The Centralization of Scientific Computation in Britain 1925-1955

Mary Goretti Croarken

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Department of Computer Science
University of Warwick
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Dedication

To Julian

With The Help Of God

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Declaration

The work presented in this thesis is, except where stated, my own original work. No part of my thesis has been submitted in support of any other degree at any other university.

Summary

This study examines the organization of scientific computation in Britain over the period 1925-1955. At the beginning of the twentieth century most scientific computation was performed by individuals using logarithm tables and slide rules. By the late 1920s desk calculators and accounting machines had become common computing tools. This thesis looks at the adoption of mechanized computing methods by scientists and traces the centralization of computing effort which subsequently took place.

Chapter 1 identifies nine criteria which are used to analyse the individual computing centres discussed in the thesis, and form a basis for the study. Chapter 1 also looks at scientific computation at the beginning of the twentieth century and gives relevant background information for the remainder of the thesis.

The bulk of the thesis, chapters 2 to 6, describe the computing centres which emerged during 1925-1955. The description begins by looking at L.J. Comrie's work at the Nautical Almanac Office in the late 1920s and goes on to consider the Scientific Computing Service, the Cambridge Mathematical Laboratory, the Admiralty Computing Service and the NPL Mathematics Division. The NPL Mathematics Division is of particular importance as it was set up, in 1945, to act as a national computing centre and represents the pinnacle of centralized computing in Britain.

Similar events in the United States and Europe are described in chapter 7 and are compared and contrasted with centralized computation in Britain. The Unesco International Computation Centre is also described in chapter 7 and some conclusions about the way in which computation in Britain was centralized are given.

Abbreviations

The following abbreviations are used in the text:

ACE	Automatic Computing Engine
ACS	Admiralty Computing Service
AMP	Applied Mathematics Panel
ARC	Aeronautical Research Committee
BAA	British Astronomical Association
BAASMTC	British Association for the Advancement of Science Mathematical Tables Committee
BRL	Ballistics Research Laboratory
BTM	British Tabulating Machines Company Limited
CME	Control Mechanisms and Electronics Division, NPL
DSIR	Department of Science and Industrial Research
DSR	Director of Scientific Research, Admiralty
DVL	Deutsche Versuchsanstalt für Luftfahrtfor - German Aeronautical Research Institute
EBD	External Ballistics Department, Ministry of Supply
HMSO	His/Her Majesties Stationary Office
IBM	International Business Machines Corporation

IPM	Institute für Praktische Mathematik at the Technical Hochschule in Darmstadt
MAIN	Mathematical Institute of the Soviet Academy of Sciences
MAP	Ministry of Aircraft Production
MIT	Massachusettes Institute of Technology
NBS	National Bureau of Standards
NDRC	National Defense Research Committee
NAML	National Applied Mathematics Laboratories
NAO	Nautical Almanac Office
NPL	National Physical Laboratory
OSRD	Office of Scientific Research and Develpoment
PRO	Public Records Office
RAE	Royal Aircraft Establishment
RSMTC	Royal Society Mathematical Tables Committee
SCS	Scientific Computing Service Limited
SR(A)	Manchester Differential Analyser Group, Ministry of Supply, Headquarters Division
SRE	Scientific Research and Experiment Department, Admiralty
TRE	Telecommunications Research Establishment

Chapter 1
Introduction and Background

1.1 The Research Topic

1.1.1 Computing Centres

At the beginning of the twentieth century demand for computation was considerably lower than it is today. Those individuals who needed to carry out any significant amount of numerical work (for example, scientists, mathematicians, statisticians, engineers, astronomers and surveyors) had, in the main, to perform it themselves using logarithmic tables, slide rules or desk calculators. There were no computing centres to which scientists could turn for advice. The onus was, therefore, upon individuals to perform their own calculations even though few were trained to do so.

The demand for computation grew as a result of the increase in scientific activity between the two World Wars and the need for computing centres began to arise for two equally important reasons. Firstly, no one individual could possess all the different types of computing machine available: desk calculators, adding and listing accounting machines including punched card machines, and various types of analogue instrument. Each machine had its own special features making it more suitable for certain types of calculations than others. Therefore it was usually desirable to have access to a selection of devices. Secondly, trained computers were needed to make effective and efficient use of the machines for a wide variety of problems.

Two computing laboratories, at University College, London and at Edinburgh University, were set up in Britain before the First World War. Each possessed a range of computing equipment but their services were not normally available to anyone working outside those establishments. Over the following four decades several computing centres were set up which offered their services to a wider range of scientists. Scientific computing in Britain gradually became much more organized and centralized until in 1945 a Mathematics Division at the National Physical Laboratory (NPL) was established to act as a national computing resource to which scientists in government service, in industry or the universities could apply for computational assistance. It also played an important role in the development of both numerical methods and computing machinery. Although not the only institution in Britain to carry out scientific computation, the NPL Mathematics Division was the most important computing centre in the country in the late 1940s.

From the 1950s onward, as electronic stored program computers began to be installed in various institutions, a growing number of computer, rather than computing, centres were established until they became common place.

1.1.2 Description of the Thesis

This dissertation will examine the organization of scientific computation within British universities and government research establishments during the period 1925-1955. It will focus on the computing centres which emerged during the 1920s, 1930s and 1940s culminating in the formation of the NPL Mathematics Division in 1945. The computing centres which were set up during this period divide naturally into four categories. Those directly influenced by L.J. Comrie (chapter 2); those which evolved as a result of the differential analysers at Manchester and Cambridge (chapter 3); those created through necessity during the Second World War (chapter 4); and the NPL Mathematics Division (chapter 5) which was set up after the war. The year 1925 is an appropriate one in which to begin the study. In October of that year L.J. Comrie, one of the most influential pioneers of mechanical computation, joined the Nautical Almanac Office (NAO) and began to revolutionize the computing procedures there.

Apart from one important exception, no major computing developments are believed to have taken place in industry or the commercial sector during 1925-1945 and therefore computation carried out in this field will not be considered. The exception is a company set up in 1937 by L.J. Comrie called the Scientific Computing Service Ltd. (SCS). The SCS, which arose from Comrie's work at the NAO, was the first computing centre to be run as a commercial venture and will be described in chapter 2 in context with Comrie's other work.

To provide a framework in which to assess these computing centres nine characteristics of a computing centre have been identified. The characteristics are

1. USERS: What group of people did the centre serve and how easy was it for them to access it?
2. PERSONNEL: How large a staff did the centre support? Did the staff consist of both trained computers and experienced mathematicians?
3. MACHINERY: What range of computing machinery did it have available?
4. COMPUTING ACTIVITY: What type of computations were carried out? Did they cover a wide range of computing techniques and a wide range of applications?
5. ADVISORY ROLE: Did the centre provide an advisory service to users on the best way to approach a problem in the early stages of an investigation and to users who wished to carry out their own computation?
6. NUMERICAL RESEARCH: Did the centre undertake research into numerical techniques either independently or on behalf of its users?
7. COMPUTING MACHINERY RESEARCH: Did the centre undertake research into new, or improved, types of computing machinery?
8. PUBLICATIONS: Did the centre publish the results of its work or in some other way attempt to educate its users and disseminate information about the latest computing techniques?
9. LIBRARY FACILITIES: Did the centre maintain a specialist library which its users could consult?

The characteristics above can be identified in varying degrees in the computing centres discussed in chapters 2 to 5 and illustrate an evolution from localized computation at the NAO towards a national computing centre at the NPL. Chapter 6 discusses post war computing centres other than the NPL Mathematics Division. The chapter looks at how pre-war and war-time computing resources developed and continues the histories of institutions discussed in earlier chapters. The role and influence the NPL Mathematics Division had relative to these later computing centres is also discussed.

The second part of this chapter, section 1.2, will provide a background for the events to be described in chapters 2 to 5. It will examine the different types of calculating machines and instruments available at the beginning of the century and consider why scientists were slow to take full advantage of desk calculators. In this way the revolutionary nature of Comrie's actions at the NAO (described in chapter 2) and the subsequent centralization of scientific computation can be better understood.

To supplement the background information provided in the present chapter, chapter 7 reviews the organization of scientific computation in Europe and the United States during the period considered by the dissertation, 1925-1955. Section 7.3 discusses the formation of an International Computation Centre by Unesco. Although the centre was set up in 1958, discussions for its establishment had begun in 1948 and therefore a description of an international computing centre makes an appropriate closing section to the dissertation. This review, based on the secondary literature, follows rather than precedes the descriptions of British computer centres given in chapters 2-6 to allow a comparison of the events taking place in the different countries to be made. A more global picture of the period is therefore presented which will illustrate the extent to which events in Britain were influenced by those happening abroad.

1.1.3 Motivation

Most of the work done in the History of Computing field has tended to focus on Charles Babbage, the large relay calculators of the late 1930s and 1940s, the ENIAC and the subsequent development of electronic stored program computers. Much of this work is excellent but the period between Babbage and the late 1930s has been largely ignored.

There are, however, a few notable exceptions to this. Randell's *The Origins of Digital Computers: Selected Papers* (1982) gives a balanced view of the main events which led up to the development of computers in the late 1940s. Randell also supplies the most comprehensive bibliography of the history of computing that has yet been published. A second extensive bibliography is given by Cortada (1983) which covers a range of calculating machines from the abacus to computers of the early 1980s. Goldstine's *The Computer: from Pascal to von Neumann* (1972) gives an excellent overview of the major computing developments before going on to describe the ENIAC, EDVAC and subsequent computer projects. A popular, but very informative and interesting, account of the history of computing is *A Computer Perspective,* edited by G. Fleck (Eames and Eames 1973), which surveys in picture form many relevant, and irrelevant, aspects of both digital and analogue computation. Surveys of desk calculators have also been given by Chase (1980) and Last (1962). Although several studies have concentrated on the early work of IBM and the development of IBM punched card machines, few have dealt with the use of IBM machines for scientific computation. The recent Charles Babbage Institute reprint series of classic texts for the computer historian includes titles dating from the pre-electronic computer age[1] and illustrates an awakening of interest in the period.

Only a few of the recent publications have attempted an examination of the environment in which desk calculators, accounting machines, punched card machines, differential analysers and other analogue machines were used for scientific computation and the effect they had on the scientists of the period. Brennan's history of the Watson Astronomical Computing Laboratory (1971) describes the foundation and the activity of that establishment without dwelling on the mechanical details or operation of the punched card machines used, but discusses the need for such an institution and its users. The early computing activity at Los Alamos has also been briefly described by Feynman (1976) and Metropolis and Nelson (1982) and illustrates how computation was carried out within

1. Horsburgh 1914 and Eckert 1940.

research establishments in the United States before the ENIAC became available to them. Todd's "John von Neumann and the National Accounting Machine" (1974) also hints at how different types of computing machinery were used in British government institutions in the early 1940s.

The context in which different types of computing machines were used is an important part of understanding their value as practical computing devices for scientists. Although relay and electronic calculators were being constructed during the 1940s their use was limited to a relatively few individuals. An examination of the organization of scientific computing during the first half of the twentieth century provides a good background against which the subsequent development of computers can be studied.

It is to partly fill the need for an assessment of computing during the 1920s, 1930s and 1940s that this study has been undertaken. While recognizing that the actual invention and mechanical development of calculating machines is an important area for study, this dissertation will focus on the adoption of certain forms of calculating machine by scientists and the ways in which computation was institutionalized and centralized to make computing machinery available to a range of people. In particular it will examine the centralization of scientific computation during this period. The dissertation also looks briefly at events in Europe and the United States to present an outline of similar events abroad.

1.1.4 Sources

The previous section and the bibliography illustrate that there are few secondary sources of direct relevance to the main thesis which concerns the emergence and organization of computing centres. There are, however, several books which give general descriptions and lists of different types of computing machinery. Particularly reliable and comprehensive are Horsburgh 1914, Turck 1921, Martin 1925, d'Ocagne 1928, Couffignal 1933, Murray 1948 and Hartree 1950. Several journal articles also give surveys of particular classes of machine. Use has been made of Baxendale 1929a and 1929b, Lilley 1942, Frame 1945, and Comrie 1947.

The primary sources used in this study have been diverse. The most accessible source of information has been the published literature of the period and this has been used extensively. In addition to the published literature several archive collections have been consulted. A scant, but illuminating, collection of papers left by L.J. Comrie at the NAO held at the Royal Greenwich Observatory, Herstmonceux Castle, Sussex has been used. Another small, but useful, archival source has been the company records of the Scientific Computing Service Ltd. which still exists today. Especially informative concerning the creation of the Cambridge Mathematical Laboratory were the papers of Sir Lennard-Jones held in the archives of Churchill College, Cambridge and documents deposited in Cambridge University Library by M.V. Wilkes. The NPL Division of Numerical Analysis and Computation library has been a source for several unpublished papers by NPL Mathematics Division staff as well as relevant published literature.

The richest source of material relating to government establishments has been the Public Records Office at Kew. The ruling which prevents most documents under thirty years of age being accessed was not found to be a serious handicap as this study has largely concentrated on events which took place before 1953. Most of the documents which appeared to be of interest could therefore be consulted. The public records are an extensive and fruitful source for the science historian but have not been indexed to facilitate the retrieval of technical information[2].

Personal interviews and correspondence with people involved in the events described have been a rich and very stimulating source of information relating to peoples' motivations and opinions. May (1973) warns of the inherent difficulty in accurately recalling events which took place 40 or 50 years ago and the inevitable biases which are introduced into such recollections, and therefore care has been taken to cross check facts emerging for

2. A recent report by Jubb (1984), *Guide to the Records Relating to Science and Technology in the British Public Record Office: A RAMP Study*, would have been of some help in this area but does not really cover the computational aspect of scientific research.

such sources. In most cases interviews and personal letters have been used to supplement the basic information and to gain a feel for the period and the institution under discussion.

The primary sources used have thus been varied and it is hoped that the identification of some of these records will be of use to future historians.

1.2 Early Calculating Machines and Instruments

1.2.1 The Introduction of Desk Calculating Machines into Britain

Desk calculating machines did not become commercially available in Europe until the mid-1800s. Although many machines had been designed and built since Pascal's machine of 1642[3], the first commercially manufactured calculating machine was designed in 1820 by Thomas of Colmar and called the "Arithmometer". Thomas's Arithmometer was based on the Leibnitz stepped wheel designed at the end of the 17th century, and was used mainly by banks, shops and other businesses for the summation of long columns of numbers. By 1878 over 1500 Arithmometers had been manufactured and sold (Martin 1925). Following the success of Thomas's Arithmometer several machines of this type appeared on the European market. Some of the better known arithmometer type machines on sale in Britain were the Burkhardt Arithmometer (1878), the Tate (1883), the Saxonia (1895), the Peerless (1904), the Archimedes (1906), the TIM (1906), the Madas (1908), and the Rheinmetall (1924)[4].

Towards the end of the nineteenth century Baldwin in the United States and Odhner in Europe patented similar machines in which the Leibnitz stepped wheel was replaced by a much smaller pin wheel which considerably reduced the size of the machine. In 1892

3. For several centuries Pascal's calculating machine has often been regarded as the first practical invention of a calculating machine until in 1957 Franz Hammer discovered the prior claim of the Schickard machine of 1623. Unlike Schickard's machine, however, Pascal's calculator had a significant influence on the subsequent development of calculating machinery (Goldstine 1972).

4. The main sources of information regarding calculating machines are Turck 1921, McCarthy 1924, Martin 1925, d'Ocagne 1928 and Baxendale 1929a.

Grimme Natalis and Company in Germany began to manufacture these machines under the trade name "Brunsviga" and many were exported to England. The Brunsviga rapidly became a popular machine and, by 1912, 20,000 machines had been produced (Baxendale 1929a). It remained a much used device for over fifty years. Machines of the Brunsviga type were sold under many different names including Monopol-Duplex (1894), Bernolina (1901), Triumphator (1904), Marchant (1911), Colt's Calculator (1912), Rema (1915), Facit (1918), Hannovera (1921) Britannia (1922), Mulvido (1924) and Eos (1923)[5].

Like the Arithmometers, the Brunsviga and other Odhner, or pin wheel, type machines performed multiplication and division by repeated addition and repeated subtraction. Odhner type machines usually had two registers, a multiplier register and a product register, with capacities of up to 10 and 18 digits respectively. Odhner type machines had two advantages over arithmometer machines. Firstly, in Odhner type machines subtraction could be performed by simply turning the crank handle backwards and was a natural operation to perform. In arithmometers a sliding knob had first to be placed in the subtraction position before turning the crank handle making subtraction a slower process on arithmometers than on Odhner type machines. Secondly, Odhner type machines were smaller and lighter than arithmometers (McCarthy 1924).

In the late 1880s Eugene Felt brought out the Comptometer. The Comptometer was a key-driven device and well suited to the rapid summation of columns of figures because each key depression made when setting the numbers into the machine automatically operated the adding mechanism. Hence the additional handle turn required by other machines was eliminated. The Comptometer was, therefore, very popular with banks and accountants where the majority of the work involved the summation of numbers of many figures. The Comptometer could also be used for subtraction by keying in complements. Multiplication and division were carried out by repeated addition or subtraction.

The inconvenience of having to use complements on the machine for subtraction and

5. Turck 1921, McCarthy 1924, Martin 1925, d'Ocagne 1928 and Baxendale 1929a.

division, meant that the Comptometer, and other key driven machines which subsequently appeared on the market, were less popular with casual scientific users than the Brunsviga or arithmometer machines. In an article in *Nature* comparing the Comptometer with arithmometers Boys (1901) concluded that "the comptometer ... is not so convenient as the arithmometer for reducing and computing observations in the laboratory" (p.268). As a further criticism of the machine Boys wrote "the comptometer makes a most aggravating noise, like a typewriter through a megaphone; but other arithmometers are noisy, none, however, are as bad as this machine" (p.268).

Practical adding and listing accounting machines were first produced by Felt in 1889 and Burroughs in 1892 and became very popular with banks because they provided a printed record of the additions and subtractions the machine performed. They were therefore used to produce statements of account for bank customers (Turck 1921 and d'Ocagne 1928). Adding and listing machines were not immediately taken up by scientific computers because, in general, they were restricted to addition and subtraction (multiplication by repeated addition being inconvenient to achieve), but by the 1920s they began to be applied to tablemaking (see p.39).

A slightly different type of calculating machine was the Millionaire which became commercially available in 1899. It was based on a machine designed by L. Bollée eleven years previously (Martin 1925). The Millionaire was unusual in that it did not perform multiplication by repeated addition but used a mechanical multiplication table. Once the multiplicand, or dividend, had been set on the machine the crank handle had only to be turned once for each figure in the multiplier, or divisor. The Millionaire was therefore a very fast machine for multiplication and division. It was, however, about four times as big as the standard Brunsviga and was sometimes sold complete with legs to form a complete desk. The Millionaire was approximately twice as expensive as the Brunsviga (McCarthy 1924).

This brief overview illustrates that by 1900 several types of calculating machine were on the market and, as original patents expired, many different makes began to appear. Martin (1925) lists 229 different types of calculating machine commercially available during the period 1820 and 1925. The majority of the calculating machines on sale in Britain were manufactured in Germany or the United States with some from Switzerland and Austria. Very few calculating machines were made in Britain but most types were available in this country, sometimes sold under different trade names.

Calculating machines, particularly the Brunsviga, were thus available to scientists and engineers at the beginning of the twentieth century. For example, the Brunsviga was being advertized in *Biometrika,* a journal for the statistical study of problems arising in biology, as early as 1901. Some scientists very quickly replaced their logarithmic tables and slide rules with desk calculators but many others did not. Comrie (1925a p.243) cites Boccardi's *Guide du Calculateur* (1902) in which the author "speaks very disparagingly" of calculating machines as an example of the type of criticism surrounding their use at that time. Comrie does, however, point out that Boccardi's experience of calculating machines had been limited to early and crude models. In contrast it is evident from a remark made in the journal *Observatory* that the Brunsviga, and other calculating machines, were known to astronomers by 1905. The author of "From an Oxford Notebook" [6], which appeared regularly in *Observatory,* enthusiastically described the use of Brunsvigas in the Egyptian Survey Office in Cairo and applauded their efficiency for routine work (Anon. 1905 p.362). Although the author assumed that his readers, professional and amateur astronomers, were aware of what a Brunsviga was and what it could do, the tone of the article did not suggest that all would be familiar with its use.

A few individuals did adopt calculating machines for their work during the early part of the century and subsequently introduced them into the university laboratories where they worked. One of the most important to do so was Karl Pearson, the statistician and tablemaker. In 1903 Pearson used part of a biometric research grant to buy a

6. "From an Oxford Notebook" was written anonymously by H. Turner, Savilian Professor of Astronomy at Oxford University, and was an amusing account of Turner's activities, travels, astronomical observations and comments on life.

Tate Arithmometer and went on to use desk machines for the very substantial amount of statistical work he performed as part of the work of the Biometrics Laboratory, University College, London. Pearson himself favoured the Brunsviga and photographs of Pearson as early as 1910 sometimes show a machine beside him (Yule & Filon 1938 facing p. 70 and E.S. Pearson 1936 facing p. 222).

E.T. Whittaker, professor of mathematics at Edinburgh University, was another important and influential figure. In 1913 he set up a Mathematical Laboratory at Edinburgh and began to run lecture courses on numerical mathematics and computation[7]. The Laboratory was well equipped with mathematical tables and a wide range of calculating machines including an Archimedes, several Brunsvigas, a Burroughs adding and listing machine, a Comptometer, a Mercedes-Euklid, a Millionaire and a Tate Arithmometer (Horsburgh 1914). Unlike the Biometrics Laboratory at University College, London, which used calculating machinery as a tool to carry out statistical research, the Edinburgh Mathematical Laboratory was created for mathematicians in the university to use for their work. Whittaker and Robson's classic *The Calculus of Observations* (1924) arose as a result of Whittaker's lecture course and the work of the Mathematical Laboratory (preface to Whittaker and Robson 1924).

Whittaker, however, was not so much interested in the use of calculating machines as in numerical methods in general. In the preface to the first edition of *The Calculus of Observations,* Whittaker listed the essential tools of the computer as "a copy of Barlow's tables of squares, etc., a copy of Crelle's 'Calculating Tables', and a seven place table of logarithms" (Whittaker and Robson 1924, p. vi). He did, however, acknowledge that the use of desk calculating machines could save time and effort in some computations. Whittaker's somewhat academic experience of computation is illustrated by some of the methods given in *The Calculus of Observations* which were not practical where large

7. The term "Numerical Analysis" did not come into use until after the second world war. D.R. Hartree was one of the first to use the term (Wilkes 1984) to describe the study of numerical methods. In 1946 Hartree began to give a series of lecture courses at Cambridge under the title "Numerical Analysis" which formed the basis of his book of the same name (Hartree. 1952).

problems were involved. The most obvious example is the method given to solve simultaneous equations using determinants (p. 75)[8].

Although primarily a mathematician rather than a computer, Whittaker recognized the importance of calculating machines and gave his students the opportunity to gain familiarity with machines in the Mathematical Laboratory. This was, perhaps, the most important aspect of Whittaker's work as it was due to his influence that numerical computation courses were begun in other British Universities principally at Imperial College, London by H. Levy and at Leeds University by G. Smeal (Rosenhead 1954).

1.2.2 The Adoption of Calculating Machines by Scientific Workers (1913-1925)

Despite the work of Pearson and Whittaker and the introduction of calculating machines into their laboratories, there are clear indications that the use of desk calculating machines among British scientists did not become widespread until at least the mid 1920s. The 1912 report of the Royal Astronomical Society, which included a report by H.C. Plummer (1912) which dealt with logarithmic tables and tables of logarithmic values of the trigonometrical functions, illustrated that logarithmic tables were the main computing tool used by astronomers in the 1910s.

The activities of the British Astronomical Association (BAA) confirm that desk calculators were not common among astronomers even by the early 1920s. In 1920 the council of the BAA asked L.J. Comrie to undertake prediction calculations for phenomena of the satellites of Saturn for 1920-1923 (Massey 1952, Porter 1951). This led to the proposal that a computing section be formed within the BAA to perform "work, especially predictions, which are in some cases a little difficult for the amateur observer, and which lie outside the scope of the professional astronomer" (Comrie 1921g, p.1). The section was constituted in October 1920 with Comrie as its first director supervising 24 volunteer members working primarily with logarithmic tables. Its purpose was "to help other

8. In *Numerical Analysis*, (2nd edition 1958, p.166), Hartree noted that the direct evaluation of determinants is "*never*" the best way to solve a set of simultaneous equations.

members of the Association by undertaking calculations beyond the powers of such applicants, or by supplying formula, or data, or information about tables" (BAA 1921a, p.52). The work of the Computing Section was carried out by individual volunteers, most of whom were amateurs, using logarithmic tables. There was no expectation that BAA members would have access to desk calculators.

One of the most striking examples of an institution which carried out large scale computations, but which did not quickly adopt calculating machines, was the Nautical Almanac Office (NAO). The NAO annually published navigation tables and ephemerides which involved a very large amount of computation. Up to 1926 the work was, on the whole, performed using logarithmic tables. There are two main reasons why the NAO did not adopt calculating machines to speed up its routine work. Firstly the work of the NAO consisted primarily of constructing tables by interpolation and checking the tables by forming and examining their differences. As differencing requires only simple subtraction, the process would not have benefited from the application of calculating machines, although the interpolation procedure would have been simplified. Secondly, and more significantly, most of the work carried out by the NAO was performed outside the Office by retired members of staff (Graves 1953, p.295). This system was easy to administer and maintain as those involved were familiar with the work. The main disadvantage was that the geographical distribution, and possibly the age of the workers, made it very difficult to introduce new methods into the Office.

Another example of an organization which might have been expected to use modern computing techniques was the British Association for the Advancement of Science Mathematical Tables Committee (BAASMTC). The committee was set up in the eighteen seventies, just as calculating machines were beginning to appear, to report on and, if necessary, compute mathematical tables. Although the committee published tables on a fairly regular basis in the British Association Annual Reports, they did not apply calculating machines to their work until L.J. Comrie joined the Committee in 1928 (Anon. 1948).

The slow adoption of calculating machines by scientists in general is further illustrated by the *Handbook of the Napier Tercentenary Celebration* (Horsburgh 1914). The handbook was produced as a review of calculating devices since Napier and as a guide to an exhibition of Napier artifacts. In the *Handbook* the mathematical tables section covered 30 pages of which half was devoted to a history of mathematical tables in keeping with the Napier tercentenary celebrations. The other half of the mathematical tables section gave a working list of mathematical tables with the emphasis on tables "useful to those actually engaged in computation" (p.47). In contrast, the calculating machine section covered 65 pages which included general articles on calculating machines and their capabilities plus detailed descriptions of all the principal types of machine available. No analysis was given of the suitability of different types of machines for particular types of calculation. The conclusion to be drawn from these two different treatments is that in 1914 calculating machines were still a novelty and mathematical tables a commonplace tool.

There were four principal reasons why desk calculating machines were not widely used by scientists before the mid-1920s. Firstly the machines were, initially, quite costly in comparison with books of tables. In 1901, an 18x10 figure Brunsviga cost £27.10s.0d. and a Tate Arithmometer £40 while mathematical tables could be purchased for anything from 4s. to £2. When it is considered that the average income per capita in 1900 was approximately £40 per annum (Mathias 1983), a desk calculator was relatively expensive. The high cost of a desk calculating machine was acceptable in a mathematical or statistical laboratory where machines could be made available to a number of workers and could therefore be almost continually in use, but desk machines were expensive for the individual. Thus Pearson and Whittaker could make use of machines while the mathematicians of the BAASMTC or astronomers of the Royal Astronomical Society and British Astronomical Association, who worked as individuals, could not.

Secondly, many of the first machines to appear on the market were large and cumbersome to use (they often took up the complete working surface of a desk and needed two men to lift) and some of the very early models were also unreliable or difficult to use. As designs improved, however, the machines became very dependable (Comrie 1925a). They could also be regularly serviced by the manufacturer or selling agent thus increasing their reliability. Improved manufacturing and engineering techniques also led to a reduction in the size and weight of the machines. M.R. Williams (1982) notes that the compactness and light weight of a machine became a manufacturer's selling point and this is confirmed by the data presented in McCarthy's catalogue of business machines published in 1924.

Thirdly, the bulk of all computation done since the time of Napier had been performed using logarithms. There was, therefore, a considerable range of logarithmic tables easily available. More importantly, tables of logarithmic values of the basic trigonometrical, exponential, and hyperbolic functions were also readily available. Calculations done using machines required natural and not logarithmic values of these functions but there were few tables of the natural values of functions at the turn of the century. By 1918, in a response to the increasing need for tables of the natural values of trigonometrical functions, at least five sets of such tables had been published[9]. Of particular interest is Lohse's *Tafeln fur Numerisches Rechnen mit Maschinen* (1909) which were constructed especially for use with desk calculating machines. Gifford's tables of *Natural Sines* (1914) were also published to provide tables which could be used with desk calculators. In 1915 E. Gifford summed up the situation regarding the need for natural tables to be published. She wrote "I suppose the general use of logarithms had to wait until logarithmic tables of sines and tangents were compiled, just as now the use of calculating machines is hampered by the want of natural numbers" (E. Gifford, "New Tables of Natural Sines" pp.287-298 in Knott 1915).

9. Andoyer, H. *Nouvelles Tables Trigonometriques Fondamentales (Valeurs Naturalles).* 3 vols. 1915, 1916, 1918. Hermann, Paris; Burrau, C. Tafeln der Functionen Cosinus und Sinus. Reimer, Berlin 1907; E. Gifford *Natural Sines,* Manchester 1914; Lohse,O.W. *Tafeln fur numerisches Rechnen mit Machinen,* Engelmann, Leipzig 1909; J. Peters *Einundzwanzigstellig Werte der Funkionen Sinus und Cosinus,* Reimer, Berlin 1911.

Fourthly, while calculating methods for use with logarithms were well established those using desk machines were not. This was obviously an obstacle to the adoption of calculating machines by the ordinary computer. Comrie later, in the 1920s and 1930s (see chapter 2), developed many techniques for use with desk calculating machines which increased their usefulness for scientific computers. Pearson and the staff of the Department of Applied Statistics, University College, London (which had been created in 1911 from the existing Biometrics and Eugenics Laboratories) went some way in trying to educate computers in practical numerical methods suitable for use with desk calculating machines. In 1919 the Department of Applied Statistics started to produce a series of booklets under the title *Tracts for Computers* which were intended to be short monographs on various mathematical techniques including interpolation, quadrature and mechanical integration, calculating machines, bibliographies, and new or reprinted tables designed to be of practical aids to computers (K. Pearson 1919). However, only five of the twenty-six *Tracts* in the series described mathematical techniques. Numbers 2 and 3 dealt with the subject of tablemaking and interpolation. *Tracts* 6, 7 and 8 discussed smoothing, the evaluation of the incomplete B-function, and quadrature and cubature respectively. *Tract* 13 gave a bibliography of mathematical tables. The remaining *Tracts* consisted of a variety of mathematical tables. Of these, *Tract* 5 was the most relevant to general computers as it gave a table of co-efficients for Everett's central difference interpolation formula. A.J. Thompson's "Logarithmetica Britannica" took up nine *Tracts* (11, 14, 16-22). The other ten tracts were devoted to tables used by statisticians.

As desk calculating machines improved and suitable natural value tables of common functions became available, the use of desk machines spread. For example, during the First World War A.V. Hill led a team, which included D.R. Hartree, which applied desk machines to exterior ballistics research. The Department of Applied Statistics at University College, London, which already used calculating machines in its own statistical work, offered its services to the Government on the outbreak of war and performed calculations for: the Department of Trade; the Royal Aircraft Factory, Farnborough; the Admiralty

Air Department; the Anti-Aircraft Section of HMS Excellent (A.V. Hill's group); the Ordnance Committee; and the Ministry of Munitions (K. Pearson 1918).

By the mid-1920s the use of calculating machines had become more common as scientists became more aware of their capabilities. In his 1925 report on mathematical tables to the Royal Astronomical Society Comrie noted

> the appearance of a remarkable group of tables, thoroughly indicative of modern tendencies. They indicate very clearly that progress is being made ... in the adoption of calculating machines by scientific computers, which is made manifest by the publishing of extensive tables of the natural values of the trigonometrical functions (Comrie 1925b, p.386).

Seven years later he felt able to report stronger evidence of the use of desk calculating machines.

> The new tables reflect the modern tendency towards the use of calculating machines in three ways - first, by the extensive use of machines in their making, as reported in prefaces; secondly, by the fact that logarithmic values are tending to be superseded by natural; and thirdly, because the possession of a machine is virtually assumed in tables of special functions, where a wide interval is used and several even orders of differences provided. (Comrie 1932, p.338-339)

It is fair to conclude that by the early 1930s desk machines had replaced 4, 5, 6 and 7 figure logarithms as the most common method of large scale computation used both by individuals and institutions.

1.2.3 Mathematical Instruments

Parallel to the introduction of desk calculators during the late 19th century a second class of computing machines emerged. These were the mathematical instruments. In desk calculating machines numbers were represented as individual digits and arithmetic was performed to an accuracy determined by the number of digits the machine could record. They could be used to perform any calculation which could be broken down into a series of arithmetic stages. Today desk calculators would be described as a type of digital machine[10]. In mathematical instruments numbers were represented by physical quantities such as the length of a rod, the rotation of a wheel, the level of a liquid, or the level of a voltage. Their accuracy was therefore limited by the precision to which measurements could be taken. Such instruments are generally called analogue machines and were often built to perform a specific function, for example integration or harmonic analysis.

The most common form of analogue calculating instrument was the planimeter. Planimeters were used to measure the area of a closed curve obtained from a series of experimental readings. Planimeters were used chiefly by engineers and designers to calculate cross sectional areas which would otherwise have to be found numerically using Simpson's or Tchebycheff's rules. The first planimeter to be commercially manufactured was designed by Oppikofer in 1826 and sold by Ernst of Paris. Throughout the nineteenth century planimeters were manufactured and sold in increasing numbers as their accuracy improved. In 1856 J. Amsler designed the polar planimeter "which in consequence of its simplicity, handiness in use, and low price, soon drove all the older forms which, when well made were necessarily expensive, out of the field" (Henrici 1894, p.508). By 1884 over 12,000 Amsler planimeters had been sold (Bromley 1984) and the instrument continued to be widely used during the late nineteenth and early twentieth centuries.

In some cases very accurate results were required and the errors introduced by the planimeter (due to the slight variation between the theoretical and actual construction of the planimeter) had to be taken into account (Horsburgh 1914). The error in the results given by Amsler planimeters could not be adequately determined and hence in some cases Amsler planimeters were not sufficiently accurate. In 1880 Coradi, a firm of instrument

10. The terms "digital" and "analogue" were introduced in the late 1940s to describe the distinction between these two classes of machine and were not in use during the 19th and early 20th centuries.

makers based in Zurich, began to produce the compensating planimeter which measured a given area from two different positions allowing the error in the result to be significantly reduced. The compensating planimeter was, hence, a much more accurate device and it was used alongside standard Amsler planimeters.

Planimeters were manufactured by several companies besides Amsler and Coradi. For example A. Ott of Kempton in Bavaria, Starke of Vienna, Whelti of Zurich, and Richard Frères of Paris all manufactured and sold planimeters. In addition to the commercially available planimeters used by engineers, many specialized planimeters were constructed by individual scientists but were not widely used.

Integrators too were a common form of analogue calculating machine used in the late 1800's and early 1900's. Integrators were devices which, like planimeters, measured the area of a given closed curve but also gave the first, second and sometimes third moments of the curves. They were used mainly by engineers and designers to compute centres of gravity, sheer force and bending moments, and stability calculations. The most widely available forms of integrator were manufactured first by Amsler and later by Coradi. The machines were sold throughout Europe.

Mathematical instruments which solved linear differential equations by tracing the integral curve of a given equation were called integraphs. The most well known integraph was manufactured by Coradi and based on a design by Abdenk-Abakanowitz in 1878. Several other types of integraph were constructed by individual scientists but these were usually one-off machines and not commercially sold. Although integraphs are described in the literature alongside planimeters and integrators (d'Ocagne 1928, Baxendale 1929b) they were not used on nearly so large a scale. In 1914 A.M. Robb, of the Department of Navel Architecture at Glasgow University, observed that while planimeters and integraphs were in daily use in British shipyards integraphs were not. Robb thought that there were "probably only three or four [integraphs] in this country" (Horsburgh 1914, p.207).

Another important, although not commonly used, class of mathematical instruments were the harmonic analysers. Harmonic analysers were used to determine the Fourier coefficients of a periodic function expressed as a curve usually obtained from a series of experimental readings. The first harmonic analyser was constructed by Lord Kelvin in 1876 and was housed in the London Meteorological Office. Unlike planimeters and integrators, harmonic analysers were large, cumbersome and complex devices that were not easily portable. Several other harmonic analysers were built by individual scientists for their own use such as Henrici, 1894, Yule, 1895, Michealson and Stratton, 1898, and Boucherot, 1913. Henrici's machine was subsequently improved and manufactured on a limited scale by Coradi. Many numerical and graphical methods of harmonic analysis were available during the late nineteenth century and this, along with the high cost of building such complex machines goes some way towards explaining why harmonic analysers were not more common. In the Harmonic Analysis section of the *Handbook of the Napier Tercentenary Celebrations* (Horsburgh 1914, pp.220-248) arithmetical methods of harmonical analysis were presented as well developed and in common use.

A further class of mathematical instruments built during the nineteenth and early twentieth century were the algebraical equation solvers. Like harmonic analysers, equation solvers were not usually commercially manufactured and tended to be built by individuals. Reviews of early equation solvers are given by Jacob (1911), Horsburgh (1914) and Frame (1945) and illustrate the wide variety of different types of machine which were built. One of the most common types of equation solvers were based on systems of mechanical linkages but others used pulleys and liquid level balancing mechanisms.

Equation solvers were usually one-off instruments and not generally available to the public. In fact Baxendale, curator of scientific instruments at the Science Museum, South Kensington, was dismissive of equation solvers as a whole. In his review of mathematical instruments for the *Encyclopeadia Britannica* in 1929 Baxendale wrote,

"Many instruments have been designed for the mechanical solution of algebraic equation. These are in general more remarkable for the ingenuity displayed in their design than in the practical value of the results obtainable. No instrument of this type has been brought into extensive use, but a few of them have found a limited application in cases where a considerable number of approximate results are required." (Baxendale 1929b, p.69).

However, the importance of mathematical instruments at the beginning of the twentieth century is illustrated in the *Handbook of the Napier Tercentenary Celebrations* (Horsburgh 1914). Almost one third of the book is given to describing the use and design of a wide range of mathematical instruments. It is interesting to note that many of the exhibits discussed in the section were contributed by the Department of Natural Philosophy at Edinburgh University and not the Mathematical Laboratory which contributed desk machines, computing forms and mathematical models. While physical scientists were interested in devising instruments to help them with specific aspects of their work, computers used more general tools such as logarithms and desk calculators.

Mathematical instruments were, on the whole, designed, built and used by individuals in their own laboratories. Desk calculating machines were commercially manufactured in their hundreds and were available to all. Desk machines were also much more general purpose devices applicable to any calculation which could be broken down into a series of arithmetical steps. Mathematical instruments had, usually, only one application. Because of this, mathematical laboratories which were designed to undertake a significant amount of general computation were usually equipped with desk calculators. The use of mathematical instruments was mainly restricted to those whose computing need was limited to one particular type of calculation, say harmonic analysis. Nevertheless the use of mathematical instruments continued during the first part of the twentieth century.

1.2.4 Nomograms

Another form of calculating tool available to scientists at the beginning of the twentieth century was the nomogram. Nomograms are graphs which represent a solution for a particular class of problem. A nomogram can be difficult to construct but once it has been prepared it is relatively simple to read off the required data either as a point on the nomogram or as a line. Nomgrams were made popular, particularly in France, in the late 19th century by d'Ocagne (see p. 256) but some earlier examples have been found. For example, Evesham (1985) draws attention to Lalanne's "Universal Calculator" published in England in the 1840s. This nomogram could be used to perform multiplication, division, raising to integer powers, the extraction of roots, multiplication and division by 2π, the calculation of areas of circles, and the determination of volumes of spheres. Lalanne's "Universal Calculator" was in direct competition with the slide rule.

Nomograms were used principally by engineers, land surveyors, and the military. Specialist nomograms for particular applications, such as trajectory calculations, were readily available. Once the nomogram had been constructed and published, it was an easily portable, simple and accurate computing tool. Nomograms were more popular in continental Europe than in Britain where they were overshadowed by the slide rule.

1.2.5 Summary

The range of calculating tools available in the 1900-1920 period can be classified into three groups.

1. Logarithmic tables, slide rules, and nomograms.
2. Desk calculators.
3. Mathematical instruments.

Of the first group logarithmic tables and slide rules were very common among British scientists at the beginning of the century. They were cheap, easy to use and readily available. In many cases, particularly among scientists performing large, routine and varied types of computation, logarithmic tables and slide rules were replaced by desk calculators during the early 20th century. Desk calculators could be used to carry out all the tasks which could be performed using slide rules or logarithmic tables and could do so more quickly and accurately. Desk calculators could also be applied to computations too large or too complex to be performed using the older methods.

Mathematical instruments were a less common but not unusual method of calculation, specific instruments being used to perform specific types of computation. They were less widely available than logarithmic tables, slide rules or desk calculators and in many instances were designed by individual scientists for their own use.

Numerate scientists at the beginning of the 20th century used a combination of logarithmic tables, slide rules, desk calculators and mathematical instruments in their work. This chapter has described the machinery available to scientists at the beginning of the twentieth century and has shown that there was little organization or centralization of scientific computation. The following chapters will build on this introduction to describe the emergence of computing centres in Britain.

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Chapter 2

L.J. Comrie : The Mechanization of Routine Computation at the NAO and the Establishment of the Scientifc Computing Service Ltd

2.0 Introduction

During the 1910s and 1920s scientists were, in general, slow to adopt desk calculating machines for their work. Small computing centres had been set up by Pearson and Whittaker (see p.11-12) but in most other institutions large routine computations were carried out using logarithmic tables and not desk calculating machines. In 1925 L.J. Comrie (1893-1950) joined the Nautical Almanac Office (NAO) and completely revolutionized the computing methods used by the Office. Over a period of eleven years Comrie installed desk calculators, carriage controlled adding and listing machines, and punched card machines into the NAO and developed efficient numerical methods for use with them. By publishing the results of his work, lecturing widely and taking on consultancy work, Comrie greatly influenced the way in which scientific computation was performed in the late 1920s and the 1930s.

In order to understand the revolutionary nature of Comrie's work the computational work undertaken by the NAO before Comrie joined the Office is outlined in section 2.1. Section 2.1 also describes Comrie's early career and briefly considers his computing experience before joining the NAO. In 1926 Comrie was promoted to Deputy Superintendent of the NAO. Section 2.2 focuses on Comrie's work as Deputy Superintendent, 1926-1930, in mechanizing the routine computations carried out by the NAO. The section concentrates on three main areas of Comrie's work during this period: the development of interpolation techniques; the application of desk calculators and the Burroughs Class 11 machine to building up functions from their derived second differences; and the use of Hollerith punched card machines for calculating the position of the moon.

In 1930 Comrie was appointed Superintendent of the NAO. The principle features of Comrie's work during his time as Superintendent (1930-1936), and his continued efforts to mechanize routine computations, are discussed in section 2.3. In particular Comrie's installation of a National Accounting Machine at the NAO, his further development of interpolation techniques, and his continued application of punched card machines to the work of the Office are described. Another important aspect of Comrie's work during 1930-1936 was the amount of outside consultancy and additional computational work he took on; this too is discussed in section 2.3.

On his resignation from the NAO in 1936, Comrie set up the Scientific Computing Service Ltd. (SCS). The SCS was a commercial computing bureau to which scientists from government establishments, universities and industry could bring their computational problems. The SCS was the first institution in Britain to provide a widely available and comprehensive computing service. The reasons behind Comrie's resignation from the NAO are considered in section 2.4 which also describes the formation of the SCS and its work up to the beginning of the war in 1939. By 1939 the SCS had become well established as a computing centre.

Comrie was a prolific writer and this contributed substantially to the influence Comrie had on the wider introduction of machine methods of computation during the late 1920s and 1930s. Because of the importance of Comrie's writing, a list of his published books and articles is given at the end of this chapter. The list is thought to be complete but there may, of course, be some accidental omissions. To have included a list of Comrie's work among the references given for chapter 2 would have made such a list unnecessarily large and therefore the two have been separated. However, to keep the method of referencing consistent with the remainder of the thesis, where Comrie's work has been used directly in the chapter the appropriate entry has been made in the list of references for chapter 2.

2.1 Comrie's Early Career

On Armistice Day (11th November) 1918 Comrie received his first lesson on a Brunsviga calculator from Karl Pearson of the Biometric Laboratory, University College, London (Tee 1981). Pearson was an experienced computer and statistician who greatly influenced Comrie's opinions on the importance of maintaining high standards in computational work. In 1944 Comrie partly acknowledged his debt to Pearson by quoting from the preface to *Tracts for Computers No. 1* in which Pearson's views on the necessity of providing adequate training in numerical computation were plainly expressed (Pearson 1919, p.1-2; Comrie 1944c). It is clear from his work that Comrie adopted the standards set by Pearson and applied them to his work over the following thirty years.

After serving with the New Zealand Expeditionary Forces during the First World War (in which he lost a leg), Comrie enrolled as a post-graduate student in Astronomy at Cambridge in 1919. He had previously graduated from University College, Auckland, New Zealand in Chemistry in 1915. While a student at Cambridge Comrie spent two months working at the Royal Observatory at Greenwich. Greaves, Comrie's obituarist, brother-in-law, fellow student, and the Astronomer Royal for Scotland 1938-1950, reported that, even at this early stage of his career, Comrie was forthright in condemning the computing methods used at Greenwich (Greaves 1958, p.297). Comrie also took an active role in the work of the British Astronomical Association (the BAA). In 1920 he set up the Computing section of the Association and organized the computations carried out by the 24 volunteer members of the section. While still a postgraduate student Comrie had, therefore, gained considerable experience in organizing and administering a team of computers. In 1922 Comrie resigned his directorship of the BAA Computing Section and was succeeded by Major A.E. Levin.

Comrie received his Ph.D. in astronomy in 1923 and left Cambridge to spend two years teaching astronomy in the United States; first at Strathmore College, Philadelphia, and later at North Western University, Illinois. At both institutions he introduced practical computing courses into the curriculum. Comrie also spent some time studying the advantages of mechanical computation and, during his time in the United States, he published the first of many papers on the use of desk machines for scientific computation (Comrie 1925a).

Comrie returned to England in 1925 and took up a post as an assistant at the NAO in October of that year. Much of the work carried out at the NAO involved the routine tabulation of annually published ephemerides. The work was shared internationally by five offices - the British, American, German, French and Spanish[1]. The British Office had the task of providing the predicted positions of the sun, moon and planets and the apparent places of the stars. In some tables all the values tabulated were individually computed but, in order to reduce the amount of computation which had to be performed, certain tables were produced by interpolation between independently calculated pivotal values.

Checking computed tables was an equally important part of the NAO's work and was performed largely by differencing the computed tables. Checking tables by recomputation was not only a costly procedure but also provided no guarantee against the repetition of any particular error. By differencing a function tabulated at uniform intervals of the independent variable until the differences oscillated in sign, the behaviour of a function could be examined. If an error occurred in the tabulation of a function it propagated through the difference columns. An examination of those columns revealed not only whether an error had been made but also the position and magnitude of that error.

In the 1920s most of the computational work carried out by the NAO was performed by hand using logarithmic tables (Greaves 1953). Desk calculators were not used. P.H. Cowell, Superintendent of the NAO since 1910, had also replaced much of the permanent staff of the Office with experienced outside workers. On Comrie's arrival at the NAO the methods of computation used and the organizational structure of the Office were

1. Today this work is still shared between international offices although many organizational changes have occurred. In 1960 the British *Nautical Almanac* and the *American Ephemerides and Nautical Almanac* were unified into a single publication under the latter title. This title was changed in 1981 to *The Astronomical Almanac* which is again jointly published by both offices.

unsatisfactory for two reasons. Firstly most of the computational work and proof reading was performed outside the Office by retired members of staff. This proved to be a trouble free system to administer but had the obvious disadvantage that it was very difficult to introduce new methods into the Office due to the geographical distribution and, possibly, the age of the workers involved. There was also the danger that in the future the NAO would be left with no well trained, experienced computers. Secondly, and partly as a result of the widely dispersed computing staff, much of the computation was carried out by hand using logarithms despite the availability of calculating machines.

One of the few exceptions to the almost complete lack of machine computing methods used at the NAO, was the application in 1912 of a specially commissioned Burroughs adding and listing machine by T. C. Hudson for the tabulation of a function from its finite differences. This machine, described in the *Handbook of the Napier Tercentenary Celebration* (Hudson 1914, p127-131), could perform addition and direct subtraction (then a novel feature) in either decimal or sexagesimal notations. From independently computed pivotal values Hudson used a graphical method to derive the last digit of each intermediate function value. From the last digits of the function values the last digits of the first and second differences could be easily found. In many cases the full second difference could be inferred by examination of the original pivotal values. Hudson used the Burroughs machine to build up and print the complete first differences by setting and accumulating the inferred second differences on the machine. By feeding the paper through the machine a second time the function values could be built up by setting the already printed first differences on the machine. As the first differences set on the machine were printed over the previously printed first differences, the process provided a check on the accuracy of the machine operator because any error in setting the first differences onto the machine would immediately show up on the printed listing. In this way a complete table including the first and second differences could be computed and printed.

The machine, which was still used at the NAO in the late 1920s, was used only to build up tables of functions for which the second difference was derivable from its last digit because Hudson's graphical method for finding the last digit of the interpolates was not suitable for deriving difference columns higher than the second. In any case the paper carriage on the machine was not wide enough to accommodate the function and difference columns higher than the second on a single sheet. The Burroughs machine was regularly used to prepare a wide range of tables including the daily heliocentric places of Venus, the daily heliocentric places of Mars, the Moon's hourly place and the co-ordinates of the Sun for every noon and midnight. Although the machine was used successfully it was an exception in the Office and not the rule.

2.2 The Mechanization of Computation at the NAO 1926-1930

In March 1926 Comrie was appointed Deputy Superintendent of the NAO. As Cowell was due to retire in 1930, Comrie was practically assured of succeeding him as Superintendent. D.H. Sadler, Comrie's successor as Superintendent at the NAO, recalled that very soon after his appointment as Deputy Superintendent, Comrie began to make his presence felt (Greaves 1958, p.297). Almost immediately Comrie began to introduce calculating machines into the NAO, to develop numerical techniques for their application to the work of the NAO, to build up a staff of machine computers, and to gradually change the methods of computation used[2]. By June 1927 an electric Monroe, a Nova Brunsviga, and a Comptometer had been installed at the Office (Comrie 1927b). At first these machines were used simply to speed up processes previously done mentally or performed using logarithmic tables. But replacing tables in this way was not sufficient. Comrie began to develop numerical methods to reduce much of the work performed at the NAO to a series of routine steps which could be carried out by junior staff. Even where suitable desk or accounting machines were not available Comrie revised existing hand

2. In addition to changing the computing methods employed at the NAO, Comrie also redesigned the *Nautical Almanac, Abridged for the Use of Seamen* for 1929 and completely revised the *Nautical Almanac* for 1931. A detailed discussion of Comrie's work in this area is outside the context of this thesis.

computing methods to make them more efficient. As Deputy Superintendent of the NAO during 1926-1930, Comrie's work in revising the computational methods used in the Office took on three important aspects. First, he developed the end-figure method of interpolation. Second, he applied the Brunsviga-Dupla and the Burroughs Class 11 adding and listing machine to subtabulation from second differences. And third, he installed Hollerith punched card machines for the computation of tables of the position of the moon.

Because interpolation was such a fundamental part of the NAO's work, it was important that the process be performed as efficiently as possible. In the 1920s the two interpolation techniques most commonly used were the Lagrangian method and the building up of interpolates by continuous summation from columns of finite differences derived from the Everett, the Newton-Bessel, the Newton-Stirling, or the Newton-Gauss interpolation formulae. Comrie objected to both procedures on the grounds of laboriousness and poor accuracy. He outlined their disadvantages in a paper written in 1928 (Comrie 1928b). Hudson's graphical method of deriving the last digit of each interpolate and then building up the function from the inferred second differences was also in use at the NAO at that time. Hudson's graphical method led Comrie to develop a numerical method of deriving the last *two* digits of the interpolates from which the last two figures of the first and second differences could be obtained and used for interpolation by building up the function from those differences. Comrie called this process the end-figure method of interpolation.

The end-figures of the interpolates were obtained from a series of 2-figure double entry tables based on Bessel function coefficients. Once the end-figures had been found they were differenced until a complete column of differences could be inferred from the end-figures, usually the second or the third. The development of the complete interpolate then followed by continuous summation from the complete difference column. In 1928 Comrie compared his end-figure process to Hudson's graphical procedure and stated that his own method was "more accurate and better suited to routine work, especially as it may be done without skilled labour" (Comrie 1928b, p.523). Comrie quickly introduced the method into the routine work of the NAO and gave a complete description of the method along with the necessary tables of Bessel coefficients in the 1931 *Nautical Almanac* (Comrie 1929a).

Comrie's end-figure method of interpolation was an important part of his revision of computing methods at the NAO because it provided an accurate and clearly defined way of deriving the differences required to subtabulate particular functions. There was, however, no advantage in using desk calculators for the derivation of the end-figures as only trivial two figure additions were required. Differencing the end-figures required only simple subtractions and so, again, little was to be gained by the use of desk calculators. The only part of the process that could be mechanized successfully was the final stage of the procedure, that of building up of the function by continuous summation from the derived differences. Mechanizing the subtabulation of a function from its second differences was the second major aspect of Comrie's work as Deputy Superintendent.

Hudson's Burroughs machine, which was already installed at the NAO, could have been used for subtabulation using differences derived from Comrie's end-figure method. However, the machine had to be used twice for each function tabulated and both the second and the first differences had to be manually entered into the machine. This made the process very time consuming and Comrie searched for a machine which could produce a table in one run without the computed first differences having to be reset on the machine.

By March 1928 Comrie had developed a method of building up a function from its second differences using a Brunsviga-Dupla calculating machine which first appeared on the market in 1927. The Brunsviga-Dupla had two important features which made it suitable for building up a functions from their second differences and which did not appear together in other calculating machines of that period. Firstly, in addition to the standard product register and multiplier register found in other Brunsviga machines, the Brunsviga-Dupla had an extra product register into which numbers could be entered via thumb wheels situated on the front of the machine without disturbing any number already set on the setting levers of the machine. Secondly, numbers could be transferred from either register onto the setting levers. It was this second feature which made the machine particularly suitable for subtabulation from second differences because the computed first difference could be automatically transferred to the setting levers to be used to calculate the next function value without the risk of introducing errors into the computation by resetting the first difference. In applying the Brunsviga-Dupla to the subtabulation of a function from its second differences the multiplier register was used to hold the argument, the function was developed in one product register, the setting levers were used to hold the first difference and the second differences were entered into the other product register using the thumb wheels. The main disadvantage of using the Brunsviga-Dupla to build up tables was that the machine lacked printing facilities. Copying down results from the machine by hand introduced the risk of transcription errors in the completed table.

In 1929 Comrie installed a Burroughs Class 11 adding and listing machine at the NAO and immediately began to use the machine for the preparation of tables for publication. Unlike the early Burroughs machine, which had only one register, the Class 11 had both a register and an additional crossfooting device[3]. It was also fitted with a mechanical method of transferring numbers between the crossfooter and the register. The machine could be applied to the subtabulation of a function from its second differences by entering the second differences on the keyboard, accumulating the first differences in the crossfooter, and simultaneously accumulating the function in the register. The Burroughs Class 11 was also equipped with a movable printing carriage which allowed the argument (set on the far left of the keyboard and automatically incremented by the machine), the function, and the two columns of differences to be printed across the page in one passage through the machine.

3. The crossfooter was an accumulating mechanism into which numbers from the keyboard were added or subtracted. In the Burroughs Class 11 machine it acted as a register.

The third main feature of Comrie's work while Deputy Superintendent was the complete revision of the methods used to compute tables of the position of the moon. Tables giving the position of the moon for every noon and midnight were first included in the Nautical Almanac in 1923. The positions of the moon were derived by the summation of harmonic terms given in Brown's *Tables of the Motion of the Moon* (1919) and, although the existence of Brown's *Tables* made the calculation conceptually easy to perform, it was a major undertaking for the NAO keeping two computers fully occupied all year round. Brown's *Tables* were made up of 108 individual tables covering 660 pages and represented the harmonic terms required for specific periods. The *Tables* were arranged in order of increasing time.

The extraction of the required terms from Brown's *Tables* was not difficult but it was extremely laborious with eight to twelve terms, each from a different table, being required for the calculation of a single value. Once the table entries for the first date in a sequence of calculations, for example, January 1st, 1938, had been determined, they were copied down and totalled. The entries for consecutive dates followed serially in the tables hence their location presented no difficulty but the copying down and summation of the terms was a tedious task and one which introduced the danger of transcription errors. Each table entry was used on several occasions but identical combinations of entries did not recur. Occasionally discontinuities had to be introduced into the sequential table reading to compensate for the inaccuracies of the tabulated periods.

In 1929 Comrie automated this process of Fourier synthesis using Hollerith punched card machines[4]. The four types of table which made up Brown's *Tables,* single entry, double entry, long period nutation and short period nutation were punched onto 45

4. Although both Hollerith and Powers punched card machines were functionally very similar they operated on different principles. Comrie chose to use the Hollerith machines of BTM over those of Powers because they gave the user more control over the wiring of the machines for any particular job. The Powers machines operated using prewired connection boxes specified by the user but supplied by the manufacturer, whereas the user could wire up the Hollerith machines for any task on site. Hence the Hollerith machines offered the greater flexibility to scientific users.

column cards[5]. A group of adjacent columns was called a field and represented a particular entity, for example date. Once the cards had been punched, it was important to check the accuracy of the transcription. In commercial installations this was usually done using a device called a verifier which was used to "repunch" the cards from the original data to catch any discrepancy in the punching. Comrie, however, did not use this method of verification. In order to relieve junior punch operators of the responsibility of verifying the accuracy of the punching, Comrie had the cards listed on the tabulator and used experienced proof-readers already employed at the NAO to check the printed copy against the original tables (Comrie 1932c, p.700).

The punched cards representing any one of the tables in Brown's *Tables* were stacked individually and their original sequence retained. The starting point within each table was determined and the cards representing the necessary terms, or table entries, were grouped together by hand. The following groups were taken from the card stacks in sequence in the same manner with the required discontinuities being made where necessary.

The tabulator was the principle machine in the punched card system. It performed addition from selected fields of the cards into any combination of its five 9-figure counters. The tabulator was also used to list the cards, print totals and print sub-totals. The selected cards were then passed through the tabulator which totalled each subsequence of cards representing a single computed term and printed them alongside identifying data. Because British tabulators could not perform direct subtraction from the card, as the later American IBM machines did, all the table entries were punched in both direct and complementary form to deal with negative and positive values. At the end of a run the cards were passed through a sorter which separated out the cards into groups of the same argument to be returned to the table stacks.

5. Other card capacities also existed. 80 column cards of the same dimensions became the most common card capacity but 34 or 60 column cards were also available.

Comrie's application of Hollerith punched card machines to the calculation of the position of the moon was significant for two reasons. Firstly, the application itself greatly reduced the effort and cost of annually producing tables of the position of the moon for publication in the *Nautical Almanac*. The work was begun in late 1928 when Comrie took on extra staff to prepare the cards. Transferring Brown's *Tables* onto punched cards took about six months. The rest of the work was completed in seven months during 1929 on machines hired from the British Tabulating Machine Company (BTM) and installed at the NAO. To have completed the calculation for the following ten year period (1935-45) was all that was strictly necessary at the time. However, as the most expensive part of the calculation had been its organization and staff training required, Comrie decided to take the calculation on to the year 2000 as an alternative to repeating the work ten years later. Comrie further justified the continuation of the calculation by expressing the opinion that there was "little likelihood of Brown's *Tables* being superseded before the end of the century; any acquisition to our knowledge during the next seven decades is almost certain to be expressed in the form of corrections to Brown's *Tables,* not in the form of new tables" (Comrie 1932c, p.706)[6]. Due to the expiry of the lease on the Hollerith machines not all of the entire computation up to the year 2000 was completed. Although all the necessary cards had been prepared, the calculations for the latitude, longitude and horizontal parallax were only taken up to 1950. The cards were stored in anticipation of the calculation being completed in the future. Comrie estimated that the cost of the computation, including the hire of the machines, came to less than £1,500. The cost of manually carrying out the work up to the year 2000 would have totalled over £6,000. Therefore a great financial saving had been made (Comrie 1932c, p.706).

The second, and more important, consequence of Comrie's application of Hollerith punched card machines was that it opened up the possibility of using this type of

6.In this assumption Comrie was not entirely correct. From 1960 the published positions of the moon, or lunar ephemerides, were calculated directly from Brown's theory using electronic computers without the use of the *Tables*. In 1954 corrections, based on the new calculations, to the already published lunar ephemerides were released and subsequent tables were entirely calculated in this way. Thus Comrie's computations for the years 1960-2000 were superseded.

equipment for other scientific problems when the calculation was of a suitable nature and required on a large enough scale. Having demonstrated the use of punched card machines for Fourier synthesis in calculating the position of the moon, Comrie went on to explore further uses of the machines. For example he proposed using punched cards to produce sums of products of the type used in multiple correlations which became one of the principle uses of punched card machines by statisticians.

By 1930, then, Comrie had made substantial revisions to the computing methods used by the NAO, particularly in the development of the end-figure method of interpolation, his application of the Burroughs Class 11 adding and listing machine to subtabulation of a function from its second differences, and his application of Hollerith punched card machines to calculating the positions of the moon.

2.3 The NAO as a Mechanized Computing Centre 1930-1936

On Cowell's retirement in August 1930 Comrie was appointed Superintendent of the NAO and, according to Sadler, then Deputy Superintendent, Comrie "intensified his campaign for the increased use of modern calculating machines and methods of computation" (Greaves 1958, p.298). Comrie was an impatient, uncompromising man and had difficulty dealing tactfully with Admiralty administration. When Comrie presented proposals for change at the NAO the Admiralty, understandably, wanted to consider them at some length. Comrie saw these slow deliberations as incompetence on the part of the Admiralty and found it impossible to wait patiently for their approval. The Admiralty needed to be persuaded that change was necessary as all had appeared well under Cowell's administration and they would not have been encouraged by Comrie's attitude towards them. These problems with the Admiralty were, mainly, the result of Comrie's strong personality and his "fanaticism" (Greaves 1958, p. 294) about his work. They caused considerable friction between Comrie and the Admiralty throughout Comrie's Superintendentship.

Nevertheless, Comrie continued to mechanize the routine work of the NAO and by 1932 had replaced all the Office's logarithmic tables with desk calculators (Comrie 1932d, p. 523) and built up a new staff consisting of both junior machine operators and experienced computers. He also continued to develop new numerical techniques for use with machines. The Burroughs Class 11 adding and listing machine which Comrie installed in 1929 could only be used for functions for which the second difference column could be deduced, was continuous or was oscillatory. The machine could not be used to build up a function from its third or higher differences in one application of the machine. For many functions the third or higher differences could be found more easily than the second. By the early 1930s larger Burroughs machines had become available, for example, the Class 16 equipped with 6 registers plus a crossfooter. These larger Burroughs machines were not, however, suitable for application to the building up of a function from its sixth differences because all inter-register transfers had to be made via the crossfooter thus disproportionately increasing the number of operations to be performed in computing any one function value.

In 1931 Comrie overcame this problem and "discovered" (Comrie 1932a, p.28) that the National Accounting Machine Class 3000 (then sold under the trade name of Ellis) could be used to build up a function from its sixth differences. The National machine had six registers into which numbers could be directly added from the keyboard; registers 1 and 3 accepted numbers either positively or negatively. Any register could be totalled or sub-totalled and the contents of any register could be added directly into any other register. There was no intermediate crossfooting device through which transferred numbers had to pass and hence the National machine could efficiently be applied to the summation of finite differences up to the sixth. The destination of a number (*ie* the register into which it was to be added or subtracted) was controlled by interchangeable stops which acted on control arms. The number to be printed and/or entered was supplied by the 11-column keyboard or by selection of a register via the control keys on the extreme left of the keyboard. The machine was activated by the depression of the motor bar on the right of the keyboard.

In applying the National Accounting Machine to subtabulation of a function the known sixth difference was set on the keyboard and added into the register accumulating the fifth difference column. The other difference columns and the function value were formed in a similar fashion. At the end of a cycle the argument, function value and successive difference columns were printed across the page and the process continued. The National Accounting Machine could thus build up a function from its sixth, or lower, differences. It therefore significantly eased the burden of table making and interpolation. In 1936 Comrie described a method of interpolation from fourth differences based on Everett's interpolation formula, which had been in use at the NAO since 1933, and was directly applicable to the National machine (Comrie 1936b)[7].

The second important application of the National Accounting Machine was the converse of summation from finite differences: the differencing of functions up to the fifth difference. This application was an extremely useful one at the NAO where it was used as a powerful method of checking computed tables. Because the process required only trivial subtraction, it was of no advantage to use desk calculators and the work was done by hand. Comrie found that by using the National it was possible to mechanically difference a function to fifths much more quickly than it could be done by hand (Comrie 1936b, p.102). At each step in the cycle of operations successive differences were formed and stored in individual registers. At the end of each cycle the function value, argument and successive difference columns were printed. When the completed difference table had been produced the smoothness of the differences could be examined and any errors present detected.

In addition to its application as a difference engine, Comrie further explored the use of the National for the formation of moments in statistical analyses and for more general

7. Todd (1974) gives an account of how, during the Second World War, he and John von Neumann devised a method of interpolating cubic functions to halves in which the error was minimal. The account gives a feel for the use of the machines and for the war-time conditions under which scientists were working.

purpose calculations. At a cost of £500-£600 for the full 6-register machine, the National was an important addition to the NAO[8].

Apart from introducing the National Accounting Machine into the NAO, Comrie continued to work on finding further scientific applications for punched card machines. Besides the preparation of tables of the position of the moon computed using Brown's *Tables* the only other calculation of any size Comrie performed for the NAO using punched card machines was the conversion of hundreds of polar co-ordinates to rectangular co-ordinates. This was a relatively simple job and involved using a Hollerith multiplier to form the necessary products. The work was carried out in 1933 on machines at BTM's premises in Victoria House in London because the task was not large enough to warrant the reinstallation of Hollerith machines at the NAO. Although Comrie did not use punched card machines for any other major computation at the NAO, he was aware of the potential of the machines. He suggested, for example, that punched cards could be used to tabulate the apparent places of the stars published annually. In the 1930s this work was shared by four international offices and thus the amount of computation carried out in any one country could not support a punched card installation in any one location.

In addition to mechanizing the computation carried out by the NAO and revising the *Nautical Almanac* itself, Comrie also took on a considerable amount of table making work which was unconnected with his work for the NAO. Comrie personally employed at least one computer to help him with this outside work. For example, in 1930 he edited a new edition of *Barlow's Tables* (Comrie 1930a) and, in the following year, published a set of four figure logarithmic tables with L.M. Milne-Thomson. Comrie was also secretary of the British Association for the Advancement of Science Mathematical Tables Committee (BAASMTC) 1929-1936 and during that time not only performed several computations on behalf of the committee (BAASMTC 1935, 1937, 1946) but was also concerned with the publication of the tables produced during that period. Comrie used a National to perform

8. In the early 1930s a desk calculator, eg. a Brunsviga-Dupla, could be purchased for about £70.

work for the BAASMTC before he installed a machine at the NAO.

One of Comrie's most extensive table making projects while Superintendent at the NAO was undertaken in collaboration with the German table maker Johann Peters. This collaboration began after a meeting between Comrie and Peters at the Astronomische Gesellschaft in Budapest in 1930. Their aim was to produce a set of 12-figure tables of the natural values of the six trigonometrical functions to every second of arc and to publish nine volumes of 7-,8- and 10-figure tables. Peters supplied the pivotal values for the tables to Comrie who interpolated between them using the NAO Burroughs Class 11 machine in 1931. Because of publication difficulties only the 8-figure tables of the four principle trigonometrical functions (sine, cosine, tangent and cotangent) were published (Comrie and Peters 1939b).

In addition to his table making work Comrie regularly published descriptions of his work and of the use of calculating machines in scientific and business journals and in encyclopaedias (see the list of Comrie's publications). Comrie also lectured frequently on the use of calculating machines. In 1929 he gave a series of six lectures at Imperial College, he also taught a six week course at the University of California in 1932, gave the Newmarch lectures at University College, London in 1933 and presented papers to the Royal Astronomical Society (Comrie 1932c, 1932d, 1932e and 1932f), the Office Machinery User's Association (Comrie 1930c, 1932a) and the Royal Statistical Society (Comrie 1936b).

Because of the success of his work Comrie was consulted by many different people on computing methods and on the purchase of computing machines. In the mid-1930s Comrie was advising both the Powers and the Hollerith punched card companies on the capabilities of their machines (Desborough 1932-1934, British Tabulating Machine Company Ltd. 1936-1937). He also received requests from academics wanting to set up computing laboratories at their universities (Carroll 1933, Grace 1934). Government establishments too acted upon his advice, for example the Ballistics Research Department at Woolwich installed a National Accounting Machine on his recommendation (Comrie 1932a, p.17).

Comrie also gave practical assistance to those who came to him with a problem. For example at a lecture to the Royal Statistical Society at Cambridge in 1936 (Comrie 1936b) Comrie invited queries on the subject of mechanical computation. G. B. Hey, a mathematician working on an agricultural statistical investigation concerning optimum sample sizes, subsequently approached Comrie and explained the difficulties he was encountering. Comrie invited Hey, and his colleague H.G. Hudson, to the NAO at Greenwich to discuss the problem. Through Comrie's personal connections with BTM, for whom he undertook consultancy work, Hey and Hudson went to the Hollerith factory at Letchworth. As a result all their data was punched onto Hollerith cards and they were able to use BTM E6/6 tabulators to form the required totals and sums of products by a summary multiplication technique. Because of the extent of the calculation, the tabulator which Hey and Hudson used was fitted with additional relays and distributers by BTM (Comrie, Hey and Hudson 1937b).

Because there is little documentation concerning Comrie's private work it is difficult to pinpoint whom Comrie assisted in other capacities. It is clear, however, that during 1936 Comrie became involved with artillery survey problems (Comrie 1942a) which were undoubtably stimulated by the worsening political situation in Europe in the mid-1930s and the approach of war. Comrie devoted a considerable amount of energy to them and devised powerful computing methods using the Brunsviga Twin 13z calculating machine. For example, he used the machine for the determination of bearings and/or distances from a variety of positions, intersections, and resections. Comrie's work in this area was so successful that the War Office adopted both twin machines and Comrie's methods in those artillery and survey divisions which regularly carried out such calculations. Indeed Comrie produced a booklet (1938b) on the application of the Brunsviga 13z twin machine which gave procedures for the survey problems given in the 1932 HMSO *Manual of Artillery Survey*.

By installing desk and accounting machines at the NAO, almost completely mechanizing the computation performed there, building up a well trained staff, publishing the results of his work, expanding his work to include other table making activities and acting as a consultant to those who approached him, Comrie created a well known computing centre at the NAO.

2.4 The Formation of the Scientific Computing Service Ltd

In August 1936 Comrie resigned his position as Superintendent of the NAO. According to his obituarists (Greaves 1953, Massey 1952, Porter 1951), wife (Atkinson 1984) and colleagues (Burrough 1983, Hey 1983, Miller 1979), Comrie was an impatient and forthright man who did not wait patiently while cautious civil servants debated particular points and yet he is also remembered as a kind and generous person. Relations between Comrie and the Admiralty were never smooth as Comrie felt that the Admiralty was deliberately putting obstacles in his way. The amount of outside computing and consultancy work which Comrie performed was also a cause for dispute between him and the Admiralty. It was simply not done for a civil servant to undertake such work. Although none of his obituarists give reasons for his resignation other than vague statements about poor relations between Comrie and the Admiralty, it seems likely that the increasing amount of outside work which Comrie took on contributed to bringing the disagreements to a head. That is, the use of the NAO as a computing service centre was not acceptable to the Admiralty.

The amount of consultancy work Comrie had been performing while Superintendent at the NAO had proved that some sort of scientific computing service was needed in Britain at that time. Comrie, therefore, privately set up the Scientific Computing Service (the SCS) in 1937 which he ran first from his home and then from the BTM service bureau at Clifton House, Euston Road, London. Still retained by BTM as a consultant and something of a casual salesman, Comrie was not strictly an employee of the company and, although he rented office space from the Hollerith company, the SCS was an independent organization. Despite being so closely connected with BTM, Comrie's Scientific Computing Service was not restricted to providing a service based on punched card machines and was equipped with a variety of calculating machines. Comrie invited Hey and his private, non-civil service staff from Greenwich to join him and the service came into operation. On 28th January 1938 the Scientific Computing Service became a limited company with a staff of 16 and soon afterwards moved into its own premises at 23 Bedford Square, London.

In 1938 Comrie formalized the role he saw the SCS playing in the scientific community. In a booklet describing the activities of the company he stated that the main purpose of the SCS was to provide a "recognized organization or institution to which the investigator could turn with assurance that he would find his language understood, and the confidence that the facilities of experienced computers and mechanical equipment could be put at his disposal" (SCS 1938b, p. 3). There was, until that time, no one in Britain to whom scientists and statisticians working in government, industry or the universities could bring computational problems.

The new company utilized a wide variety of machines. In addition to access to the full range of punched card machines available at BTM's premises in Clifton House, the SCS was equipped with several Brunsvigas (models 13z, 20 and Twin 13z), an electric Mercedes model 38 MSW, an electric Madas, an electric Facit, a 10-column electric Victor adding and listing machine with sexagesimal keyboard, a 10-column electric Continental adding and listing machine, a 12-column 6-register National Accounting Machine and a 135 character typewriter for the preparation of printers copy. With such a wide range of equipment available and a trained staff the SCS offered an extensive list of services. These were

1. Scientific calculations generally, especially on a large scale, in cases where the worker concerned did not have access to or knowledge of the most efficient machines and techniques.
2. Table making and interpolation on the National machine.
3. Mathematical statistics eg. correlation, variance analysis and regression using

punched card machines for the formation of sums of products.

4. Analysis of market research questionnaires by tabulation using punched cards.

5. Fourier analysis and synthesis. Comrie already had experience in this field with his 1929 work on Brown's *Tables*. There had also been suggestions as early as 1929 that the technique be used for X-ray crystallographic analyses (Hartree 1929).

6. Survey calculations not now restricted to military applications to include determination of longitude and latitude from star altitude observations, the adjustment of triangulations, the calculation of map projections and conversions between co-ordinate systems.

7. The numerical solution of differential equations and evaluation of finite integrals in some cases utilizing the National to build up the integral from finite differences.

8. To provide an advisory service on the type of machines to buy or use for a particular calculation. It was stressed that this advice was given impartially and that most machines suitable for scientific work were available for inspection at Bedford Square "without the embarrassment of the presence of importunate salesmen" (SCS 1938b, p.5).

9. Provision of courses in mechanical computation arranged to suit individual requirements.

10. To act as a publisher and specialist bookseller of mathematical tables and notes on calculating machines and methods.

11. The preparation of printers copy and proof reading.

12. Demonstrations and lectures on mechanical computation.

(paraphrased from SCS 1938b)

Thus by 1938 Comrie had defined his terms of reference and was providing a unique and valuable service. In the first two years the SCS performed most of their proposed activities. Some of the work undertaken during this time made use of Hollerith punched card machines and reflects the early association with BTM (for example, a market research analysis for Radio Luxemberg and an analysis of the Family Allowance Budget Survey). Comrie's earlier application of punched card machines to Fourier synthesis in the prepartion of tables of the position of the moon led to the SCS performing an investigation into the use of punched cards for crystallographic work. Comrie's experience of computing navigational tables at the NAO also brought the SCS work in the preparation of Hugh's *Tables for Sea and Air Navigation* (Comrie 1938d). Exhibitions too were not uncommon. For example, the SCS demonstrated at the British Association meeting at Cambridge in August 1938 and at the Royal Physical Society exhibition at South Kensington in January 1939 (Burrough 1938-1939). At such exhibitions the SCS usually displayed the flexibility of Hollerith machines by illustrating their use for the summation of products, for integration from sixth differences (using a rolling total tabulator), and the analysis of lines in spectra. The tablemaking capabilities of the National were also demonstrated at such functions along with a variety of smaller, less specialized calculating machines.

In addition to these standard types of computation the SCS carried out a number of unusual and difficult scientific computations in the pre-war period. The most notable of these was the work the SCS carried out for Appleton and Weekes in the analysis of the height variations in the E-layer of the ionosphere (Appleton and Weekes 1939). A less well known job, but a no less significant one, was the solution of a series of second order integro-differential equations in 1939 for Buckingham and Massey at University College, London which arose from their work on the scattering of neutrons (Buckingham and Massey 1941).

Comrie also offered a consulting service. His letter headings stated that he was a consultant on "Calculating Machines", "Mechanical Calculation" and "Mathematical Tables". For example, in 1938 he was advising the Ordnance Committee of the War Office on the purchase of National Accounting Machines for the calculation of trajectories (Comrie 1938e) and assisting the Jute Research Institute of Calcutta on the range of commercial calculating machines available and their individual merits and costs (Comrie 1938f).

During 1937 and 1938 work for the SCS was plentiful and Comrie employed a staff of around twenty which, in between large jobs, was kept occupied doing large scale triangulations for survey maps involving the solution of over a hundred simultaneous equations on Mercedes calculators. On September 3rd 1939 Britain declared war on Germany and over the following six years Comrie and the SCS were widely used by the scientific community and the service ministries. The SCS was the only commercially run scientific computing centre to exist at that time.

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Chapter 3
The Influence of Analogue Machines in the 1930s: The Manchester and Cambridge Differential Analysers

3.0 Introduction

During the 1930s the use of desk calculators and accounting machines for scientific computation became increasingly common as Comrie, and others, developed numerical techniques for use with these machines. In contrast to the growth in popularity of desk calculating machines, the use of mathematical instruments by British scientists did not increase on anything like the same scale. Planimeters, integraphs and harmonic analysers were still being manufactured, but the mathematical laboratories set up within university departments during the late 1920s and early 1930s were, in general, equipped with desk calculators and not mathematical instruments (see p.47). Some scientists, however, found the use of desk calculators too slow or too tedious to undertake and during the 1930s many different types of large analogue machines were built in Europe and the United States. Of the few analogue calculators constructed in Britain during the 1930s, only the differential analysers enjoyed any measure of success. Two full sized differential analysers were built in Britain in the 1930s, one at Manchester University and the other at Cambridge University. Both had a very great influence on scientific computation in Britain before and during the war. The differential analyser at Manchester was a much used machine and attracted scientists from industry and government research laboratories. After the war it became part of the National Physical Laboratory Mathematics Division and continued to be used by a variety of people. The differential analyser at Cambridge led directly to the creation of the Cambridge University Mathematical Laboratory which was the first computing centre to be set up in Britain to serve the computational needs of *all* departments within a large institution.

In order to describe the computing centres which grew up around the Manchester and Cambridge machines, it is important to place the differential analysers within the context of other analogue machines built in Britain in the 1930s. Section 3.1, therefore, examines the types of analogue calculating machine developed in Britain during this period and shows that the majority of these machines were obscure and relatively unimportant devices. The following section, section 3.2, goes on to describe the construction of a model differential analyser by D.R. Hartree at Manchester University and the later installation of a full sized machine. Also discussed is the use to which the Manchester differential analyser was put and the kind of computing centre which built up around it. Section 3.3 relates how J. Lennard-Jones at Cambridge, following Hartree's lead, also built a model differential analyser. This model resulted in the creation of a computing centre at Cambridge University based around the full sized differential analyser which was later installed. The concluding section, 3.4, describes the other model differential analysers built in Britain as a result of the work at Manchester and Cambridge. This chapter therefore looks at the significant effect which the Manchester and Cambridge differential analysers had on scientific computation and contrasts this with the relatively small influence of other analogue machines built during the same period.

3.1 Analogue Computing Machines of the 1930s

A search through the indices and abstracts for 1930-1939[1] revealed that so few British books or articles published during this period described new or improved mathematical instruments. The literature clearly illustrates that interest in constructing mathematical instruments was greater in Europe and the United States than in Britain[2]. In the United States, for example, at the Massachusetts Institute of Technology (MIT) the design of large mathematical instruments was an established research program (see p.228). In Britain there were no such research programmes and very few large mathematical instruments were designed or built. Goldstine (1972) remarks that it is curious to find that very few British physicists or applied mathematicians did any work on constructing calculating

1. *Subject Index to Periodicals*, The Library Association, London; The *British Museum Subject Index; Science Abstracts- A Physics*, Institution of Electrical Engineers.

2. This literature search revealed published descriptions of only four analogue calculating machines designed in Britain during 1930-1939 whereas there were at least thirty American and European machines were discussed.

devices between Kelvin in the late 1800s and Hartree in the 1930s. Those machines which were built in Britain were designed by engineers and scientists who felt that the disproportionate amount of time they were spending on numerical work could be better applied to their own research.

The device built by E.C. Bullard[3] and P.B. Moon in 1931 to solve second-order differential equations serves as a good example of the type of instrument built in Britain during the early 1930s. Bullard and Moon were involved in geophysical research at Cambridge in 1931 and found the solution of second-order differential equations which arose from their work "extremely tedious" (Bullard and Moon 1932, p546). Bullard and Moon were aware of Kelvin's work on a machine to solve second-order differential equations (Thomson and Tait 1890, pp. 497-499), but considered that the mathematical manipulations needed to get the equations into the right form for use with such a machine involved an unacceptable amount of work. They therefore attempted to build a machine to solve second-order differential equations which would require less manipulation of the original equations.

The Bullard and Moon machine consisted of a conducting coil suspended in a magnetic field. The current fed to the coil was varied by the movement of a pointer by an operator along a curve representing a second-order differential equation. A small mirror which reflected a spot of light from a fixed source was mounted on the suspended coil. The movement of the suspended coil, which represented the integrated equation, was recorded by an operator tracing the movement of the light spot. The authors reported an accuracy of "a few percent" (p.549).

Although the motivation for building the machine had been to reduce the amount of effort required to solve second-order differential equations, it appears that a considerable amount of numerical work had still to be done not only to reduce equations to the appropriate form but also to manipulate the boundary conditions in order to minimize

3. Bullard later became director of the NPL 1950-1955.

errors in the machine. The device also required two operators, one to follow the input function and one to follow the light spot. The principle source of error was caused by the failure of the operators to accurately follow the curve or light spot.

The Bullard and Moon machine displayed four characteristics typical of this type of mathematical instrument invented in Britain during the late 1920s and early 1930s. Firstly, the machine was designed and built by individuals rather than commercially manufactured by an instrument maker. Secondly, the development of mathematical instruments or computing machines was not the main interest of the inventors; Bullard and Moon were physicists who suffered computing difficulties and made a direct attempt to solve them by the construction of a machine. Thirdly, as far as can be established, the machine was the only one of its kind to be built. Fourthly, the machine had no influence on future computing machine developments.

An example of a more widely publicized analogue calculating machine designed and built in Britain was the Mallock Machine. The machine was designed by R.R.M. Mallock in 1931 to solve linear simultaneous equations and used a series of interconnected transformers to represent the unknowns in the system of linear simultaneous equations. Adjustable coils on the transformers represented the coefficients in the equations. Power was applied to the transformers and when the machine had reached an equilibrium the solutions to the equations were read from the machine as a series of voltages.

The Mallock Machine differed from the Bullard and Moon machine in several important respects over and above differences in function and construction. Like Bullard and Moon, Mallock had found the labour of numerical computation very laborious and designed a machine to overcome the problem. As in Bullard and Moon's case, the design of computing machines or mathematical instruments was not Mallock's main career; Mallock was a demonstrator at the Cambridge University Engineering Laboratories. Unlike the Bullard and Moon machine which the inventors constructed themselves, the Mallock Machine was built under Mallock's supervision by the Cambridge Instrument Company in 1933. Although the agreement reached between Mallock and the Cambridge Instrument

Company for the construction of the machine clearly shows that the company planned to manufacture further Mallock Machines (Camb. Inst. Co. and Mallock 1937), there proved to be no demand for the machine because of its inability to handle ill-conditioned equations.

Unlike any other British analogue machine of the early 1930s, the Mallock Machine was a well publicized device. The machine was exhibited at the Royal Society Conversazione and the International Congress of Applied Mathematics in 1933 and 1934 respectively and four descriptions of the device appeared in the contemporary literature[4]. Because of the publicity the Mallock Machine received it was a fairly well known machine and has very often been included in reviews of analogue computing machines which have since been published[5].

The machine was also used experimentally by several people. The most notable of these were staff of the Royal Aircraft Establishment at Farnborough and A.C. Aiken, the Edinburgh mathematician. The use of the Mallock Machine by scientists from outside Cambridge contrasts sharply with machines such as the Bullard and Moon integrator which was unlikely to have been used in this way.

Again unlike any other British analogue calculating device of the early 1930s, the Mallock Machine directly influenced the construction of another device. In 1936 a patent was taken out by Electrical Improvements Ltd. and C. Blackburn for a network calculator based on Mallock's construction of a series of interconnected transformers. Although the Blackburn Network Calculator was built to simulate electrical power networks, it could be applied to more general problems involving the solution of simultaneous equations. Like most of the other analogue instruments built in Britain in the 1930s, the Blackburn Network Calculator did not have a noticeable influence on scientific computation.

4. Mallock 1933, Anon. 1933, Anon. 1934, and Anon. 1935d.

5. See for example Lilley 1942, Comrie 1944, Frame 1945, Murray 1948, Hartree 1950, Engineering Research Associates 1950, and Goldstine 1972.

The only class of analogue machines to be used successfully in Britain during the 1930s were the differential analysers.

3.2 The Manchester Differential Analyser

In 1930 V. Bush built a machine at MIT called a differential analyser that was designed to solve differential equations up to the sixth order (see p.229). The machine consisted of six integrating units connected together by bus shafts (Bush 1931). Each integrating unit was made up of a horizontal disc with a vertical wheel resting upon it. The output shaft from each integrating unit was connected to the bus system through a torque amplifier. The torque amplifier allowed each integrator to exert sufficient force onto the bus system to drive other components in the machine without causing slip between the integrating disk and wheel. Input tables, output tables, and multipliers were also attached to the bus system.

In constructing the machine one of Bush's aims had been to produce a flexible and rugged machine which operated to a reasonable precision. Bush gave a precision of one part in one thousand in each of the integrators and stated that the expected overall precision would be slightly lower than this (Bush 1931, p. 450). The machine was successful in achieving these aims and several copies based on Bush's original design were constructed in other countries. The first differential analyser to be built in Britain was a model of Bush's machine constructed in 1934 by D.R. Hartree, Professor of Applied Mathematics at Manchester University.

Hartree's principle research area was the application of wave mechanics to the study of electron densities in molecular crystals. This involved the determination of wave functions by the numerical solution of differential equations. Although in most cases the calculations required were not difficult, they were extremely tedious to carry out for large numbers of high order differential equations. Darwin, Hartree's biographer, states that the Bush differential analyser greatly interested Hartree who immediately saw how it could alleviate the amount of numerical computation he regularly performed (Darwin

1958, p.107).

In 1933 Hartree visited Bush at MIT and took the opportunity to use the differential analyser for his work on the approximation of the atomic field and wave functions of mercury. On his return to England, Hartree continued the work manually using desk calculators and found that the immense amount of labour required to complete the calculations emphasized the value of the differential analyser (Hartree 1934). In order to demonstrate the principles of the differential analyser Hartree built a Meccano[6] model of the Bush machine. Hartree recalled that

> the first results were successful beyond my expectations and suggested that it would be practicable to build such a model to do serious work on problems for which high accuracy was not required in the results (Hartree 1940a, p.160).

As a result of his successful experiments, Hartree and a research student, A. Porter, built a complete four integrator model differential analyser largely from standard Meccano parts. The machine, which cost approximately £20 to construct (considerably less than the cost of a Brunsviga of the same period), is fully described by Hartree and Porter (1935).

The model differential analyser was a useful machine and original work was performed using it. Soon after it was completed Porter used the machine to determine the approximate wave functions for chromium as part of his M.Sc. thesis. By using the model to perform useful work, and hence demonstrating the potential usefulness of installing a differential analyser at Manchester, Hartree managed to secure a gift from Sir R. McDougall, the deputy treasurer of the University of Manchester, to build a full sized differential analyser at Manchester. With the help and advice of Bush, who supplied drawings of his original machine and suggested possible improvements, Hartree arranged for the construction of a four integrator differential analyser by the Metropolitan-Vickers Electrical Company Ltd. In the period prior to the delivery of the differential analyser

6. Meccano was a constructional toy widely sold in Britain.

Hartree prepared for its arrival by using the model machine as an experimental device with which to gain experience in preparing and setting up equations for solution on a differential analyser (Hartree and Porter 1935).

The full sized four integrator differential analyser was installed in the basement of the Physics Department of Manchester University (Anon 1935c) and was formally opened in March 1935. Contemporary descriptions of the machine are given in Hartree 1935, Anon. 1935a, 1935b and 1935c. Almost immediately McDougall presented a second gift to the university for the construction of a further four integrators for the differential analyser, which brought the total donated to £6000. The completed machine had eight integrating units and could therefore be applied to ordinary differential equations up to the eighth order.

The differential analyser was very much Hartree's machine which he ran with the assistance of interested members of staff and research students. Porter had been involved in the construction of the model machine and was an important assistant after the full size machine was installed. Research students and staff became informally attached to the differential analyser through the work they performed on it. However, despite the absence of any formal operating staff, the Manchester differential analyser was a well used machine.

Hartree had primarily installed the machine for work on electron distribution in atomic fields but the full sized machine was never used for this purpose. In the period just before the full sized machine was installed work by Hartree and Fock on the behaviour of electrons had led to a reappraisal of the method of finding electron distributions. The new technique did not require the solution of differential equations on the differential analyser and therefore the machine was never used for this purpose. However, Hartree was awarded a Department of Scientific and Industrial Research (DSIR) grant for the further development of the differential analyser at Manchester and the investigation of problems applicable to it. Hartree, with his research assistants and students, used this grant to carry out a wide range of calculations including several industrial problems. In cases where industrial research work was carried out on the differential analyser Hartree liaised with staff from the companies concerned. One particular investigation into potential distribution in valves involved three different companies and was undertaken by Hartree in conjunction with staff from the the M.-O. Valve Co. on behalf of the General Electric Company Ltd. and Marconiphone Ltd. (Crank, Hartree, Ingham and Sloane 1939).

Additional units were made for the differential analyser for particular types of calculation. For example, for one problem concerning computations investigating time-lag in control systems carried out for ICI (Alkali) Ltd., a special purpose input table was constructed and attached to the machine (Callender, Hartree and Porter 1936; Hartree, Porter, Callender and Stevenson 1937). Some of Hartree's colleagues at Manchester also took an interest in the differential analyser and began to use it in their work or to develop attachments for it. P.M.S. Blackett, professor of physics at Manchester University, became interested in the technical side of the differential analyser and, with F.C. Williams of the Electro-technics Department, developed an automatic curve follower for the machine.

Hartree also carried out investigations chosen specifically for the unusual operation of the differential analyser which they required. One such computation was an analysis of train running times (Hartree and Porter 1938). This application used required discontinuous data which represented track gradients and speed limits and therefore counters, rather than the standard graphical tables were used as input devices.

Before the war the machine was therefore used for a large number of applications by many people. Darwin (1958) summed up the position of Manchester Differential Analyser. He wrote

> With his invariable generosity Hartree gave service with it to a very great number of enquiries, and the service included giving them his intimate experience of the general way that numerical problems could be solved (Darwin 1958, p.107).

The Manchester differential analyser was not initially installed in order to provide a computing service inside or outside Manchester University but rather it was intended to be a research tool for Hartree and his group. However, the DSIR grant which provided Hartree with the financial support needed to maintain the machine meant that the differential analyser was used as an additional computing facility for those British research scientists who approached Hartree from industry, government or universities. At this time, 1935-1939, there was no other full size differential analyser in Britain and a specialized computing centre developed around the Manchester machine. The group had little formal organization but scientists who needed faster methods of solving complex or high order differential equations came to Manchester to use the machine.

Hartree also published descriptions of the differential analyser and explained what type of problems the machine was capable of solving. Between 1935 and 1940 he published 4 accounts of differential analysers[7] and co-authored several papers describing applications which arose from the research work carried out on the machine[8]. This publicity, and the respect Hartree commanded as a mathematician, encouraged scientists to come to Manchester to use the machine. The success of the Manchester differential analyser brought an increased awareness in the need for large scale computing devices to be made available to scientists and led to the construction of several model differential analysers at several institutions. The earliest of the model machines was built in Cambridge and resulted in the installation of a second full size differential analyser in Britain.

3.3 The Cambridge Differential Analyser and the Foundation of the University Mathematical Laboratory

In 1932 John Lennard-Jones took up the Plummer Chair of Theoretical Chemistry at Cambridge University and began to establish a school of theoretical chemistry there. The

7. Hartree 1935; Hartree 1938; Hartree 1940a; Hartree 1940b.
8. For example, Hartree and Ingham 1938; Hartree and Porter 1938; Hartree, Porter, Callender and Stevenson 1937; Callender,Hartree and Porter 1936; Copple, Hartree, Porter and Tyson 1939; Crank, Hartree, Ingham and Sloane 1939; Hartree, D.R., Nuttall, A.K. and Porter, A. 1936.

group's main interests concerned the behavior and distribution of interatomic particles. By 1935 the work of the group had reached a point where the amount of computation necessary, primarily the solution of differential equations, was becoming too large and too complex to be carried out by hand. According to Mott (1955), his colleague and obituarist, it had become obvious to Lennard-Jones by 1935 that some form of mechanical computing aid was necessary. Hartree and Porter's work on the differential analyser at Manchester was well reported in the contemporary literature and Lennard-Jones saw that a differential analyser could be applied to the differential equations arising from his own work.

Lennard-Jones approached Hartree about the possibility of building a model differential analyser at Cambridge. Hartree and Porter offered help and advice to Lennard-Jones based on their own experience in constructing the Meccano differential analyser at Manchester and suggested ways in which a model machine might be improved. As a result a Meccano differential analyser was built in 1935 in the Physical Chemistry Department of Cambridge University by J.B. Bratt under the supervision of Lennard-Jones for use by the theoretical chemistry group (Lennard-Jones, Wilkes and Bratt 1939). Lennard-Jones's model differential analyser was heavily based on Hartree's model machine at Manchester but was a more accurate and reliable machine.

The most important difference between the Manchester and Cambridge model differential analysers was the design of the torque amplifier. The torque amplifiers gave the output shaft of each integrator enough power to drive the other mechanisms within the machine. The torque amplifier which Hartree had built was a simplified version of the one stage device used by Bush; it had an amplification factor of approximately 80. Hartree also used ground glass integrating disks to increase the friction between the disk and the integrating wheel and hence provide a greater initial torque. When the fourth integrator was added to the Manchester model, the torque amplifier was redesigned as a two stage device to improve amplification to an order of approximately 2000. Lennard-Jones adopted the two stage torque amplifier design but further improved the amplification. All the integrating disks on the Cambridge model were made of plate glass as the added friction afforded by ground glass was no longer necessary. Apart from the torque amplifiers there were several other, less important, differences between the Manchester and Cambridge model machines which consisted mainly concerned of changes to the arrangement of components.

The model machine was situated in the Physical Chemistry Department at Cambridge University for use by the theoretical chemistry group, but other members of the university began to take an interest in the device. In particular the machine attracted the attention of M.V. Wilkes, a research student in the Cavendish Laboratory at Cambridge. Wilkes attended a demonstration of the model in March 1936 and saw that a differential analyser could be used to solve the differential equations which resulted from his work on the propagation of radio waves (Wilkes 1985). Wilkes expressed his interest in using the differential analyser for his work and was given permission to use the machine. When Bratt left Cambridge in late 1936 Lennard-Jones offered Wilkes the job of providing technical assistance to other users of the differential analyser. The job paid a small salary and gave Wilkes access to the machine which he used to finish his Ph.D thesis. Unlike Hartree, who was very closely associated with the construction and operation of the model differential analyser at Manchester, Lennard-Jones was not personally involved with the running or maintenance of the Cambridge machine. Having initiated the project and obtained the necessary funding Lennard-Jones left the day to day running of the model differential analyser to Bratt and, later, Wilkes.

On seeing the success and usefulness of the model machine, Lennard-Jones began to press the University authorities to install a full size differential analyser at Cambridge to continue and expand on the work of the model. He was not, however, working for the installation of a large differential analyser for the use of the theoretical chemistry group alone. Lennard-Jones recognized that such a facility should be made officially available to Cambridge University research staff as a whole. This formal organization differs from the situation at Manchester where there were few official channels and the differential analyser was used by scientists from inside or outside the university who directly approached Hartree.

Lennard-Jones was, moreover, concerned that something more than an isolated differential analyser was needed by Cambridge scientists. He wanted to establish a computing laboratory to house the model differential analyser, a full size differential analyser, and a range of other computing machines. The laboratory was to be equipped with a sufficiently large range of calculating machines to perform the scientific computations generated by all university departments. Lennard-Jones was thus proposing to centralize scientific computation within Cambridge University.

In December 1936 Lennard-Jones succeeded in getting the University Faculty Board of Mathematics to prepare a report on the need for a computing laboratory at Cambridge (Univ. of Cambridge, Faculty Board of Mathematics 1936). This report presented a general case for the establishment of a computing laboratory. Despite Lennard-Jones' involvement there is nothing in the preamble describing the university's need for computation to suggest that the driving force behind the document came from the theoretical chemistry department. The report first discussed the need to alleviate the long laborious calculations carried out by astronomers and went on to present the case that all physical scientists were encountering problems which could not be solved analytically and thus required arduous numerical work.

The report noted the recent improvements to desk calculating machines and their increased use for scientific work. At the same time it was remarked that the number of desk machines in Cambridge was very limited but that an improvement in this situation could be achieved at a relatively low cost. The recent application of punched card machines to harmonic analysis and the development of linear simultaneous equation solvers (particularly the Mallock Machine at the Cambridge Engineering Laboratories) were also cited to demonstrate the advances in mechanical computation over the preceding decade. The Bush differential analyser, Hartree's work at Manchester, and the existing model at Cambridge were then discussed and the case for a full sized differential analyser at Cambridge presented.

The Faculty Board of Mathematics said it was satisfied that the model differential analyser had proved the need for the installation of a full sized machine at Cambridge. It dismissed the suggestion that it would be better to employ a staff of trained computers equipped with desk calculators on the grounds that the differential analyser could give reliable results to complex, laborious problems in a few days while it would take many weeks or months to do same work using desk machines. If desk machines were the only calculating devices available many exploratory calculations would not be carried out as the time scale involved would have been too long to be useful. Hence the differential analyser could be used as a convenient research tool opening up problems which would otherwise remain unexplored. The Faculty Board of Mathematics concluded that the installation of a full size differential analyser would be more useful than a team of computers to assist research at Cambridge and considered it "essential in the interests of the physical sciences in Cambridge to develop a computing laboratory" (University of Cambridge, Faculty Board of Mathematics 1936, p.4).

The report of the Faculty Board of Mathematics went on to make definite proposals concerning the organization and cost of such a laboratory. It was suggested that the laboratory be attached to the Mathematics Faculty and set up close to both the Mathematical Institute and the Cavendish Laboratory. The laboratory was to be equipped with a full size 8-integrator differential analyser to be extended as soon as possible to a 12-integrator machine, the model differential analyser, a Mallock simultaneous equation solver, and a wide range of desk calculating machines. It was estimated that the initial cost of equipping the laboratory would be £9000. In addition to the installation of computing machinery a technician to maintain the machines was to be employed. Research workers using the laboratory would operate the machines themselves under the supervision of the technician and the laboratory director who should, it was recommended, be a professor from the Mathematics Faculty. It was planned that a reserve fund for the laboratory be created to finance any machine developments which took place as research scientists used and gained familiarity with the machines. The Faculty Board of Mathematics was prepared to donate £2500 to the creation of the laboratory.

The report of the Faculty Board of Mathematics was then circulated to the other faculties in the School of Physical Sciences (Physics, Chemistry, Geology, Geography and Engineering). These faculties approved the scheme to set up a computing laboratory and the Council of the School of Physical Sciences prepared a report which it presented to the General Board of the University (Univ. of Cambridge, General Board 1937a). This report agreed with, and was essentially the same as, the report of the Faculty Board of Mathematics with a few exceptions and additions. For example, the Council called for the installation of a National Accounting Machine and a significant increase in the number of desk machines to be installed in the laboratory. It was also suggested that a lecturer attached to the Mathematics Faculty should be assigned part time to the laboratory to take responsibility for the desk machines and lecture on numerical computation thus extending the role of the laboratory to include undergraduate teaching.

The Council also made further suggestions as to how the money needed to set up the laboratory was to be found. It was suggested that most of the money was to come from the development funds of faculties using the laboratory. This was to be supplemented by the £2500 promised from the Mathematics Faculty and £1750 donated by the Engineering Faculty to purchase the Mallock Machine which was then situated in the Engineering Laboratories but which was not University property.

Besides the Council of the School of Physical Sciences the departments of Economics and Politics, Biology, and Agriculture also expressed an interest in using a computing laboratory and gave their support to the project. On 23 February 1937 the University of Cambridge approved, in principle, the creation of a computing laboratory (Univ. of Cambridge, Regent House 1937) and over the next few months moves were made to achieve this. After much discussion it was decided to name the computing laboratory the "Mathematical Laboratory". This title was chosen as "non-committal" and allowed both desk calculator work and differential analyser work to be performed in the laboratory

(Lennard-Jones 1937). Lennard-Jones, along with others, felt that the words "computing" or "calculating" did not adequately describe the analytical function of the differential analyser. It was also anticipated that the name of the laboratory should be general enough to allow computing machine developments to take place in the laboratory. The final plans for the Mathematical Laboratory were approved in May 1937 and the Laboratory opened the following October.

Lennard-Jones was appointed part-time director of the Cambridge University Mathematical Laboratory and Wilkes took up a post in the laboratory as university demonstrator. Wilkes was responsible for supervising the construction of the full sized differential analyser and visited Hartree in Manchester to learn what he could about the machine there. Metropolitan-Vickers undertook the construction of the full size differential analyser but progress was slow due to the increasing number of military contracts which the company was obliged to take on (Wilkes 1985). The machine was not delivered to Cambridge until late 1939 after the start of the war.

The Mathematical Laboratory did not, at first, have any accommodation. The machines attached to the laboratory remained where they had been previously: the model differential analyser was situated in the theoretical chemistry department; the Mallock Machine (bought by the university in June 1937) was located in the engineering laboratories; and the few desk calculating machines which had been allocated to the laboratory were scattered throughout the university. A National Accounting Machine had not been purchased. The Laboratory had been given accommodation in the Old Anatomy School but a significant amount of work needed to be done to refurbish the building before the Mathematical Laboratory could move in. Thus, although active from October 1937, the Mathematical Laboratory did not physically come together in the Old Anatomy School until October 1939. By this time war had been declared, Wilkes had left Cambridge for war service and the Ministry of Supply had requisitioned the Laboratory's facilities for the duration of the war (see p.96).

Although the different machines which equipped the Cambridge Mathematical Laboratory were not brought together until after the laboratory had been requisitioned by the Ministry of Supply, the laboratory had already been operating on a restricted basis for two years. The effectiveness of the laboratory had also been reduced by the delay in the delivery of the full sized differential analyser which was to form the centre piece of the laboratory. The desk machines, model differential analyser, and Mallock Machine were seen as auxiliary computing machines.

In principle, therefore, the Cambridge University Mathematical Laboratory was the first mathematical or computing laboratory to be established as a computing centre for all the scientists working in a particular university. It did not achieve its aims in practice until after the war (see p.196). Nevertheless, the reports of the General Board and the Faculty Board of Mathematics clearly show that the concept of centralizing computing power within a university was well understood in Cambridge by 1936.

3.4 Other Differential Analysers in Britain

There is no doubt that Hartree's work at Manchester led to the construction of the model differential analyser at Cambridge and, subsequently, to the establishment of the Cambridge University Mathematical Laboratory in 1937. However, during the late 1930s and early 1940s several other model differential analysers were built in Britain. The most well known of these was the model built in the Physics Department of Queen's University, Belfast by H.S.W. Massey and his colleagues (Massey et al 1938). Massey, who was aware of both Bush's work in the United States and Hartree's work at Manchester, felt that a differential analyser would be a valuable computing tool. Because of the great cost of installing a full sized machine Massey decided to construct a model differential analyser and contacted Hartree and Porter in Manchester. With help and advice from Porter a four integrator model differential analyser was built in Belfast. It was not constructed from Meccano but from parts obtained or made by the Queen's University Science Workshops. The machine cost approximately £50 and was, Crank (1947) suggests, a much inferior device to the model differential analyser built at Cambridge.

In 1938 Massey was appointed Goldsmid Professor of Mathematics at University College, London and brought the differential analyser with him to London. There was no suggestion at Queens in Belfast or at University College, London, that the model was a demonstration device intended to illustrate the need for a larger machine. The model differential analyser was for use by Massey and his colleagues. During the war Massey's model differential analyser was destroyed during an air raid.

In several cases work done by Hartree on behalf of a government research establishment or company led to the construction or acquisition of a model differential analyser by the institution concerned. For example, staff at the Coast Artillery Experimental Station and at the General Electric Company Ltd. constructed model differential analysers for their internal use after working with Hartree at Manchester. At the beginning of the war J.R. Womersley (see p.130), who had previously worked with Hartree on the mechanical solution of partial differential equations (Hartree and Womersley 1937), began to build a machine for the Armament Research Department at Woolwich. It, like Massey's machine, was destroyed. In the early 1940s the Valve Research Department of Standard Telephones and Cables Ltd. installed a model differential analyser which had originally been built by an actuary to solve differential equations which arose from his work in insurance (Beard 1941). Another three model differential analysers are known to have existed. One was built by a Maccelsfield schoolmaster, a second was constructed in the Physics Department of Birmingham University and a third was developed before the war in the War Office Projectile Development Establishment, Fort Halstead.

Hartree's work, particularly the construction of the Meccano model, gave rise to the construction of several model machines but it is interesting to note that only at Manchester and at Cambridge did any kind of computing centre emerge. At Manchester this focused mainly on the full sized differential analyser to which scientists in industry and government research establishments brought problems. At Cambridge, however, the construction of the model differential analyser initiated the establishment of the University

Mathematical Laboratory which was designed as a more general computing centre for the use of university members. When war was declared in 1939 both the Manchester and Cambridge differential analyers were given over to war work and inevitably changes, discussed in the following chapter, overtook the computing centres which had built up around the machines. At Manchester a more formal computing centre was established but at Cambridge the concept of a widely accessible computing centre was destroyed by the Mathematical Laboratory being taken over and used by a single research group.

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Chapter 4

World War II

The Emergence of Government Computing Centres

4.0 Introduction

The work of Comrie, Hartree, and Lennard-Jones during the 1930s had done much to develop both calculating machines and computing techniques. They had also provide computational resources for particular groups of scientists. However, by 1939 the only organization to which scientific workers in government research establishments could apply for computational advice or practical assistance was Comrie's Scientific Computing Service (the SCS). When war was declared there was no suitable administrative structure within government research establishments to cope with the increased computing demands of the service ministries. Section 4.1 discusses the different ways in which government departments coped with the increasing demand for computation caused by the war. This section includes a brief survey of the war work done by the SCS for government departments, the requisition of the Cambridge and Manchester differential analysers by the Ministry of Supply, a description of an attempt to install Hollerith punched card machines at the Royal Aircraft Establishment at Farnborough, and a discussion of the work performed by the NAO on behalf of other ministries.

As a result of the increasing amount of outside, war-related work which the NAO was being asked to perform, a computing service was set up within the Admiralty late in 1942. The main aim of the service was to perform computational tasks for Admiralty research establishments which were ill-equipped to tackle such problems because of the shortage of computing machinery and the lack of expert staff. This service, the Admiralty Computing Service (ACS), embodied many of the principles of a centralized computing facility. Section 4.2 will examine the proposal made to set up the ACS and will look at its initial formation. A review of the ACS as a centralized computing facility and how far it went towards achieving such a goal is discussed in section 4.3.

The significant role played by the Admiralty and the ACS in prompting the Department of Scientific and Industrial Research (DSIR) to consider the creation of a National Mathematical Laboratory is described in section 4.4. In 1944 the DSIR set up an Interdepartmental Technical Committee to consider the proposal. The report which this committee produced led directly to the creation of the NPL Mathematics Division. The background of the committee membership and the computing needs of the departments it considered are examined in section 4.5.

4.1 Computation Within The Service Ministries, 1939-1942

The advent of the Second World War brought an increased demand for computation in terms of both bulk and mathematical complexity. This increase was most pronounced in two major classes of calculation undertaken by government establishments. First trajectory calculations. In the period of rearmament directly preceding the war and, more urgently, after the outbreak of war in 1939, an effort was made to provide the armed services with ballistic tables and trajectory data for all types of weapons then in use. To try to deal with the heavy load of computation this required, the War Office and the Air Ministry enlisted the help of both the SCS and the NAO to compute the tables (Astronomer Royal 1939; SCS 1950). But this was not sufficient: further research was needed to find more rapid methods of calculating trajectories.

The second expansion in computing requirements experienced by the service ministries arose as a result of the acceleration of applied research concerning weapons, ships, aircraft and defence systems prompted by the war. This affected most government research establishments and, in the majority of cases, was a problem which remained unresolved. Within certain organizations, however, efforts were made to find alternative ways of performing the necessary calculations.

The only readily available and well equipped computing centre to which scientists could apply for computational assistance was the SCS. Although it is widely acknowledged that the SCS made a very great contribution to the war effort, there are few surviving accounts of the work it actually performed. This is partly due to the classified nature of much of the work carried out during the war and partly due to the scarcity of records Comrie left behind. Most of the details known about the war work of the SCS have been extracted from SCS information pamphlets (SCS 1938b, 1946, 1950), Comrie's own reminiscences (Comrie 1948b), and from publications describing work to which the SCS contributed (Comrie 1942a, Hodgkin 1949, Jones 1978).

Before the war Comrie had performed triangulation calculations for the War Office (see p.52) and throughout the war the War Office continued to use the SCS. Comrie was fond of boasting that within three hours of war being declared War Office officials approached him with an urgent request for the computation of a set of ballistics tables for the control of certain types of anti-aircraft gun in which predictors were not used. War Office workers had asked for three months to complete the three sets of tables required. In 24 hours Comrie had planned and begun the first of these tables and undertaken to prepare a second. In twelve days the two sets of double entry tables had been computed on the SCS National Accounting Machine, proof read, printed and bound. War Office staff computed the third set in three weeks (Comrie 1948b).

The SCS also carried out triangulation work for the conversion of Prussian latitude and longitude co-ordinates to rectangular co-ordinates used by the British armed forces, and an investigation into Kine Theodolite calculations[1] for the War Office. SCS war work for other government bodies included computations for Air Intelligence in 1940 to establish the location of German radio guidance transmitters (Jones 1978, p.142), a calculation concerning the demagnetization of ships, the preparation of wind graphs for the

1. Kine Theodolites were used to photograph objects from known positions. By inspection of the developed photograph through an evaluator (an instrument providing illumination, magnification and scaling data) the displacement of the photographed object from the central position could be determined. Using Kine Theodolite readings on the same object taken two or three miles apart the height and bearing of the object could be calculated using triangular geometry. To use this type of data effectively it was essential that the results of these calculations were found as quickly as possible. Comrie found that the single Marchant was the most suitable machine for this task.

analysis of sound ranging, ballistic tables for the United States Air Force, and the determination of the crystalline structure of penicillin for the Medical Research Council (Hodgkin 1949).

Most of the SCS's work was carried out at its premises in London but some of the larger jobs required the use of punched card machines and were performed on whatever machines were available at the time. For example, SCS work was carried out using the Customs and Excise Hollerith installation in Buxton and at the Milk Marketing Board at Cirencester. The SCS also used punches belonging to the Ministry of Aircraft Production's administrative installation in Mill Bank.

Although the SCS was widely used by government departments during the war, it was not funded by the government and had to operate on a commercial basis. The terse minutes of the company board meetings do not contain many financial details (the early accounts of the company are also poorly preserved), but certain conclusions can be drawn from the contents of the minutes. Before the war the company was financially stable and reasonably profitable. But, as the war continued into 1942 and 1943, the company rapidly expanded in terms of both staff employed and machines acquired. Work being done by the SCS was not invoiced quickly because of the intense pressure of computational work. The result of these two factors was a cash flow problem for the company. To try to relieve the problem Comrie is recorded as having waived his salary rights on several occasions (SCS 1938a). By 1944 things had improved, payments had been made and the company was again in profit.

At the beginning of the war the only service ministry to make special provision for the increased demand for scientific computation was the Ministry of Supply. The Ministry of Supply was created in August 1939 and took over the supply departments of the War Office and the Air Ministry. It also incorporated the Ordnance Board and the Research and Design Departments of the War Office. The Ministry of Supply was therefore responsible for armament research carried out in the Research Department and the separate ballistics research carried out by the External Ballistics Department of the

Ordnance Board. In 1938 revisions were made to the theory concerning the air resistance of cylindrical projectiles which had to be incorporated into the trajectory calculations and ballistic tables of both new and old weapons. Having to recompute ballistic data for weapons already in use disproportionally increased the amount of computation required. Although the Ordnance Board had installed National Accounting Machines for the calculation of trajectories in 1938, these were not sufficient to meet all the computational requirements of the Ordnance Board.

In August 1939, as the political situation in Europe worsened, the Directorate of Scientific Research of the Ministry of Supply arranged for Lennard-Jones to form a research team at the Cambridge University Mathematical Laboratory to be formally attached to the External Ballistics Department of the Ordnance Board (Lennard-Jones 1946; Ordnance Board 1945). On 1 September, 1939, two days before the declaration of war, the Ministry of Supply took over the Cambridge Mathematical Laboratory under a lease agreement and Lennard-Jones began work for the External Ballistics Department. Under Lennard-Jones' direction a team was built up at Cambridge to carry out ballistics work for guns and rockets, research into high explosives theory, and sound ranging . The Mathematical Laboratory was equipped with the model differential analyser already housed in the Laboratory, the full size differential analyser delivered to the Laboratory by Metropolitan-Vickers in late 1939, the Mallock Machine, and a range of desk calculators.

The full sized differential analyser was the most important piece of equipment in the laboratory and it was because of this that the Ministry of Supply had wanted to take over the Mathematical Laboratory. Although the accuracy of the differential analyser was too low for the routine calculation of trajectories[2], it was used successfully for irregular and experimental work. By 1942 the laboratory was generating enough work to keep the differential analyser in operation 12 hours a day (Lennard-Jones 1942, 2 September). Despite the large amount of work being performed on the differential analyser only a

2. A conclusion also reached by the Aberdeen Proving Ground in the United States (Ministry of Supply nd.).

small staff, which varied between 2 and 4, worked full time on the machine. The bulk of the External Ballistics Department staff based in the Cambridge Mathematical Laboratory used desk machines for their work[3]. The Cambridge Mathematical Laboratory primarily performed ballistics based work and seldom took in computations from outside the Ministry of Supply. Access to the Cambridge facilities by outside workers was occasionally permitted: for example, de Havillands', the aircraft manufacturers, used the Mallock Machine for war-related work (Wilkes 1946). Before the war the Cambridge Mathematical Laboratory had been a centralized computing facility for Cambridge University. After it was taken over by the Ministry of Supply, the Cambridge University Mathematical Laboratory was almost exclusively used by a single research group.

Hartree's differential analyser group at Manchester also became attached to the Ministry of Supply at the beginning of the war. Initially the connection was an informal one but, in 1942, the group became part of the Headquarters Section of the Ministry of Supply and became known as SR(A) (Hartree 1946). The Manchester differential analyser group was very different to that at Cambridge. At Cambridge the differential analyser was part of the computing facilities used by the External Ballistics Research group based there. At Manchester the differential analyser group acted primarily as consultants to a wide range of people inside and outside the Ministry of Supply. At first the Manchester group performed primarily ballistics calculations, including some for the External Ballistics Department of the Ordnance Board before the Cambridge differential analyser becoming fully operational. Later the Manchester differential analyser was used for the calculation of heat flow in rocket tubes, for studying servo-mechanisms particularly in relation to fire control equipment[4], the propagation of blast waves and many other applications (see Hartree 1947).

3. E.T. Goodwin was a member of Lennard-Jones' staff at Cambridge but later joined the Admiralty Computing Service (see p.105) and, in 1945, the National Physical Laboratory Mathematics Division (see p.136).

4. Fire control equipment were analogue control mechanisms for targeting anti-aircraft guns and similar weapons.

The group working at Manchester was quite small. At the beginning of the war the group consisted of Hartree and two others. Hartree, however, left the group to take up a post elsewhere in the Ministry of Supply and, although the staff was reduced to one in 1940, by 1942 it had risen to four. In 1941 Hartree was transferred to Ministry of Supply Headquarters and was again able to supervise, and sometimes contribute to, the work performed on the Manchester differential analyser. Also in 1941 Hartree formed a second group at Manchester which used the differential analyer for its work on the radar magnetron. This group was attached to the Admiralty but reached an agreement with the Ministry of Supply which allowed it access to the differential analyser.

Although the Cambridge Mathematical Laboratory and the Manchester SR(A) group were affiliated to separate Ministry of Supply departments, it is important to note that both groups liaised with each other and with other groups working in the same field. For example, the Cambridge and Manchester groups both worked towards finding more rapid methods of calculating trajectories using desk machines in cooperation with other branches of the External Ballistics Department and the collaboration led to a significant improvement in the use of desk machines for ballistics calculations (Ordnance Board 1945). The Cambridge and Manchester groups also contributed to a series of External Ballistics Department Reports (referenced E.B.D.) on ballistics based numerical and computational work. In one instance, E.B.D. 10, the report was written jointly.

Of the two Ministry of Supply differential analyser facilities, the Manchester SR(A) group, because of its attachment to the Headquarters department, was used for a wider variety of problems. In many ways it continued to operate as it had done before the war except that most of the investigations it carried out were war-related and undertaken for government departments or research establishments. Problems were not carried out for their academic interest alone. The Ministry of Supply had recognized at the beginning of the war that the increased demand for ballistic data would present computational difficulties. By gaining access to the Manchester differential analyser and taking over the Cambridge Mathematical Laboratory, the Ministry of Supply went some way towards resolving some of the difficulties.

Other parts of the Ministry of Supply had localized collections of computing equipment. For example, the External Ballistics Department establishment at Woolwich contained several National Accounting Machines, but they were not used to perform any outside work. Apart from the Ministry of Supply, only a few government departments tried to install extensive computing facilities to cope with the large amount of computation created by the war. In some research establishments solutions to the problems were put forward during the war but not taken up until after 1945. One example of such an installation was the Royal Aircraft Establishment (RAE) at Farnborough.

In the mid 1930s A.G. Pugsley and R.A. Fairthorne of the Structural and Mechanical Engineering Department at the RAE had been trying to find efficient methods of solving large systems of linear simultaneous equations and calculating determinants which arose from their work on structural stress in aircraft bodies. Pugsley had installed desk machines at the RAE for this work and had also experimented with the Mallock simultaneous equation solver at Cambridge. In 1938 Pugsley and Fairthorne discussed the possibility of using Hollerith punched card machines to perform the calculations and, over the following months, discussed the matter with Comrie, S. Chapman (see p.205), and the British Tabulating Machine Company.

As a result of his investigations, Pugsley presented a paper to the relevant subcommittee of the Aeronautical Research Committee (ARC) in February 1940 proposing the use of Hollerith machines for the calculation of determinants[5]. The report outlined a method for calculating determinants using punched cards machines and recommended that further investigation into such techniques be carried out. Pugsley's preliminary work was followed by two later reports presenting a more detailed discussion of the possibility of using punched card machines for scientific work (Frazer 1940; Schmidt and Fairthorne

5. The ARC was an advisory committee which directed aeronautical research in the Air Ministry, the Ministry of Aircraft Production (created in 1940) and at the NPL Aeronautical Division. Although influential it had no executive powers nor any financial control over the establishments it advised.

1940). In October 1940 the committee chairman acknowledged the need for an improvement in computing facilities at the RAE but remained unconvinced that a Hollerith punched card installation within the Structures and Mechanical Engineering Department would be fully utilized and, hence, would be uneconomical (ARC 4/10/40). Due to the intense pressure of work during the war and the national shortage of any sort of adding and listing equipment Pugsley abandoned this line of investigation until much later in the war[6] (see p.192).

Admiralty establishments too were experiencing computational difficulties during 1939-1942. Unlike any other ministry the Admiralty already had a well equipped computing centre in the NAO which, while not openly available for other establishments to use, was reasonably well equipped with machines and, perhaps more importantly, had an experienced computing staff. Consequently the NAO received many requests from Admiralty research establishments and other service ministries to carry out different types of computation. Although NAO facilities were officially unavailable to personnel from outside the Office, D.H. Sadler (Comrie's successor as Superintendent at the NAO) took on as much additional war related work as he could. By January 1942 30 per cent of the Office's time was spent performing special war related computations (Astronomer Royal 1942). In addition to ballistic table preparation carried out for the Ordnance Board and the Air Ministry, the NAO also computed bomb ballistic tables for the Ministry of Aircraft Production, and prepared Astrograph Tables and Star Curves for the Astrograph on behalf of the Air Ministry. The staff at the NAO also performed calculations of a more theoretical, less repetitive, nature for other Admiralty establishments particularly on mine design.

Like other government establishments, the amount of work which the NAO was asked to perform, over and above outside work, increased during the war. One of the

6. During the war punched card equipment was heavily used by the armed services for administration and logistics. The Hollerith and Powers factories too were partially given over to the manufacture of supplies for the armed services. Thus a shortage of punched card machines developed during the course of the war.

main areas in which the NAO's work load increased during the war was the computation of places of stars which would, under peace time conditions, have been the joint responsibility of several international offices. To perform this work quickly and effectively Sadler proposed using a Hollerith multiplying punch to compute the required tables. The Office did not have a Hollerith installation having, in the past, borrowed such equipment when necessary. Although Sadler had informed the Treasury in October 1940 of his intention to utilize a Hollerith multiplying punch for the task, the shortage of this type of equipment meant that BTM did not have a multiplying punch available at the time. Thus, after many delays, Sadler was given permission to engage the services of a BTM service bureau in April 1941 to carry out the necessary work.

The NAO did not, and could not, accept all the work which was brought to it during the early stages of the war. It had neither the staff nor facilities to do so. For example, in May 1941 the Assistant Director of Research, Ministry of Supply approached Sadler concerning the preparation of a set of firing records for the External Ballistics Department of the Ordnance Board based at Woolwich. Sadler had to refuse the work on the grounds that his staff were over stretched. The Office was already engaged in several large scale jobs for the Ministry of Supply in addition to work for other Admiralty establishments and the Air Ministry. By July, however, Sadler was able to contact the Assistant Director of Research and accept the job on the basis of two changes in circumstance which had occurred. Firstly several jobs had been completed leaving time available. Secondly, and more significantly, Sadler was able to state that the

> Admiralty have recognized that there is a considerable amount of computational work required at the present time, and that this Office is ideally equipped to undertake it. They have accordingly sanctioned the appointment of an additional temporary assistant (Sadler 1941, 8/7/41).

Thus the use which other ministries and research establishments were making of the NAO facilities was officially acknowledged. The NAO was seen as a resource which should not, in war time at least, be confined to the preparation of astronomical data but should be made more widely available. In effect the Admiralty had acknowledged that the NAO was acting as a limited computing centre to all the service ministries.

4.2 The Formation of the Admiralty Computing Service

Recognition by the Admiralty that the NAO was becoming heavily involved with additional military computations was, in itself, not enough to prompt the creation of a formal computing service. Sadler, because of his continual involvement with the work, was aware that the problem of insufficient computing facilities was not confined to the Admiralty alone but to the whole of the scientific civil service and the other service ministries. Consequently, in 1941, he proposed that a central computing facility be set up for use by all government research establishments and the armed forces (Conolly 1947, p.88). His proposal came to nothing because recognition of the problem was not yet widespread. The less ambitious suggestion to centralize computation within the Admiralty came as a result of other Admiralty personnel reaching the same conclusions as Sadler.

In 1942 J. A. Carroll, professor of Natural Philosophy at Aberdeen University, joined the Scientific Research and Experiment Department (SRE) of the Admiralty as Assistant Director of Scientific Research. The prime function of SRE was to administer Naval research establishments from Whitehall and serve as a means of communication and liaison between them. It also had the task of keeping Admiralty establishments informed of scientific developments taking place outside the ministry and of employing external consultants when required. In the autumn of 1942 John Todd[7] also became attached to the SRE department. On the outbreak of war Todd, a mathematician, had been assigned first to a degaussing range and then to the Mine Department of HMS Vernon. At the former Todd came to the conclusion that he was not an applied mathematician nor an experimental physicist, and at the second found himself employed doing minor calculations concerning electric circuits. Todd recalls

7. Later Todd played a principal role in creating and running the Admiralty Computing Service.

> Observing this and similar matters I realized that pure mathematicians, such as I, could be more useful in dealing with computational matters and relieve those with applied training and interests from what they considered as chores (Todd 1983).

In 1942 Todd was transferred to the SRE department under Carroll.

Before joining the Admiralty, Carroll had developed an interest in table making and had consulted Comrie on the merits of desk calculators for such work (Carroll 1933). Soon after his appointment to SRE, Carroll became aware that a significant amount of time was being spent by experimental staff performing calculations. In some cases, where the calculations were inseparable from their experimental background or where they were brief, this was not important. Carroll, however, concluded that scientific effort was being wasted in performing long, repetitive calculations particularly in cases where the specialized machinery or knowledge needed to efficiently perform the work was not available. With the war-time pressure for the rapid production of research results Carroll felt that it was important that computation be handled quickly and effectively by specialists (Sadler and Todd 1946, p. 571; Conolly 1947, p. 85).

As a result of these feelings within the SRE department Sadler was asked, in late 1942, to investigate the computational requirements of Admiralty research establishments. Sadler reported his findings to the Director of Scientific Research (DSR):

> (a) Some of the computation arising in the establishments staffed by D.S.R. can, with advantage, be centralized.
>
> (b) Research and experiment give rise to a proportion of work unsuitable for centralisation so that there will always be a need for local facilities and, in some cases, specialized local staff.
>
> (c) Centralisation would not only lead to acceleration in the presentation of results but would make possible theoretical research involving calculations too lengthy to be tackled locally (Carroll 1943 p.1).

It was thus anticipated that a central Admiralty computing centre would undertake long, routine calculations, calculations for which equipment or expertise did not locally exist, mathematically complex work, and work which would, under normal circumstances, not have been undertaken at all.

This report confirmed the opinions of Carroll, Todd, and Sadler, and moves were made to establish an Admiralty Computing Service (ACS) at the NAO early in 1943. Permission from the Astronomer Royal regarding the use of NAO staff and facilities was sought and granted. Additional mathematical and computing staff were attached to the NAO to carry out the work of the Service and were all trained by Sadler. Individual Admiralty establishments were to approach the NAO for assistance through a small administrative staff at the SRE department in Whitehall under Todd. The ACS, therefore, operated on two levels: it was administered from Whitehall and the actual work passed on to the NAO.

There were three reasons for this two tier administrative system. Firstly, issues of priority would naturally arise where several establishments were competing for resources. It was felt that questions of priority would be more smoothly overcome by the SRE department rather than the NAO as the former was an already recognized line of communication between Admiralty establishments. Secondly, it was decided that the staff of the ACS would include a number of experts from various mathematical, statistical and computational fields. This was to be achieved by employing mathematicians and scientists working in other Admiralty departments, other service ministries and universities as consultants to the ACS. The SRE department already employed outside specialists from a variety of fields and thus, again, it was the obvious administrative procedure. Thirdly, it was proposed that SRE act as a clearing house for all the problems brought to the ACS. Todd's staff divided the work sent to them into two classes; mathematical and computational. Those problems which were mathematically complex did not usually raise any questions of security and could be quickly passed to the appropriate consultants. Once the mathematical problems had been solved the individual establishments were asked to make the decision locally as to whether the work could be carried out on site or whether it should be performed at the NAO. If the latter course was chosen then the SRE department handled the necessary arrangements.

The role of the SRE department was to liaise between the individual Admiralty establishments and the NAO. In cases where the NAO was not suitably equipped to carry out the work, that is, if Hollerith machines or large analogue devices were required the SRE department was to make arrangements for it to be carried out elsewhere. The main disadvantage of the system was that Sadler and his staff at the NAO had very little contact with the Admiralty establishments in which the work originated. This meant that the NAO often had no background of the physics behind a calculation and had no control over the way in which data was recorded or presented (Sadler 1984a, 1984b). On the other hand, the system did relieve the already hard pressed NAO from the burden of carrying out the considerable amount of administration which was required in running such a service.

Thus, by March 1943, the ACS had been set up and was functioning as a computing service for Admiralty establishments. Todd visited all the Admiralty research establishments which came under SRE jurisdiction to inform them that the ACS had been set up. Sadler too visited some establishments to advise on computing machinery to be installed there (Sadler 1984a). Due to the difficulties of obtaining experienced computers the ACS began on a limited scale. Sadler recruited a number of computers to the NAO including L. Fox, F.W.J. Olver, K. Blunt, E.T. Goodwin and H.H. Robertson (all of whom were later to join the NPL Mathematics Division). Although the annual reports of the Astronomer Royal from 1943 to 1945 are not available, it is obvious from subsequent reports that a large proportion of the work carried out by the NAO during those dates was for the ACS at the expense of astronomical and navigational computations (Astronomer Royal 1946).

The initial objective of the ACS was "to obtain the numerical results required in problems of war research and to make those results available to the particular establishment concerned as early as possible" (Sadler and Todd 1947, p. 290). The preparation of reports and publication of results was therefore of less immediate importance. At first the few reports which were prepared were distributed by the NAO (usually in the form of duplicated manuscript, or occasionally typescript, copies). However, by 1944 the publication of a series of monographs describing pure and applied mathematical techniques had begun which were distributed to the establishments administered by SRE department. The purpose of these monographs was to familiarize scientific workers with these techniques so that they could deal locally with computations which were to small to be efficiently centralized and recognize when a problem could be solved by a standard method. The SRE/ACS report series also included mathematical tables which were either unpublished, or not published in a convenient form. Table 4.2.1 gives a selection of the titles in the SRE/ACS series. Many of the SRE/ACS reports are anonymous but others were prepared by the consultants associated with the ACS.

Table 4.2.1 Incomplete List of SRE/ACS Reports

Number	Title
7	Summation of Certain Slowly Convergent Series
8	Mechanical Quadrature
9	Table of $f(x,y)=2\pi^{\;1}\int_0^{2\pi} e^{x.\cos\theta\quad y.\cos 2\theta}\,d\theta$
18	Cable Tables
19	Tables of the Incomplete Hankel Functions
20	Trajectory of a Body Moving with Resistance Prohibited
21	Calculations Involving the Airy Integral for Complex Arguments-First
22	Tables of Integrals $A(x)=\int_0^x \frac{\cos(\pi t/2x)}{1+t^2}dt; B(x)=\int_0^x \frac{\cos(zt/x)}{1+t^2}dt;$ and $C(x)=\int_0^x \frac{\cosh(zt/x)}{1+t^2}dt$
26	Asymptotic Expansions
31	Calculations Involving the Airy Integral for Complex Arguments-Second
35	Rapid Calculation of Bearing Tables
37	An Electronic Differential Analyser by J.M. Jackson. Reprinted from a U.S. Navy publication.
39	Calculations Involving the Airy Integral-Third
40	Rangefinder Performance Computer
46	Calculations Involving the Airy Integral-Fourth
47	Tabulation of the Function $f(x,y)=\int_0^x e^{\;k}[J_0(kx)\cosh(ky)-1]$
51	Tables of Angular Quarter Squares

52 Tables of Certain Integrals
53 Dictionary of Laplace Transforms. Part 1
55 Calculations Involving the Airy Integral for Complex Arguments-Fifths
62 Tables of the Function $f(x)=e^{x}\int_0^{\pi/2} e^{x\cos\theta}\sin^2\theta\, d\theta$
65 Tables of Legendre Functions
68 Dictionary of Laplace Transforms. Part 2A
71 Dictionary of Laplace Transforms. Part 2B
76 A Statistical Investigation into Night Vision of Watches at Sea
80 Probability Charts for Destructive Tests
82 Zeros of Laguerre Polynomials
89 Solution of Integral Equations Occurring in an Aerodynamical Problem (Supersonic Flow)
90 Tables of Integrals $C(t)=k^{1/2}\int_0^{\infty} e^{u} \cos(2tk^{1/2}u-ku^2)\,du$; $S(t)=k^{1/2}\int_0^{\infty} e^{u} \sin(2tk^{1/2}u-ku^2)\,du$
91 Miscellaneous Information Sheet III
92 Lateral Vibration of Beams of Conics
93 Tables for the Summation of Triangulations
95 Stresses in Turbine Rotors
96 Computation of an Integral Occurring in the Theory of Water Waves
97 Tables of the Incomplete Airy Integral
101 Dictionary of Conformal Representations Part I
102 Dictionary of Laplace Transforms Part 3A
106 Asymptotic Expansions (update os SRE/ACS 26)
107 Dictionary of Conformal Representations. Part II
108 Dictionary of Laplace Transforms. Part 3B
109 Dictionary of Conformal Representations. Part III
110 Dictionary of Conformal Representations. Part IV
111 Dictionary of Conformal Representations. Part V
112 Alan Baxter (1910-1947). The Fourier Transformer

Details of individual computations carried out by the ACS are not preserved but it is clear that a wide range of problems was dealt with including the theory of supersonic flow, trajectory work, stresses in turbines, and a statistical investigation into the night vision capabilities of naval personnel. Hence it can be concluded that many of the Admiralty research establishments to which the ACS was available were making use of the service. In 1946 Sadler and Todd stated that by the end of the war

> "the Admiralty Computing Service was providing a fairly comprehensive mathematical and computational service which was not only meeting all the demands from Admiralty sources but was also able to offer informal assistance to the other Services, Government departments and contractors who had no comparable facilities at their disposal" (Sadler and Todd 1946,p. 571).

But how far did the ACS go towards a truly comprehensive computing facility?

4.3 The ACS as a Computing Centre

The organization and work of the ACS can best be described within the framework of the list given in section 1.1.2 which gives nine factors to be considered when analysing computing centres. The nine factors discussed are the centre's users, the personnel employed, the machinery used, what computations were performed, the advisory role played, the amount of numerical research carried out, the amount of machinery research carried out, the number of publications arising from the work of the centre, and whether or not the centre maintained a library. The position of the ACS will be considered within this framework.

Admiralty research establishments were the only official users of the ACS, although informal advice was given to workers outside the Admiralty when requested. All users had first to approach Todd at SRE before their problems were passed on either to a consultant or to the NAO. In this respect the two tier administrative structure was a cumbersome one for users as they never had direct contact with computing staff.

All the routine work performed by the ACS and the administration of the computations were carried out by junior NAO personnel. The Admiralty did, however, employ a number of senior computers specifically as ACS staff. From the outset, however, the ACS suffered from a shortage of trained senior staff. It is difficult to determine how many computers were employed by the ACS as they were well integrated with the staff of the NAO and directly supervised by Sadler, but at any one time there were approximately eight. This shortage of experienced staff was due, in part, to conscription but was aggravated by the lack of training in practical computing techniques given in British universities. This lack of trained computers caused considerable concern and was to result in a number of articles, written after the war, calling for such courses to be introduced[8].

The list of consultants who offered their services to the ACS is impressive. They include N. Aronszajn, W.G. Bickley, L.J. Comrie, E.T. Copson, J. Cossar, A. Erdèlyi, P.P. Ewald, H. Kober, J. Marshall, J.C.P. Miller, E.H. Neville, and H.L. Seal and S. Vajda from the Admiralty statistical section. Thus the ACS reaped some of the benefits of a large staff, experienced in a wide range of fields without their being full time employees of the ACS. The ACS was not large enough to justify a large highly qualified staff on a full time basis, nor would it have had the income to do so.

The type of machinery used to perform ACS computations was limited to that already available at the NAO, ie. desk calculators and National Accounting Machines. A comprehensive computing service of the early forties might have been expected to possess a differential analyser, a Hollerith installation, and perhaps several more specialized pieces of equipment. The ACS was not sufficiently large to justify the expense of either a differential analyer or a Hollerith installation. Sadler and Todd (1946) reported that, between 1943 and 1946, the need for a differential analyser never arose and that a Hollerith installation would only have been used, on average, for two months of the year. Todd had considered installing Hollerith equipment (Hartley 1946, p.176) and was caught

8. For example, see Erdèlyi and Todd,1946 and Sadler and Todd, 1946.

between the two pressing factors of computing efficiency and financial economy. He resolved the problem by making arrangements to borrow machines as necessary.

The type of work performed by the ACS fell into two main classes: large, repetitive calculations and those involving complex mathematics. The other role the ACS played was that of an advisory body which Admiralty establishments could consult on computational techniques and on the use of the machinery at its disposal. By 1947 the ACS had performed over 100 investigation besides dealing with enquiries which required only advisory assistance (Conolly 1947).

In cases where mathematical or numerical research was required for the solution of a particular problem the ACS consulted experts in the appropriate field and developed the ideas which they supplied. The SRE/ACS reports were often the results of these investigations. Thus the ACS did carry out a degree of research and development into numerical methods. In most cases they were carried out on the behalf of ACS users, but reports such as the Dictionary of Laplace Transforms (SRE/ACS nos. 53, 68, 71, 102 and 108) illustrate that mathematicians, such as Cossar and Erdèlyi, were using the ACS to develop methods and provide computing tools for the scientific community at large.

The ACS was not equipped, nor was it set up, to undertake research into the design and subsequent development of calculating machinery. It did, however, offer information to Admiralty establishments on a wide range of computing equipment, from desk calculators and Nationals to punched card machines, differential analysers and, after the war, the ENIAC. The one exception to this was the design of an electromechanical device by A. Baxter, from the SRE department in Whitehall, which calculated the root and mean square errors made by trainee rangefinder operators. This was however not a usual part of the work performed by the ACS.

Beginning in 1944 the ACS published reports of its work and distributed them to interested parties as well as to individual Admiralty establishments. These SRE/ACS reports (table 4.2.1) were, after the war, reviewed on several occasions in *Mathematical*

Tables and other Aids to Computation where their contents were of interest to its readers. An article describing the ACS itself was also featured in 1947 (Sadler and Todd). *Nature* also published an item concerning the ACS (Sadler and Todd 1946). The ACS, therefore, not only published reports of its work but also, after the war, made the public aware of its work.

It is unlikely that the ACS would have had a library of its own but would have made use of the existing collections at the NAO and at the SRE department. At the SRE department in Whitehall an Admiralty Technical Records Section was maintained for the use of Admiralty establishments. A set of the SRE/ACS monographs would have been held here and thus were available to all users. It would hence have been superfluous to create an additional library for the ACS.

There are no direct records available to determine what attitudes different Admiralty establishments had towards the ACS. Sadler and Todd (1946) and Conolly (1947), who later took over the administration of the ACS, have both stated that the ACS was successful in easing computing problems in the Admiralty within the limits of its terms of reference. Thus it succeeded in fulfilling the aims of its administrators and creators.

Despite the partial, and in some cases total, fulfillment of the nine criteria of a computing centre listed above, the ACS failed to provide a complete service on three counts. Firstly its use was officially restricted to Admiralty personnel; secondly it had a limited range of calculating machinery in its possession and access to larger devices elsewhere was by no means automatically available; and thirdly it did not undertake research into new machines. In addition to these limitations the ACS also did not fulfil the entire concept of a computing centre in another important respect. It was divided, both physically and conceptually, between the NAO at Bath and SRE department in London. Therefore, although the ACS was a practical solution to problems which existed at the time, it did not totally embody the centralized computing principle. It was, however, an extremely important step towards that goal.

4.4 The DSIR Initiative

Within a year of the Admiralty Computing Service becoming operational Todd, Sadler and A. Erdèlyi, an Admiralty scientific consultant during the war, realized that the degree of centralized computation they could offer within the Admiralty did not go far enough. The ACS did not operate on a large enough scale to economically support a fully equipped computing service with a full range of computing machinery. In some cases computing efficiency was sacrificed by the unavailability of the most suitable type of equipment for certain calculations. Hence it was felt within the Admiralty that only centralization at the national level would achieve the economies of scale necessary to provide a fully equipped service.

As a result of these feelings, Carroll made an approach to Sir Edward Appleton, secretary of the Department of Scientific and Industrial Research (DSIR), proposing that a central computing organization be set up. This proposal was accompanied by a supporting document probably written by Todd, Sadler and Erdèlyi, "Memorandum on the Centralization of Computation in a National Mathematical Laboratory" (Anon. nd). From this document it is clear that the motivation behind the proposal was the obvious need within the other service ministries for a facility similar to the ACS. The memorandum was based on the NAO's experience of performing computations on behalf of several government departments, the experience of the ACS, the work of Comrie at the SCS, and the existence of the New York Mathematical Tables Project (see p.238).

The memorandum proposing a National Mathematical Laboratory was very similar in content to the 1942 proposal which led to the establishment of the ACS but the later document envisaged a computing service for a much broader range of users. However, it did contain a number of important differences and extensions as a result of the experience gained through running the ACS. The main case for centralization presented by the Admiralty memorandum was the same as that presented for the ACS:

1. efficiency of computing methods by trained staff and specialists with access to a

wide range of calculating machines and

2. economy of machines and staff.

As a result of having run the ACS on this basis a further four additional arguments in favour of centralization were added to the list.

3. The benefit of accumulated computing experience by a regular staff which could efficiently deal with the recurrence of similar problems which may stem from a variety of sources.

4. The ability of trained staff to identify, and hence carry out, areas in which research into new numerical methods and machines are most needed.

5. The benefit of having a central, specialized library of books, tables, reports, and papers on computational and allied subjects.

6. A central administrative structure to act as a liaison between establishments and provide for the organized and systematic dissemination of relevant information.

Thus it was already recognized that the role of a National Mathematical Laboratory extended beyond running a service bureau to which the user presented a problem and received a solution in return. Such an establishment, it was proposed, should also carry out research, into both machines and numerical techniques, and act as a clearing house to hold and pass on information. In conclusion the Admiralty stated several features which it saw as desirable in a National Mathematical Laboratory and outlined how such a laboratory should be run.

The first feature suggested in the memorandum was that any National Mathematical Laboratory should "Act generally in the sphere of (numerical) mathematics and computation in a way similar to that in which the National Physical Laboratory acts in the sphere of physics" (Anon. nd., p.3). That is, the proposed National Mathematical Laboratory was, initially, to take on all kinds of computational work for government departments but, later, to extend its facilities to undertake work for industry and the universities in addition to carrying out fundamental research into numerical methods and machines. The laboratory was to become the authority on computational methods in Britain.

Secondly, the memorandum advised that the National Mathematical Laboratory be non-departmental and should, therefore, come under Department of Scientific and Industrial Research administration. This followed naturally from the two tier administration of the ACS and the proven advantages of having a central body to objectively discuss priorities.

The memorandum next outlined five individual sections, devoted to different types of computational work, which the Admiralty saw as making up a comprehensive computing centre. The different sections were:

(i) Mathematics, applied to numerical computation

(ii) The provision of a comprehensive collection of Mathematical Tables, and the computation of such new tables as may from time to time be required.

(iii) General computation by machines including Hollerith, National and other installations. The development of methods and machines.

(iv) General computation by instruments such as Differential Analysers, Cinema Integraphs, Fourier Transformers, Mallock Machines, *etc.* This section might include graphical and nomographical methods. The development of such instruments to meet requirements.

(v) Statistical mathematics, tables, methods and computation (but not the collection of data). (Anon. nd., p.3).

The remainder of the memorandum concentrated on the three ways in which the Admiralty saw the National Mathematical Laboratory being used. Firstly, it was to carry out all types of computational work for government departments which required it and make computational facilities available to those who chose to perform their own work but did not have the necessary equipment. Secondly, it was to advise all government departments on the installation of computing facilities and liaise with the Treasury over such matters. Thirdly, the laboratory was to liaise closely with non-government departments such as university mathematical laboratories, the British Association for the Advancement of Science Mathematical Tables Committee and overseas computing centres. Any new developments in computing technique could therefore be made available to government establishments through the laboratory.

The most significant departure from the original ACS concept is demonstrated by the title "National Mathematical Laboratory". The Admiralty, more specifically Todd, Sadler and Erdèlyi, were proposing more than a large scale version of the ACS. They were presenting the case for a national effort to be made to develop numerical mathematics and computing as a specialized subject. The ACS was never intended to fulfil this more general role; it was created to supply the computing power necessary under wartime conditions. The proposed National Mathematical Laboratory was intended to be a more permanent and well developed organization.

Unlike the proposal which Sadler had made in 1941, this approach to the DSIR in 1944 bore fruit and moves were made to consider the question further. There were three reasons why this later proposal was more seriously considered. Firstly, this proposal made to the DSIR had the approval of the Director of Scientific Research (Admiralty) whose high rank led to the proposal's prompt consideration by the DSIR. Secondly, the proposal was based on the experience of the ACS and not just the work of the NAO: the ACS had successfully demonstrated the need for such a service. Thirdly, and perhaps most importantly, the question of establishing a National Mathematical Laboratory had already been voiced in other quarters.

One such voice was that of Sir Charles G. Darwin, Director of the NPL. In March 1943 Darwin informally expressed to the DSIR Advisory Council the opinion that a Mathematical Department should be set up at the NPL to carry out the computations arising within government establishments (DSIR 1942-47 AC Minute 61 1942-43). He was, in essence, calling for the establishment of a national computing centre. The possibility of a National Mathematical Laboratory was also being freely discussed in a variety of circles and Darwin had sounded out the views of his contemporaries. For example the establishment of such a Laboratory was discussed over lunch by Lennard-Jones, Darwin and R.H. Fowler during May 1943 (Lennard-Jones 1943, 27 May 1943, part 3) and the possibility of the Cambridge Mathematical Laboratory taking on the prescribed role mooted. From this conversation it is evident that Hartree too had been consulted on this issue.

Thus, before the Admiralty proposal had been submitted, the ground work had already been done in bringing the problem to the attention of influential scientists. As a result, the proposal from the Admiralty was considered and the DSIR contacted various ministries which were thought to have an interest in the work such a laboratory might perform. On the results of this preliminary survey it was agreed that the proposal to set up a National Mathematical Laboratory be further investigated by an Interdepartmental Technical Committee to "examine the question of whether it is desirable to establish under government control a Central Mathematical Station, and, if so, to make recommendations on the form it should take" (DSIR 1944, p1).

4.5 The Report of the DSIR Interdepartmental Technical Committee

The Interdepartmental Technical Committee set up by the DSIR to consider the question of a Central Mathematical Station drew its 20 members from 11 different government departments. It was chaired by Darwin in his dual role of Director of the NPL and Chief Scientific Advisor to the War Office. Table 4.5.1 lists the committee members. The number of representatives from each department illustrates their relative importance as users of such a station. Four of the twenty committee members was taken from the Admiralty; Sir Harold Spencer-Jones, the Astronomer Royal, Carroll from the SRE department, Sadler from the NAO, and Todd as ACS organizer. Of these Carroll, Todd and Sadler had been partly responsible for bringing the question to the attention of the DSIR and had practical experience of running the ACS.

Table 4.5.1 DSIR Interdepartmental Technical Committee Membership

Sir Charles Darwin (Chairman)

Member	Representing
Sir Harold Spencer-Jones	Admiralty
Prof. J.A. Carroll	Admiralty
Mr. D.H. Sadler	Admiralty
Mr. J. Todd	Admiralty
Dr. F. Yates	Agricultural Research Council
Prof. W.J. Duncan	Ministry of Aircraft Production
Dr. S.H. Hollingdale	Ministry of Aircraft Production
Mr. J.R.N. Stone	War Office, Central Statistical Office
Mr. A.W. Taylor	Customs and Excise
Dr. Christopherson	Ministry of Home Security
Dr. David	Ministry of Home Security
Prof. D.R. Hartree	Ministry of Supply
Dr. J.W. Maccoll	Ministry of Supply
Mr. J.R. Womersley	Ministry of Supply
Major Gen. G. Cheetham	Ordnance Survey Department
Mr. A.W. Mattocks	Treasury
Mr. G.F. Peaker	Treasury
Major E.H. Thompson	War Office, Directorate of Military Survey
Dr. S. Goldstein	DSIR

The Ministry of Supply was also well represented providing three members of the committee: Hartree, Maccoll and Womersley. Hartree was an acknowledged computing expert having had considerable computing experience during the First World War under A.V. Hill and later guiding the work performed on the Manchester differential analyser. Maccoll represented the Armament Research Department under Lennard-Jones and was involved with the external ballistics work performed at the Cambridge Mathematical Laboratory. Womersley, the third Ministry of Supply representative, was working in the Quality Control Department of the Ministry of Supply.

The Ministry of Aircraft Production (MAP) had two representatives, Duncan and Hollingdale. Duncan was a member of the Aeronautical Research Council, in particular he had sat on the Oscillation Sub-Committee to which Pugsley had presented the case for the installation of Hollerith machines at the RAE in 1940 (see p.192). During the war Duncan was involved in a wide range of aeronautical and defence projects at the RAE and at the Air Defence Department at Exeter. He was thus well informed regarding the computational requirements of the MAP.

With the exception of the two Treasury representatives and Cheetham from the Ordnance Survey Department, the remainder of the committee represented departments with primarily statistical interests.

The first task undertaken by the Committee was a review of the computational and mathematical work of government departments. They were also asked to predict their expected post-war needs and assess what use they would make of a Central Mathematical Station. This survey included all the departments represented on the Committee, except the Treasury, plus the Medical Research Council and the Ministry of Works. This review, given in Appendix A of the report and summarized in table 4.5.2, does not convey a universally enthusiastic welcome for the proposal and, in some cases, it was clearly stated that only very limited use would be made of such a service.

The only department consulted which declared that it would not use a Central Mathematical Station was the Ministry of Home Security. During the war the Ministry of Home Security was engaged in mathematical work concerned with civil defence and operational research. It was unlikely that this work would continue after the war and hence the Ministry could not foresee that it would have a need for the Station. H.M. Customs and Excise also stated that it would have only a limited use for such a Station as it performed very little mathematical work. It was willing, however, to allow access to their large punched card installation during idle periods, if there was a central administration to handle the arrangements[9].

Only the Admiralty and the War Office anticipated using the Station on a regular basis. The Admiralty foresaw that the Station would take over the computational work of the ACS and relieve the NAO of its ACS responsibilities. The War Office suggested that its Directorate of Military Survey would continue to require the preparation of Geodetic Tables and the computation of triangulations after the war and would, therefore,

9. During the war the SCS had made considerable use of the Customs and Excise Hollerith installation at Buxton.

Table 4.5.2 Projected Uses of a Central Mathematics Station

	Computing Bureau	Complex Jobs	Advice	Take On Work	Maths/ Stats	Keep Own Machines	Valued
Admiralty	X	X	X		M	X	X
Agricultural Research Council		X			S	X	X
MAP	X				M	X	
Customs and Excise				X	S	X	
Ministry of Home Security					M/S		
Medical Research Council	X				S	X	
Ordnance Survey Department			X		M	X	
DSIR	X				M	X	
Ministry of Supply		X			M/S	X	
War Cabinet, Central Statistical Office		X			S/M	X	X
War Office	X		X		M	X	X
Ministry of Works			X		S	X	

make use of such a Station. During the war the SCS carried out a considerable amount of this type of work and the War Office stated that this could be taken over by the Central Mathematical Station.

Three other departments considered using the Station as a computing bureau: the Ministry of Aircraft Production, the Medical Research Council and the DSIR. All of them stated clearly that they could use the facilities of such a Station for a small part of their work or on occasions when they had too much work to handle locally. Indeed, in every case considered, with the exception of the Ministry of Home Security, the individual department consulted wanted to maintain its own computing staff and equipment.

Four departments, the Admiralty, the Agricultural Research Council, the Ministry of Supply, and the War Cabinet Central Statistical Office welcomed the proposed Station as an avenue through which they could channel the complex and specialized problems which occasionally arose. In a similar way the Ordnance Survey Department of the War Office, the Ministry of Works and the Admiralty felt that the existence of a centre to which they could go for advice would be an important feature. Of the twelve departments reviewed, only the Admiralty, the Agricultural Research Council, the War Cabinet Central Statistical Office, and the War Office conveyed any expression of enthusiasm for the establishment of such a Station.

As a conclusion to the review of computing and mathematical activities prepared for the Committee's report, a brief mention was made about the work being done outside the scientific civil service. The extent of Hartree's work on the differential analyser at Manchester University and the uncertain future of the Cambridge Mathematical Laboratory were put before the Committee. The most important comment in this section was made under the heading "Scientific Computing Service Ltd" and added further weight to the argument that a Central Mathematical Station was necessary. It was reported that the

> "Scientific Computing Service Limited., accepts contracts to carry out computations. This it had done over a wide variety of subjects. The successful establishment of such a business and its expansion shows that there has been a real need for it" (DSIR 1944 Appendix A, p.3).

The Committee was presented with the very diverse needs of a set of departments of which almost one half were concerned with statistical and not mathematical work. In reply the Committee categorized the functions of a Central Mathematical Station into two classes: general mathematical computation and statistics. In both areas the Committee considered that the most important role of a Central Mathematical Station would be the existence of a body of experts which would undertake work not only on special problems supplied to it but would also develop new computing machines and techniques. The computing service which such a station would provide was always seen as fundamental to the station's role and as a source of income to help fund the research activities of the station.

The conclusions of the DSIR Interdepartmental Committee were presented to the DSIR Advisory Council on 10 May 1944 (DSIR 1944) and its report provided for the facilities required by all the departments which had been consulted. The final report recommended that a Central Mathematical Station be set up and that it should

(a) "deal with problems arising out of statistical science, especially in the principles of its application to industrial research, development and production, including users' requirements, but not to handle detailed statistical problems of a descriptive type such as arise in economics, sociology and biology, though it would be ready to act as consultant on the mathematical aspects if required";

(b) "provide computing services for Government Departments, industry and Universities. In cases where the work of a Department is continuous, voluminous, uniform or specialized in character, such Department could employ a whole time staff of its own"; and

(c) "act as consultant for Government Departments, industry and Universities in the use of mathematical and statistical techniques. The centre would undertake work in cases where a Department needs it only at irregular intervals. It could also help in carrying overloads, and in arranging for any one Department which was incompletely occupied for a time to help in carrying the overload of another".

However, the Committee took the suggested role of the proposed Mathematical Station further than these three recommendations. The Committee perceived

(d) "research into new computing methods, including the design of new instruments" as the most important function of the Station. This new emphasis on machine research was a result of the interests and experiences of the individual Committee members all of whom appreciated the need for continuous research.

The remaining two functions outlined in the Committees list of six were:

(e) to act as a liaison between British workers in the field, to collaborate with the BAASMTC and the University Mathematical Laboratories, and to disseminate information on computing machines and methods by the distribution of reports and the establishment of a library of mathematical tables;

(f) to consider the need for mathematical tables and, if necessary, compute them.

It is interesting to compare this list with the functions of a proposed National Mathematical Laboratory put forward by the Admiralty memorandum to the DSIR (see p.113). All of the Admiralty proposals were contained in the six functions listed by the DSIR Committee; but the Committee put a much greater emphasis on research and development of new machines as a critical part of the station's work. To the Admiralty the concept of a computational and advisory service was of greater importance than the development of new machines and methods, although this was by no means rejected as a function of such a Laboratory. The consultation process and the committee membership, had, therefore, changed the proposed National Mathematical Laboratory from an enlarged ACS-like organization to an institution which was to perform basic research into numerical mathematics and computing machinery in addition to acting an advisory centre and computing bureau.

Having established a need for a Central Mathematical Station and set down its primary functions, the Committee turned its attention to the practical requirements and location of such a laboratory. The conclusions reached were based on the experience of the NAO, the work of the differential analysers at Manchester and Cambridge, and the role played by the Ministry of Supply Central Statistical Office set up in 1939 to prepare production forecasts. It was proposed that the Station be provided with a staff of 25

Scientific Officers and about 50 ancillary staff. Table 4.5.3 illustrates how the staff were to be distributed. The cost of such a staff was estimated at approximately £34,000 per annum. The Station was to be

Table 4.5.3 Breakdown of Estimated Staff Requirement for the NPL Mathematics Division

	Scientific Officers	Ancillary Staff
General Computation and Research	12	24
Instruments eg. DA	3	6
Statistics	7	14
Expected inc. for new machines	3	6
Total Estimate	25	50

equipped with a variety of desk machines, adding and listing accounting machines, a Hollerith installation, a differential analyser of larger capacity than any other in Britain, a Mallock Machine, and a few minor special machines[10]. The cost of the machines was estimated at under £50,000 at 1938 prices plus between £2,500 and £4,000 per annum rental for the Hollerith equipment. It was also decided to locate the Station at Teddington, near the National Physical Laboratory, on the grounds of close proximity to an established intellectual centre, accessibility to government departments, and on-site workshop facilities. The benefits of an established administrative structure and direct access workshops resulted in the decision to set up the Central Mathematical Station as a division of the NPL.

On receiving and considering this report the DSIR Advisory Council recommended that "the proposed scheme for the establishment of a Central Mathematical Station be proceeded with, subject to consideration by the Chairman of any observations or recommendations made by the Executive Committee of the NPL" (DSIR 1942-47, AC Minute 88 1943-44, 10 May 1944). By 12 July 1944 the NPL Executive Committee had approved the proposal (Advisory Council Minute 96 1943-44, 12 July 1944) and by October Treasury approval had been granted (Advisory Council Minute 3 1944-45, 11 October

10. The inclusion of a Mallock Machine in this list probably owes more to Darwin as ex-chairman of the Cambridge Instrument Company, the manufacturers of the machine, rather than the success Maccoll at Cambridge or Duncan from the Ministry of Aircraft Production had had using the machine.

1944).

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Chapter 5
The NPL Mathematics Division:
A National Computing Centre

5.0 Introduction

By autumn 1944 Treasury approval had been granted for the establishment of a Mathematics Division at the National Physical Laboratory, Teddington, Middlesex. Section 5.1 describes the actions taken during 1945 to set up the Mathematics Division and the way in which John Womersley, the Superintendent of the new Mathematics Division, assembled staff and equipment.

The work of the Division during its first few years of operation can be divided into two areas: the computing service work of the Division, and the research work carried out. Section 5.2 discusses the service work of the General Computing, Punched Card, Differential Analyser and Statistics Sections, and illustrates the large number of NPL users. The development of the Pilot ACE was the most significant piece of research carried out by the Mathematics Division during 1946-1952. The work of the ACE Section, and the varied research carried out by other sections, is described in section 5.3.

In 1952 the Pilot ACE went into regular service and brought a new dimension to the work of the NPL Mathematics Division. Not only was the Division reorganized to accommodate the Pilot ACE and the new differential analyser installed in 1954, but the amount of service work undertaken by the Division also increased. These changes in the work of the Mathematics Division are discussed in section 5.4 which also examines how the research undertaken in the Division took on a different character. This section also considers how far the Division had gone in achieving the aim of creating a national computing centre.

The final section, 5.5, considers the changing role of the NPL Mathematics Division in the late 1950s as the demand for computation using electronic computers rose and looks at how the service work of the ACE Section increased at the expense of the work of the other sections in the Division. These changes, the work of the Division during this period, and how the work of the Mathematics Division in the late 1950s corresponded to its original terms of reference are considered in this section. This section illustrates that the role of the Division changed from a national computer service bureaux to a local computing centre by the mid-1950s.

5.1 The New Mathematics Division: 1945

Even before Treasury approval for the establishment of a national computing centre at the NPL had been officially granted, the Executive Committee of the NPL had begun the process of appointing a Superintendent. As early as June 1944 a sub-committee had been set up to interview and select suitable candidates. The sub-committee was almost entirely made up from members of the Executive Committee. Its members were D. Brunt, FRS; R.H. Fowler, FRS (later replaced by S. Chapman because of ill health); D.R. Hartree, FRS, responsible for the Differential Analyser Project at Manchester University; A.V. Hill, FRS, chairman of the NPL Executive Committee; and J. Lennard-Jones, FRS, founder of the Cambridge Mathematical Laboratory. The Ministry of Labour and National Insurance was also represented on the sub-committee (NPL 1942-47, Minute 4221, 20 June, 1944). Hartree was the only member of the sub-committee to have been a member of the 1944 DSIR Interdepartmental Committee which recommended the establishment of a National Computing Centre at the NPL.

The sub-committee interviewed only two candidates, D.H. Sadler and J.R. Womersley, both of whom had sat on the DSIR Interdepartmental Committee. Sadler, Superintendent of the Nautical Almanac Office, had been invited to apply for the post by Darwin, Director of NPL, but had been unenthusiastic about taking up such an appointment (Sadler 1984a). Womersley was, at that time, working in S.R.17, a Ministry of Supply statistical group. By September 1944 the sub-committee had reported and the Superintendentship of the Mathematics Division offered to Womersley.

From late 1944, therefore, Womersley had the task of building up the NPL Mathematics Division from the terms of reference given in the Interdepartmental Report. These were to:

1. Undertake research into new computing methods and machines,
2. Encourage research and disseminate information concerning computation,
3. Undertake work and perform research in mathematical statistics,
4. Advise on and prepare mathematical tables,
5. Provide a computing service,
6. Act as consultant to government, industry and the universities.

It had also been proposed in the report that the Division should initially install desk calculating machines, Hollerith machines, a differential analyser and several more specialized machines, such as a cinema integraph.

To supplement this general outline of what the Division's activities were to be, the Interdepartmental Technical Committee provided an initial research programme in Appendix B of its report. This programme, given in table 5.1.1 and analysed in table 5.1.2, outlined twelve areas of research which the Committee felt should be the concern of the Division. In several items (3, 5, 7 and 12) the Committee recommended that machines be constructed to perform specific types of calculation. The closest the programme came to recommending general research on computing machine technology was item 2, which called for an investigation into the possible application of telephone equipment to computing machinery. Five of the twelve items listed in the research programme were directly related to statistics, hence representing fairly the large number of statistical users which the DSIR had consulted (table 4.5.2). In addition to the research programme presented in the Interdepartmental Committee's Report, the NPL Research Programme for 1945-46 included the "Development of electronic counting devices for rapid computing" as one of the establishment's research projects (NPL 1942-47, Minute 4228, Report E851, October 1944).

Table 5.1.1 Provisional Research Programme for the NPL Mathematics Division. May 10th, 1944

1. The development of methods for the solution of large numbers of simultaneous equations, such as arise in triangulations and in Southwell's relaxation process.

2. The application of automatic telephone equipment to computing.

3. The development of methods and/or instruments for the solution of integral equations.

4. The development of methods of finding the characteristic values of Lagrangian systems.

5. The development of methods and machines for the Fourier analysis of both periodic and aperiodic curves, and for evaluating inverse Laplace transformations.

6. Numerical and mechanical solutions of partial differential equations.

7. The development of instruments for the direct solution of vibration equations with given initial conditions without the use of the Differential Analyser.

8. The development of new methods of statistical planning of industrial experiments for maximum economy and efficiency. Application of these methods to problems of testing and standardisation.

9. The collation and analysis of accumulated results of Quality Control with a view to discovering general principles, such as the performance of different types of machine tools and the nature of the frequency distributions which arise in manufacturing processes.

10. The statistical formulation of problems of design and assembly.

11. The improvement of Quality Control methods, and of methods of Acceptance Sampling Inspection.

12. The invention of new instruments for convenient use in industrial firms and research establishments for their statistical work.

(From the Report of Interdepartmental Technical Committee on a Proposed Central Mathematical Station, Appendix B).

In the light of these guidelines, and his own experience at S.R.17 and, earlier, at the War Office, Womersley presented his plans for the Mathematics Division to the NPL Executive Committee in December 1944. Womersley proposed to organize the Division into three separate sections to deal with different aspects of the Division's work. The sections were to deal specifically with:

Table 5.1.2 Classification of the Proposed Research Programme for the NPL Mathematics Division. 10th May 1944 (Table 5.1.1)

Research Project	Statistical	General	Specific	Machine Development	Numerical Methods
1			X		X
2		X		X	
3			X	X	X
4			X		X
5			X	X	X
6			X	X	X
7			X		X
8	X		X		X
9	X		X		X
10	X		X		X
11	X		X		X
12	X	X		X	
Total	5	2	10	5	10

i) computing on commercial machines,

ii) analytical engines and computing development, and

iii) statistical methods.

The first of these three sections, computing on commercial machines, was to undertake the non-statistical computing bureau and consultancy functions of the Division. It was proposed that it should take over the role played by the Admiralty Computing Service and any numerical research being carried out under its name. Womersley went so far as to suggest that staff from the ACS be transferred to the NPL. No attempt was made, at this point, to elaborate on the types of machine with which this section was to be equipped. It was also suggested that this section build up a specialist library which was to be more extensive than either the SCS or Admiralty collections and which would include all the known published mathematical tables.

Womersley proposed that the major task of the section devoted to analytical engines and computing machinery development would be the construction of a large differential analyser initially having 18 integrators but with provision for expansion to 24. Womersley also suggested the development of a "production model" differential analyser. This device was to be considerably smaller than the large machine proposed and was to be suitable for laboratory use. The possibility of constructing other analogue machines to evaluate integrals, solve simultaneous equations, and calculate the roots of complex polynomials was also put forward.

Womersley, however, was aware of the economic and philosophical conflicts between the construction of specialist machines and the development of efficient desk machine techniques to carry out the same type of calculation (see p.189). He discussed with the Executive Committee the importance of carrying out research into the possibility of using electronics, particularly automatic telephone equipment, as general purpose computing devices. He anticipated that to carry out research into machines using electronic components the NPL would need to contract out the construction of electronic components. Womersley stated that he was soon to take a trip to the United States on behalf of the Ministry of Supply and would take the opportunity to "undertake a comprehensive tour of universities and Government and commercial organisations interested in the field covered by his plans" (NPL 1942-47, 19 Dec 1944 p.6). It was thus anticipated that the type of machinery developed by the Mathematics Division might be influenced by events in the United States.

Womersley had also made plans for the third Mathematics Division Section, Statistics. Because of his current position within the Ministry of Supply, Womersley had reached agreement with the Ministry's statistical group (S.R.17) to limit the group's activities to production problems for the armed services. All other statistical work covering ballistics, quality control, etc., but not operational research, was to be channelled to the NPL.

This initial proposal concerning the work of the Mathematics Division made few references to the type of machinery to be installed, the number of staff to be taken on or any potential users of the Division's facilities. It clearly stated that the Division was going to provide a computing service, play a consultancy role, undertake numerical research, investigate and construct new types of computing machinery and maintain a specialist library.

Once Womersley had established these broad, long term plans for the NPL Mathematics Division, he gave the Executive Committee a brief outline of how he intended to put these plans into operation during 1945. He stated that the majority of 1945 would be devoted to the acquisition and training of staff and to performing computations for other NPL Divisions. He anticipated that very little work would be done towards the construction of the new differential analyser. Unfortunately recruitment to the Mathematics Division was delayed because of restrictions imposed by the Ministry of Labour and National Insurance governing the appointment of staff before the end of the war had been officially declared. In March 1945 the Ministry of Labour denied the NPL permission to advertize for staff and agreed only to the appointment of 6 senior staff and 6 assistants by personal recommendations (NPL 1942-47, Minute 4250, 20 March 1945). The appointments were not filled until Womersley returned from the United States in April 1945.

To coincide with Womersley's official appointment as Superintendent of the new Mathematics Division on 1st April, 1945 the NPL issued press releases to *Nature* (Anon 1945a) and the *Journal of Scientific Instruments* (Anon 1945b.). The press releases stated that a Mathematics Division was to be set up at Teddington and outlined Womersley's initial plans. From then on Womersley quickly began to assemble his staff and to equip the Division. Although many of the early staff officially took up their appointments at the NPL in the autumn of 1945 and the spring of 1946 many had already begun work by the summer of 1945[1].

Womersley, straying slightly from his original plans, initially organized the Division into four sections: Mathematical Statistics, Punched Card Machines, General Computing, and Analogue Machines. To form the first of these sections, Statistics, Womersley invited several members of his staff from S.R.17 to join him at the NPL some of whom came as early as June to begin work. The Punched Card Section also became operational during

1. This discrepancy was due to the variation in the release dates of personnel from their war time postings.

summer 1945. T.B. Boss was transferred from the RAE, where he had spent some time with Fairthorne's Hollerith group (see p.192), to head the NPL section. Boss began to equip the Section with punches, verifiers, a tabulator and a sorter. By September, Boss had taken on four school leavers who immediately started punching cards for the Statistics Section (Curtis, J.M. 1983). Before the end of the year these four girls had been given a short course in the use of Hollerith machines by BTM and had subsequently trained new members of staff as they arrived.

Womersley had originally proposed that all the Admiralty Computing Service staff stationed at the NAO in Bath be transferred to Teddington to form the General Computing Section of the NPL Mathematics Division. However this proved to be impossible for two reasons. Firstly, some of the staff wished to go elsewhere after their release from war time duties in the civil service and, secondly, the NPL was not prepared to take on the entire junior staff. Goodwin was offered the senior appointment in the General Computing Section and with him came L. Fox, P.H. Haines, F.W.J. Olver, H.H. Robertson and J. Staton from the ACS (Goodwin 1984). Goodwin arrived at the NPL in mid-August and was quickly followed by the others from Bath. Again several school leavers were taken on as junior computers. Womersley initially equipped the General Computing Section with several hand operated desk machines, principally Brunsvigas, Marchants and Fridens and two electric machines, a Madas and a Monroe. Goodwin and the others from Bath brought with them unfinished ACS problems and work in the Section began immediately.

During the autumn of 1945 Womersley decided, as a stop-gap measure before the construction of the large differential analyser could begin, that the NPL Mathematics Division should take over Hartree's Differential Analyser group at Manchester University. The NPL did not take over this machine until 1st January, 1946 when the Differential Analyser Section was established at Manchester and not at Teddington. The Differential Analyser Section was the last of the four initial sections to become operational.

The most significant change Womersley made to his original proposal during 1945 resulted directly from his American tour earlier that year. Through his contacts with

Hartree, Womersley had become aware of the importance of the ENIAC project and had been given permission to visit the Moore School to observe the machine. Womersley was the first principle British visitor to the machine (Goldstine 1972). Womersley was also aware of Alan Turing's work on computable numbers (Turing 1936) and, vaguely, of his work at Bletchley during the war[2]. Womersley contacted Turing offering him a post at the NPL to design and construct an electronic digital computer. Turing jumped at the chance. He took up his appointment in October 1945 and produced his now famous proposal for the development of an Automatic Computing Engine (ACE) (Turing 1946).

Thus by the end of 1945 the NPL Mathematics Division had been set up and was "functioning on a limited scale" with a staff of 22 (NPL 1942-47, 23 October, 1945). The ACE project had also been initiated and was to dominate the Division over the following decade.

5.2 Early Computing Service and Consultancy Work

During 1946 the NPL Mathematics Division expanded rapidly and by the end of the year employed a staff of fifty. The work of the Division was divided into two main activities: the provision of a computing service and original research. By acting as a computing bureau and advisory service to government, industry and the universities the Division was fulfilling points (b) and (c) of the recommendations made by the DSIR Interdepartmental Committee Report (see p.122). The service bureau work of the General Computing Section, the Punched Card Section, the Differential Analyser Section and the Statistics Section will be considered within the framework of each Section's users, staff, machinery, the computing service it provided and its advisory work.

5.2.1 The General Computing Section

The General Computing Section was responsible for all calculations carried out on desk machines and on the National Accounting Machine. It was commonly called the

2. During the war Turing had been involved with the design and construction of code breaking machines at the Government Code and Cypher School, Bletchley. See Hodges, 1983.

Desk Machine Section but in this dissertation it will be referred to by its formal name, the General Computing Section. Because many of the General Computing Section staff had been transferred from the ACS, much of the early work performed by the section consisted of the completion of unfinished ACS jobs. For some time requests to undertake computations came to the individual section members on an 'old boy' basis (Vickers 1984) or directly to Goodwin as section head. Despite this informal structure, which operated in all sections of the Division during the first few years, the General Computing Section was approached by a wide variety of users. Table 5.2.1, lists some of the more important users of the General Computing Section during 1946-51.

Table 5.2.1 General Computing Section Users 1946-1951(*)

NPL Aerodynamics Division
NPL Physics Division
Road Research Laboratory, DSIR
Building Research Station, DSIR
BAASMTC/RSMTC
Ministry of Supply
Admiralty
British Iron & Steel Association
Mechanical Engineering Reseach Organization, DSIR
Colonial Survey Department
RAE, Farnborough
Ministry of Aircraft Production
Armanment Research Establishment
AERE, Harwell
Ministry of Civil Aviation
Sir Edward Appleton
British Electricy Authority
British Railways

(Source: Reports of the NPL 1946-1951)

(*) The major source of the data in this table and the following tables, was obtained from the annual reports of the NPL. The reports tend to present the Division's work in a good light and consequently the level of detail in uneven and the data not totally reliable. The ordering presented in the table is intended to give some indication of the more important users. It based on the annual reports and other diverse sources and should not be taken as a fixed list of NPL users.

The Admiralty, Ministry of Supply, and the DSIR (particularly the Building Research Station and the Road Research Laboratory) were the most frequent customers of the section. On the industrial side, the section carried out jobs for the British Iron and Steel

Association, British Railways and the British Electricity Authority. Few universities made use of the NPL desk machine facilities or expertise during this period. The desk machine section also assisted other NPL Divisions in their work.

The General Computing Section was staffed in a way which clearly illustrated the nature of its work. Firstly, it had a strong team of mathematicians, including Goodwin, Fox, Wilkinson (part-time)[3], which concentrated mainly on numerical research. Secondly, the desk machine computations were carried out by a team of more junior staff led by T. Vickers. This part of the section had three main tasks: first to become expert in the choice of desk machines; second to exploit the National 3000 Accounting Machine; and third to undertake computational work submitted to the section. The two parts of the section collaborated. Where jobs required non-standard techniques or research, the mathematicians of the section supplied the necessary expertise while the desk machine operators carried out the bulk of the computing work. The number of General Computing Section staff grew from 13 in 1946 to approximately 20 in 1952. The section thus had a fairly large and very experienced staff.

Because part of the General Computing Section's job was to become familiar with, and hence advise on, all types of desk calculating machine, a large collection was built up. Initially the number of machines installed in the Division was small due to the difficulty of obtaining any equipment of this sort immediately after the war. Womersley did, however, ensure that several machines were available on Goodwin's arrival at NPL. At first it was not easy to acquire many more machines. Vickers recalls,

> Originally machines were scarce or needed dollars (also scarce). We were helped by 12 Brunsvigas "found" in Germany by our marauding forces. A "survey" throughout the other 9 Divisions of NPL found one or two in "cubby holes". (Vickers 1984)

3. Officially, Wilkinson spent half his time in the General Computing Section and half with Turing in the ACE Section. Wilkinson, however, spent most of his time working with Turing only exercising his right to go elsewhere when it was advisable to stay out of Turing's way (Wilkinson 1971).

As Britain recovered from the war time restrictions and shortages, the availability of calculating machines increased and the Division was supplied with each new machine which came onto the market by His Majesty's Stationary Office (HMSO). The section tested each machine and reported on its usefulness to HMSO, which supplied calculating machines throughout the Civil Service. In addition to these machines the section maintained a National 3000 Accounting machine which was used for table making and interpolation.

It is difficult to be precise about the exact nature of the computations carried out by the General Computing Section. Sources (mainly NPL Reports and personal recollections) which mention individual Mathematics Division users rarely give any mathematical details. From the wide range of users, however, it can be inferred that the the type of work was very varied. It ranged from the preparation of tables of empirical data for other NPL Divisions and the Ministry of Supply, and tables of fundamental functions for the Royal Society Mathematical Tables Committee to solving simultaneous equations for the Admiralty and Building Research Station.

The consultancy role which the Desk Machine Section played was an important one. From the first, the section was advising the Colonial Survey Department and the Ministry of Civil Aviation as had been suggested in the Report of the 1944 DSIR Interdepartmental Committee. It was also asked to guide the work of first the British Association Mathematical Tables Committee and later its successor the Royal Society Mathematical Tables Committee. Fox and Goodwin, particularly, were heavily involved in this work. The section was responsible for advising other NPL Divisions on computing methods and on the type of desk machines which they should install in their own Divisions.

5.2.2 The Punched Card Section

Much of the first years' work of the Punched Card Section was spent training staff to use the Hollerith machines efficiently. Several jobs were taken on which, although of limited mathematical interest, were useful from a staff training point of view. The section also began to train staff from other institutions to use punched card equipment, usually as a precursor to the installation of their own machines. In 1946 four people were given six month training courses by the Punched Card Section. By 1947 the facilities available in the NPL Punched Card Section were becoming more widely known amongst scientific workers and this led to an increase in the amount of work carried out by the Division (NPL 1949b). The Punched Card Section had, between 1946 and 1951, over 18 different users. Many of these used the section annually to compile tables of statistics. Table 5.2.2, which lists the major customers of that period, illustrates that the range of users covered government departments, industry and the universities.

Table 5.2.2 Punched Card Section Users 1946-1951(*)

'F'-Division, DSIR
Electrical Research Association
Civil Service Commission
Admiralty
Road Research Laboratory, DSIR
Ministry of Supply
Ministry of Works
Oxford University Crystallography Group
Ministry of Health
Intelligence Division, DSIR
NPL Aerodynamics Division
NPL Metallurgy Division
United Steel Companies Ltd.
London Passenger Transport
Bank of England
Fuel Research Station, DSIR
Building Research Station, DSIR
DSIR Headquarters
Statistics Department, UCL
Home Office

(Source: Reports of the NPL 1946-1951)

(*) See note to Table 5.2.1.

The section was mainly staffed by junior female personnel. They worked in teams of one to three depending on the complexity and size of the job. Each team took jobs from their planning, plugging and running stages, through to the presentation of the results. The Section did not work in isolation, and performed work for other sections in the Division. Mathematicians in the General Computing Section took an interest in the work of the section and devised numerical methods applicable to the machines (see, for example, Fox, Huskey and Wilkinson 1948).

The Punched Card Section was initially equipped with the basic Hollerith machines (punches, verifiers, two sorters, two reproducers, an interpreter, and a tabulator) but gradually a substantial collection was built up. One of the section's early tabulators was the machine which G.B. Hey had had modified by BTM while working with Comrie on the 1936 investigation into the spacing of sugar beet (see p.47). This tabulator differed from standard machines in that it was fitted with additional relays and distributers, and decimal rather than sterling counters. It was not, however, a reliable machine. It was old, much used and, Hey (1983) suggests, once dropped off the back of a lorry. In 1948 an IBM Pierce Tabulator from Bletchley Park was installed which was fitted with alphanumeric printing sectors, unlike the British tabulators which were already installed at the NPL. In 1951 an IBM 602A electromechanical calculator was installed which, along with the Bull 506 Multiplying Punch which arrived two years later, allowed the Section to increase the amount of mathematically orientated work it carried out rather than the adding and listing work which was performed. Thus the section was well equipped, having a complete range of machines.

Initially the work carried out by the Punched Card Section consisted mainly of large-scale statistical investigations for DSIR Divisions and industrial research associations. The 1946 Report of the NPL conceded that the work done during the year had been "of limited interest from the mathematical point of view" (NPL 1949a, p. 35) and that in order for the section to carry out more scientific work some technical modifications would have to be made to certain machines. This, along with the installation of more sophisticated multipliers and calculators, allowed the work of the section to become more mathematical. One of the first of the more scientifically orientated jobs which the section performed involved the application of the Hollerith machines to harmonic analysis for Sir Edward Appleton in 1947. Although the technique was not new (Comrie had used punched cards in 1929 for the construction of tables of the position of the moon) it was the beginning of NPL's use of punched cards in this way. Over the next few years the Punched Card Machine Section, in co-operation with the General Computing Section, developed techniques for the solution of simultaneous equation, Fourier synthesis and analysis, and attracted more scientific custom from both inside and outside the NPL. Table making, which used the tabulator as a difference engine, also became an important task of the section. By the early 1950s the section was taking on more and more work for the Ministries of Supply and Civil Defence. Throughout this period the section continued to perform statistical work.

The amount of consultancy work carried out by the Punched Card Section was largely limited to training outside staff in preparation for the arrival of their own installation. Interchange between the NPL and other scientific Hollerith installations also took place particularly with the RAE, and the NAO installation at Herstmonceaux (see pp. 192 and 198 respectively).

5.2.3 The Differential Analyser Section

The Differential Analyser Section, renamed the Analytical Engines Section in 1950 but commonly referred to by its former title, was not as extensive as the Desk Machine and Punched Card Sections. Table 5.2.3 lists the major Differential Analyser users over the 1946-51 period.

Table 5.2.3 Differential Analyser Section Users 1946-1951(*)

NPL Aerodynamics Division
NPL Ship Division
NPL Metrology Division
Australian National Standards Laboratory
Swedish Government Computing Laboratory
Admiralty Establishment, Gottingen, Germany
Sperry Gyroscope Co. Ltd.
Manchester University
London University
Birmingham University
British Iron & Steel Research Association

(Source: Reports of the NPL 1946-1951)

(*) See note to Table 5.2.1.

The section carried out few actual computations but did perform a large and varied amount of advisory work. There were three reasons for the small amount of computation carried out by the Differential Analyser Section. Firstly the small staff. In 1946 the NPL took over operation of the Differential Analyser at Manchester University. Although the Differential Analyser staff, originally under Hartree, were officially transferred to the NPL some did not take up their posts and, after their release from their war-time postings, moved elsewhere. Others recruited to the section moved to other sections as their interests changed. By 1949 the Differential Analyser Section had a staff of only four. This was not enough to keep the machine in continuous operation. Secondly, in November 1948 the differential analyser was moved from Manchester to Teddington and required a great deal of attention to restore it to full working order. This meant that for a time the machine was not available for service work and that the staff was very tied up. Thirdly, the Mathematics Division was committed to the construction of a larger differential analyser. Much of the senior staff's time was therefore spent working with the Control Mechanisms Section of the NPL Metrology Division on the design of such a machine. In March 1949, however, a contract was signed with the German company Schoppe & Faeser for the construction of a differential analyser for the NPL. This was meant to relieve the work load on the section head J.G.L. Michel and allow more service work to be done in the Section. The staff, however, became heavily involved in the installation and testing of the machine and made frequent trips to Germany before the machine was installed in 1954. Thus very little service work was carried out during this five year period.

From the outset the Section advised existing Manchester University users. The advice of the Section on the construction of differential analysers was also requested internationally by the Australian National Standards Laboratory, the Swedish Government Computing Laboratory, and the British Admiralty Establishment in Gottingen, Germany[4]. The Universities of London and Birmingham also consulted the NPL Differential

4. This project was part of the British Governments rehabilitation plan for German scientists and technologists.

Analyser Section on the construction of machines at their institutions. By 1950 the section was not only giving advice on differential analyser techniques but also on other analogue forms of computation including nomograms and harmonic analysers. The renaming of the Section to the Analytical Engines Section in 1950 reflects this diversification in the interests of the section. The section did, therefore, offer a limited consultancy and computing service during 1946-1951 but was not as active as the Desk Machine or Punched Card Sections.

The Differential Analyser Section was initially equipped with the 8-integrator Manchester University differential analyser which was later replaced by the German machine in 1954. Unlike its totally mechanical predecessor, the German machine operated using electronic servo-mechanisms. It was also a more accurate machine. The German differential analyser was of a larger capacity than the Manchester differential analyser. It had 20-integrators as compared to 8. This allowed larger, more complex problems to be solved on the machine and, because the units of the machines were connected together using a plugboard arrangement and not by a series of gear chains, the machine could be used for up to three separate problems at one time. Thus it greatly increased the computing power of the section. Womersley, and the 1944 DSIR Interdepartmental Committee, had intended the Division to be equipped with other analogue machines, such as a cinema integraph and a simultaneous equation solver, but these plans came to nothing as digital computing methods took over. The Differential Analyser Section was the most poorly staffed and, until 1954, most ill-equipped section of the Mathematics Division. However it did offer a limited computing and advisory service and had a varied selection of users.

5.2.4 The Statistics Section

The Statistics Section provided a computing and consultancy service to government and industry. The principle work of the Statistics Section during 1946-51 consisted of data analysis, production efficiency analysis and quality control analysis. Table 5.2.4 lists the Section's principle users during this period. The major Statistical Section users were

Table 5.2.4 Statistics Section Users 1946-1951(*)

Ministry of Supply Inspectorate
Treasury Training Division
NPL Divisions
Board of Trade
Medical Research Council
Ordnance Survey
British Cotton Industries Research Assoc.
Ministry of Civil Aviation
Interdepartmental Committee on Servo Mechanisms
War Office
Ministry of Agriculture
Ministry of Education
Home Office
British Standards Institute

(Source: Reports of the NPL 1946-1951)

(*) See note to Table 5.2.1.

the Ministry of Supply, the Treasury, and industry. Of all the Mathematics Division sections the Statistics Section had the strongest links with industry.

The Statistics Section had approximately six staff but did not possess a significant amount of computing machinery for its own use. Consequently it used the services of the Desk and Punched Card Machine Sections very regularly. During the late forties there were frequent personnel changes which seriously affected the research work of the section but did not prevent the service and advisory work from continuing.

Much of the Section's work was advisory, particularly after it took over the role of the Ministry of Supply Advisory Service on Statistical Methods in 1947. From 1950 it fell to the section to provide lecture courses on statistical methods for Civil Servants at the request of the Treasury Training Division. The work of the Statistics Section came from a variety of sources and required anything from "half an hour's oral advice to investigations demanding extensions of existing theory and detailed analyses covering several weeks' work" (NPL 1949a).

5.3 Research in the NPL Mathematics Division 1946-1951

The General Computing, Punched Card, Differential Analyser and Statistics Sections all contributed to the bureaux and consultancy functions of the NPL Mathematics Division but each section also undertook a certain degree of research and development in its own field. First let us consider the work into developing new machines or improving existing devices.

5.3.1 Machine Developments

In March 1946 the NPL Executive Committee had drawn up a list of computing machinery development projects which the Mathematics Division was to undertake. This list named the projects in the following order of priority:

(1) ACE machine;

(2) a small Fourier Synthesis machine for use by x-ray crystallographers in their own laboratories;

(3) a production model differential analyser;

(4) O/C Osser-Jofeh[5] machine to combine the functions of

  (a) Fourier analysis,

  (b) Fourier synthesis, and

  (c) an Electric Isograph;

(5) a large Differential Analyser.

Of this list only the ACE and large Differential Analyser projects were undertaken.

The ACE Section

Of the five Mathematics Division Sections the Automatic Computing Engine Section (the ACE Section) was the only one set up solely to carry out research into computing

5. Details of an Osser-Jofeh machine are not available in the usual sources concerning calculating machines of the late 1930s and early 1940s. It is assumed that someone on the NPL Executive Committee, possibly Darwin or Hartree, had some connection with the machine and hence it came to be included in this list.

machinery. All the other sections had service roles, but the ACE section did not undertake any work for outsiders until after the Pilot ACE had been fully installed in 1952. A thorough discussion of the design and construction of the Pilot ACE is beyond the scope of this dissertation. Descriptions of different technical aspects of the ACE project have been given elsewhere (Campbell-Kelly 1981, Huskey 1984, Lavington 1980, Wilkinson 1975, Woodger 1958).

In February 1946 Turing's proposal for an Automatic Computing Engine (Turing 1946) was presented to the NPL Executive Committee accompanied by a supporting document written by Womersley (NPL 1942-1947, 19th March 1946). The papers were discussed by both the Executive Committee and the DSIR Advisory Council before Treasury approval for the project was granted in the summer of 1946. During that time, while Turing continued to work on the design of the ACE, the Section was slowly built up. In May 1946 J.H. Wilkinson joined the NPL Mathematics Division officially spending half his time with Turing and the other half in the General Computing Section under Goodwin (Wilkinson 1975). Four months later M. Woodger joined the ACE team to be followed, in January 1947, by H.D. Huskey, an American who had been involved in both the ENIAC and EDVAC projects, and who was to spend a year at Teddington.

During 1946 Turing, Wilkinson and Woodger worked on the logical design and instruction set of the ACE. However, as Turing was the only member of the ACE Section to have any experience with electronics it was expected that the actual construction of the machine would be done outside the NPL (Huskey 1984 and Woodger 1977). Consequently, an arrangement was made with the Post Office Research Establishment at Dollis Hill for work to be carried out on developing the mercury delay lines which were to from the memory units for the ACE. The Post Office was, however, reluctant to undertake any further development work for the NPL. Darwin, on behalf of the Mathematics Division, then approached F.C. Williams, from the Telecommunications Research Establishment and later Manchester University, and M.V. Wilkes, from the Cambridge Mathematical Laboratory, who were both becoming involved in computer projects at that time.

Although Womersley conducted negotiations with both Williams and Wilkes no external contract for the construction of the ACE was signed. Williams wished to pursue his own line of research separately from Turing, and Turing's design differed considerably form the machine Wilkes was proposing to build. Therefore, by April 1947, it had been decided that the NPL would construct its own machine (Womersley, 10 April 1947, in Woodger 1977).

After this decision had been taken Huskey proposed that, rather than build a full size machine, the Mathematics Division construct a Test Assembly to test the feasibility of the design. Because of the limited experience in the Mathematics Division in the use of electronics, Darwin took responsibility for all the hardware construction out of the hands of Mathematics Division (Huskey 1984)[6]. The construction of the Test Assembly was abandoned and replaced by a plan to build "a small-scale pilot model" of the ACE in the newly formed Electronics Section of the NPL Radio Division which would test the feasibility of the ACE design (NPL 1949b). The Electronics Section became independent of the Radio Division in 1948.

Turing, never in favour of building a pilot model, preferring the immediate construction of a full sized machine, left the NPL in October 1947 for a sabbatical year at Kings College, Cambridge. He never returned to the NPL but took up a post at Manchester University (see p.212). Wilkinson took over as section head and began to recruit more staff to the project.

Although the Mathematics Division's main responsibility was for logical design and programming, in August 1948 four members of the ACE Section (Wilkinson, Woodger, Alway and Davies) were seconded to the Electronics Section to work on the construction of the pilot machine. Throughout 1949, 1950 and 1951 work continued both on the construction of the Pilot ACE in the Electronics Section, and on programming in the

6. C. Darwin had been very influential in bringing about the 1944 Interdepartmental Committee and in persuading the Committee to establish a National Computing Centre at the NPL (see p.116). During the first few years of its existence Darwin kept in close contact with Womersley and the work of the Division.

Mathematics Division. Although the machine carried out its first automatic calculation in May 1950, it was not completed until late 1951 after which it was moved to the Mathematics Division in early 1952. While waiting for delivery of the machine, the General Computing Section had prepared for its installation by producing a number of subroutines for performing factorization, quadrature, integration of simple differential equations, and the solution of simultaneous equations. Thus when it was finally installed it was immediately put into service.

The Differential Analyser Section

Unlike the ACE Section, the Differential Analyser Section did not design and build its own machine. Until late 1948, after the transfer of the Manchester differential analyser to Teddington, Michel, head of the Differential Analyser Section, had been working on the design of a 24-integrator differential analyser to be built at the NPL. But, in March 1949, it was decided to install the 20-integrator differential analyser which was being built on behalf of the Admiralty in Germany by Schoppe & Faeser. Consequently most of the Differential Analyser Section staff spent much time between 1949 and 1954, when the machine became operational, in Germany or in the preparation of accommodation for the machine at the NPL. The delivery of the separate differential analyser units caused a further increase in work for the Differential Analyser Section staff because, although the NPL placed a contract with Metropolitan Vickers for the inter-unit wiring of the machine, the installation still put additional pressure on Michel and his staff. Thus while there was great activity in preparing for the installation of the machine and wiring it up, no fundamental hardware research was carried out by the section staff.

The Punched Card Section

On an even smaller scale to the hardware developments in the Differential Analyser Section, the Punched Card Section, with BTM's co-operation, made some changes to the Hollerith machines installed at Teddington. The most significant of these was an extension to the multiplying punch by E.J. York. The modification consisted of an additional gear for the multiplier which allowed the machine to take two 8-figure signed numbers and punch the signed 16-digit product (previously the BTM Multiplying Punch had not been able to deal automatically with signed numbers). The modification, completed in 1947, increased the usefulness of the multiplier for scientific work particularly the manipulation of complex matrices.

Minor modifications to the tabulator were also made in 1947 and investigations into anti-vibration mountings and card deterioration in long term storage were carried out. Modifications were later made to a Hollerith Punch by the ACE Section to adapt the device to an input/output device for the Pilot ACE. In addition circuits were designed in 1949 for the BTM Multiplying Punch which enabled it to compute recurrence formulae in a single card passage. No details of these modifications appear to have survived.

Summary

By far the most significant piece of hardware development undertaken by the Mathematics Division was the Pilot ACE, which, along with the Cambridge and Manchester computer projects, was one of the first stored program computers to be built in Britain. The differential analyser was seen by the Differential Analyser Section staff as a general purpose analogue computer and not simply a device for solving differential equations (Michel 1955) but it never had the impact of the ACE project. The cost of these two very large projects in both financial and labour terms effectively ruled out the construction of the more specialized machines originally proposed. Thus the remainder of the research carried out by the NPL Mathematics Division during 1946-51 concerned the development of numerical methods.

5.3.2 Numerical Methods Research

Within the Punched Card Section the numerical research carried out was oriented towards the development of computational methods using punched card machines. The section worked closely with both the Statistics and General Computing Sections to develop applicable numerical methods. The main investigations of this type were concerned with correlation methods for use with numbers with many digits and the solution of differential equations. Other investigations were usually prompted by incoming requests to the Division such as the Fourier Analysis application for Appleton in 1947 and an indexing and classification experiment done on behalf of the DSIR Intelligence Division (NPL 1949b).

The output of papers from the Statistics Section during 1946-1951 was modest (the reports of the NPL list only 17) but illustrate the type of research undertaken by the Section. Some of them were prompted by work carried out for others while the remainder were individual research papers (see list of publications by NPL Mathematics Division staff given at the end of the chapter). One of the more important investigations carried out was undertaken for the Interdepartmental Committee on Servo-mechanisms in 1947 on the properties of high order auto-correlated time series. The remainder of the Section's research work involved the compilation of a bibliography of practical applications of statistical theory and reviews. The relatively small amount of research carried out by the Statistics Section was a cause of concern. No reference to the work of the Section appeared in the 1948 Report of the NPL and the description of the Statistics Section's work in the 1949 Report opens with an apology for the low level of research being undertaken. It gives the high turnover of staff and the difficulty of recruitment as a reason for not maintaining a consistent research programme.

The numerical research work of the Differential Analyser Section was limited. The research carried out consisted primarily of developing differential analyser techniques or analysing parts of the machine and resulted in a few published papers (see list of NPL staff publications). During this period two papers concerning other subjects were published by members of the Differential Analyser Section. One reported the results of an investigation carried out in the Division; the other discussed nomograms and reflected the wider interests of the section.

The bulk of the numerical research work carried out by the NPL Mathematics Division was performed by the mathematicians of the General Computing Section. Much of the research reflected the individual interests of the staff or the needs of the Royal Society Mathematical Tables Committee. Other areas in which the section worked included the solution of simultaneous equations, matrix algebra, the solution of integral equations, differential equations, and algebraic equations of high order. Because of the distinction between mathematicians and desk machine operators in the General Computing Section, the senior staff were not overwhelmed by the amount of service work which was performed and could therefore devote much of their time to research. Over the next decade this core of mathematicians at the NPL gave rise to its international recognition as a centre for numerical analysis.

Unlike the original plans for the hardware research of the Mathematics Division, which were only partially undertaken, the numerical research of the Division compares favourably with the research programme drawn up by the 1944 DSIR Interdepartmental Committee and given in table 5.1.1 (see p.132). Items 1, 3, 4, 5 and 6 were all relevant to the General Computing Section and were all investigated as independent research projects. Items 8, 9, 10, 11 and 12 all related to statistical work and, although many of them were touched upon in relation to the Statistics Section's service work, they were not thoroughly taken up as independent research projects. Item 2, the application of telephone equipment to computing, was initiated and undertaken by the Post Office for the NPL. The development of instruments for the direct solution of vibration equations, item 7, was not taken further. The Pilot ACE and, to a lesser extent, the 20-integrator Differential Analyser overtook the proposed development of other computing machines due to their wide applicability and their cost in both financial and staff resource terms.

The NPL Mathematics Division, therefore, not only provided a computing and advisory service to a wide range of users during 1946-1952 but also undertook a considerable amount of numerical research and computing machinery development. Thus up to 1952, before the Pilot ACE and the German Differential Analyser went into regular service the NPL Mathematics Division was supporting a wide range of users and carrying out the functions outlined by the report of the 1944 DSIR Interdepartmental Committee. It was also successful from the user's point of view as it offered service backed by a wide range of machines and expertise[7]. Because numerical research was being continually carried out the Division was able to advise on the latest techniques it was able to offer.

5.4 The 1952 Reorganization : Causes and Results

By mid-1949 both the Pilot ACE and the German Differential Analyser projects were underway and it was becoming obvious that the arrival of these machines, particularly the Pilot ACE, would greatly affect the work of the Mathematics Division as a whole. In May 1949 Womersley prepared a memo titled "Mathematics Division Policy: effect of ACE and new Differential Analyser on Organisation, Staff Requirements, and Accommodation" which outlined his plans for the arrival of the two machines (Womersley 1949a). Womersley anticipated that the Pilot ACE would be in operation by the end of 1949, and that the 20-integrator Differential Analyser would be in working order by June 1950; the actual dates were 1952 and 1954 respectively.

Figure 5.4.1 The NPL Mathematics Division 1949

Superintendent
(J.R. Womersley)

General Computing Section (E.T. Goodwin)	Punched Card Section (T.B. Boss)	Differential Analyser Section (J.G.L. Michel)	Statistics Section (E.C. Fieller)	ACE Section (J.H. Wilkinson)

Figure 5.4.1 shows the structure of the NPL Mathematics Division as it stood in 1949. The ACE and the Differential Analyser Sections were separate from the General Computing Section. The ACE and Differential Analyser Sections contained mathematicians working with specific machines (Wilkinson, Woodger, D.W. Davies; Michel) while the General Computing Section accommodated those working in numerical analysis (Fox,

7. For Punched Card Section users it was also an economical service because the price of the cards used in a job were not charged to the customer. This was because HMSO supplied cards to the NPL free of charge and hence the Mathematics Division did not have the accounting mechanisms to charge customers for their use. This may not, however, have been significant as the cost of cards was cheap compared to the cost of labour. Cards were approximately 6/- per thousand. A change in the accounting mechanism of HMSO eventual stopped this anomaly. (Curtis, A.R. 1983)

Goodwin, Olver). Programming the Pilot ACE would be a new skill for which there were no trained assistants for the mathematicians to draw upon (as for desk machine or punched card work). To overcome this problem, Womersley proposed to transfer some of the General Computing Section staff into the ACE Section. This new section was to consist initially of the ACE designers, mathematicians experienced in numerical methods, and competent assistants from the Desk Machine Section to be trained as programmers. The section would not undertake any desk machine work.

This reorganization, Womersley stated, would "form a nucleus of staff at all levels" (Womersley 1949a). The NPL Electronics Section was to maintain the machine. From this "nucleus" Womersley intended to build up the ACE Section to a staff of 29 (14 scientific officers and the remainder assistants), 8 of which were to come from from the Electronics Section to continue the development of computing machinery.

Using the same argument, that is the need to bring together mathematical and technical talent to form a nucleus of staff, Womersley proposed to combine Differential Analyser Section staff with some General Computing Section staff. Womersley stated that, on delivery of the German machine, the Manchester differential analyser would fall into disuse but, in the intervening period, it should be used to train new members of staff in differential analyser techniques. Acting on advice from Hartree, Womersley forecast that three teams each consisting of 3 senior staff plus assistants would be necessary to keep the 20-integrator machine in operation. Womersley was requesting a more than four-fold increase in Differential Analyser Section staff over a two year period. Thus the five separate sections of the Division were to remain but the staff distribution between them would differ.

This relocation of personnel was to be an emergency measure to cope with the imminent arrival of two powerful computing machines and was to be followed by the gradual recruitment of additional staff. To counteract the break up of the General Computing Section caused by the relocation of staff, Womersley proposed to relieve the section of much of the routine desk machine work carried out as part of the Division's service work.

The work was to be done by Scientific Computing Service Ltd. (SCS) either under contract to the NPL or independently, with the NPL advising users of the company's existence. The arrangement had two advantages. Firstly it would remove some of the pressure from the General Computing Section while the staff was being rebuilt (recruitment was difficult owing to government restrictions on the intake of staff to the Civil Service at that time). Secondly it kept the SCS, which was experiencing difficulties at that time, in operation (see p.185).

To complement this structure Womersley also put forward plans to formalize the procedure which dealt with incoming problems to the Division. It was anticipated that the Pilot ACE would attract an increasing amount of work to the Division for which the existing informal procedure would be insufficient. Womersley proposed that the acceptance or rejection of a problem should be the responsibility of the Superintendent after consultation with his staff. Previously any job which had come directly to Womersley had been passed to the appropriate section head. The Superintendent was to formulate a policy for problem acceptance and give broad indications of priority. On the basis of these, problems would be accepted or rejected. He did not clarify what such an acceptance policy would consist of. If accepted the problem would be put before a steering panel made up of senior Mathematics Division staff (Goodwin, Fox, Wilkinson and Michel) which would determine a programme of work for each job. There were to be three distinct stages in the execution of problems; planning , programming and operation. The steering committee was to allocate staff to each of the stages[8].

Therefore, Womersley planned to reorganize the Division in order to fully exploit the Pilot ACE and 20-integrator Differential Analyser when they were installed. By passing on some of the more routine work to the SCS in a controlled manner Womersley was continuing to provide a service to government, industry and the universities while retaining a high research content in the Division's work. In September 1950, before either of these

8. At Cambridge too a priorities committee was established to accept and plan jobs to be run on the EDSAC.

machines arrived and before the reorganization, Womersley resigned as Superintendent of the Mathematics Division to take up a post with BTM. His plans, therefore, were never put into operation.

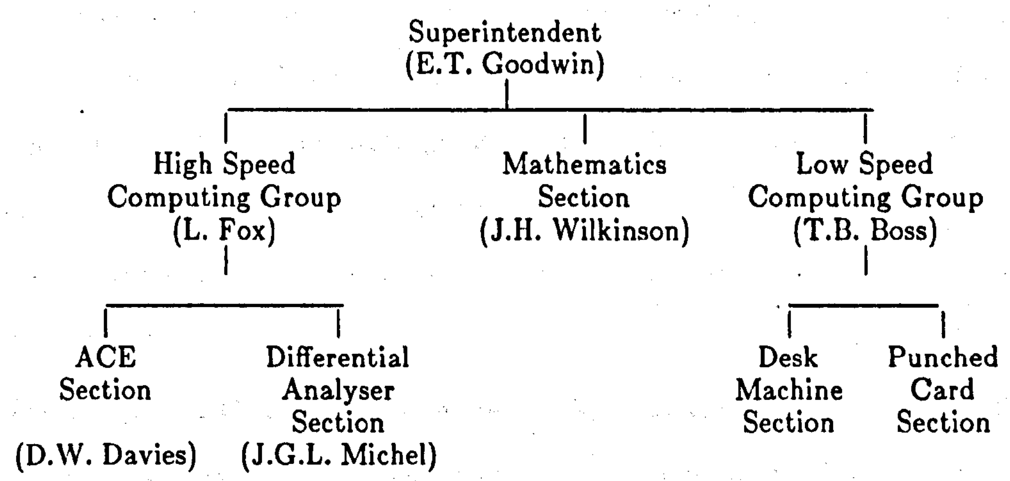
In February 1951 Goodwin succeeded Womersley as Superintendent. Goodwin had now to apply himself to the imminent installation of the Pilot ACE. It was again obvious that more staff would be needed in the ACE section to keep the Pilot ACE fully occupied. Because of the government freeze on recruitment to the Civil Service the additional staff necessary had to be found from within the Division itself. Goodwin felt that the Statistics Section "had never been fully integrated into the rest of the Division" (Goodwin 1984). This was, to a large extent, true. Many of the original Statistics Section staff had been transferred directly from the Ministry of Supply and were therefore an almost autonomous group. In addition staff turnover within the Statistics Section had been high during the past few years which added to the disunity between the Statistics Section and the rest of the Division. There had also been little contact between the Statistics Section staff and the mathematicians of the General Computing Section because although the Statistics Section used the desk machine and punched card facilities, their work differed considerably with that of the rest of the Division. In the original 1944 DSIR Interdepartmental Technical Report the separateness of the Statistical work of the Division had been acknowledged:

> if the expansion in statistical work that is adumbrated should take place, it might be advisable later to split off the Statistical Section from the Mathematical Division (DSIR 1944, p.6).

For these reasons Goodwin came to the conclusion that "the only way we could recruit to man the electronic computer was to find a niche in another Ministry for our Statistics Section while retaining their posts" (Goodwin 1984, pp. 6-7). As a result, the Ministry of Supply announced in 1951 that it was going to reestablish its own statistical group and stated that it would accept the transfer of the NPL Statistics Section to this group. The Ministry of Supply was expected to continue the service and consultancy role played by the NPL Statistics Section and thereby fulfil the statistical needs of other ministries[9]. The Mathematics Division therefore gained approximately six posts to which it recruited personnel for the ACE Section.

In 1952 the Statistics Section transferred to the Ministry of Supply and the Pilot ACE went into regular service. These changes led Goodwin to restructure the Division in February of that year. The reorganization differed slightly to that proposed by Womersley three years previously. Goodwin divided the staff of the Mathematics Division into three groups as illustrated in figure 5.4.2.

Figure 5.4.2 The NPL Mathematics Division 1952



The first of these groups, Fox's High Speed Computing Group, consisted of the old ACE and Differential Analyser Sections. The ACE section now consisted primarily of hardware development and operational staff (D.W. Davies, York (part-time) and Vickers). Vickers was responsible for the staffing and day to day running of the ACE. The Differential Analyser Section remained intact. Later, when the 20-integrator Differential Analyser came into operation, Vickers took charge of the programming staff of both machines. This section prepared and ran programs for the ACE and Differential Analyser as part of the growing NPL computing service.

9. The survey carried out in 1944 by the DSIR Interdepartmental Committee, shown in table 5.1.2, illustrated that half of the ministries/departments questioned required a statistical rather than a mathematical service.

The Mathematics Section constituted the senior programming staff of the former ACE section and the remainder of the Division's numerical analysts. It formed a "pool" of scientific, rather than assistant, staff on which the High-Speed and General Computing Groups could draw. It was headed by Wilkinson and included York (part-time), H.H. Robertson, M. Woodger, J.G. Hayes, G.G. Alway and B. Curtis. The work of the section over the following two to three years concentrated primarily on building up a library of subroutines for the Pilot ACE rather than on other types of numerical work. The Reports of the NPL covering the period 1952-1955 indicate that Goodwin was concerned that the Mathematics and ACE Sections were spending too much time on service problems and not enough on basic research. In 1954 Goodwin tried to solve this problem by formally dividing the ACE section and that part of the Mathematics Section most concerned with electronic computers into two separate groups; a research group and a operational group. This allowed the more routine problems to be passed directly to the latter group which had now gained programming experience and hence left the senior staff more time to devote to research.

The Low Speed Computing group was made up of the Desk Machine and Punched Card Sections. It was nominally headed by Boss who, relieved by F. Rigg as head of the Punched Card Section, took responsibility for the computing machinery advisory service the Division provided to the Treasury and HMSO. The Desk Machine and Punched Card Sections continued to work on incoming jobs which were unsuitable for transfer to the ACE. The Desk Machine Section carried out small calculations which would have taken a disproportionate amount of time to program for the value of the results or very complex calculations which involved a very large amount of complex programming. Other jobs, such as those involving repeated calculations on a very large amount of data or those which required much data manipulation, were more easily performed using punched card machines than on the Pilot ACE which had, initially, only 320 32 bit words of memory. Some numerical research was carried out in the Desk Machine Section by the mathematicians who remained.

From the original memo outlining this organizational change (Goodwin 1952) it is clear that Goodwin intended the senior staff of the Desk Machine Section to eventually transfer to the Mathematics Section and the junior staff to move to the ACE and differential analyser programming teams as electronic computers became more dominant. Thus Goodwin was creating an environment for the further use of electronic computers and further fundamental research in numerical analysis.

5.5 After the Pilot ACE : 1952-1957

The installation of the Pilot ACE initiated a substantial increase in the amount of work which came into the NPL Mathematics Division and it became necessary to introduce a shift system in order to fulfil the demands on machine time. Table 5.5.1 lists some of the more important ACE Section users during the 1952 to 1957 period. Several customers made regular use of the NPL facilities particularly the RAE, English Electric, the Ordnance Survey Department, the Ministry of Supply and, later, the United Kingdom Atomic Energy Authority (UKAEA).

From 1948 English Electric had been working closely with the NPL Electronics Section in order to produce an engineered version of the Pilot ACE, the DEUCE. The DEUCE, was delivered to the NPL in 1955 and prompted a further increase in custom for the High Speed Computing Group. At the same time the NPL lost two of its heaviest customers when a DEUCE was delivered to the RAE, which meant that Farnborough staff no longer used the NPL facilities, and English Electric kept two DEUCE machines for its own use. Despite the loss of these two regular users there was a steady increase in the number of users between 1955 and 1957. The DEUCE was also put into operation in the evenings and on weekends in order to cope with the demand for its services.

As demand for electronic computing grew the work load of the other NPL service sections began to decline. The 20-integrator Differential Analyser, although considerably more powerful than the Manchester machine, was never used as heavily as the Pilot ACE or the DEUCE. The principle users of the Differential Analyser, listed in table 5.5.2, were

Table 5.5.1 ACE/DEUCE Section Users 1952-1956(*)

RAE, Farnborough
English Electric
Ordnance Survey
UKAEA
AERE, Harwell
European Council for Nuclear Research
Aircraft Manufacturers
NPL Aerodynamics Division
NPL Metrology Division
NPL Physics Division
NPL Light Division
Inland Revenue
Road Research Laboratory, DISR
Mechanical Engineering Research Station, DSIR
Torry Research Station, DSIR
Water Pollution Research Laboratory, DSIR
Ministry of Civil Aviation
Norweigen Defence Research Dept.
Admiralty
National Coal Board
Royal Dutch Shell Co.
Physics Department, UCL
Oxford University
Chemical Research Laboratory, DSIR
Post Office
Central Electricity Authority

(Source: Reports of the NPL 1952-1956).

(*) See note to Table 5.2.1.

aircraft manufacturers, the RAE and other NPL Divisions.

Table 5.5.2 Differential Analyser Users 1952-1956(*)

NPL Electricity Division
NPL Physics Division
NPL Ship Division
NPL CME Division
NPL Director
Admiralty
RAE, Farnborough
Cambridge University
National Coal Board
English Electric
Standard Telephones & Cables
Aircraft Manufacturers

(Source: Reports of the NPL 1952-1956).

(*) See note to Table 5.2.1.

By 1953 it had become obvious to Goodwin that the future lay in the development of electronic computers and methods for use with them, and not in the construction of analogue machines. Goodwin writes,

> I think that it is also fair to say that I was much less enthusiastic about the Differential Analyser than Womersley was. I was quite convinced that the Electronic Computer would soon oust the analogue machines and, though Jack Michel worked manfully to keep the D.A. fully operational and doing useful jobs the writing really was on the wall soon after I took over (Goodwin 1984, p7).

Use of the Differential Analyser stopped in 1958.

After the installation of the Pilot ACE and the DEUCE the number of Desk Machine Section users was drastically reduced due to the calculations traditionally performed by the section being undertaken by the High Speed Computing Group. Some of the remaining users are given in table 5.5.3.

Table 5.5.3 Desk Machine Section Users 1952-1956(*)

RSMTC
NPL Aerodynamics Division
NPL Metrology Division
NPL Physics Division
NPL Light Division
UKAEA
Admiralty
London Hospital Medical College
University of Singapore

(Source: Reports of the NPL 1952-1956).

(*) See note to Table 5.2.1.

The number of staff in the section also diminished as they gradually transferred to Vickers' programming team. *Ad hoc* or exploratory calculations for other Mathematics Division sections or other NPL Divisions soon became the mainstay of the Section's work. In contrast to this the work of the Punched Card Section, surprisingly, increased. Although the High Speed Computing Group took over much of the work formerly carried out by the

Punched Card Section, particularly the matrix manipulation work, during 1953-1956[10] the section performed an increasing amount of service work.

Table 5.5.4 lists some of the major Punched Card Section users for 1952-1956 but does not truly represent the increase in work experienced by the Section because this enormous influx of work came from a single user - the United Kingdom Atomic Energy Authority (UKAEA).

Table 5.5.4 Punched Card Section Users 1952-1956(*)

UKAEA
AWRE, Aldermaston
AERE, Harwell
NPL Aerodynamics Division
NPL Metrology Division
NPL Physics Division
Institute of Oceanography
U.S. Air Force
Headquarters, DSIR
Ordnance Survey
Admiralty
Ministry of Supply
National Blood Transfusion Service
Home Office
BBC & Nuffield Foundation

(Source: Reports of the NPL 1952-1956).

(*) See note to Table 5.2.1.

As part of their research programme the UKAEA used the Monte Carlo technique to simulate the behaviour of neutrons under certain conditions. Although the Atomic Energy Research Establishment (AERE) at Harwell acquired a punched card installation in 1954 equipped with IBM 602A and 626 calculators and operated by staff trained at the NPL, there was still a high demand for this type of work from the Authority. The installation in 1955 of an IBM 626 calculator at the NPL was directly attributable to this work and was followed a year later by a second machine paid for by the UKAEA. In 1957 the Atomic Weapons Research Establishment (AWRE) at Aldermaston installed an IBM 704

10. Although this section discusses the Mathematics Division up to 1957 there is no comparable data available for 1957 because the reorganization of the Division led to a change in the way information was given in the annual Reports.

computer and a year later a Ferranti Mercury arrived at Harwell. These machines took over the Monte Carlo, and other, calculations the NPL had been performing on behalf of the UKAEA and the work load of the Punched Card Section fell dramatically.

In 1954 the NPL Electronics Section and the Control Mechanisms Section of the Metrology Division were combined to form the Control Mechanisms and Electronics Division (CME). The role of the CME Division was to develop both computational and automatic control mechanisms. Both parts of the new Division had been involved in the development of computing hardware for the Mathematics Division; the Electronics Section worked on the Pilot ACE and the DEUCE, and the Control Mechanisms Section had been heavily involved with the installation and testing of the German differential analyser and the design of an automatic curve follower for the machine. In 1954 the CME Division began work on the full sized ACE. This effectively took almost all research on computing machinery out of the hands of the Mathematics Division. Consequently the type of research carried out by the Mathematics Division concentrated on numerical analysis, applied mathematics and programming.

Once the High-Speed Computing Group had prepared the basic subroutines for the Pilot ACE and the DEUCE, the operational staff took over most of the electronic computer service work leaving the mathematicians to concentrate on numerical research. Much of the numerical research undertaken was on problems or methods applicable to electronic computers, in particular the Division gained a high reputation for its work on matrices. Some research stemmed from investigations and computations which the Division had been asked to perform. Others reflected the interests of the Divisional staff for example asymptotic expansions, matrices, differential and integral equations, integrals, and table making. In addition to the publication of papers concerning the research work within the Division, the NPL also fulfilled its obligation (under recommendation b of the Report of the 1944 DSIR Interdepartmental Committee) to disseminate information by holding a four day conference on Automatic Digital Computers in March 1953 (NPL 1954). The purpose of this conference was to bring together people working in the electronic computer field. NPL staff contributed six papers to the conference.

Another aspect of the work of the Mathematics Division was the liaison role it played. An important part of this function was the Division's accommodation of research visitors and trainee staff from other establishments. From 1945 the Punched Card Section had regularly trained staff to apply Hollerith machines to scientific problems and had permitted heavy users to visit Teddington to run their own jobs on NPL machines. This practice continued in the mid-fifties with the training of UKAEA staff prior to the installation of its own machines. The bulk of the programming for the Pilot ACE and the DEUCE was done by NPL staff, but some users were permitted to program their own work.

The accommodation of research staff was also an important role for the NPL. For several years English Electric personnel worked in both the Electronics Section and the Mathematics Division. From 1952-1955 RAE staff were almost constantly at the NPL to make use the Pilot ACE and the computing expertise to be found there. Research staff from universities also came to the Mathematics Division spending several months using the machines available to complete their research.

As the Mathematics Division became a recognized computing centre the advisory role it played took on a new facet when its opinion began to be sought by universities considering setting up their own computing laboratories. It also became involved, as part of the NPL's work on standards, in devising acceptance tests for computers delivered elsewhere. The first of these acceptance tests was for a Ferranti computer being delivered to to the Royal Dutch Shell company (NPL 1955).

The Mathematics Division's terms of reference of 1944 had included a commitment to the preparation of mathematical tables but, until the mid-1950s, this function had taken second place to the development of electronic computers and the provision of a computing service (NPL 1956-66, Vol 1, Fox 1956). Some tables had been prepared as part of the Division's service work but had usually consisted of tables of empirical data and were of limited interest. When the tables had been of some mathematical interest they had been published in relevant journals (for example, Goodwin and Staton 1948a, 1948b). The Mathematics Division had also contributed to the work of the Royal Society Mathematical Tables Committee, and its predecessor the British Association Mathematics Tables Committee, and sponsored the preparation of tables of Weber Functions by the SCS.

In 1954 the NPL decided to prepare and publish its own series of mathematical tables. The NPL series was not designed to overlap the Royal Society series of tables but rather to supplement it by publishing tables of fundamental mathematical functions which were of less widespread interest. The tables were to be produced in smaller volumes than those published by the Royal Society which, it was hoped, would lead to faster publication. The first volume in the series (NPL 1956-66, Vol 1, Fox 1956) dealt authoritatively with the use and construction of tables. This was followed by seven further volumes over the period 1958 to 1966. The rapid publication objective was not always achieved. The preparation and publication of the NPL Mathematical Table Series completed the achievement of all five of the initial Mathematics Division objectives.

In 1952 the Mathematics Division had been reorganized into the High Speed Computing Group, the Low Speed Computing Group and the Mathematics Section. In 1957 the organizational structure was changed for the second time. The Mathematical Division was divided, as illustrated by figure 5.5.5, into three groups.

Figure 5.5.5 The NPL Mathematics Division 1957

Superintendent
(E.T. Goodwin)

General Computing	Numerical Methods	Applied Mathematics
(T. Vickers)	(F.W.J. Olver)	(J.G.L. Michel)

The Numerical Methods Group, under F.W.J. Olver, consisted primarily of the old

Mathematics Section and those mathematicians previously based in the High Speed Computing Group. Its main areas of interest were to be Numerical Analysis, including error analysis, the development of numerical techniques suitable for application to electronic computers, and the continuation of the work on both the Royal Society and NPL Mathematical Tables Series. This group, with staff from the CME Division, was responsible for software research on the DEUCE after its installation in 1955. For example, an important programming scheme, Generalized Interactive Program (GIP), was developed for matrix work which became one of the most common DEUCE programming systems in the late 1950s (Campbell-Kelly 1980c).

The second group, Applied Mathematics headed by Michel, was created from the Differential Analyser Section and dealt with the numerical side of the work. It was not responsible for the operation of the Differential Analyser. The Differential Analyser Section had been involved in practical problems for the RAE, the Admiralty, the Ship, Physics and Light Divisions of the NPL and others. Most of their work had dealt with the solution of differential equations and other forms of applied mathematics. In 1958, on the recommendation of a Review Committee set up in 1957, a Theoretical Physics Section was added to the Applied Mathematics Group and worked closely with the Basic Physics and Metallurgy Divisions.

The DEUCE, Desk Machine, Punched Card Sections and the operational side of the Differential Analyser Section were brought together under Vickers to form the General Computing Group. All the service sections were therefore collected into one group and not separated into distinct sections by machine type. This arrangement reflected the increasing dominance of electronic computers and the subsequent decline of other computing machines.

The reorganization, coupled with the earlier loss of responsibility for hardware research to the CME Division, changed the emphasis of the Division's work. It no longer fulfilled the recommendations of the 1944 Interdepartmental Committee's Report to carry out research into new computing machinery. But the environment in which the Division operated had also changed. It was no longer necessary for a national computing centre to develop electronic computers for they were being manufactured and sold commercially by English Electric, Ferranti, Lyons and IBM.

As other research establishments and universities began to install computers the amount of service work required by these large NPL users fell while the demand and need for numerical research increased. Although the General Computing Group continued to receive incoming work for several years it gradually became a local computing service for other NPL Divisions and not a national facility. The main work of the Division was now concerned with numerical and programming research. Its interests were turning it into a National Mathematical Centre rather than a National Computing Centre.

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Chapter 6

Other British Post-War Computing Centres and Thier Relationaship with the NPL Mathematics Division

6.0 Introduction

The NPL Mathematics Division was set up to act as a national computing centre and was intended to serve most of Britain's computing needs. It epitomized the centralization concept both by providing computing services of all kinds and by carrying out research into new computing machinery. Despite the existence of the NPL Mathematics Division several institutions continued to perform their own computing work. Some acquired extensive facilities while others began to develop electronic computers, but none of these institutions developed into a comprehensive computing centre in the sense of the NPL Mathematics Division. This chapter both continues the histories of the Cambridge University Mathematical Laboratory, the RAE, the NAO, and the SCS begun in earlier chapters, and illustrates how these different computing centres developed in parallel with the NPL Mathematics Division.

In post-war Britain two types of computing centre emerged: those which carried out computation using desk calculators, Nationals and punched card machines, and those which designed and built electronic computers. The chapter is divided into two parts and represents the basic distinction between the two types of computing centre discussed. The first part of the chapter, section 6.1, discusses the first type of computing centre while section 6.2 describes the computing centres at Cambridge and Manchester Universities which carried out significant computing machinery research.

Section 6.1 is itself divided into two parts. Section 6.1.1 describes the work, and decline, of the SCS during the period 1945-1950. The SCS continued to operate in much the same way as it had done before the war and did not become involved with computing machinery research. Section 6.1.1 also considers Comrie's continuing influence on the way in which computation was performed in Britain and the relationship between the SCS and the NPL Mathematics Division. Although the NPL Mathematics Division and the SCS were set up to provide computing services for a wide range of users, several local computing centres began to emerge after the war. Section 6.1.2 reviews some of these local computing centres, particularly those at the RAE and at Liverpool University. Both of these institutions became, in different ways, significant centres in the late 1940s and early 1950s but neither were as comprehensive as the NPL Mathematics Division. The remainder of section 6.1.2 briefly considers the computing activities of other institutions which began to improve their computing facilities during the post-war period and discusses the connections these institutions had with the NPL Mathematics Division.

The second part of chapter 6, section 6.2, discusses the emergence of two of the most important post-war computing centres to carry out research into electronic computers: those at Cambridge and Manchester. Section 6.2.1 describes in some detail how Wilkes reestablished the Cambridge University Mathematical Laboratory as a university computing facility after its war time occupation by the Ministry of Supply and follows the changing role of the laboratory from a service and teaching facility to an important centre for electronic computer research. This section also considers the relationship Wilkes had with Womersley and the NPL Mathematics Division. The Cambridge Mathematical Laboratory is particularly interesting because it represents a transition from its pre-war situation of a local computing centre set up to provide computing facilities for university staff to an internationally renowned centre of computer research.

The other centre of computer research to emerge during the late 1940s was based at Manchester University and, along with the NPL and Cambridge, constituted the mainstream of computing machinery research in Britain. Before the war an informal computing centre had built up around Hartree's differential analyser but Manchester's involvement with electronic computers developed *independently* of Hartree's work. Section 6.2.2 describes the creation of the Royal Society Computing Machine Laboratory at Manchester University and the work of F.C. Williams, T. Kilburn, M.H.A. Newman and A. Turing in developing the range of Manchester computers. Unlike section 6.2.1 where original documents concerning the Cambridge University Mathematical Laboratory have been used, the description of the events which took place at Manchester has largely been taken from published literature and does not, therefore, go into the same level of detail.

Although sections 6.1 and 6.2 overlap chronologically, conceptually they are quite distinct. The computing centres described in section 6.1 represent a continuation of the type of computing centres which were beginning to appear before the war and which began to disappear during the late 1950s and early 1960s as computers became more easily accessible. They represent the use of tried computing machines to provide a service for a specific range of users and correspond to the work of the General Computing and Punched Card Sections of the NPL Mathematics Division. Section 6.2, on the other hand, discusses developments which are characteristic of the post war era and corresponds closely with the research work of the ACE Section of the NPL Mathematics Division. By the early 1950s the computers developed at Manchester, Cambridge and Teddington were beginning to provide computing services and were thus becoming national computing service centres in addition to their research roles.

6.1 Post-War Computing Service Centres

6.1.1 The SCS 1945-1950

Both before and during the second world war Comrie's Scientific Computing Service was heavily used by government departments but, after 1945, the demand for computation began to decline. The SCS no longer received urgent requests from the Admiralty, Air Force or Ministry of Supply for the preparation of ballistic tables and other computations. Consequently after the war the work of the SCS began to take on a different character as the company took on the preparation of mathematical tables and large crystallography jobs.

The largest job undertaken by the SCS during the post-war period was the revision of *Chamber's Mathematical Tables* (Comrie 1948a, 1949, 1950). Towards the end of the war W. & R. Chambers Ltd. approached Comrie on the recommendation of W.H.M. Greaves the Scottish Astronomer Royal (also Comrie's bother-in-law) and A.C. Aitken, the Edinburgh mathematician. Chambers asked Comrie to report on their seven figure tables and to consider the possibility of updating them. After reviewing the tables Comrie declared that the tables and existing printers plates were useless and undertook a complete revision of the tables.

Over the following three years much of the work performed by the SCS involved the computation and proof reading of the revised tables. Apart from typographical alterations and the recomputation of the tables using National Accounting machines, Comrie introduced several major changes to the content of the tables. He argued that seven figures were rarely used by general computers because, in the majority of cases, five or six figures would suffice. Consequently Comrie reduced the table to six figures. He also omitted many of the specialist nautical, astronomical and survey tables which were available elsewhere and included tables of the exponential, hyperbolic, inverse hyperbolic and inverse circular functions which had come into general use since Chambers's *Tables* were first published in 1884. In all Comrie and his staff computed and proof read five volumes of tables. Two volumes constituted the main tables, one containing the natural values of functions the other the logarithmic; one volume titled *Chambers's Shorter Six-Figure Mathematical Tables;* and two volumes of four-figure tables.

Comrie was very concerned about the accuracy of the tables and encouraged his staff to detect errors by offering monetary rewards. For example, he paid 2d. for every error found in the first proofs and charged 6d. for every error missed. For errors found in plate proofs he offered 5/-. By the time the tables were published in 1947 Comrie was so confident of the absence of errors exceeding +/- 0.51 in the last decimal that he offered a £5 reward for their detection (Comrie 1948a). Comrie himself knew of less than five errors in the tables and these he left uncorrected as "an uncomfortable trap for any would be plagiarist" (Comrie 1950, p.vi).

The other major computation carried out by the SCS during the late 1940s was a crystallography analysis for Bragg and Perutzi at Cambridge University on the molecular structure of haemoglobin. During the war the SCS had used IBM tabulators at the Milk Marketing Board at Cirencester to perform the Fourier analysis required for x-ray crystallography. The use of American machines was critical in this work because they allowed direct subtraction from the card. British tabulators, manufactureed by BTM, did not. Through BTM, the SCS acquired an IBM tabulator which Comrie installed in a converted wool shop in Wimbledon. By using this machine and other punched card machines in different installations all over London, the SCS completed this and several other crystallography jobs (Gittus 1983).

Because information regarding the post-war activities of the SCS is scarce (the principal sources are the personal recollections of Comrie's staff) it is difficult to list the other computations carried out by the company during this period with any degree of accuracy. What is clear, however, is that apart from the recomputation of *Chamber's Mathematical Tables* and the few large crystallography jobs which were undertaken, the SCS performed only small calculations. There are three main reasons for this. Firstly, there was no longer the high demand for computing which the war had caused. Secondly, the NPL Mathematics Division began operation in 1945 and took in computing work from government departments which might otherwise have gone to the SCS. Thirdly, several research establishments began to install improved computing facilities of their own and therefore no longer needed the services of a computing bureau. Because of the decline of the computing service side of the business, the publishing work of the SCS began to take on a greater importance.

The most important book published by the SCS was Fletcher, Miller and Rosenhead's *An Index of Mathematical Tables* in 1946. During the war Comrie learnt of a project being undertaken at Liverpool University by A. Fletcher, J.C.P. Miller (who later came to work for Comrie) and L. Rosenhead to compile a practical guide of published mathematical tables. The guide included information on the numbers of figures given in each table listed, the size of the interval, whether or not differences were provided to facilitate interpolation, authorship, and overall quality of the tables. The tables were both grouped together by function tabulated and listed by author in a comprehensive bibliography. As Comrie himself had been privately working on a similar project for a number of years, he was very interested and offered to publish the book. After many delays, due to the amount of war related work the printers were committed to, the first edition of the *Index of Mathematical Tables* appeared in 1946 and received many enthusiastic reviews throughout Britain and the US. Almost immediately an expanded second edition was begun which included an important section listing the known errors in published tables based on Comrie's work in this area. This second edition was published in 1962 and carried Comrie's name as the main contributor of the new section.

Apart from publishing the *Index of Mathematical Tables* and other tables, the SCS also acted as a specialist bookseller of mathematical tables and relevant literature. A list of the stock carried by the SCS in 1950 revealed the extent of the SCS collection (SCS c.1950b). The SCS held all the tables published by the British Association Mathematical Tables Committee from 1931, the Annals of the Computation Laboratory of the Harvard University, the tables published by the United States National Bureau of Standards Mathematical Tables Project, and 71 other publications.

In addition to his work with the SCS Comrie continued to write and lecture on computing methods and machines. In October 1945 he visited the United States to chair a conference organized by the National Research Council Committee on Mathematical Tables and other Aids to Computation at MIT (Archibald 1946). At the conference Comrie delivered a paper on "The Scientific Application of Commercial Calculating Machines" which gave an historical account of the development of calculating machines and their use for scientific work (Comrie 1946b). While in the United States, Comrie visited the Watson Computing Laboratory at Columbia University, the U.S. Navel Observatory, the U.S. Coast and Geodetic Survey Office, the National Bureau of Standards, Harvard University and the Moore School of Electrical Engineering.

Although he visited both the Automatic Sequenced Controlled Calculator at Harvard and the ENIAC at the Moore School of Electrical Engineering in Pennsylvania, Comrie remained cautious about these new developments. Comrie was well known for making disparaging remarks about those who constructed large, expensive, specialized machines. In his view most computing work could be more economically carried out using desk calculators and commercial adding and listing machines. For instance, following a paper read by Beevers before the Physical Society in 1939 which described a machine to perform the Fourier series summations required in x-ray crystallography analyses, Comrie made the following remark which summarized his views on specialized computing devices and the benefits of centralized computation. He said

> I have always advocated, as a policy, that the capabilities of existing commercial machines should be fully exploited before the laborious and costly task of designing and making special apparatus is embarked upon. In this case the nature of the problem points to the use of punched-card machines, which have been successfully applied to Fourier synthesis in the summation of harmonic terms in the moon's motion. I am not convinced of the curt dismissal of these machines. (Comrie 1939a, p.664).

Likewise in 1944 he dismissed the Mallock and Wilber simultaneous equation solvers by stating that the designers were "suffering from the common delusion that such solution is difficult" (Comrie 1944c, p.134). Two years later he reiterated this point of view in a statement made during the discussion of a paper read to the Royal Statistical Society by H. O. Hartley, a senior employee of the SCS, describing methods of mechanical computation. Comrie is reported to have said:

> He was glad that no one had got up that evening to talk about making special machines, because, before they made special machines to do things, it was well to explore the possibility of existing machines. (Hartley 1946, p. 177).

Comrie was much less critical of the large calculators and computers which began to appear at the end of the war, possibly because they were not specialist machines capable of only a few limited applications but were more general purpose devices. Comrie did, however, gently question whether the expense of the Automatic Sequence Controlled Calculator built by Howard Aiken at Harvard was justified when the main published examples of the machine's work could have been performed using desk calculators (Comrie 1946a, p.568).

Through his acquaintance with Womersley, Superintendent of the NPL Mathematics Division, Comrie was aware of the activities of the NPL Mathematics Division from a very early stage. Comrie is reported to have discussed the role of the NPL Mathematics Division with Womersley on several occasions and may have influenced Womersley's plans for the Division (Goode 1983, Miller 1979). Comrie had some very definite ideas about the formation of the NPL Mathematics Division and saw the NPL's role as a centre for the development of computing methods and machines. He envisaged the SCS complementing the work of the NPL by providing a computing service and by performing large, complex calculations some of which would be sent to it by the NPL (Woodger 1977, item 1). The NPL Mathematics Division did supply the SCS with some work in 1946 when the SCS was asked to undertake the computation of tables of Weber parabolic cylinder functions for a fee of £1,200 (DSIR 1946) but the flow of work from the NPL to the SCS which Comrie expected never really began. Rather the NPL Mathematics Division developed its own service role as the 1944 DSIR Committee had envisaged.

Despite the failure of Comrie's plans for the NPL to supply the SCS with work, when the business began to get into financial difficulties because of the lack of incoming work, Womersley did his best to help out. In 1949 Womersley put his opinion of the position of the SCS to Darwin, Director of the NPL. Womersley stated that "in view of possible future emergencies it is in the National interest that Scientific Computing Service Ltd. should be kept going" (Womersley 1949b). Womersley implied that government computing resources had not yet reached a level where they would not require outside help in any future war or national emergency. Womersley, who knew of the financial difficulties being experienced by the SCS, maintained that the important role the SCS had played during the war justified the NPL supporting the company. At the same time Womersley produced a document which outlined his future plans to reorganize the NPL Mathematics Division in which he intended to recruit programmers for the Pilot ACE from the General Computing Section of the Mathematics Division (see p.154) (Womersley 1949a). To compensate for the removal of staff from the General Computing Section (government restrictions made it impossible to recruit additional staff to the Division) Womersley proposed to relieve the remaining staff of much of the routine work they were called upon to perform. The work was either to be subcontracted to the SCS or turned down by the NPL who would then recommend the SCS to the user. Womersley favoured the former suggestion as bringing more stability to the SCS which would then be assured of work but was uncertain about the ethics of allowing certain types of work coming from other DSIR stations being performed by the SCS. Womersley's plans were never implemented as he left the NPL before the Pilot ACE had been installed, but the example does serve to illustrate the connections which existed between Comrie and Womersley.

In 1948 Comrie, his wife and W.E. Block of Block and Andersons Ltd., the U.K. Brunsviga agents, toured first Comrie's native New Zealand and then Australia (Block, Comrie, and Comrie 1948). Throughout the tour Comrie lectured and advised on computing methods to government departments, universities and commercial companies. In 1947 Comrie appointed J.C.P. Miller Technical Director of the SCS and left Miller in charge of the company during his tour. During this time the company made a financial loss (Miller 1979, Atkinson 1984). Soon after his return from Australasia Comrie suffered a stoke from which he never fully recovered. Because of his ill health and the decrease in the demand for computation, Comrie was unable to restore the financial success of the company.

The principal reasons for the decline of the SCS was Comrie's deteriorating health aggravated by the low demand for computation caused partly by the existence of the NPL Mathematics Division. Because Comrie's health was failing others had to take over the administration of the company but it was very difficult for any one person to step into Comrie's shoes as an expert in computation and typography, and as an astute businessman with a good reputation and a large circle of acquaintance. Thus although the company was run by experienced businessmen and talented mathematicians the SCS was not successful after Comrie's trip to New Zealand and Australia in 1948/1949. Comrie died in December 1950 nine months after being elected a Fellow of the Royal Society.

Soon after Comrie's death J.C.P. Miller, Technical Director of the SCS, left the company; although he did remain a board member until 1958. The company was then run, reluctantly, by Comrie's widow. P.H. Prail acted as business manager of the company while D.C. Gilles organized the technical side of the business. The SCS continued to lose money and, although attempts were made to introduce computer programming into the services offered (Gilles 1983) they came to nothing. Throughout the 1950s and early 1960s publishing and bookselling was the mainstay of the company's business. In 1954 Prail left the SCS. He was soon followed by Gilles who recognized that without the large injection of capital needed to introduce computers into the SCS the company would decline further (Gilles 1983). In 1964 G. Norton bought the majority of company shares including those of Comrie's widow. Soon afterwards the SCS ceased trading and all the computing staff left. In 1973 the SCS was taken over and today operates as a computer programming service.

6.1.2 The RAE, Liverpool University and Other Local Post-War Computing Centres

The only government establishment, apart from the NPL, to develop an important computing centre during the late 1940s was the Royal Aircraft Establishment (RAE) at Farnborough.

A.G. Pugsley, head of the Structural and Mechanical Engineering Department of the RAE, had been trying to improve computing methods within his department since the mid-1930s (see p.99), but is was not until 1944 that the Ministry of Aircraft Production granted the necessary permission and finance to install Hollerith punched card machines at Farnborough. The machines were installed in August 1945[1] and became the basis of a Computing Laboratory which was set up to serve the Structures Department of the RAE. The Computing Laboratory was initially equipped with several desk calculators, a National Accounting Machine Class 3000 and the punched card installation which consisted of a sorter, a collator, a reproducer, an IBM 601 multiplying punch, and a E6/6 tabulator. The E6/6 tabulator was an old BTM model which did not have the facility to transfer numbers between registers. This machine was soon replaced with a Senior Rolling Total Tabulator which had inter-register transfer as a standard feature and allowed the RAE to carry out more complex work such as matrix multiplication.

R.A. Fairthorne was responsible for running the Computing Laboratory which was housed in an army hut at Farnborough and, at first, T.B. Boss assisted Fairthorne in setting up the new installation. Boss had already been appointed head of the Punched Card Section of the NPL Mathematics Division and his work at the RAE gave him valuable experience in setting up a scientific punched card installation. In September 1945 Boss left the RAE to take up his position at NPL and Fairthorne acquired several more members of staff to run the laboratory. In 1948 a new Mathematical Services Department was set up at the RAE under S.H. Hollingdale. The new department was made up from the separate computing facilities in different RAE departments including Fairthorne's Computing Laboratory and several analogue machines which had been in use in the Aerodynamics Department.

The Mathematical Services Department was set up to provide a centralized computing facility for the RAE but did not successfully achieve this aim. Centralization of the computational work of the RAE was often impossible. Fairthorne observed that,

Departments, even without the security restrictions within a service depart-

1. Three months after Pugsley had left the RAE to become Professor of Civil Engineering at Merchant Venturers' College, Bristol, the Structural and Mechanical Engineering Department was reformed as the Structures Department under P.B. Walker.

> ment, are ever watchful of extra-departmental infiltration. This made centralized computing rather ineffective.... You can't do applied maths or applied computation properly without knowing quite a lot about the application. At any time this is a problem. In an institution that, rightly, had very tight security on much of its projects, and was fragmented by departmental chauvinism I had to exercise much tact and know a lot more than I was supposed to know in order to get any work done at all. (Fairthorne 1983b, p.1-2)

To try to dispel the reluctance on the part of RAE staff to allow others to perform their numerical work and encourage them to make use of the considerable computing power available to them, Fairthorne and his staff prepared a report which was intended to explain how the RAE punched card installation could be applied to a number of problems (Staff of the Mathematical Services Department 1952).

The report outlined the basic principles of punched card machines and gave an indication of how they could be applied to scientific work. The report then gave several examples of both successful and unsuccessful calculations which had been performed using the RAE punched card installation and tried to analyse why some jobs had been less successful than others. The report also put forward ways in which the methods used could have been improved if Mathematical Services Department staff had been given some background of the physics behind the problem or had been consulted on what format experimental readings should have been taken. One of the most successful jobs which the RAE punched card installation performed, an analysis of flight recorder records, owed much of its success to the type of interdepartmental cooperation being advocated. Because Fairthorne was personally acquainted with the person in charge of the investigation, he was able to arrange for data to be transcribed directly onto punched cards and hence not only eliminate one stage of the process but also reduce the danger of transcription errors entering the computation. In the published form of the report (Fairthorne, Griffith and Woollett 1958) the value of consulting the Mathematical Services Department was again emphasized by the example of the flight recorder analysis job. The report noted that:

> For this job all people concerned co-operated before actual experiments were done. Thus the recording instruments themselves, the records and their monitoring and measurement, the analysis and its final presentation were all designed to match. The total time from trial to publication was reduced to less than one-thousandth of that previously needed. (Fairthorne, Griffith and Woollett 1958, p.24).

In addition to being distributed internally, the report was published as part of the Aeronautical Research Council's Reports and Memoranda series with the intention of bringing the RAE punched card installation to the attention of all those engaged in aeronautical research. Because of administrative problems, however, the report was not published until 1958 (Fairthorne, Griffith and Woollett 1958) by which time it was largely obsolete as the RAE had by then installed a DEUCE computer.

Because the RAE punched card installation was not used to any great extent by RAE staff, the Computing Laboratory, and later the Mathematical Services Department, took on outside work. Some of this work, including jobs for the Building Research Station and the Cambridge Language Unit, came to Fairthorne through BTM which passed on the more mathematical problems received by its service bureaux. The RAE punched card installation was also used by the Royal Society Mathematical Tables Committee (RSMTC) in 1949 to prepare tables of binomial co-efficients for volume 3 of the Royal Society Mathematical Tables Series (Miller 1954, Woollett and Simm 1949). The National Accounting Machine too was used for outside tablemaking work. The most well known outside job on the National was the calculation of eigenvalues for a portion of the Hilbert Matrix for J.C.P. Miller (Fairthorne and Miller 1949).

The Mathematical Services Department also carried out of advisory work. From August 1945 when the Computing Laboratory was first set up, people came to the RAE for advice on punched card machine techniques. One of the first visitors to the RAE Computing Laboratory was Womersley who was collecting information in preparation for punched card machines being installed at the NPL. During the late 1940s, Fairthorne and his staff had a considerable amount of contact with the NPL Mathematics Division concerning punched card machines which developed later into an interest in electronic computers. The RAE also advised the Ministry of Works and the Ministry of Civil Aviation.

Although the RAE Mathematical Services Department was set up to provide centralized computing facilities at the RAE, it had a much wider range of users than simply the staff at Farnborough. The Mathematical Services Department also carried out research on computing machinery. A relay calculator, the RASCAL, was designed at the RAE in the late 1940s (Petherick 1949) but later a decision was made to build the machine using electronic components. Although the design for the RASCAL was complete by 1953, the machine was never finished (Campbell-Kelly 1980c). Because of its service work both inside and outside the RAE, the RAE Mathematical Services Department was one of the more important computing centres of the late 1940s and early 1950s.

In the same way the Liverpool Mathematical Laboratory was set up to serve the staff of the Applied Mathematics Department at Liverpool University, but it too took on outside work (although on a much smaller scale than the RAE) and can, therefore, be regarded as a computing centre. The Mathematical Laboratory of the Applied Mathematics Department at Liverpool University was set up in 1933 by L. Rosenhead, Professor of Applied Mathematics. It was initially equipped with desk calculating machines supplemented by a collection of mathematical tables and was intended to be a teaching laboratory for students. The Liverpool Mathematical Laboratory was not created to be as a centralized computing facility for Liverpool University but rather as a laboratory for use by the Applied Mathematics Department alone. One of the most well known projects undertaken by the laboratory was the preparation of a working index of mathematical tables. Although Rosenhead temporarily left Liverpool University in 1940 for war service with the Ministry of Supply, Fletcher and Miller continued to work on the index which was published as the *Index of Mathematical Tables* in 1946 by the Scientific Computing Service after Comrie had become involved in the project (see p.187)[2].

2. Remains of Fletcher's work on the *Index* are held by L.M. Delves of the Statistics and

Apart from their work on the *Index* the Liverpool Mathematical Laboratory computed a considerable number of tables. Miller was a member of the British Association Mathematical Tables Committee and used the facilities at Liverpool to compute tables for that Committee (Miller 1979). In February 1946 the British Association Mathematical Tables Committee sent the Liverpool Mathematical Laboratory a National Accounting Machine Class 3000 on indefinite loan[3]. Although the machine was used to compute tables for the British Association Mathematical Tables Committee (and later the Royal Society Mathematical Tables Committee which took over the British Association's responsibilities in 1949), the Liverpool Mathematical Laboratory was responsible for the machine's insurance and maintenance. Under the conditions of the loan, the machine was also to be used for teaching by the laboratory and to carry out research into numerical methods for use with Nationals. Over the next eight years the machine was used extensively for Mathematical Table Committee work (Bickley, Comrie, Miller and Sadler 1952, Jones 1952, Royal Society Mathematical Tables Committee 1954, Miller 1954) and, to a lesser extent, for other outside tablemaking work.

In the early 1950s a certain amount of research work was also carried out by the Liverpool Mathematical Laboratory, particularly by A. Young who joined the Liverpool Mathematical Laboratory in 1951. In particular Young explored the use of the National Accounting machine for integration and for the summation of products (Young 1954). It is interesting to note that the use of Hollerith punched card machines for scientific work was introduced to the Liverpool Mathematical Laboratory by E. Gittus who had joined the Social Science Department at Liverpool in 1951. She had previously worked for the SCS under Comrie and had had considerable experience in handling the x-ray crystallography work done by the company. Although Young experimented with Hollerith machines at the Royal Assurance Company Ltd., punched card machines were not installed at

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Computational Mathematics Department, Liverpool University.

3. As this machine had been used by the Committee since 1933, it seems reasonable to assume that this is the machine Comrie used before installing a National at the NAO (see p.45).

Liverpool during the early 1950s.

The Liverpool Mathematical Laboratory was not set up as a computing centre for the university as a whole or as a service centre for outside workers but, through its work on the *Index of Mathematical Tables* and its work for the British Association and, later, the Royal Society Mathematical Table Committees it became quite a well known computing centre. The main work of the Liverpool Mathematical Laboratory was, however, as a teaching facility for mathematics students at the university.

Apart from the RAE and Liverpool University few of the other computing facilities set up in Britain performed any degree of outside computing work but some did, however, expand or create internal computing facilities. For example, in 1945 the NAO was relieved of its Admiralty Computing Service responsibilities and the additional staff which had been assigned to the Office were transferred to the NPL Mathematics Division. The NAO no longer took on outside work but concentrated on astronomical calculations for its own use. The NAO continued to develop numerical procedures for use with desk machines and the National (for example, Carter and Sadler 1948). However, following the removal of the Royal Greenwich Observatory to Herstmonceaux Castle in Sussex in 1949, punched card machines were installed at the NAO. The installation included an IBM 602A calculating punch, one of the first in Britain, and much work was done to develop the use of this machine and the rest of the installation for the work of the NAO. The NAO thus continued its pre-war role as a well equipped establishment which performed a considerable amount of computation in its work but which did not take on outside work.

Like the NAO several other government establishments installed punched card machines in the late 1940s and early 1950s. For example, the Statistics Department of the Rothampsted Experimental Station at Harpenden installed punched card machines in 1949 at the request of the Ministry of Agriculture and Fisheries. The installation was used primarily for the processing of agricultural surveys but was found to be "relatively ineffective" as complex calculations were required on small portions of data at frequent and intermittent intervals which necessitated numerous machine interruptions (Yates and

Rees 1958). Rothampsted replaced the installation in 1954 with an Elliot 401 computer.

Other establishments had more success with their punched card installations which were sometimes installed as a result of work done using the NPL Hollerith installation. In 1946 the Ministry of Works was one of the first institutions to second staff to the NPL in preparation for its own installation. The two largest punched card installations to result from the work of the NPL Punched Card Section were set up at the Atomic Energy Research Establishment at Harwell and the Atomic Weapons Research Establishment at Aldermaston. At Harwell the Hollerith installation was part of the Harwell computing group which was originally set up in 1947 for the use of the Theoretical Physics Division but by 1950 had expanded to provide computing services for the whole of the establishment. At Aldermaston, however, the punched card installation was an isolated facility used only by the Physics Division. These installations were, again, only used by the departments in which they were installed. Both installations were based on experience gained at the NPL which carried out preliminary research into using punched card machines for Monte Carlo calculations. In both cases the installations were run by staff trained at the NPL. The computational demands at Harwell and Aldermaston were so great that computers were rapidly installed at both institutions to first supplement the punched card installation and later replace them.

6.2 Computing Machine Developments at Cambridge and Manchester

6.2.1 The Cambridge University Mathematical Laboratory

In 1942 Lennard-Jones, Director of the Cambridge University Mathematical Laboratory, was appointed Chief Superintendent of Armament Research, Ministry of Supply and, although his work took him away from Cambridge, he maintained personal contact with the laboratory and the Ministry of Supply staff working there. During a period of intense post war planning in February 1945, Lennard-Jones met the University authorities to discuss the future of the University Mathematical Laboratory (Lennard-Jones 1944-46). Lennard-Jones stated that the three main functions of the University Mathematical

Laboratory were firstly to develop new types of computing machines, secondly to teach practical computing techniques and thirdly to provide a computing service to Cambridge scientists. These functions differed slightly from the original aims of the laboratory which placed a greater emphasis on the provision of a well equipped computing centre to which scientists could come to carry out their own computation (University of Cambridge, General Board 1937a). The war had, however, revealed both a need for improved computing machines and the need for practical computation to be taught at undergraduate level.

In August 1945 Lennard-Jones took up the post of Director-General of Scientific Research (Defence) of the Ministry of Supply and could no longer act as Director of the Mathematical Laboratory. In Lennard-Jones's place the University of Cambridge General Board appointed Wilkes, who had worked in the Mathematical Laboratory before the war, as acting Director of the laboratory with the position of temporary university lecturer in Mathematics. Wilkes returned to Cambridge from war service in September 1945. Although the Ministry of Supply had been due to release the University Mathematical Laboratory in September 1945, no alternative accommodation could be found for the Ministry of Supply group and the laboratory remained occupied until 5th January 1946.

From August 1945 onwards, when his appointment as acting Director was announced, Wilkes began to plan the reorganization and future of the Mathematical Laboratory. Wilkes was in contact with both Comrie and Womersley. Comrie wrote to Wilkes in late August outlining how he saw the role of the Cambridge Mathematical Laboratory (Woodger 1977, item 1). Comrie envisaged a "triangular team" comprising of the NPL Mathematics Division, the SCS and the Cambridge University Mathematical Laboratory. In Comrie's opinion, the role of the Cambridge Mathematical Laboratory would be to teach computation to science students and undertake a considerable amount of numerical research. That of the NPL Mathematics Division would be to build computing machinery and develop methods for their use. The SCS would continue to provide a computing service to government research establishments, industry and the universities. Cambridge was to become the source of "computing minded mathematicians" for

Teddington and to encourage this the SCS would employ some mathematics students during the vacations.

Wilkes, however, did not foresee the Mathematical Laboratory fitting into the role which Comrie had proposed. Rather, Wilkes saw his first tasks as equipping the laboratory to serve as a university computing centre and planning the future teaching responsibilities of the laboratory. To do this, Wilkes sought the help of Comrie, Womersley and Fairthorne each of whom had experience in setting up and running computing laboratories. Wilkes visited both Womersley at Teddington and Fairthorne at Farnborough (Fairthorne 1983c) for advice and support and received practical help from Comrie. In late 1945 Comrie helped Wilkes to acquire desk machines and sold him a second hand National Accounting Machine for the Mathematical Laboratory.

In February 1946, a month after the Ministry of Supply had released the University Mathematical Laboratory, Wilkes prepared a report for the Faculty Board of Mathematics which outlined the work which he had done in re-establishing the University Mathematical Laboratory and briefly described his plans for the future (Wilkes 1946b). By February 1946 Wilkes had appointed a technician to help him run the machines in the laboratory and was in the process of setting up a workshop which would be used to maintain the differential analyser and the other computing machines in the laboratory. He reported that both the full size differential analyser and the model machine were in working order but that the Mallock Machine needed extensive rewiring. Wilkes had also acquired two electric Marchant calculating machines, six Brunsvigas, an electric Victor adding and listing machine for the laboratory, and had the authority to purchase two more electric and five hand calculators once the Board of Trade had issued the necessary licences[4]. Wilkes had also made provision for the National Accounting Machine and had reserved laboratory space for the installation of a set of Hollerith punched card machines. With the help of Comrie Wilkes had established a library of mathematical books and

4. Immediately after the war calculating machines of all kinds were in short supply and permission was needed from the Board of Trade before any machine could be purchased.

tables and had obtained over one hundred titles. The equipment which Wilkes planned to install in the Cambridge University Mathematical Laboratory was very complete and appears to have been modelled on the different sections of the NPL Mathematics Division. The staff of the Cambridge University Mathematical Laboratory was, however, much smaller than that of the NPL Mathematics Division. Apart from Wilkes himself, the only other member of staff was the technician but Wilkes had plans to employ an assistant to run the differential analyser and six computers to operate the calculating and accounting machines.

In his report Wilkes outlined what he saw as the two primary functions of the Cambridge Mathematical Laboratory. The first of these functions was to provide a course on practical computation for all science undergraduates at Cambridge. Although Wilkes had not, in early 1946, planned such a course in any detail nor employed a lecturer to run it, he proposed that the "course should be thoroughly practical and should aim at giving sound advice on how to tackle the ordinary problems likely to be met with, and how to make the best use of modern calculating machines and aids to computation" (Wilkes 1946b, p2).

The second important function of the Mathematical Laboratory was to provide a computing service for Cambridge research staff. Wilkes had already begun to establish a well equipped laboratory which research workers could use to carry out their own work using desk calculators or the Mallock Machine. The staff of trained computers which Wilkes proposed to employ would be on hand to offer advice and assistance to workers using the laboratory. The computers would only take on large, repetitive computing jobs for research workers after the problem had been reduced to routine steps. Wilkes was insistent that any work performed by the laboratory computers would have to be supervised by the research worker involved and not by Wilkes himself or senior Mathematical Laboratory staff. The Mathematical Laboratory did not, therefore, propose to provide a complete computing service in the same sense as the SCS did, but rather offered workers the facilities to carry out their own computational work.

The use of the differential analyser by Cambridge research workers fell into a different category as experienced staff were needed to operate the machine properly and work which required the use of the differential analyser would, therefore, have to be carried out by laboratory staff. Wilkes envisaged that those wishing to use the model differential analyser, particularly research students, would want to operate the machine themselves and he had no objection to this.

In his report Wilkes stressed that the facilities provided by the University Mathematical Laboratory, with the exception of the Mallock Machine, should not be made available to workers outside Cambridge University. Apart from Wilkes's prediction that the laboratory would be heavily used by Cambridge workers alone, the system of individuals supervising and performing their own work could not be adopted if the research worker was not resident in Cambridge. Because the Mallock Machine was the only one of its kind, Wilkes proposed that it be made available, for a fee, to outside workers.

While the provision of a well equipped computing laboratory and the laboratory's teaching role are the two functions emphasized by his report, it is clear that Wilkes also perceived the laboratory undertaking two different types of research. Firstly, research into numerical procedures for use with calculating machines which would arise naturally from the various computations carried out by the laboratory. Secondly, Wilkes suggested that the University Mathematical Laboratory should carry out research into new types of electronic calculating machine and try to "catch up some of the lead which the Americans have in the subject" (Wilkes 1946b, p.6). This second research area was where Wilkes' main interests lay.

As a result of this report, and a statement from Lennard-Jones indicating that he did not wish to continue as Director of the Mathematical Laboratory when he returned to Cambridge, Wilkes was appointed Director of the laboratory for a period of five years from October 1946. At the same time a Mathematical Laboratory Committee consisting of members from all interested faculties was set up to which Wilkes was responsible

(University of Cambridge, General Board 1946). During 1946 Wilkes's ideas on the type of computing machinery research which the Mathematical Laboratory was to carry out began to crystalize.

In early 1946 Hartree, who had returned from a trip to the United States, told Wilkes of the work being done on the ENIAC at the Moore School of Electrical Engineering in Pennsylvania (see p.242). Comrie too visited the United States and on his return lent Wilkes a copy of von Neumann's "First Draft of a Report of the EDVAC"[5]. In the summer of 1946 Hartree arranged for Wilkes to attend the now famous Moore School lectures where Eckert, Mauchly, Goldstine, von Neumann, Burks and others lectured on their work with electronic computing machines including the proposed EDVAC machine (Chambers 1947).

Wilkes returned from the United States bursting with ideas to build an EDVAC type machine. Hartree, who sat on the NPL Executive Committee and who had special responsibility for the work of the Mathematics Division, encouraged Wilkes to approach Womersley with a view to collaborating on the construction of such a machine. At this time, autumn 1946, Turing was working on the design of the ACE machine at Teddington. As the Mathematics Division did not intend, at that time, to build the machine at Teddington, Hartree saw the possibility of collaboration between the NPL and the University Mathematical Laboratory. Wilkes prepared a proposal for the construction of a prototype machine based on the EDVAC (Woodger 1977, item 9). Turing disagreed with the suggestions Wilkes put forward and told Womersley that they were "very contrary to the line of development here [at Teddington], and much more in the American tradition" (Woodger 1977, item 11). Despite Turing's disapproval of Wilkes's proposed machine, Womersley continued to consider the possibility of asking Cambridge to build a machine on behalf of the NPL. After months of delay during which F.C. Williams, from

5. Although only intended for limited circulation this document was the first written account of the stored program computer concept. The document was widely distributed and greatly affected future computing projects.

the Telecommunications Research Establishment and later Manchester University, turned down a contract with the NPL, the NPL decided to construct a machine themselves (see p.149). In April 1947 Womersley wrote to Wilkes stating quite clearly that no such contract was to be made (Woodger 1977, item 15). In the meantime, however, Wilkes had began the construction of his own machine, the EDSAC.

In July 1947 the Mathematical Laboratory Committee prepared a progress report which it presented to the Faculty Board of Mathematics (University of Cambridge, Mathematical Laboratory Committee 1947). The report stated that, besides Wilkes, the staff of the Mathematical Laboratory now consisted of a research assistant working on the differential analyser with two "boys" to assist him, a technician, a mathematician, one secretary and three computers. Wilkes found it impossible to find suitable computing staff and never took on the six computers proposed earlier. The report noted that the laboratory was equipped with 12 desk calculators, a National Accounting Machine, a Victor adding and listing machine, the model and full sized differential analysers, and the Mallock Machine, which had been extensively rewired. A set of Hollerith punched card machines on loan from BTM were also about to be installed in the laboratory. These machines had previously been used by S. Chapman at Imperial College for tidal motion calculations. When Chapman moved to Oxford in 1946 he suggested that Wilkes, who had an interest in the work, take over the calculation and the machines. Wilkes had always intended to install punched card machines in the laboratory (Wilkes 1946b) and gratefully accepted the offer. Although the Hollerith machines were used to continue Chapman's work their principle use at Cambridge was for x-ray crystallography work by a team from the Cavendish Laboratory led by W. Cochran (Wheeler 1983a, Hodgson, Clews and Cochran 1949).

The 1947 progress report listed the five major functions of the Cambridge University Mathematical Laboratory. These were

(i) Research in computational methods and on all kinds of calculating machines.

(ii) The carrying out of computational work by the Laboratory staff for research workers in all faculties.

(iii) The provision, in co-operation with the Faculty Board, of teaching on computation and on the construction and use of calculating machines.

(iv) The provision of advice on all questions concerning computation.

(v) The provision of computing rooms and machines for the use of individual research workers.

(University of Cambridge, Mathematical Laboratory Committee 1947, p.4).

It is interesting to note how the emphasis placed on the different aspects of the laboratory's work in the 1947 report differed from those outlined in Wilkes's report a year previously (Wilkes 1946b). In the earlier report Wilkes had clearly stated that the two most important functions of the Mathematical Laboratory were to provide computing facilities for university staff and to run courses for undergraduates. By 1947, however, the main emphasis had shifted towards computing machinery research. Although the Cambridge Mathematical Laboratory provided both computing facilities for Cambridge scientists and courses on computational mathematics[6], the main work of the laboratory was the design and construction of an electronic computer called the EDSAC. With the help of finance from the Department of Scientific and Industrial Research, the University Grants Committee and J. Lyons & Company (which also seconded staff to Cambridge) the EDSAC was rapidly built. It ran its first automatic calculation in May 1949 and went into regular use early in 1950.

Although the University Mathematical Laboratory was always first and foremost for the use of Cambridge research workers, the laboratory soon became an important national computing centre. In 1947 a series of Thursday afternoon seminars began, which ran for

6. The most important of these courses was the annual lectures on Numerical Analysis given by Hartree who moved to Cambridge in October 1946 to take up the Plummer Chair of Mathematical Physics. The lecture courses, which began in 1947, resulted in Hartree's book of the same name which was published in 1952.

several years, and attracted people from all over Britain who were interested in the electronic computers. In June 1949 Cambridge hosted a computer conference (University of Cambridge 1949) which was attended by nearly all those working in the field. The Mathematical Laboratory was also an important training ground not only for Cambridge students, but for other institutions which seconded staff to Cambridge, for example the Atomic Weapons Research Establishment at Aldermaston sent A.E. Glennie and K.N. Dodd to Cambridge, and P.Taylor was sent from the Telecommunications Research Establishment.

After the EDSAC went into regular service in 1950, the Mathematical Laboratory began to take in work from outside Cambridge. To deal with the large number of Mathematical Laboratory users a priorities committee was set up to allocate time on the EDSAC and to advise users. Because programmers were relatively few most users had to do their own programming and in this way also the Mathematical Laboratory became a training ground for many early computer users (Campbell-Kelly 1980). During the 1950s the Cambridge Mathematical Laboratory became an important national computer centre chiefly because of its research into computing machinery and programming systems, and the computing service it subsequently offered.

6.4 The Royal Society Computing Machine Laboratory at Manchester University

Although a significant computer centre had been built up around Hartree's differential analyser at Manchester University before and during the war, the post war research on electronic computers at Manchester was virtually unconnected with the previous differential analyser work.

In October 1945 M.H.A Newman took up the Chair of Pure Mathematics at Manchester University. Newman came from the Government Code and Cypher School at Bletchley Park where he had been involved in the war-time development of the Colossi and Heath Robinson machines which were built in conjunction with staff from the Post

Office Research Station at Dollis Hill[7]. Through this work and his acquaintance with Turing, who had also been at Bletchley, Newman was aware of some of the work being done on electronic computers. One of Newman's reasons for accepting the post at Manchester was that he hoped to be able to set up a computing laboratory at the University in order to study advanced pure mathematical problems using computers (Newman 1946). P.M.S. Blackett, professor of Physics at Manchester University, had held several important scientific and administrative posts during the war and was conversant with the work at Bletchley, and elsewhere, concerning computers. Blackett too was keen to see a computer laboratory set up at Manchester and encouraged Newman to apply for a Royal Society grant to fund such a project (Randell 1980).

In February 1946 Newman applied to the Royal Society for a grant to set up a computer laboratory at Manchester. Newman proposed that, rather than working on the design and construction of electronic computers, his group in the Mathematics Department would concentrate on the "mathematical and logical problems of finding the best use of such machines and investigate their effect on the development of mathematics" (Newman 1946). When sufficient engineering progress had been made towards the construction of a working machine, either in Britain or the United States, Newman intended to use the grant to purchase the necessary components to construct a machine.

The Royal Society set up a committee to consider Newman's application for a grant to establish a computer laboratory at Manchester University. The committee membership comprised of Blackett, who supported the project, Hartree, Darwin, W.V.D. Hodge and J.H.C. Whitehead. Darwin, as Director of the NPL and an instigator of its Mathematics Division, was strongly opposed to awarding such a grant. He felt that the creation of a computer laboratory at Manchester would undermine the NPL's ACE project. When

7. Although much work was done on electronic computers at Bletchley during the war, much of which has only recently come to light, it was in no sense a scientific computing centre. The work carried out was not scientific; it was mainly concerned with code breaking and was a large scale data processing application. In addition, the work carried out at Bletchley was highly classified and its facilities were not used by outsiders. Because Bletchley was not a computing centre in the sense used in this dissertation, a description of the work carried out there has not been included.

completed the ACE was expected to serve the needs of the whole country. Darwin was also concerned that Newman would enlist the help of T.H. Flowers to assist him (Hodges 1983). Flowers, an old colleague of Newman's from Bletchley, was then working at the Post Office Research Station at Dollis Hill which had been commissioned by the NPL to develop delay lines for the ACE (see p.148). Despite Darwin's objections the committee, in June 1946, granted Newman £35,000 for the establishment of a Computing Machine Laboratory at Manchester (Royal Society 1946, 13th June). The Royal Society awarded the grant on the understanding that the machine Newman proposed to build at Manchester would be different in several respects from the NPL ACE. In addition it stated that Newman's machine would not duplicate activity at the NPL because it was to be used for pure mathematics and not numerical computation as was intended at Teddington. The Royal Society therefore agreed to support Newman's project as on the grounds that the machine was to be used for pure, rather than applied scientific research. £20,000 of the money was to be spent on the construction of a suitable machine and the remainder was allocated to staff salaries over five year period.

Although Newman received the Royal Society grant in summer 1946 and used it to send D. Rees, whom Newman had brought with him from Bletchley, to America to attend the Moore School lectures in July and August 1946, there was little Newman could do until someone, either in Britain or the United States, constructed a working machine or a working memory unit. Newman was a mathematician and had no intention of trying to design and build a machine himself.

The development of computer hardware at Manchester University sprang from the appointment of F.C. Williams as Professor of Electrical Engineering in December 1946. Before the war Williams had been an assistant lecturer at Manchester and had worked with Blackett in designing the automatic curve follower for Hartree's differential analyser (Blackett and Williams 1939, Williams 1939). During the war, Williams had been heavily involved in the development of radar at Bawdsey and at the Telecommunication Research Establishment, Malvern (TRE). During two trips to the Radiation Laboratory at MIT, the first in November 1945 and the second in June 1946, Williams learnt about the work being done in trying to use cathode ray tubes (CRTs) as storage devices. This application of CRTs greatly interested Williams and he began to carry out experiments.

The work at Dollis Hill on delay line stores for the NPL proceeded slowly. In May 1946 Darwin and Womersley approached Williams and the staff at TRE asking if they would undertake development of a delay line store for the ACE project. This did not, however, coincide with Williams's interest in CRTs and Williams spent more time developing CRTs than looking at delay lines. Because of Williams' move to Manchester and the transfer of other staff to the Department of Atomic Energy, TRE no longer felt that it had the expertise to undertake the work which the NPL required. Darwin and Womersley were still hopeful that Williams would carry out the necessary work. Consequently they approached Williams directly and offered him a contract under which Williams would construct an electronic storage device and other components for the NPL to his own design. Hodges (1983) points out the absurdity of asking Williams to develop a CRT store for the NPL when Turing's design for the ACE was based around the use of delay lines. Hodges remarks that "Very probably Darwin and Womersley did not appreciate that the storage medium dictated many aspects of the design of the machine and its programming" (Hodges 1983, p.350). Williams turned down the contract with NPL preferring instead to work independently.

When Williams moved to Manchester in December 1946 he arranged for his assistant, T. Kilburn, to be seconded to Manchester from TRE to finish his Ph.D. TRE continued to support Williams's research after he moved to Manchester which, along with Kilburn's seconded position, meant that TRE was able to supply components to Manchester (Lavington 1975). Williams' work on computing devices at Manchester was not, therefore, funded by Newman's Royal Society grant. Indeed Newman's only contributions to William's work over the following two years, apart from moral support, was the supply of war surplus equipment from Bletchley and a brief explanation to Williams of the principle of store numbers and instructions. Williams recalled:

> I never was, never have been, and never will be a mathematician. I did not even know that there was any system of numbers other than the scale of ten, but when the specification of a storage system was explained to me I could grasp what was wanted (Williams 1975, p.327).

Development of the CRT store proceeded quickly and by autumn 1947 the Williams tube was able to store 2048 bits. Following this a "baby" machine, which first ran successfully on 21st June 1948, was built to test the store. Although very small, the memory had only 32 words of 32 bits each, the machine was an important one. Not only did the machine prove that a computer could be built around a CRT memory, but it also won the necessary finance for Williams to continue his development work independently of Newman's Royal Society grant.

Blackett saw the baby machine in operation soon after it was built and contacted Sir Ben Lockspeiser, Chief Scientist of the Ministry of Supply. Lockspeiser went to Manchester to see the machine and was sufficiently impressed to arrange a meeting between Williams and Ferranti Ltd., the electronics manufacturers, in October 1948[8]. Lockspeiser then obtained a £100,000 grant from the Ministry of Supply to fund the manufacture of a computer by Ferranti to Williams's designs (Williams 1975).

Because of the money put forward by the Ministry of Supply, Williams again had little need of Newman's Royal Society grant. The Royal Society Computing Machine Laboratory at Manchester University consisted only of a single room which housed the evolving prototype machine. Throughout 1948 and 1949 Williams, and his growing team in the Electrical Engineering Department which by now included D.G.B. Edwards, G.C. Tootill, A.A. Robertson and G.E. Thomas, continued to develop the prototype machine. In late 1949 the design was sufficiently finalized to be handed over to Ferranti.

As the installation of a computer at Manchester began to become a more concrete possibility, Newman started to develop the Royal Society Computing Machine Laboratory

8. Williams had collaborated with Ferranti during the war over the development of a radar device for identifying friendly aircraft.

and to establish the programmer and user support which would be needed once a machine had been installed. In March 1948 Newman asked the University to create a readership for Turing, who was then on sabbatical at Kings College, Cambridge from the NPL Mathematics Division. Turing's salary was to paid from the Royal Society grant. Turing, disillusioned with the ACE project at the NPL, accepted the post. Although he did not take up the appointment until September 1948, Turing wrote to Williams during the summer months asking for machine details so that he could begin to write programs for the machine.

Although Turing held the nominal title of Deputy Director of the Royal Society Computing Machine Laboratory under Newman, neither Newman or Turing had any influence on Williams's team's designs. Newman worked on developing mathematical problems for the machine until his interest dwindled towards the end of 1949. With Tootill and Edwards, Turing developed a programming system for the prototype Mark I machine using teleprinter codes. He also prepared a programmers manual and began to write basic programs for the machine.

In preparation for the arrival of the engineered version of the Mark I from Ferranti, the staff of the Royal Society Computing Machine Laboratory increased in October 1949 with the appointment of C. Popplewell as Turing's assistant and was paid out of the Royal Society grant. A. Bates, a post-graduate student working under Turing, also arrived around this time. Both women at first shared an office with Turing and both contributed to the programming work. The construction of a new building designed to house the Ferranti machine was also paid for out of the Royal Society grant. The building was completed in January 1951 and the staff, which expanded in mid-1951 to include R.K. Livesley and N.E. Hoskin, quickly moved in. The Ferranti Mark I was installed in February 1951. To coincide with the inauguration of the Ferranti Mark I Manchester hosted, in July 1951, the second British Computer Conference. Like the 1949 conference at Cambridge nearly all those working in the field in Britain attended. At about this time Turing's interests turned from computers to morphogenesis but, although Turing was no longer directly involved in the work of the Royal Society Computing Machine Laboratory, he continued to be an important machine user.

The Ferranti Mark I provided more computer power than the small Royal Society Computing Machine Laboratory required in 1951 and, consequently, outside users came to use the machine (Lavington 1975). The computer service run by the university was supported by Royal Society Computing Machine Laboratory staff who both wrote system software and assisted, advised and trained outside users who were charged £20 per hour to use the machine. Some of the income generated by offering a computer service to outside users was used to fund further machine development at Manchester. The remainder helped to keep the service in operation and was supplemented by the university and by the DSIR which had taken over the Ministry of Supply's responsibilities concerning the machine. P Machine development was the most important aspect of the work at Manchester where the provision of a computing service was not the main interest of the individuals involved. This contrasts sharply with the NPL Mathematics Division where the original aim was to provide a national computing service. At the Cambridge Mathematical Laboratory the initial aim had been only to provide local computing facilities but when the EDSAC went into regular operation its services offered to outside users. The service was, however, controlled by the Priorities Committee which ensured that the needs of Cambridge staff were not neglected.

A.E. Glennie, an early user at both Manchester and Cambridge, recalls a different atmosphere between the two centres (Glennie 1978). He found that while there was considerable freedom at Manchester to experiment with different programming methods, there was very little in the way of user support. At Cambridge there was plenty of user support but access to the machine was restricted and the programming methods used well established. The NPL Mathematics Division and the Cambridge Mathematical Laboratory saw themselves as computing service centres but Manchester did not adopt this attitude quickly. From the outset Williams's interest had been an academic one of trying to devise a working machine. Newman too had not intended to run a service but to use the machine for mathematical research. Thus the work done at Manchester during the late 1940s was not aimed at providing a computing service. The early programming system, for example, was based on teleprinter codes and was not user friendly.

Although Williams's interest turned from computers to other aspects of electrical engineering, computer development continued at Manchester under Kilburn. Over the twenty years following the installation of the Ferranti Mark I the collaboration between Manchester University and Ferranti produced four other commercially available computers. The Mercury, the Met-Vickers MV 950, the Atlas and the ICL 2980. Thus Manchester University continued to be a centre for the development of computer hardware. Manchester was also responsible for several significant software developments, particularly the Autocode which R.A. Brooker developed for the Mercury machine. These innovations and the range of users which came to Manchester to work on the machine (including A.E. Glennie, K.N. Dodd and C. Strachey) combined to make Manchester a very important computer centre.

6.3 Summary

It is clear that in the late 1940s and early 1950s several computer centres existed. The most important was the NPL Mathematics Division. It embodied all the characteristics of a computing centre given in chapter 1. It had a wide range of machines and an experienced staff which was used to provide a national computing service. The NPL Mathematics Division also carried out machine and numerical research. The present chapter has shown that the remainder of the post war computing centres divided into two categories: those which ran a computing service using traditional computing tools and those which developed electronic computers. The Cambridge Mathematical Laboratory and the Royal Society Computing Machine Laboratory at Manchester University fall into the second category. Although Manchester University became a very important computer centre over the following thirty five years, during the late 1940s its only computing activity was the development of electronic computers. It was not until 1951, when the

Ferranti Mark I was delivered to the University, that the Royal Society Computing Machine Laboratory began to provide any kind of computing service. Neither Williams nor Newman was concerned about setting up such a service. Neither did they liaise closely with each other to get the project going. On the other hand, the Cambridge Mathematical Laboratory had a history of providing computing facilities for university staff. It also ran courses in numerical computation and provided computing machines for its users as well as carrying out research into the construction of electronic computers. When the EDSAC went into regular service in 1950 this facility was offered to first to university staff but also to outside workers.

Institutions such as the SCS and the RAE Mathematical Services Department of the RAE ran computing service bureaux. They carried out some machine research and practical numerical methods evolved as a result of their work[9]. Other computing centres were primarily for use at the local level such as the Liverpool Mathematical Laboratory, the NAO punched card installation and punched card installations in government research establishments. These local computing centres did not undertake any significant amount of computer research but were indicative of the type of computing centres which emerged during the late 1950s, 1960s and 1970s. As computers became commercially available research institutions began to install computers for use at the local level. For example, the RAE installed an English Electric DEUCE in 1955; Aldermaston purchased a Ferranti Mark I* in 1954 and Harwell a Mercury in 1958 to replace the Dekatron machine which had been built by the Electronics Division of the AERE seven years earlier. As more and more people installed computers local computer centres began to develop as a direct result of the work done by the NPL Mathematics Division, the Cambridge Mathematical Laboratory, Manchester University and others.

9. A relay calculator, the RASCAL, was designed at the RAE but it was never built. At Harwell too there was some machine development with the construction of the Dekatron machine. Neither of these machines were computers but rather further developments of the old technology.

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Chapter 7

Computing Centres Outside Britain 1925-1955

7.0 Introduction

The previous chapters have presented a detailed account of the computing centres which developed in Britain during 1925-1955 but have largely ignored events happening abroad during this period. This chapter will review computing developments in the United States and in Europe and will compare the emergence of computing centres in Britain with those abroad.

Much of the detail contained in this chapter is taken from secondary sources and from published reminiscences of the people involved. Because of the recent interest in the United States in the history of computing, the literature largely concentrates on computing activities in the United States during and after the Second World War. Those projects which led to the development of electronic stored program computers are particularly well represented. Conversely there are few references to pre-war and war-time activities in Europe. Consequently section 7.2, which discusses European activities, is incomplete. Literature searches and enquiries have not elucidated any further information and the organization of scientific computation in Europe remains a topic for further investigation.

The emergence of computing centres in the United States is discussed in section 7.1. The section is broken down into five sub-sections. The first, 7.1.1, describes the computing centres, at Iowa State College, Columbia University and MIT during the late 1920s and early 1930s[1]. These three computing centres displayed very different characteristics. At Iowa State University a punched card installation was created specifically as an inter-departmental computing facility. The punched card installation at Columbia was established as a computing bureau specializing in astronomical calculations open to astrono-

1. There is no evidence to suggest that Strathmore College and North Western University developed significant computing resources following Comrie's introduction of computation courses at these institutions (see p.33).

mers all over the United States. In complete contrast to the punched card computing centres at Iowa and Columbia, MIT did not provide a widely available computing service but concentrated on the design and construction of large calculating machines.

Section 7.1.2 considers the period covering the late 1930s and the very early 1940s just before the United States entered the war. This section looks at the two different types of computing centre which emerged during this period. First the work of Atanasoff, Stibitz and Aiken on the design and construction of automatic calculating machines is discussed and the extent to which computing centres became established around their machines during the pre-war period is examined. Secondly, the New York Mathematical Tables Project is described. The New York Mathematical Tables Project was not a computing service bureau but a government agency set up in 1938 to prepare and publish fundamental mathematical tables under a predetermined programme.

Section 7.1.3 describes the organization of scientific computation in the United States during World War II. One of the most significant institutions to be created during the second world war was the Applied Mathematics Panel set up in 1942 to coordinate war related computation. The Applied Mathematics Panel did not maintain computing facilities of its own but subcontracted work out to computing centres all over the United States. The Applied Mathematics Panel was an important stage in the centralization of scientific computation in the United States because it represented a realization that computation needed to be encouraged and centrally coordinated. Section 7.1.3 also describes the activities of the Astronomical Computing Bureau at Columbia during the war. The other major computing centres to develop during the war are also discussed. These include the facilities developed at Los Alamos, Harvard University, the Moore School of Electrical Engineering, and Bell Laboratories.

In 1945, at the end of the war, details of the ENIAC machine built at the Moore School began to become available and this prompted the start of many computing machine projects in the United States. Some of these projects are mentioned briefly in section 7.1.4 but the section concentrates on the creation of computing centres during the post-war period rather than on the machine developments which took place. Of particular interest in 7.1.4 is the creation of the National Applied Mathematics Laboratories and their similarity to the NPL Mathematics Division in England. The post war developments at Columbia and Harvard are also discussed and their continued importance as computing centres examined. Section 7.1.5 concludes the description of centralized computation in the United States by considering what influence, if any, events in America had on computation in Britain.

Section 7.2 gives an overview of the most important computing developments in continental Europe, particularly France and Germany, during 1925-1955. In Germany the most important computing machine developments of the 1930s and 1940s were carried out by Zuse and, although a computing centre did not develop around Zuse, his work will be described. The Institute für Praktische Mathematic at Darmstadt was one of Germany's best known centres for applied mathematics and the work carried out at Darmstadt, particularly on the application of punched card machines to scientific computations, is described. The early work of d'Ocagne and Couffignal in France is discussed but their work did not really contribute to the centralization of computing power. .Much of the detail given in this section about other European countries concerns post war computation and the development of electronic computers and the centres which were set up around them.

Section 7.3 describes the International Computation Centre set up in Rome in 1957. This should have been the natural conclusion to the concept of centralized computation and resulted in international cooperation. However the international centre did not play an important role; partly because by the time it was set up computers had become commercially available and the centre was no longer needed by the majority of the computing community.

The final section, section 7.4, completes the dissertation by discussing how the level of centralized computation in Britain fell after the mid-1950s when computers became more readily available and introduces the idea that scientific computation once again became a decentralized activity.

7.1 The Centralization of Computation in the United States

7.1.1 The Late 1920s and Early 1930s: Iowa State College, MIT and Columbia University

As in Britain most scientific computation performed in the United States during the 1910s and 1920s was carried out by the individual scientist using logarithmic tables, slide rules, or desk calculators. Desk calculators became increasingly popular throughout the 1920s. Indeed W.J. Eckert recalls that by 1926 desk machines were just beginning to replace logarithmic tables as the standard method of performing astronomical calculations (Eames and Eames 1973, p.114).

One of the few institutions to introduce more sophisticated methods of scientific computation in the mid-1920s was Iowa State College. In the early 1920s H.A. Wallace[2] was working on a project to determine the factors which produced high corn yields. His work involve much statistical analysis of experimental data and Wallace devised methods of performing this work on desk calculators and punched card machines (Eames and Eames 1973). In 1924 Wallace gave a series of lectures at Iowa State College at which he demonstrated his computing methods to statisticians and scientists from different departments of Iowa State College. By 1927 several departments, including statistics and mathematics, had jointly installed a set of IBM punched card machines at the College and had established a Mathematical Statistical Service. The installation was used primarily by staff of Iowa State College for biometric work and other complex statistical analyses (Snedecor 1928). What is most significant, however, is that the Mathematical Statistical Bureau at Iowa State College was set up to provide a specialized computing facility for a specified range of users and thus constituted a localized computing centre.

2. Wallace was a well known agricultural scientist and, later, vice-president of the United States (1940-1944).

By the mid-1930s several universities had acquired punched card machine installations. Most of the installations were used for administration and accounting purposes but Baehne (1935) lists seventeen examples of colleges and universities which used punched card machines in a variety of research areas including psychology, education, medicine, social science, economics, agriculture, law, anthropology, and literary research. Most of the installations within universities, however, did not provide computing services and were primarily used for administration and the analyse of data. The principal exception was Columbia University which set up a statistical computing bureau in 1929.

In 1928 B.D. Wood, head of the Bureau of Collegiate Research at Columbia University, approached IBM about the possibility of using punched card machines to analyse examination papers. Wood was granted an interview with Thomas J. Watson, president of IBM, who was impressed with Wood's ideas, and with the possibility of using IBM machines for educational purposes. Watson sent the machines Wood had requested to Columbia in June 1929 and the Columbia University Statistical Bureau was formed.

Although the bureau was used primarily for the analysis of examination papers within the university, it was also open to other Columbia University users for the tabulation of inventories, the preparation of mortality tables and other purposes. The link between the Columbia University Statistical Bureau and IBM remained a close one and in 1931 IBM donated a specially modified tabulator to the bureau. Instead of the standard tabulator which had five 8-figure counters the special tabulator contained ten-10 figure counters and was fitted with a then novel mechanism which permitted the contents of one counter to be automatically transferred into another. The transfer facility and the increased capacity of the machine allowed the bureau to increase the amount and complexity of work it could perform and the bureau began to accommodate users from universities all over the United States.

One of the departments at Columbia to use the Statistical Bureau for scientific rather than statistical purposes was the Department of Astronomy. W.J. Eckert, an astronomy professor at Columbia, knew of Comrie's application of punched card machines to the preparation of tables of the motion of the moon and wanted to apply IBM machines to his work at the Rutherford Observatory. Eckert was also aware that IBM had recently released a new range of punched card machines which included a multiplying punch to directly evaluate products. Eckert felt that

> the time was now ripe for the establishment of a scientific laboratory of a revolutionary nature. Whereas it had been possible in the past to accomplish important results by ingenious manipulation of the sorting and adding operations, there now were available all the necessary units for a laboratory which would automatically perform the most laborious calculations (Brennan 1971, p.7; quoting from W.J. Eckert, The Thomas J. Watson Astronomical Computing Bureau, unpublished memorandum 1945).

In 1933 Eckert presented a list of the machines he required, and details of certain modifications necessary to increase their flexibility, to Watson of IBM. Watson was pleased to discover scientific applications for IBM machines and had a set of machines delivered to the Columbia Astronomy Department in early 1934. At first Eckert's computing laboratory was used only by the staff and students of the Astronomy Department for a variety of calculations including the solution of differential equations of planetary motion, problems in lunar theory, and the preparation of star catalogues. Soon, however, Columbia began to take on work from other observatories beginning with the conversion of spherical star coordinates to rectangular coordinates for Yale.

The use of the punched card machines at Columbia by outside observatories prompted IBM to suggest that the facilities at Columbia be made officially available to other observatories on a non-profit making basis. As a result of this suggestion the Thomas J. Watson Astronomical Computing Bureau was set up at Columbia in 1937 as a joint venture between the American Astronomical Society, IBM, and the Astronomy Department at Columbia University. Eckert was appointed director of the bureau and was assisted by a board of managers which consisted of E.W. Brown, emeritus professor of Yale University Mathematics Department and author of the famous *Tables of the*

Moon (1919), H.N. Russell, director of Princeton Observatory, T.H. Brown of Harvard University Business School, C.H. Tomkinson of the IBM Commercial Research Department (who had made the suggestion to establish the Astronomical Computing Bureau), and Eckert himself. The board of managers represented all parties involved in the creation of the bureau: IBM, Columbia, and potential users. An advisory council to guide the board of managers was also created. Representatives from the principal observatories in the United States sat on the advisory council and brought the views of the major users of the bureau to the attention of the board of managers.

The Thomas J. Watson Astronomical Computing Bureau was created specifically to act as a computing centre for astronomers in the United States. All requests for computations were vetted by the board of managers which also fixed the appropriate charges. The bureau took over the existing facilities in the Astronomy Department at Columbia. The bureau was not, however, a service centre to which astronomers brought problems to be carried out by the resident staff. In most cases scientists came to Columbia and ran their own problems on the machines. Many users had had no previous experience in using punched card machines and came to rely on the "Orange Book" which Eckert wrote as a text book for scientific punched card machine users (Eckert 1940).

Astronomers came from all over the United States to use the facilities offered at Columbia. Brennan (1971) remarks that in the late 1930s the Bureau "had become a crossroads for visiting scientists" (p.9). Brennan also notes that having had the opportunity to use the machines at Columbia, astronomers did not appreciate having to return to using desk calculating machines at their own observatories and that consequently several observatories began to install punched card machines of their own.

The Thomas J. Watson Astronomical Computing Bureau was the first bureau of its kind in the United States. It was influential in making scientists aware of the possibility of using punched card machines for their work (see p.240). The research carried out by the bureau was mainly concerned with developing numerical methods for solving astronomical problems using punched card machines. Although the development of new machines was not within the Bureau's terms of reference, Eckert did have some modifications made to the machines. For example, he used a plugboard and several relays from the ten counter tabulator in the Columbian Statistical Bureau (which was no longer in use) to build the Calculation Control Switch. This device was used to control the sequential operation of the multiplier, tabulator and summary punch which could be connected together using pluggable cables. This arrangement allowed complex sequences of operation to be repeatedly carried out and was a significant step towards automatic computation. In all respects, therefore, the Thomas J. Watson Astronomical Computing Bureau was a comprehensive, if specialized, computing centre.

The other principal computing centre to emerge in the 1920s was based at MIT. It concentrated on the development of calculating machines and was not concerned with providing computing services. It was, therefore, very different to the computing centres at Iowa and Columbia. In the mid-1920s a group of students working with V. Bush of the Electrical Engineering Department at MIT devised several different types of analogue calculating machines. One of the first of these students was H. Hazen who, with Bush's support, worked with the General Electric Company, Schenectady, to build a network analyser to study the behaviour of electrical power systems. Another of Bush's students, H. Stewart, was awarded a masters degree for his work on the design of a product integraph. The product integraph used a wattmeter to integrate the product of two functions represented by varying voltage levels.

Although the product integraph could be used to solve a limited set of first order differential equations, the majority of problems which occur in electrical engineering are more complex. Bush and Hazen developed the product integraph idea by first introducing a feedback mechanism and then using an additional integrator to produce a machine which could be used to solve second order differential equations (Bush and Hazen 1927). Using this machine as a basis, Bush and his colleagues developed the differential analyser. It was the most well known device to emerge from MIT before the war. The differential analyser (which is fully described in Bush 1931) had six interconnected integrating units and could be used to solve differential equations up to the sixth order. It was, therefore, applicable to a large range of engineering problems.

The Bush differential analyser, inaugurated in 1930, was important for two reasons. Firstly it was a useful device and a wide range of problems were solved using it. Secondly, because it was such a useful machine, copies of the Bush differential analyser were made elsewhere including the Ballistics Research Laboratory of the Aberdeen Proving Ground, at the Moore School of Electrical Engineering of the University of Pennsylvania (see p.241) and at Manchester University, England (see p.74). Bush cooperated with all of these projects and gave both engineering drawings and advice to those involved.

In addition to working on the differential analyser Bush and his colleagues also built several other analogue computing machines. For example, Hazen continued his work on the development of network analysers (Hazen, Schurig and Gardner 1930) and T.S. Gray (1931) built a photoelectric integraph to integrate the product of two functions. Later Hazen and G.S. Brown redesigned Gray's machine to produce the Cinema Integraph in 1940 (Hazen and Brown 1940).

In 1931 Bush outlined the research programme he was undertaking and the motivation behind his work. Bush claimed that the use of mechanical devices to solve mathematical problems would become increasingly important in the future as

> Mathematical physicists are continually being hampered by the complexity rather than the profundity of the equations they employ; and here also even a numerical solution or two would often be a relief.
>
> Not any one machine, nor even any one program of development can meet those needs. (Bush 1931, p.448)

Bush divided his research programme at MIT into three different areas. The first research area was the development of machines to solve the linear simultaneous equations which occurred in the analysis of electrical power networks. The second was the use of optical methods to design machines to solve integral equations and resulted in first the photoelectric integraph and later the cinema integraph. The third line of research was the development of machines to solve ordinary differential equations and led to the construction of the differential analyser. These three lines of machine development continued at MIT throughout the 1930s; improvements were made to the differential analyser, the cinema integraph was developed, and the MIT network analyser completed.

In addition to the mainstream of machine research at MIT supervised by Bush, J.B. Wilber devised a mechanical simultaneous linear equation solver in 1934. The Wilber machine, which was used to solve a set of nine equations in nine unknowns, was not part of Bush's research programme. Wilber was an associate professor in the Civil Engineering Department of MIT but acknowledged that the machine owed much to Bush's advice and previous work. In his description of the machine Wilber (1936) refers to the Mallock Machine built in England several years previously (see p.71). Although both machines were built to solve sets of simultaneous equations they were very differently constructed.

In his paper "Instrumental Analysis" Bush (1931) suggested that the analogue calculating machines built at MIT were only a small part of the instrumentation needed to aid scientific and mathematical thought. In the paper Bush described the use of desk calculators and punched card machines for scientific calculations. Bush also suggested that punched card machines could be mechanically coupled together using a central controlling mechanism which would automate the process and hence make the machines more applicable to complex calculations (Bush 1936, p.654). The idea was similar to the Calculation Control Switch built by Eckert at Columbia (see p.231). Bush described the range of analogue machines available to scientists at the time but was adamant that without sufficient demand for this type of equipment from the commercial sector, not just the scientific community, analogue mathematical devices would never reach their full potential because the money to fund their refinement would not be made available.

During the late 1920s and the 1930s Bush supervised and took part in the development of a very wide range of calculating machines. Although Bush encouraged others to build machines based on his work, MIT did not operate a computing service using the machines built in the Electrical Engineering Department. The principle role of MIT was in the development of calculating machines. From his published work it is clear that Bush was concerned about the widespread availability of powerful computing machines. Although Bush's work contrasts sharply with that of Eckert at Columbia, MIT stands out as an important computing centre of the late 1920s and the 1930s.

7.1.2 The Late 1930s and Early 1940s: Iowa, Harvard, Bell Laboratories and the Mathematical Tables Project

While MIT dominated calculating machine development during the late 1920s and early 1930s, towards the end of the 1930s several other projects had begun. Most of the later computing machine projects concentrated on the design of digital rather than analogue devices. For example a digital calculating machine was built at Iowa State College by J.V. Atanasoff.

In the mid-1930s Atanasoff, assistant professor of mathematics and physics at Iowa State College, became interested in using the Iowa State College punched card installation for mathematical work. Atanasoff experimented with the machines and "began to look for a problem in theoretical physics that could be solved by IBM equipment" (Atanasoff 1984, p.232). He found, however, that the machines were not flexible enough for the type of work he wanted to perform. In 1935 Atanasoff and A.E. Brandt, assistant professor of mathematics and statistics at Iowa, built a cross-connecting board attachment for the IBM tabulator at Iowa and devised a scheme for using punched card machines for the analysis of complex spectra (Atanasoff and Brandt 1936). The cross-connecting board consisted of 8 multicontact relays connected to nine wires carrying impulses from the cards being fed through the tabulator. The device was mounted on the tabulator and allowed the same number to be entered into five different counters simultaneously thus compensating for the lack of inter-counter transfer facilities in the IBM machines at Iowa.

Despite the availability of punched card machines at Iowa, Atanasoff felt he needed a still more powerful computing tool. His poor relationship with IBM, and the conditions of the licensing agreement which Iowa State College had with IBM, prevented Atanasoff from making any modifications to the machines themselves[3]. The type of calculation which most concerned Atanasoff at that time was the solution of partial differential equations using an approximation technique which reduced the problem to solving a system of linear simultaneous equations. To get the required accuracy the number of equations had to be large, ranging from six to thirty equations in a single solution. Using desk calculators the solution of six simultaneous equations was tedious and time consuming but with thirty equations the calculation became infeasible. Atanasoff recalls reaching the conclusion that "if I wanted a computer suited to the general needs of science and, in particular, suited to solving linear algebraic equations, I would have to build it myself" (Atanasoff 1984, p.237).

By autumn 1939 Atanasoff and C.E. Berry, Atanasoff's research assistant, had built a prototype machine which demonstrated the use of electronics to solve linear simultaneous equations. Atanasoff and Berry then proposed to construct a larger machine intended to solve up to 30 simultaneous equations. They received the necessary funding in 1940 and work began on what became known as the Atanasoff-Berry Computer (the ABC). In 1942 Atanasoff and Berry left Iowa to carry out war-related work and the machine was never completed. Because of J. Mauchley's visits to Atanasoff during the 1940s the influence which Atanasoff's work had on other machines, particularly the ENIAC, has been the subject of some debate (Goldstine 1973, Ceruzzi 1983, Atanasoff 1984, K. Mauchley 1984). However, Atanasoff's machine was never fully developed and was not used; nor did any computer projects spring directly for the machine.

Computing machine design was also undertaken by Bell Telephone Laboratories during the late 1930s. In 1937 G. Stibitz, a mathematical engineer at Bell Labs, was working on the design of magnetic relays and, in his spare time, began to investigate the use of relays as adders. Throughout 1938 Stibitz continued to work on the use of relays to

3. In Atanasoff and Brandt 1936 the authors are careful to point out that the cross-connecting board was not a machine modification but an auxiliary piece of equipment.

construct computing components and demonstrated that relays could be made to perform all four arithmetical functions of a desk calculator. In the summer of 1938 Stibitz was asked by the head of the Mathematical Engineering Group at Bell Labs to develop a relay calculator which could handle complex number arithmetic. Complex number arithmetic was used extensively at Bell Labs in the design of filters and amplifiers for telephone lines. The company employed a team of 5-10 computers to perform the necessary complex number arithmetic using desk calculators (Ceruzzi 1983) but by the late 1930s the bulk of complex number arithmetic required was becoming a burden to several research groups within the company.

Stibitz's designs were approved and construction of the machine began under the engineering direction of S.B. Williams. The Complex Number Computer (later labelled the Model 1) was completed in 1939. It was a relay device which at first performed complex number multiplication and division but was later expanded to include complex addition and subtraction. The Complex Number Computer was not programmable. It was a special purpose machine in which the operations it performed were hard wired into the machine. The Complex Number Computer went into routine use at Bell Labs in 1940 where it became a well used device until it taken out of service in 1949.

Although Stibitz had plans to build a machine "that evaluated polynomials and other rational functions" (Stibitz p.481 in Metropolis, Howlett and Rota 1980) and other more general purpose relay machines, the high development costs necessary prevented Bell Labs from funding any further projects. Although a computing centre did not emerge from Stibitz's work on the Complex Number Computer, it was a well used machine within Bell Labs and led to the construction of several other computing machines by Stibitz during the war (see p.242).

The third computing machine project begun in the United States during the period preceding the Second World War was the construction of the Harvard Mark I by H.H. Aiken. In the mid-1930s Aiken, a graduate student in the Physics Department at Harvard University, was experiencing great difficulties in finding solutions to the differential equations which arose from his work. The equations would not yield to analytical solution and required a great deal of work to solve numerically using desk calculators. Consequently, in 1937, Aiken drew up a proposal for the construction of a large automatic calculating machine based on IBM punched card machines which could solve differential equations (Aiken's proposal is reprinted in Randell 1982, pp. 195-201). Initially Aiken approached the Monroe Calculating Machine Company for the financial support to construct his machine but his bid was unsuccessful (Ceruzzi 1983). Aiken did, however, meet with more approval when he brought his proposal to IBM. Through Harvard's connections with the Thomas J. Watson Astronomical Computing Bureau at Columbia (H. Shapely, director of the Harvard College Observatory, was a user and T.H. Brown of the Harvard Business School was on the board of managers) Aiken met Watson of IBM and outlined his plans. Watson was impressed with Aiken's proposal and in 1941 assigned a group of design engineers from IBM to work with Aiken to design and build a machine. The machine was largely funded by the Navy which anticipated using the device to prepare badly needed firing tables but IBM contributed most of the expertise to the project. Aiken joined the US Navy at the beginning of the war but remained in close contact with the project as a consultant to the IBM engineers constructing the machine. The machine was finished in 1943 and was immediately put into military use.

Although MIT was better known for its work on analogue calculating devices, in 1937 Bush began to investigate the use of electronics for digital computing machine components. During 1937-1938 Bush wrote a series of memoranda in which he outlined his plans for a Rapid Arithmetical Machine and in the following year some work was done on the device (Randell 1982, pp. 294-295). From a summary of the machine (Bush 1940) it is clear that Bush intended to use an electronic arithmetic unit with three paper tapes to hold the machine instructions, the input numbers and constants. Although the project continued for some time under the sponsorship of the National Cash Register Co., it was abandoned in 1942 when the personnel involved were transferred to work on the atomic bomb project.

In complete contrast to the computing machine projects which were begun in the late 1930s, another type of computing centre was set up during this period. In 1938 the National Bureau of Standards, through the Works Progress Administration, set up the New York Mathematical Tables Project as part of the employment programme run by the United States government during the Depression. The aim of the Mathematical Tables Project was to produce and publish tables of fundamental mathematical functions.

The Mathematical Tables Project, which was initially housed in a disused stable in New York, employed a small number of mathematicians but a great many computers. Initially the computers were inexperienced in desk calculator work and were divided into four sections: those who performed addition, those who performed subtraction, those who performed multiplication, and those who performed division and checking calculations. At first all the relevant instructions were posted on the wall in front of each group of computers but soon the Mathematical Tables Project became a highly efficient organization which prepared and published a large number of fundamental tables including exponential, trigonometrical, probability, Legendre and Bessel functions[4].

Before the war, the Mathematical Tables Project did not take in outside work but carried out its own work computing and publishing tables. The Mathematical Tables Project was very different to the British Association Mathematical Tables Committee in England which periodically published mathematical tables usually computed by volunteers, often academics on the committee. The British Association Mathematical Tables Committee had very little funding and did not employ large numbers of computers.

In the late 1930s there were three different kinds of computing centres in operation in the United States: a computing service bureau, a mathematical tables centre, and several computing machine research projects. Apart from Atanasoff's work at Iowa State College, all of these computing centres and machine projects expanded and gained

4. In the early 1800s d'Prony used this type of division of labour to compute his famous logarithmic and trigonometrical tables (Hyman 1982).

military support during the second world war.

7.1.3 World War II: 1941-1945

On 7th December 1941 the Japanese bombed Pearl Harbour and brought the United States into the Second World War. As a result of America's entering the war, an increased amount of military funding and support was given to computational work connected with war research.

One of the most important computing resources to be developed during the war was the Applied Mathematics Panel (AMP) set up in 1942 by the United States Office of Scientific Research and Development (OSRD)[5]. Like the Admiralty Computing Service in Britain (see p.102) the AMP did not directly carry out computations itself but passed on computational requests to the most suitable group. The AMP was set up to assist all branches of the military with the increased amount of computations arising from wartime research and development. The AMP had several computing resources available to it. It held contracts with many civilian computing centres throughout the United States including the Thomas J. Watson Astronomical Computing Bureau at Columbia, IBM, the U.S. Nautical Almanac Office, and eleven universities which had computing facilities and computing staff of their own including Princeton, New York, University of California (Berkeley), Brown, Harvard and North Western. The AMP also took over responsibility for the New York Mathematical Tables Project and made much use of the facilities which it afforded (Rees 1982).

One of the principle computing facilities available to the AMP was the Thomas J. Watson Astronomical Computing Laboratory which was turned over to war work in 1942. Eckert had left the bureau in 1940 to become director of the United States Nautical Almanac Office[6] but, under the direction of J. Schilt, director of the Rutherford

5. The Applied Maths Panel was only one of many areas in which the OSRD, under the direction of V. Bush, coordinated war time research.
6. Within a few months of his appointment Eckert had completely revised the hand computing methods in use at the NAO and installed IBM punched card machines at the Office (Brennan 1971).

Observatory at Columbia, the work of the bureau continued to increase throughout the war as the demand for ballistic tables and other military computational work rose. The installation was expanded in 1943 to cope with the increased demands being made on the Bureau. In many ways this situation parallels the use of the Scientific Computing Service by the armed forces in England during the war.

As the pressure of war related research rose, several research laboratories extended their own computing facilities. The most important research laboratory to increase its computational power was the Los Alamos Scientific Laboratory. The result of the war time research conducted at Los Alamos is well known, and throughout the war the work at Los Alamos was given both a high priority and a high budget. It was thus able to acquire extensive computing facilities which other laboratories could not.

At first the bulk of the calculations performed at Los Alamos were carried out by a team of women computers using desk calculators (mainly electric Marchants). Initially these women were drawn from the wives of Los Alamos scientists and were trained on site (Brode 1982) but after several months officially trained computers arrived at Los Alamos from the Womens Army Corps (WAC) and took over the work. By autumn 1943, however, the calculations necessary were becoming too large and too complex to be carried out effectively using desk calculators. D. Mitchall, who had previously used the machines at Columbia University, suggested that IBM punched card machines could be used to perform the same work. The machines arrived at Los Alamos in early 1944 and were immediately put to work performing implosion simulations. The work of the Los Alamos Computing Section is more fully described in Metropolis and Nelson (1982), Feynman (1982) and Brode (1982).

During the war several computing machine projects flourished. The most famous computing machine to be built during the war was the ENIAC at the Moore School of Electrical Engineering of the University of Pennsylvania which was sponsored by the

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1971).

Ballistics Research Laboratory of the Aberdeen Proving Ground. Before the outbreak of World War II P. Gillon, a lieutenant at the Ballistics Research Laboratory (BRL), was concerned about the lack of computing power at the BRL. He was particularly worried about the ability of the laboratory to prepare the firing and bombing tables which would be needed in the event of war (Goldstine 1972). Gillon applied to the director of BRL for permission to install a set of IBM punched card machines for this work. Permission was granted and the machines installed in 1940-1941. Later, in 1944, IBM delivered the first of its pluggable sequence relay calculators to Aberdeen.

Gillon also developed other computing facilities at BRL. Although BRL already had a Bush differential analyser built in 1935, Gillon took over use of the differential analyser at the nearby Moore School of Electrical Engineering for the duration of the war. In addition to expanding BRL's differential analyser facilities and installing punched card machinery, Gillon set up a training course for scientific computers at the Moore School. Women recruited by the Womens Army Corps were sent for training at the Moore School and gained experience on desk calculators, punched card machines, and differential analysers. By 1944 BRL had built up a computing staff of 176. In the course of the training programme many ballistic and related calculations were carried out at the Moore School which developed into a centre for the preparation of firing tables (Burks in Metropolis, Howlett and Rota 1980, pp.311-346).

Despite the wide range of computing facilities at Aberdeen and at the Moore School, by mid-1942 BRL staff came to realize the extensive computing facilities at BRL were not sufficient to keep up with the demand for firing tables (Ceruzzi 1983). Around the same time J. Mauchley of the Moore School suggested that an "electronic differential analyser" could be built to prepare firing tables, and in April 1943 a proposal for such a machine was put forward. As a result of the proposal the Aberdeen Proving Ground agreed to fund the development of an electronic calculating machine at the Moore School. Work began in May 1943 and the ENIAC solved its first problem in December 1945 for Los Alamos.

The construction of the ENIAC, the subsequent development of the stored program computer concept, and the course of lectures on electronic computers given in 1946, turned the Moore School into a very important computing centre in the immediate post war period. Most of the computer projects which began in the late 1940s were a direct result of the work carried out at the Moore School. The departure of Eckert and Mauchley, and Goldstine, Burks and von Neumann, from the Moore School after the war to develop their own computers, meant that the Moore School did not maintain its importance as a computing centre into the late 1940s.

Another war-time centre for computing machine construction was Bell Telephone Laboratories. Bell Labs had not continued to fund Stibitz's work on relay calculators after the Complex Number Computer had been built, but the increased computational demands of the armed services prompted the National Defence Research Committee (NDRC) to support the construction of computing machines at Bell Labs. When the United States entered the war in December 1941 the research work carried out at Bell Labs changed and the company began to work on the development of fire control devices (Ceruzzi 1983). The work on fire control devices involved the solution of many simulation calculations in order to test the accuracy of the devices. Many of the simulation calculations involved interpolation of function values from previously computed tables. Stibitz, who had left Bell Labs to work for the NDRC but still maintained close contact with the company, suggested building a relay machine to automatically interpolate the necessary values. This machine, the Relay Interpolator or Bell Labs Model 2, was funded by the NDRC and completed in 1943.

Following the design of the Relay Interpolator, Stibitz designed the Ballistics Computer, the Model 3, which was built at Bell Labs in 1944 for the Antiaircraft Board at Camp Davis, North Carolina to perform ballistics calculations. Again the machine was paid for by the NDRC. The last relay machine, the Model 5, to be designed by Stibitz and developed at Bell Labs (with NDRC support) was a more general purpose device. Two of these machines were built in 1945: one was installed at the Aberdeen Proving

Ground, and the other at Langley Field (Stibitz in Metropolis, Howlett and Rota 1980, pp.479-486).

The other major computing machine project carried out during the war was the construction of the Harvard Mark I by Aiken and IBM (see p.237). The machine was funded by the Navy. The machine was completed in 1943 and was moved from IBM's laboratories at Endicott to Harvard where it began work for Los Alamos before it went into regular service for the Navy Bureau of Ships in May 1944. Following a split between Aiken and IBM the machine, initially called the IBM Automatic Sequenced Controlled Calculator, became known as the Harvard Mark I and formed the basis of the Harvard Computation Laboratory. It was the first of a series of machines to be built by Aiken. Until the end of the war the machine was used almost entirely for war related work principally by the Navy.

Although there were several places in the United States which carried out computation or developed computing machines, there were only three institutions which stood out as computing centres in the terms outlined in chapter 1. These were the Computing Bureau at Columbia, the Applied Mathematics Panel and the Moore School/BRL association. The Computing Bureau at Columbia provided extensive computing facilities for all comers during the war, the Applied Mathematics Panel coordinated computing activity within the armed services and the Moore School/BRL prepared ballistic and firing tables using a wide range of machinery, trained staff and developed a large scale calculating machine.

7.1.4 Post-War Computing Centres in the Unites States

After the war and the publication of the work done at the Moore School on the ENIAC and EDVAC machines, many computer projects were begun in the United States. A list of all these projects will not be given in this section but rather the development of important computing centres will be discussed.

In Britain the most comprehensive computing centre to be established in the post war period was the NPL Mathematics Division. In the United States an equivalent, but much larger, national computing resource was also set up called the National Applied Mathematics Laboratories (NAML). In 1945 the United States Office of Naval Research, under which the AMP operated, conducted a survey of naval computing requirements and "recommended the establishment, with navy participation, of a national interagency computer centre that would develop and use large-scale automatic machines" (Rees 1982, p.107). Subsequently the Office of Naval Research asked the National Bureau of Standards to consider the creation of

> a centralized national computation facility, equipped with high-speed automatic computing machinery, to provide computing service to other government agencies and to play an active part in the further development of computing machinery. (Huskey in Metropolis, Howlett and Rota 1980, p.419)

In response to this request E.U. Couden, director of the National Bureau of Standards, asked his assistant, J.H. Curtiss, to investigate the need for a national computation centre. Curtiss's investigations confirmed the need for a nationalized computing facility by the armed services and, in February 1947, he drew up a prospectus for the establishment of the National Applied Mathematics Laboratories.

The 1947 prospectus outlined the motivation behind the creation of the NAMLs. It said:

> Applied mathematics is on the threshold of revolutionary developments which will permit numerical answers to physical problems to be obtained at hitherto undreamed of speeds. A strong, easily accessible, federal applied mathematics centre, operating with low overhead costs, providing economical but competent computational and consulting services, and performing forward-looking research in the newer methods of applied mathematics, is a necessity in the national research program. (from *A Prospectus* by the National Bureau of

Standards quoted by Anon 1948a, p.64).

The parallel between the aim of the NAMLs as laid down in *A Prospectus* and the functions of the NPL Mathematics Division in the 1944 DSIR proposal (see p.117) are obvious. In both cases it was intended that a centrally administered national computing centre be established to work in all areas of mathematical computation and provide a computing service for government departments.

The NAMLs were established in July 1947 and were partly funded by the Office of Naval Research. Curtiss was appointed director. At the same time the Applied Mathematics Executive Council was created to represent government agencies which wished to use NAML facilities. The Executive Council consisted of representatives from the Department of Agriculture, the Army, the Navy, the Air Force, the National Advisory Committee for Aeronautics, the Weather Bureau, the Census Bureau and the National Bureau of Standards. The Council was also attended by guests from the Bureau of the Budget and the Atomic Energy Commission. The main function of the Council was to advise the NAMLs on their research programme and budget. Rees (1982) recalls, however, that one of the most important functions of the Applied Mathematics Executive Council was to provide a forum for discussion between Curtiss and NAML users.

The NAMLs consisted of four distinct centres: the Institute of Numerical Analysis, the Computation Laboratory, the Statistical Engineering Laboratory, and the Machine Development Laboratory. The Institute of Numerical Analysis, based at the University of California at Los Angeles, was a completely new academic institution. It came into operation in 1948 and among its staff were John Todd from the Admiralty Computing Service in England, and H.D. Huskey who had returned from his year spent at the NPL Mathematics Division. Hartree was appointed acting chief of the institution during his trip to the United States in June to September 1948. The Institute of Numerical Analysis was intended to be a research institution which academics from all over the world could come to visit.

The Computation Laboratory, located in Washington along with the Statistical Engineering and the Machine Development Laboratories, developed directly out of the staff and facilities of the Mathematical Tables Project administered during the war by the AMP. The Machine Development Laboratory was divided into two groups: a mathematics group, and an electronics group which came from the National Bureau of Standards. The Statistical Engineering Laboratory was to act as a "statistical consulting service specializing in the application of modern statistical inference to the physical and engineering sciences" (Anon 1948b, p.64).

In addition to its responsibility for the NAML, the National Bureau of Standards also acted as an intermediary between government agencies wishing to purchase computers and computer manufacturers. In this capacity the National Bureau of Standards ordered a UNIVAC machine from the Eckert-Mauchley Corporation on behalf of the Census Bureau, and a machine from the Raytheon company for its own use. Huskey (in Metropolis, Howlett and Rota 1980, pp.419-431) recalls that by 1948 NAML personnel were growing impatient that progress on the promised National Bureau of Standards machine was slow and it was suggested that they build their own machine as an interim measure. A committee, whose membership included Stibitz, von Neumann and Aiken, was set up to consider the matter. After some deliberation the committee stated that the National Applied Maths Laboratories should confine their machine development activities to the design and construction of computer components. Curtiss and the Applied Mathematics Executive Council went against the advice of this committee and decided that the National Applied Maths Laboratories should build their own machine. This decision resulted in the SEAC computer built in Washington and completed in 1950. In early 1948 it was also decided that a UNIVAC machine should be ordered for the Institute of Numerical Analysis from the Eckert-Mauchley Corporation. However security problems within the Eckert-Mauchley Corporation prevented military money being spent in this way, and led to the construction of the SWAC computer at the Institute of Numerical Analysis.

The NAMLs, therefore, worked in all areas which a national computing centre could be expected to be involved in: the provision of computing and consultancy services, numerical analysis, and machine development.

After the war the Thomas J. Watson Astronomical Computing Bureau at Columbia underwent significant changes. In 1945 IBM invited W.J. Eckert to head a new Department of Pure Science within IBM. In order to maintain close links between IBM and academia the new department was established at Columbia University as the Watson Scientific Computing Laboratory at Columbia University and directed by W.J. Eckert. The laboratory was formally opened with the announcement that "The research and instructional resources of the laboratory will be made available to scientists, universities and research organizations in this country and abroad" (Brennan 1971, p.13). Thus, from the outset, the Watson Scientific Computing Laboratory was intended to be a computing service and consultancy centre as well as a research laboratory. Eckert and Watson also intended that the laboratory should develop new types of automatic calculating machine for the company.

The Watson Scientific Computing Laboratory was very successful in fulfilling its objectives. It built on the work and reputation of the Thomas J. Watson Astronomical Computing Bureau and was widely used. Machine development was also successful and the cooperation between IBM and Columbia University led to the development of the IBM Selective Sequence Electronic Calculator (SSEC). Work on the design of the SSEC began in 1945 and in January 1948, amid great publicity, the machine was dedicated and put into regular use. The SSEC was housed at IBM headquarters and was used by the staff at Columbia and by outside customers on a commercial basis. Another very important aspect of the laboratory's work was a three week computation course started in 1947 and run by laboratory staff. The course became extremely popular and ensured that the laboratory became well known throughout the country as an important computing centre.

After the war the Harvard Computation Laboratory continued to act as a computing centre accessible to Navy personnel and other scientists from all over the United States.

The amount of military work lessened and the Mark I went into routine use for the preparation and printing of mathematical tables. After the split with IBM, Aiken and his staff built several other machines. The first was the Harvard Mark II for the Dahlgren Proving Ground. This was followed by the electronic Mark III, also for Dahlgren, and the Mark IV for the United States Air Force. Although not regarded as being in the mainstream of computer research and design, Goldstine (1972) credits Aiken with the development of important methods of circuit and logic design. Ceruzzi (1983) very accurately sums up the role which Aiken and the Harvard Computation Laboratory played in the post war period.

> The fact that [Aiken's] laboratory was publicized meant that he became a clearing-house for correspondence and information about computers for those who were not privy to other sources of knowledge. As a result he was always at the centre of later computer activity, even though his aversion to electronics and to the stored program principle meant that his ideas had little influence. The Computation Laboratory was perhaps his most lasting achievement. It provided a place where a new generation of students could learn about computers, and many of his students went on to become pioneers in their own right (Ceruzzi 1983, pp.69-70).

As computer projects began to develop and computers became available during the early 1950s, many local, regional and national computer centres began to emerge. There is, however, one computing centre which is of particular interest because it illustrated the changing attitudes towards computing centres. Like other aircraft manufacturers, Northrop Aircraft Incorporated, Hawthorne, California required a large amount of computation in the course of its research work and, by the mid-1940s, had installed IBM punched card machines to expand their computing facilities. Early in 1948 Northrop engineers had developed a way of connecting IBM punched card machines together in order to make the machines carry out repeated sequences of operations and provide logical control facilities. From the work at Northrop, IBM developed the CPC machine (Card

Programmed Calculator)[7]. By 1953 Northrop had created a very well equipped computing centre containing several of the larger IBM machines and other automatic calculators. It had a permanent staff of 55. The unusual aspect of the Northrop computing centre was the way in which it was staffed.

Traditionally most computing machine specialists were mathematicians who took problems specified by engineers or physicists, performed the calculation and handed back the result. Northrop decided to employ engineers rather than mathematicians in its computing centre. Each department of the company (aerodynamics, stress and structures, thermodynamics, missile guidance and servomechanisms) had resident engineers in the computer centre to whom it brought its computational requests. Northrop found that not only did the engineers understand the problems under investigation more clearly but they were also able to make suggestions as to how the computing machines could be improved to increase their effectiveness for engineering problems.

Northrop Aircraft represented the next generation of computing centres following the establishment of national centres such as the NAMLs, the Harvard Computation Laboratory and the Watson Scientific Computing Laboratory at Columbia. It was an example of a local computing centre which not only developed computing machinery but also created an appropriate computing staff to serve the specific needs of its users.

7.1.5 Major Influences Between Britain and the United States

Whereas in Britain a direct line towards the centralization of scientific computation can be traced, in the United States such a clear pattern did not exist. Although individual computing centres, such as Iowa State College, Columbia University, MIT and the New York Mathematical Tables Project, were set up before the second world war, most of these concentrated on one particular type of machinery or type of computation. There was no equivalent of the SCS in the United States.

7. The CPC proved to be a very popular machine and provided large scale computing power before computer became readily available. Randell (1982) states that nearly 700 CPCs were sold.

During and after World War II the centralization of scientific computation took on similar characteristics in both Britain and the United States. For example the establishment of the AMP and, later, the NAML, corresponded to the creation of the Admiralty Computing Service and the NPL Mathematics Division in England. The functions of these institutions and the reasons for their creation were remarkably similar. Once computers began to become easily available in the United States and Britain a multiplicity of more localized centres appeared.

Although similar kinds of institutions were set up in Britain and the United States there was little influence between the two countries at the organizational level. The major area in which the two countries influenced each other was by the development of new types of calculating machines or by new applications of existing machines. The first American development, apart from the design and manufacture of desk calculators and accounting machines, to influence scientific computation in Britain was the differential analyser. Bush's work at MIT led directly to the installation of machines at Manchester and at Cambridge. However the British differential analysers were located in different types of institution to those differential analysers built in the United States. In the United States differential analysers were installed within institutions which already performed a considerable amount of computational work, such as the Ballistics Research Laboratory and the Moore School of Electrical Engineering at the University of Pennsylvania. At these institutions the differential analysers were regarded as additional, and very powerful, computing tools. At Manchester and Cambridge universities in England computing centres were set up around the differential analysers; the machines were not simply an additional piece of computing equipment.

Comrie's work at the NAO on the application of punched card machines to scientific computation was the main motivation behind Eckert's desire to apply IBM machines to astronomical calculations. Here again a technique developed in one country was adopted and used differently in another. In Britain Comrie was able to use punched card machines for a limited number of applications. Machines were installed at the NAO for only seven months. The SCS did not have an installation of their own but used BTM machines whenever a particular computation justified the expense. In the United States, however, Eckert persuaded IBM to install a complete set of punched card machines in the Astronomy Department at Columbia and the computing service then developed around the installation. Thus the basic technique of using punched card machines for astronomical calculations was developed by Comrie but Eckert took the idea and developed a computing centre around it.

The computing machine developments at Bell Labs, Harvard and Iowa had little technical influence on the design of computing machines in Britain. The major influence on computing machine design all over the world was the EDVAC proposal which grew out of the war time ENIAC project at the Moore School of Electrical Engineering. These proposals, which became public after the war, and the series of lectures given by the Moore School in 1946 led to the development of computers in Britain at Teddington, Cambridge and Manchester. Thus although there was a degree of technology transfer between the United States and Britain there is no evidence to suggest that the types of computing centres which emerged on both sides of the Atlantic during 1925-1955 were influenced by each other to any significant degree.

7.2 Computing Activity in Europe

Relatively little is known about the organization of scientific computation in Europe during 1925-1955. Few descriptions of European computing centres appear in the English speaking literature. Bibliographies which specialize in the history of computing, such as Cortada (1983) and Randell (1982), list only a few references which look at European events. Some recent books have given some insight into computation in Europe. Most notable are Goldstine's *The Computer: from Pascal to von Neumann* (1972) and Metropolis, Howlett and Rota's *A History of Computing in the Twentieth Century* (1980). Both of these books are, however, concerned primarily with the development of electronic computers and, consequently, do not dwell on pre-war or war-time events. Much of the information presented in this dissertation about computation in Britain has been obtained from unpublished reports, manuscript documents and public records. A search of this type of literature abroad is beyond the scope of this brief review. Because of the small amount of information available regarding scientific computation on mainland Europe, with the exception of Germany[8], this section is necessarily incomplete.

Germany

The most significant piece of work done on the development of calculating machines in Germany during the 1930s was carried out by K. Zuse. Several descriptions of Zuse's work have been published (Zuse 1962, 1970, Metropolis, Howlett and Rota 1980, Ceruzzi 1981, 1983, Randell 1982) and a full account will not be given here. It is, however, appropriate to give an outline of Zuse's work.

In the early 1930s Zuse, a civil engineering student at the Technische Hochschule at Berlin-Charlottenberg, became aware of the need to automate scientific calculations. He was particularly concerned about the solution of large systems of simultaneous equations which frequently arose from his own work on structure analysis. Zuse initially tried to improve computing methods by systematically organizing hand computing techniques using desk calculating machines and slide rules. Zuse, however, soon realized that a reorganization of existing methods was not a sufficient answer to the problem and began to construct calculating machines from telephone relays. In 1935 Zuse began work with the Henschel Aircraft Company as a stress analyst but continued to build relay calculating machines privately with the aid of friends. In 1937 Zuse succeeded in interesting K. Pannke, a calculating machine manufacturer, in his work and obtained some financial backing for the construction of his machines (Ceruzzi 1983).

8. Additional information on German computation has recently been brought to the author's attention. *Applied Mathematics Research in Germany, with particular reference to Naval applications* by J. Todd, G.E.H. Reuter, F.G. Friedlander, D.H. Sadler, A. Baxter and F. Hoyle, Report No. 79, British Intelligence Objectives Sub-Committee, is kept at the Imperial War Museum in London and is not available on loan. It is hoped that when this document is consulted that it will further clarify the state of centralized computation in Germany.

In 1939 Zuse was drafted into the German army despite the interference of H. Schreyer who wrote to the German authorities pointing out the value of Zuse's work. Schreyer was a friend of Zuse's who had spent some time working with Zuse on the construction of his electromechanical machine, and had also experimented with the use of electronic calculating machine components for which he gained a doctorate in 1941. By 1942 Schreyer had built a prototype electronic machine at the German Aeronautical Research Institute (DVL) in Berlin but the device was destroyed in 1943 during an air raid. Although Schreyer had tried to get backing from the German government to build a full scale machine he did not succeed and a machine was never built.

In late 1939 Zuse was released from the German army to work as an engineer at DVL. Here Zuse got some backing for his plans to build an automatic relay calculator and as a result the Z3 machine was completed in late 1941. The Z3 was a prototype machine designed to prove that an automatic relay computing machine could be built. Although the Z3 successfully ran several test programs it never performed useful work. As soon as the Z3 had shown that his designs were feasible, Zuse began building a full sized machine, the Z4. The Z4 was never finished and was frequently moved during the latter stages of the war to escape from the Allied bombing raids. In 1944 all Zuse's machines, apart from the half completed Z4, were destroyed during an air raid.

In addition to his work on general purpose calculating machines Zuse also built a special purpose relay machine for DVL in the early 1940s. The machine computed sums of products for the prediction of flight paths for unmanned flying bombs. The machine operated on the basis of a hard wired program built into the device.

At the end of the war Zuse and the Z4 were located in a small Bavarian village where it was impossible to continue work on the machine and during 1945 Zuse worked on more theoretical matters developing his Plankalkül (programming language) for automatic computers. Zuse knew nothing of the calculating machine developments being made in the United States during the war.

Apart from the machines built by Zuse, who initially worked without official support or colleagues, there were several other types of calculating machine developed in Germany during the 1930s. Several individuals working at separate locations throughout the country built different types of analogue calculating machine to solve a range of problems (Békésy 1937, Bode 1937, Fuss 1933, Harbon 1930, Sewig 1935, Weygandt 1933) but these machines appear to have had little impact. There were at least two differential analysers built in Germany during Second World War. One was installed at the Institute für Praktische Mathematik (IPM) at the Technische Hochschule in Darmstadt and the other at the Institute für Angewandte Mathematik at the Technische Hochschule in Aachen. Both were used extensively throughout the war.

IPM was a particularly important German computing centre during the war. The pressure of war related work, including trajectory and flutter calculations, forced A. Walther, a professor at IPM, to consider using punched card machines for this work. Dreyer (1943) states that IPM had been interested in applying punched card machines to scientific computation for several years and recalls that in 1929 punched card machines were successfully applied in Germany to Harmonic Analysis (Walther 1940, Anon 1929). The most pressing problem facing IPM was the solution of large systems of simultaneous equations and serious work on the problem using punched card machines began at the Institute in 1942. IPM itself did not have a punched card installation on site but instead used the machines and operators of the Ir. G. Farbenindustrie Corporation of Frankfurt.

In 1943 Walther applied to the German authorities for the necessary finance to build an automatic calculating machine to prepare mathematical tables as part of the war computation which IPM had been asked to perform. Funding was refused on the grounds that accounting machines, such as the National, were already available and could be used to build up tables by interpolation. However, in 1944, during the last few months of the war, IPM was given finance to construct an automatic calculator as quickly as possible (Dreyer and Walther 1946) and consequently only easily accessible machines and spare parts were employed. The device, the IPM automatic calculator, was destroyed in an air attack in 1944 and the project was prevented from restarting because of the impossibility in Germany at that time of acquiring either Hollerith machines or spare parts.

As its name suggests the Institute carried out applied mathematics research. It also carried out investigations into the application of different types of calculating machine and in the development of computing devices. Before the war several analogue instruments were designed at IPM and built by Ott, the mathematical instrument manufacturer. Considerable work was carried out on the development of differential analysers and Fourier synthesizers. Later, work was also done on modifying a National Accounting Machine to automatically carry out interpolation. Staff from IPM were also well informed about the computing machine developments which took place in the United States before the war particularly at MIT (Walther 1940). They also knew of Eckert's work on punched card machines at Columbia. In addition staff was aware of the computing machine work going on in Germany itself. For example Dreyer, Walther and W. de Beauclair, another IPM member of staff, visited Zuse in Berlin in the early 1940s to see his Z3 relay machine.

Zuse recalls that "In Germany after the war work naturally came to a halt for some years" (Zuse 1962 in Randell 1982 p. 186). Apart from Britain's attempts to construct the NPL differential analyser in Germany, work on computers did not restart in Germany until the late 1940s and early 1950s when computer research was carried out at IPM in Darmstadt, at the Technische Hochschule in Munich and at the Max Planck Institute für Physik in Gottingen.

France

In France M. d'Ocagne and L. Couffignal were the two principle figures working on improving methods of scientific computation. The majority of French references given in

Randell's bibliography (1982) are by these two men. D'Ocagne was professor of geometry at the Ecole Polytechnique and was working from the late 1800s to the 1930s. Couffignal began his work in the mid-1930s and later became involved in computer research after the war.

D'Ocagne's major contribution to scientific computation was the development and popularization of nomograms. Although work had previously been done in France on graphical computation, d'Ocagne is considered to be the founder of the field of nomography (Williams 1985). His first paper on nomography appeared in France in 1884 (d'Ocagne 1884). Nomograms were a very simple but powerful computing tool and became widely used in France by engineers, land surveyors and the armed services. D'Ocagne was also an expert on many different types of calculating machine. In 1928 he presented a classification system by which all types of desk calculators, accounting machines, and analogue instruments could be identified (d'Ocagne 1928)[9].

During the 1930s the most important work on calculating machines done in France was carried out by L. Couffignal, Professeur d'Analyse et Mécanique at the Ecole des Elèves Ingénieurs Mécaniques de la Marine. Couffignal's main concern was to eliminate the computational errors arising from incorrect use of machines or from transcription errors. This motivation led Couffignal to develop d'Ocagne's earlier classification of calculating machines and devise a new scheme within which the relative performances of each machine could be evaluated (Couffignal 1933). He placed a strong emphasis on the advantage of using machines in which operator intervention was minimal because they eliminated many possible sources of error. Couffignal was particularly interested in

9. One of d'Ocagne's preoccupations in his work on the history of calculating machines was the development of a machine which could perform the work of Babbage's proposed Analytical Engine. In 1920 the Spanish inventor Torres-y-Quevedo, a member of the Royal Academy of Sciences of Madrid and a corresponding member of the Institute of France, exhibited an electromechanical calculating machine in Paris. The device consisted of a typewriter connected to a calculating machine by means of an electric cable (Torres 1920). The device would automatically carry out an operation entered on the typewriter and print the result. Although the machine did not automatically carry out a sequence of instructions, d'Ocagne saw it as an important step towards the development of a calculating machine in the spirit of Babbage's Analytical Engine.

punched card machines and accounting machines, such as the Campos machine, which could be used as automatic calculators.

In addition to studying and classifying machines Couffignal also developed calculating devices in which he tried to eliminate operator intervention: that is he tried to produce automatic calculating machines. Couffignal's first machine was a mechanical device which automatically performed a sequence of basic arithmetical functions. In his brief description of the machine Couffignal (1930) suggested that it might be possible to connect the machine to a typewriter to automatically print the results and hence eliminate transcription errors. Couffignal also put forward the possibility of applying similar principles to punched card machines. In 1936 Couffignal began to work on the use of binary to represent numbers in calculating machines. In a thesis written in 1938 Couffignal describes an electromechanical program controlled binary calculator which he intended to construction with the aid of the Logabax Company. Because of the war the machine was never built (Randell 1982).

Distinct from Couffignal's work on digital machines, several analogue calculating devices were built in France during the 1930s. Many of the devices were integrators (Nessi and Nissole 1930, Salomon 1931, Minorsky 1936a, 1936b) but others, such as Vidal (1936), built simultaneous equation solvers and other instruments. Little is known of the computational work in France carried out at the beginning of the war before the German occupation except that the French Ministry of War was involved in developing fire control devices for antiaircraft artillery (see p.258). After the war Couffignal returned to his work on automatic calculating devices and headed a computer project at the Institut Blaise Pascal where a machine was built in cooperation with the Logabax Company.

Czechoslovakia

In Czechoslovakia some work on analogue calculating machines was done before the war. A. Svoboda and Dr. Vand worked on developing analogue fire control devices for the Czech Ministry of National Defence during 1936-1938 (Svoboda in Metropolis, Howlett and Rota 1980, pp. 578-586). When Germany invaded Czechoslovakia in 1939 Svoboda and Vand were sent to Paris by the Czechoslovak Ministry of Defence to the French Ministry of War to continue their work on anti-aircraft systems. In 1941 Svoboda escaped from occupied France to the United States where in 1943 he joined the Radiation Laboratory of MIT.

After the war, during 1946 and 1947, Svoboda toured the United States and England visiting all the major computing centres including Harvard, the Institute for Advanced Study, Bell Labs, the Watson Scientific Computing Bureau, the Cambridge University Mathematics Laboratory and the NPL Mathematics Division. In 1948 Svoboda joined the Czech Institute of Technology in Prague and began to modify punched card machines, in cooperation with the Czech punched card manufacturers Aritma (Oblonsky 1980). Two years later Svoboda left the Institute of Technology to take up an appointment at the Central Institute of Mathematics where he created a department of mathematical machines which later became known as the Research Institute of Mathematical Machines of the Czechoslovak Academy of Sciences in Prague. Under Svoboda's direction the Research Institute of Mathematical Machines became "the focal point of computer research in Czechoslovakia, covering both analogue and digital computer design and theoretical research in related fields" (Oblonsky 1980, p.287).

Russia

According to Ershov and Shura-Bura "In the USSR, World War II interrupted a series of scientific research and technical projects in the field of mathematical machines" (Ershov and Shura-Bura in Metropolis, Howlett and Rota 1980, p140). The authors did not give examples of where this type of work had been carried out but emphasised that the war had increased the need for applied numerical research and the development of fire control equipment.

In 1946, after the war, the journal *Uspekhi Mathematicheskikh Nauk (UMN)* (vol.1 1946) reviewed the state of scientific computation in the USSR in the light of war time research. The journal predicted that important advances would be made in many fields of science and technology that would require increasingly sophisticated calculating machinery and concluded that "the urgent needs of science and engineering have led to the formation of a new branch of technology which could be called the design and production of 'calculating devices'" (quoted by Ershov and Shura-Bura in Metropolis, Howlett and Rota 1980, p.141). The article went on to call for an increase in the amount of work being done in this area.

Soon after this article was published the Mathematical Institute of the Soviet Academy of Sciences (MAIN) undertook a research programme led by M.V. Keldysh. The programme was guided by a government directive. The Russian government was thus trying to set up a centre for computing machine development at an already established centre of pure mathematics.

Work on electronic computers in Russia did not, however, begin at MAIN but was started by S.A. Lebedev, director of the Electrotechnical Institute of the Ukranian Academy of Sciences in Kiev. In 1947 Lebedev initiated a research programme which resulted in the construction of Russia's first electronic computer, MESM, in 1951. Throughout the early 1950s work on computers continued in Kiev and at MAIN. Although both centres developed computing machinery and carried out numerical research, they did not provide a computing service to scientists in other institutions in the USSR. A computing service was not available in Russia until 1954 when the Computer Centre of the USSR Academy of Sciences was set up to carry out basic computer research and also to provide a public computing service (Ershov 1980).

The Netherlands

In the Netherlands in 1946 the Mathematisch Centrum was established in Amsterdam as a national computer centre (Goldstine 1972). The centre was made up of four departments: Pure Mathematics, Mathematical Statistics, Applied Mathematics, and Computation. This roughly corresponded with the establishment of the NPL Mathematics Division in England. During 1947 A. van Wijngaarden, head of the Computation Department, toured the United States and Britain to visit the major computing centres. Also members of the Computation Department, including E.W. Dijkstra, attended the Cambridge University Summer Schools in the early 1950s. Using the knowledge gained from these visits abroad, the Computation Department went on to develop first a relay calculator and then a series of electronic machines.

Italy

Filippazzi, an Italian computer scientist, dates Italy's entry into the computer field as 1955 when a Ferranti Mark I computer from Britain was installed at the National Institute for Applied Mathematics in Rome (Filippazzi 1970). Italian research into the construction of electronic machines also began in 1955 with the establishment of the Centre for the Study of Electronic Computers in Pisa at the suggestion of Enrico Fermi. At the same time Olivetti decided to enter the computer manufacturing business and set up a research centre also in Pisa.

Other European Countries

Information on computing centres in other European countries is very scarce and consists mainly of details of events which took place after the second world war. For example, in 1946 the Danish Academy of Technical Sciences set up a committee to consider the need in Denmark to build large scale calculating machines. The committee's first task was to begin construction of a differential analyser and an electronic equation solver. Following the suggestion from Unesco in 1948 to set up an international computation centre (section 7.3), the committee set up the Regnecentralen (Danish Institute of Computing Machinery) as part of the Danish Academy of Technical Sciences. With funding from the Carlsberg Foundation, the Regnecentralen became the centre of computer research in Denmark.

The Swedish government was also concerned about the need to build powerful computing machines and sent scientists to the United States during 1946-1948 to study the work going on there. In late 1948 the government set up a board to promote the development of computing machinery within Sweden. The board set up a working party based at the Royal Institute of Technology on Stockholm which went on to develop a series of computing machines.

In Switzerland interest in computing machinery was prompted by the installation of Zuse's Z4 machine at the Swiss Federal Polytechnic Institute (ETH) in 1950. In Poland also computing centres were set up: one at the Instytut Maszyn Mathemaysznych and another at the Research Institute for Electronic Computers of the Polish Academy of Sciences. Computer centres such as these began to be established in many European countries during the 1950s but the most interesting development was an attempt to set up an international computing centre.

7.3 The UNESCO International Computation Centre

By the mid-1950s national computing centres had been set up in several countries: IPM in Germany, Institute Blaise Pascal in France, Research Institute of Mathematical Machines in Czechoslovakia, MAIN and the USSR Academy of Sciences in Russia, Mathematisch Centralum in the Netherlands, Centre for the Study of Electronic Computers in Italy, Regencentralen in Denmark, the Royal Institute of Technology in Sweden, and the Institute of Electronic Computers and the Instytut Maszyn Mathemaysznych in Poland. In addition an international computing centre was set up in Rome in the late 1950s by Unesco, the United Nations Educational, Scientific and Cultural Organization.

The project began during a Unesco general conference held in 1948 when the Director-General of Unesco was asked to consider the establishment of an International Computation Centre under Unesco administration. This request was prompted by a growing feeling among member nations that computers were going to become very important scientific tools coupled with the belief that machines would not become readily available for several years to come. It was thought that an international computation centre could serve member nations which would not otherwise be able to afford to develop or install electronic computers.

In response to the proposal to create an International Computation Centre the United States National Research Council Committee on Unesco asked a specially convened sub-committee to report on the possibility of establishing such a centre. The sub-committee membership included J.H. Curtiss, director of the National Applied Maths Laboratories, W.J. Eckert, head of the Watson Scientific Computing Bureau at Columbia, H. Shapely of Harvard University Observatory and a Columbia user, C.I. Bliss of the Connecticut Agricultural Experimental Station, and P.M. Morse of MIT. The report was presented to Unesco in June 1949. In August 1949 the Unesco Committee of Scientific Experts on International Research Laboratories decided that the establishment of an International Computation Centre should be given a high priority (Anon 1949).

The United States' report of June 1949 drew responses from several countries. Denmark was particularly interested in the project and submitted a report on the subject to Unesco in December. Denmark expressed the opinion that, although a suggestion to establish the International Computation Centre in East Asia (which had been put forward by Unesco) was laudable, the centre would be better situated in Europe. Denmark put itself forward as a candidate for the location of the International Computation Centre.

In May 1951 Unesco called together a committee of experts to investigate further the establishment of an International Computation Centre and consider proposals to set up the centre in Italy, Holland and Switzerland. In the intervening period the invitation to establish the centre in Denmark had been withdrawn. L. Couffignal of France and H.H. Goldstine from the Institute for Advanced Study, Princeton in the United States were among the 12 delegates. The committee of experts recommended that the International Computation Centre should be created and administered by Unesco but that it should also have a high degree of autonomy from the organization in order to represent an international computing resource open to all-comers.

The committee of experts outlined the three principle functions the centre was to perform. These were to

(a) organize study and scientific research on questions relating to the use and development of mechanical computing devices;

(b) organize and develop a programme for the training and improvement of research workers in the field of mechanical computation;

(c) establish and maintain an advisory service dealing with queries from scientific institutions and scientists. (Anon 1951).

This description did not clearly define the intended functions of the International Computation Centre. It did not specify whether the centre would co-ordinate international computing machine research or whether it would carry out such research itself. Neither is it clear if the Centre itself would be used as a training ground, or whether training programmes developed at the centre were to be carried out elsewhere. The only point which was clearly stated was the role which the centre would play in providing an advisory service to those who consulted it. The centre was to be funded jointly by a Unesco grant, subscriptions of the member states and a loan from the host nation.

In late 1951 a conference concerning the establishment of the International Computation Centre was held in Paris. Many countries expressed an interest in the International Computation Centre and delegates from Brazil, Mexico, Peru, Belgium, Denmark, France, Italy, the Netherlands, Norway, Sweden, Switzerland, Israel, Japan, Syria, Turkey, Egypt and Liberia attended the conference. Britain and the United States chose not to send delegates to the conference, although Goldstine attended as an observer. Goldstine was also a member of the Unesco panel of experts and was deeply involved in the final choice of Rome as the site for the International Computation Centre.

Although it had been agreed to establish the International Computation Centre in late 1951, the centre did not come into operation for several years because Unesco member states were slow to ratify the conventions agreed at the 1951 conference. By

March 1957 only five countries (Belgium, Ceylon, Italy, Japan and Mexico) had ratified the conventions (Anon 1957a). Before the plans to establish the International Computation Centre could go ahead the convention had to be ratified by ten countries.

In October 1956 the committee of experts recommended that a provisional computing centre be set up as an interim measure before the International Computation Centre could be finally established. This time the role the centre was to play was more clearly expressed. The functions of the Provisional International Computation Centre were to train technical staff and research workers in computational techniques; to perform, or pass on, requests for computations by member states; to draw up a list of national and private computing concerns; and to help organize international computer conferences. The centre was thus to act as a training centre, a computing bureau and an advisory service (Anon 1957a). In April 1957 the committee of experts added "mathematical research of national or international importance" to the list of functions the centre was expected to perform (Anon 1957b, p.171).

On 1st January 1958 the Provisional International Computation Centre in Rome was set up jointly by Unesco and the Italian Instituto Nazionale di Alta Mathematica for an initial period of two years. It was controlled by a panel of experts from Unesco, the Instituto Nazionale di Alta Mathematica, and representatives from France, Italy, Japan and Mexico. The announcement of the establishment of the Provisional International Computation Centre which appeared in *The Unesco Chronicle* made it clear that the aim of the centre was to "enable countries which do not yet possess such equipment to benefit by its services" and not to replace existing computing centres (Anon 1958, p.54). This was the original motivation for the centre proposed ten years previously.

The provision of a computing service to countries which did not have access to computing facilities was one function of the Provisional International Computation Centre. The second, and perhaps more important, function of the centre was to promote international co-operation on computational problems and to act as a clearing house for information relating to computers and their application. The centre carried out this function in a variety of ways. For example, the centre organized international conferences and symposia, it funded fellowships for students from subscribing nations to study computation abroad, and it compiled and circulated a comprehensive list of computer installations all over the world.

For several months after it creation the Provisional International Computation Centre dealt with incoming requests for computations by using outside agencies. However, by October 1958, it became obvious that the centre would either have to install its own computing machinery or "relinquish its role as a computation laboratory servicing international organizations" (Provisional International Computation Centre October 1958 Nos. 2-3, p.14). By April 1959 the centre had decided to install machines donated by Olivetti-Bull and IBM-France which permitted it to provide an international computing service.

By 1961 sufficient countries had ratified the 1951 convention and the International Computation Centre was finally established as a permanent institution. The centre still exists today and is now called the Intergovernmental Bureau for Informatics. It no longer acts as a computing service centre but operates only as an advisory body and information centre to its member nations. The bureau had 37 member nations most of which are South American, African or Middle Eastern. The only European countries involved are Italy, the host nation, and France. Britain and the United States play no part in the bureau.

Although the conception of the International Computation Centre represents the culmination of centralized scientific computation on a world wide basis, the centre did not mature into an important computing centre in terms of both hardware development and numerical research. However, its creation is still of interest. It was founded to provide electronic computer facilities to scientists working in all parts of the world on the assumption that workers in most countries would not have access to such important machinery. In theory the Unesco International Computation Centre epitomizes the centralization of computing facilities and the idea that a wide range of users should be allowed access to those facilities. In practise, however, national computing centres, such as the NPL

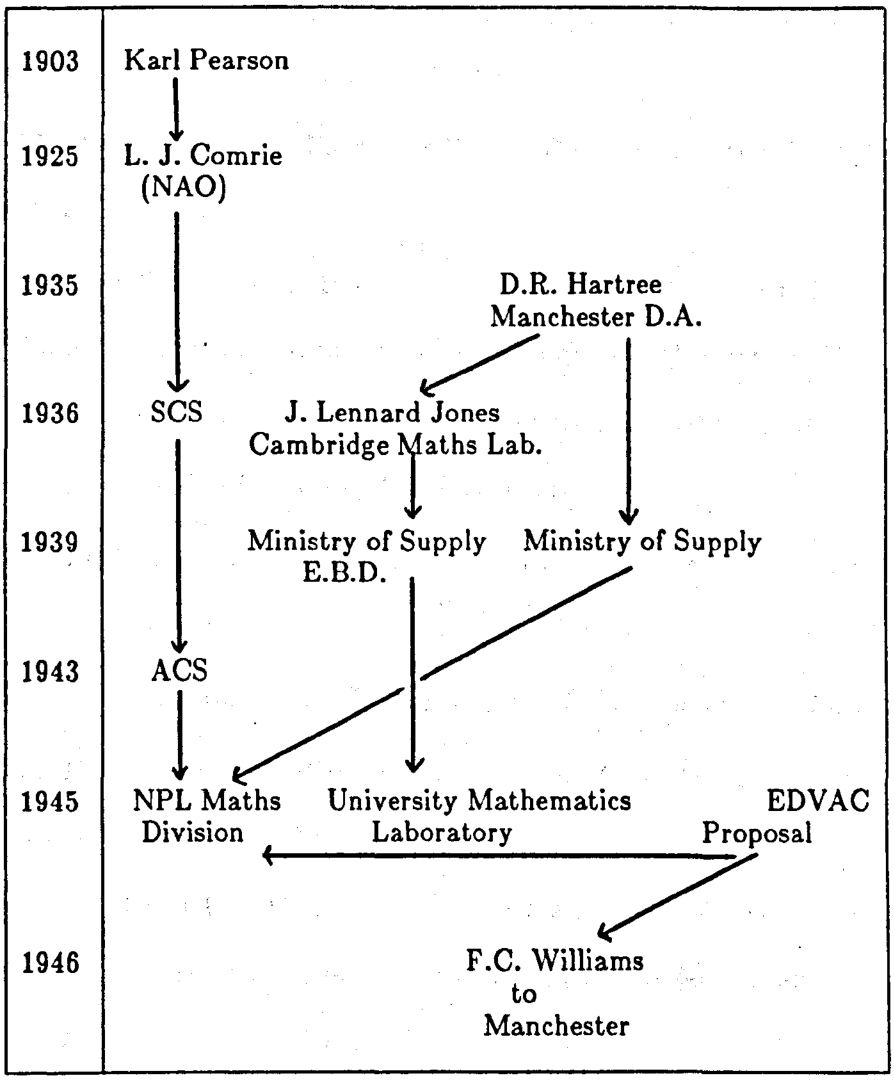
Mathematics Division, had much more influence on computing research and on the ways in which computers were used by individual nations. Another barrier to the success of the International Computation Centre was the fact that by the time the centre was set up in 1958 computers were becoming more easily available and the need for such a centre was reduced.

7.4 Concluding Remarks

The NPL Mathematics Division was created to act as a national computing centre, but even before it had been established other computing centres were being set up in Britain. Figure 7.4.1 summarizes the main events which led up to the formation of three national computing centres in the late 1940s and illustrates how the notion of centralized computing spread.

The advent of computers and their increasing availability in Britain in the late 1950s and the 1960s resulted in a move away from national computing centres such as the NPL Mathematics Division the Cambridge Mathematical Laboratory and the Royal Society Computing Machine Laboratory at Manchester. Computers began to be installed in most scientific research institutions in Britain beginning with the RAE, the AERE and the AWRE. Today there are thousands of localized computer centres and, although the increasing adoption of micro-computers by individuals might be said to reduce the need for centralized computing resources, most universities, research institutions and companies have computer centres. These computer centres all reflect the philosophy of centralizing the best commercially available computing machinery (within budget restrictions) operated by trained staff for the benefit of a wide range of users. Unlike the post war computing centres which combined computing service and computing research functions, most modern computer centres within universities, government research establishments or industrial companies today carry out only the service function. Research is left to specialists in computer science, engineering, and mathematics departments.

Figure 7.1.4 The Centralization of Scientific Computation in Britain



The creation of first national computing centres and later more localized centres was a pattern which developed in the United States, Britain and most of Europe. Because of the rapid rate at which computer hardware developed, the need for national centres equipped with this type of machinery lessened. Similarly the need for an international computing centre, which was felt in the late 1940s and early 1950s no longer existed by the time the Provisional International Computation Centre was set up in Rome by Unesco in 1957. Thus, although the creation of an international computing centre should have been the pinnacle of centralized computation, it had very little influence or purpose by the time it was formally established.

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