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-

[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).

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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)

[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.

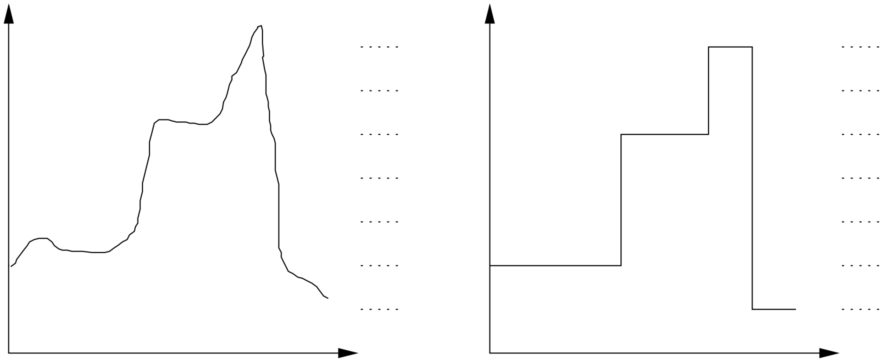

Fig. 2.1 An example of an analogue and digital signal varying over time. The signal on *the left* varies over a continuous range to the granularity imposed by physical properties. The signal on *the right* has been digitalised over a range of discrete values. Alongside analogy, continuity is a second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

[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).

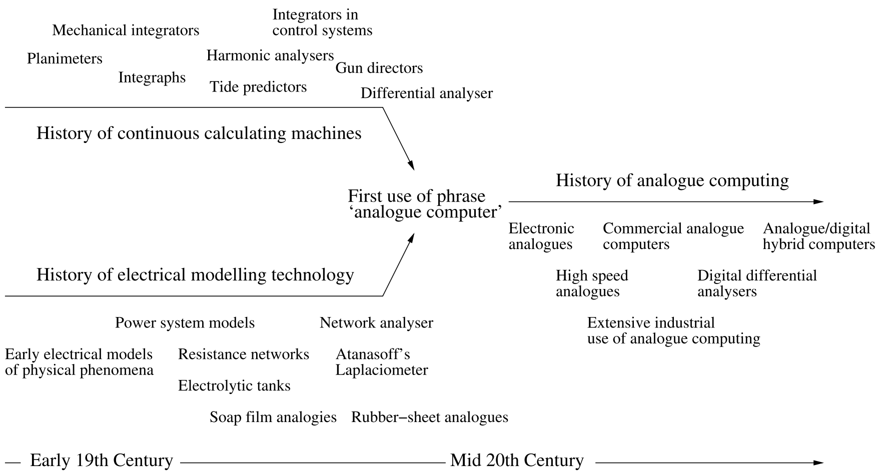

Fig. 2.2 The three strands of analogue chronology. This diagram provides a rough overview of the history of analogue computing. This rest of this chapter provides the detail of this three-stranded time line. Section 2.3 addresses the history of continuous calculating machines; Sect. 2.4 discusses the 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).

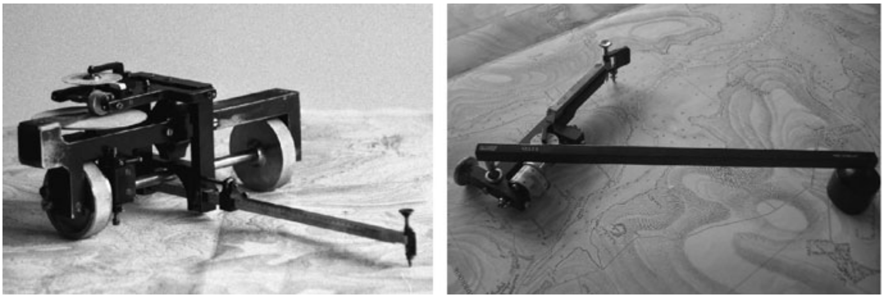

Fig. 2.3 A rolling disc polar planimeter (*left*) and a compensating polar planimeter (*right*). Images © Carina Care 2004

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).

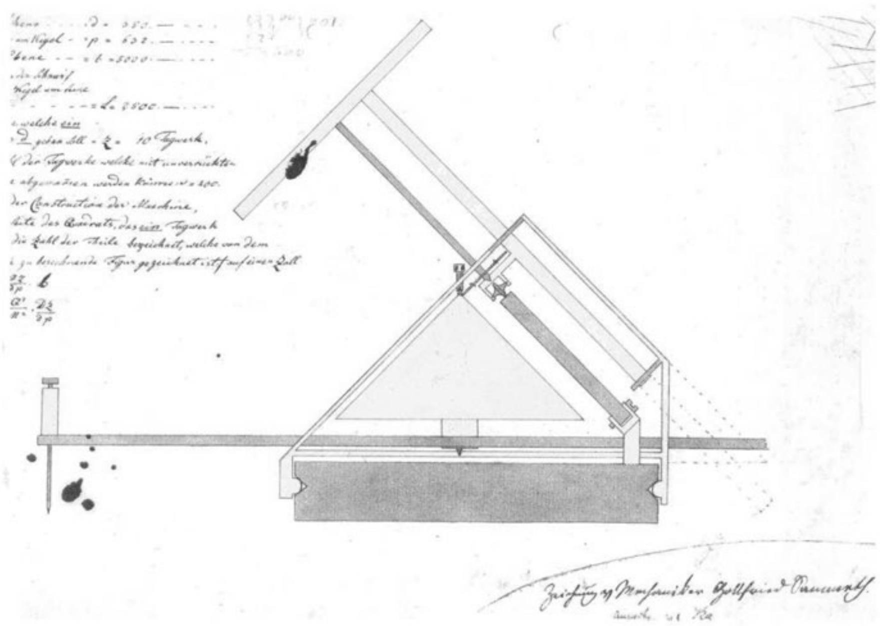

Fig. 2.4 An early drawing of the Hermann planimeter. Source: Bauenfeind papers, Deutsches Museum

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).

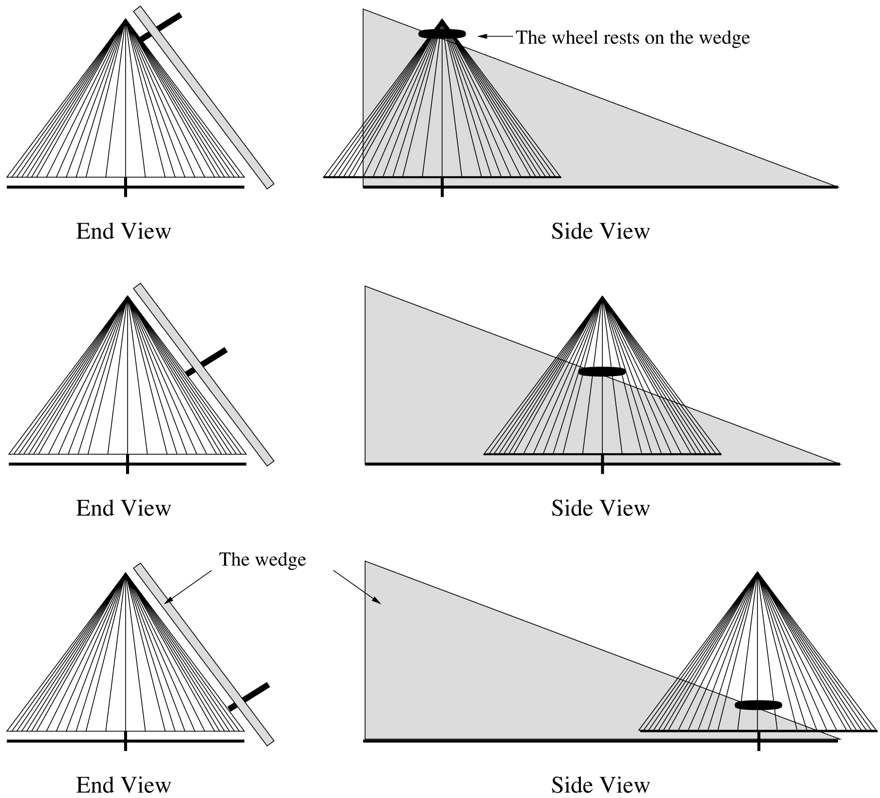

Fig. 2.5 A modern of the variable gear of the Hermann planimeter. The illustration shows how a wedge was used to guide the wheel up and down the edge of the cone as the mechanism slid along its track

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-

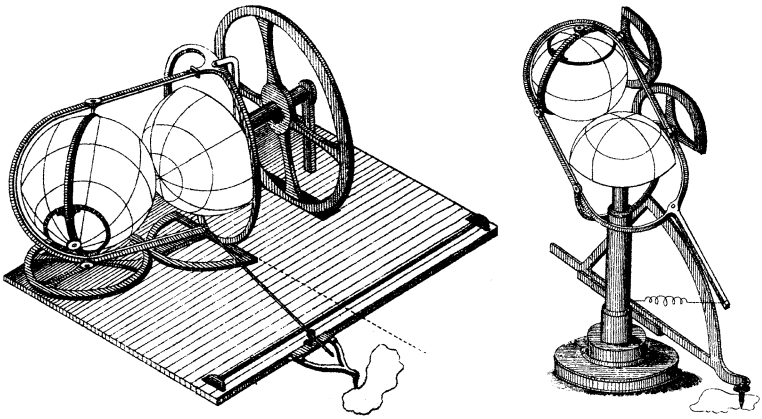

Fig. 2.6 Maxwell proposed two planimeter designs based around his pure-rolling sphere-on-hemisphere mechanism. One (*left*) corresponded to integration over Cartesian coordinates and the other (*right*) to polar coordinates. Source: Maxwell (1855b). Reproduced with the permission of Cambridge University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

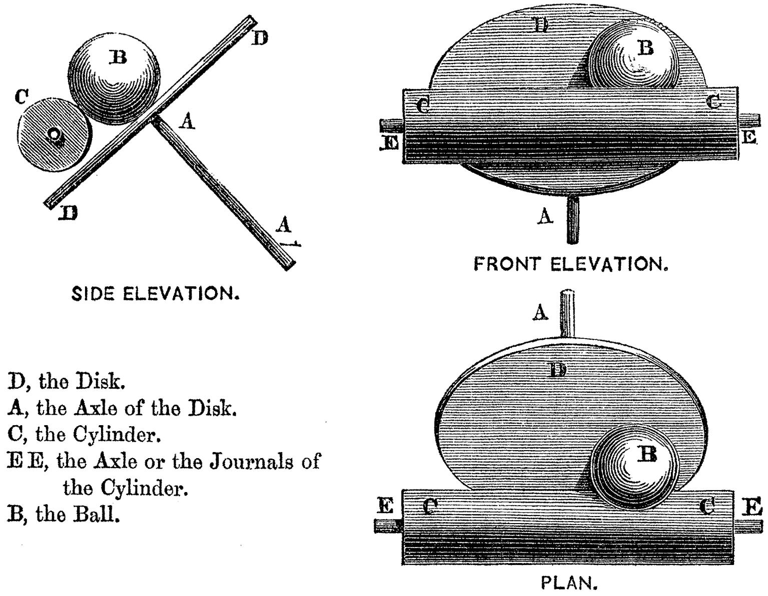

Fig. 2.7 The Thomson 'Integrator' employed a wheel and sphere mechanism. It is similar to the Wetli wheel-and-disk mechanism but uses some of the enhancements of pure rolling that Maxwell argued were so important. Source: Thomson (1876a)

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.

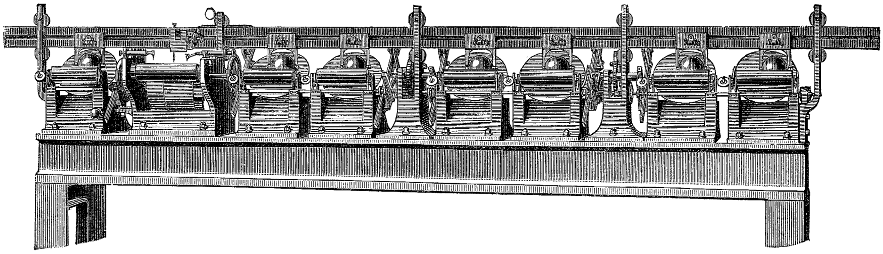

Fig. 2.8 Line drawing of the Kelvin harmonic analyser. Source: Scott and Curtis (1886)

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

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[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.

[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.

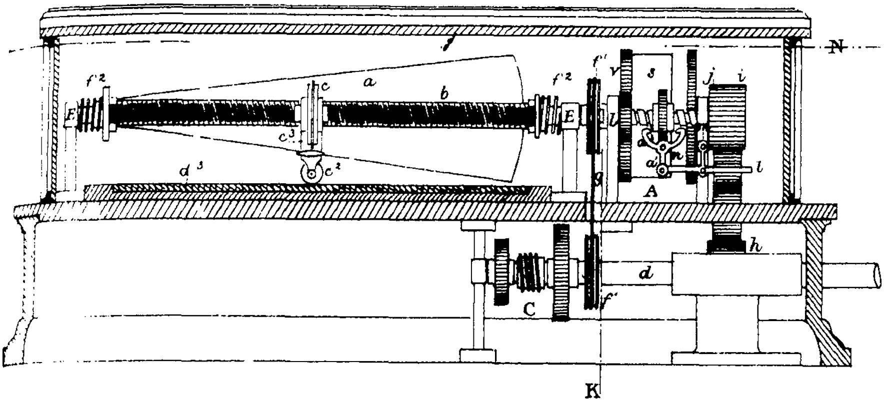

Fig. 2.9 Side elevation of the 'Blythswood Speed Indicator', the cone is clearly visible, the wheel (viewed here sideways-on) is halfway along its shaft. Source: Campbell and Goolden (1884). Reprinted with permission of The Institute of Physics

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.

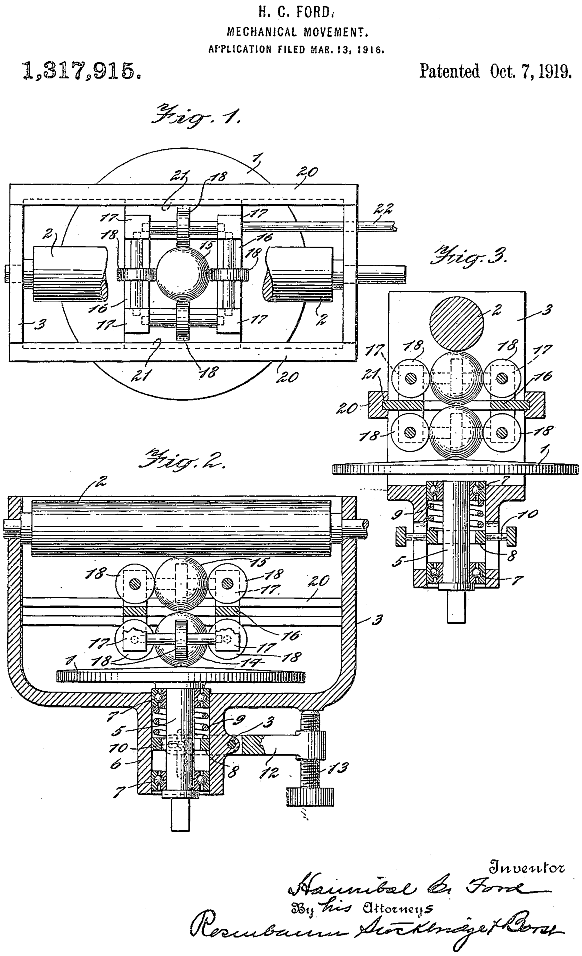

Fig. 2.10 Images from Hannibal Ford's patent for an integrator. The disk and cylinder inherited from the Thomson integrator are clearly visible. Source: Ford (1919/1916a). Ford's integrator employed a spring to compresses the disk on to a double-sphere mechanism, delivering maximum torque, an invention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

[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.

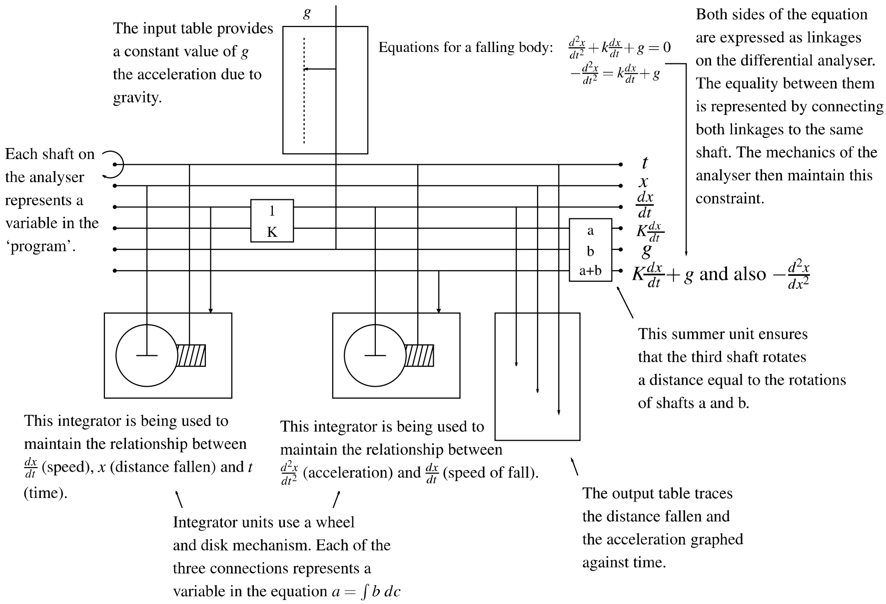

Fig. 2.11 A 'program' for the differential analyser of a free-fall problem. Each linkage between shafts corresponded to a different mathematical operator in the original equations. Based on an example given in Bush (1931) p. 457

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.

[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

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[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).

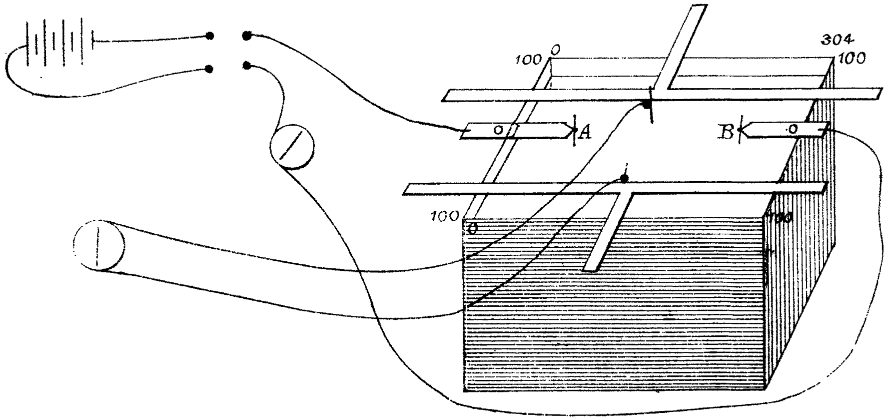

Fig. 2.12 A diagram of Adams' electrolytic tank from his original paper. The fixed electrodes are marked *A* and *B*, the mobile electrodes are connected to the T-shaped handles. Source: Adams (1876). Reproduced courtesy of the Royal Society

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

[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:

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[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).