002) p. 10.

policy defined analogue machines as a backward technology. The result was that associations began to break and the technology became redefined as laboratory equipment. Analogue'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 analogue became a kind of 'poor relation' of computing.

This technical redefinition of analogue computing triggered a redefinition of the analogue community. In terms of analogue culture, many analogue experts within higher education began to redefine their expertise and move into new fields of research. Those who were involved in analogue (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 analogue computing, but required expertise and interest in analogue electronics, digital computing, and programming. Analogue laboratories often had this blend of interests, equipment and personnel.

By incorporating labels and classifications into the history of analogue computing, we see the relationships between classification and use. Through associations embedded into classifications such as analogue–digital, a technology's theory creates structures that, in turn, shape its practice and use.

9.1.3 Analogue–Digital Debates Were Application Based not Technologically Based

Throughout the book, we have seen a variety of analogue–digital debates. In the chronology of continuous calculating machine (see Chap. 2), we have identified an early analogue–digital exchange between Hele-Shaw and Henry Babbage. Similarly, Chap. 4 discussed the work of George Philbrick and the rhetoric of his 'Lightning Empiricism'. In Chap. 5, we saw the analogue versus digital discussions surrounding how analogue computers should be funded for higher education. Within the context of meteorology there was no obvious analogue debate, but there was an empirical-computational debate over the role of physical modelling versus numerical computation.

However, a cultural split between analogue and digital was not always evident. For instance, at BP the engineers did not engage with analogue–digital rhetoric. Any perceived importance of digital over analogue 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, analogue and digital are better understood as complements. When engineers opted for analogue computers, they were not making a complete commitment to the technology. Instead they were making an assessment of its applicability to a specific application that need to be solved in a specific time frame. Engineers were content with some application areas being suited to digital and others to analogue. 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 analogue computing was replaced by digital, it is evident that there was a continuity of practice through a process of redefinition: analogue users evolving into digital users. Thus, as well as understanding the distinctions, a broader account of use must consider the coherence between analogue and digital. We have, therefore, tried to explore the coherence between the two technologies. By considering computers like the MADDIDA,[3] which borrowed technological principles from both analogue and digital, it becomes possible to separate 'analogue thinking' from 'analogue technology'. This introduces the idea of partial failure: superseded technology, but common approaches and practice. These analogue–digital debates relate primarily to the applications supported by analogue, those that supported rich interaction and visualisation. Technical enthusiasm was not based on the technology, but on the type of use it afforded. Because analogue methods evolved into digital techniques, digitalisation was only a partial 'failure' of analogue computing.

9.2 Challenges for Future Scholarship in the History of Analogue Computing

Within the theoretical theme of understanding analogue computing, this book has shown that associations between technologies and concepts were central in shaping analogue culture. Although this book has begun to investigate the formation of analogue culture, it has only begun to discuss the issues surrounding user disenrollment. Earlier we identified how university researchers redefined their analogue expertise into digital modelling and simulation. Future work should look in more depth as to how analogue users were retrained in digital methods. We also identified the importance of analogue's trustworthiness. It would be interesting to investigate how this trust in these methods was established.

One area that would particularly benefit from further scholarship is the story of hybrid computing. For many contemporary users of analogue computing, hybrid technology was the preferred way to blend the merits of analogue and digital. Although this book and previous work discuss hybrid computing, it would be helpful 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 goals of this book was to re-organise the history to reflect multiple types of use. Any future work relating to analogue computing should be informed by taxonomies of use instead of the confusing technical classifications of analogue–digital. The case studies of Part II touched on many important applications areas relating to modelling. In particular, this book has undertaken significant archival research into the histories of reservoir modelling, aeronautical modelling, and meteorological modelling. Each of these investigations could have expanded

[3] Section 2.5.2.3, p. 51, above.

into a full study and would provide an interesting topic for future research. By approaching these contexts from the perspective of modelling technology (instead of analogue computing) future investigation could show how a history of modelling technology sits across the analogue–digital boundary.

9.3 Concluding Remarks

In the centuries prior to 1900, analogue 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 analogue 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, analogue–digital becomes a less important classification. By exploiting the framework of modelling, this study has been able to look at the users of analogue 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 analogue computers, and helps explain the context of analogue–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 analogue–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 even analogue culture, all transcend the modelling medium and still exist today.

Perhaps the findings of this book imply that analogue computing should no longer be an independent area of scholarship. We see that the issues are not so much analogue versus digital, but rather modelling versus equation solving. Just as the pioneers of analogue 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 analogue computing and the use of digital modelling and simulation.

In Chap. 1, we discussed Michael Mahoney's call to consider 'software as medium of thought and action' and investigate 'how we have put the world into computers'.[4] The challenge to the next generation of scholarship is not to consider analogue 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 how these technologies fit into the wider history of computer modelling.

[4] Mahoney (2005) pp. 107–108.

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