Pre-1971 Known References to and Possible Dissemination of Ludgate's 1909 paper

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This online work-in-progress paper documents known references to Ludgate's 1909 paper and possible paths of its dissemination.

There were only two mechanical designs published for a programmable computer well before the electronic computer era, Charles Babbage's "*Analytical Engine*", published by Ada Lovelace in 1843 [1][2], and Percy Ludgate's "*Analytical Machine*", published by Ludgate in 1909 [3][4][5][6].

How widely was Ludgate's 1909 paper distributed?

Ludgate's paper "*On a proposed analytical machine*" was published on the 28th April 1909 in the Scientific Proceedings of the Royal Dublin Society, Volume 12, Number 9, pp. 77–91 [3]. Surprisingly, given the subsequent obscurity of Ludgate's paper, these proceedings were distributed very widely.[4] In [7] pp.369-370, in 1915, the Society's Registrar, R.J. Moss wrote:

> … Scientific Proceedings of the Royal Dublin Society. This is sent in exchange to all the important scientific societies in the world; the number on the exchange list at present is 474, so that wide publicity is ensured for every paper published in the Proceedings.

Then in 1981 [8] p.214 stated:

> The list was 375 institutions in 1899, and 567 in 1953.

This wide distribution makes the subsequent obscurity of Ludgate's 1909 paper very puzzling.

Where are the pre-1971 references to Ludgate's work?

Given how low profile Ludgate's work was until Randell's 1971 paper [9] and 1973 book [10], the question arises: where are the pre-1971 references to Ludgate's work? To establish some concrete primary facts, we have conducted an academic literature search with the aim to find early direct and indirect references to Ludgate's paper describing his analytical machine in the 1909 Scientific Proceedings of the Royal Dublin Society. Here we relate the results of this search in chronological order. Items that directly cite Ludgate's 1909 paper are of the most interest.

1909: A brief summary in *English Mechanic and World of Science* in May 1909 [11] states: "*Scientific News: No. 9 of the Scientific Proceedings of the Royal Dublin Society … interesting paper by Mr. Percy E. Ludgate describing a proposed new analytical machine.*", i.e. a direct but incomplete citation.

1909: A review in the June 1909 *IEE Science Abstracts* [12], with wide circulation in the UK, USA and Italy:

> 963. *Analytical machine.* **P. E. Ludgate.** (Roy. Dublin Soc., Proc. **12.9.** pp.77-91, April, 1909.)

1909: Professor Charles Vernon (C.V.) Boys' review in *Nature* in July 1909 [13], again with wide circulation:

> Percy E.Ludgate, On a Proposed Analytical Machine, pp.77-91, Vol.12, No.9, Scientific Proceedings of the Royal Dublin Society, 28-Apr-1909.

1909: A detailed summary in *Engineering* in August 1909 [14] that did not include a citation, but provided extensive explanations and also included a diagram of part of the machine:

> **A proposed analytical machine.** In a paper read not long ago before the Royal Dublin Society, Mr. Percy E. Ludgate has revived again the idea of constructing such a machine.

1909: A detailed summary in *English Mechanic and World of Science* in September 1909 [15], again without a citation but with the same extensive explanations and diagram (attributed to *Engineering*, see above):

> **A proposed analytical machine,** Mr. Percy E. Ludgate has revived again the idea of constructing such a machine.

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[3] Brian Randell, School of Computing, Newcastle Univerity, <brian.randell@newcastle.ac.uk>
[4] See further below for details of which institutions hold Ludgate's 1909 paper and its *Nature* and *IEE Science Abstracts* reviews.

1909: A brief review [16] in a 1909 German astronomical yearbook of C.V.Boys' *Nature* article [13] stated:

> The author briefly outlines the general principles of a calculating machine proposed by P. E. Ludgate in the April number of the "Scientific Proceedings of the Royal Dublin Society" in which the logarithmic method is to be used.

1913: An offprint of Ludgate's 1909 paper somehow ended up in the 1913 catalogue of the library of the Deutsche Seewarte (*Reichsinstitut Deutsche Seewarte*, i.e. German Maritime Observatory) in Hamburg [17]:

> **Ludgate, P. E.** On a proposed analytical machine. (Sonderabdr.) Dublin 1909). 8 º. (31018)

1914: *Handbook of the Napier Tercentenary Celebration* (ed. E.M. Horsburgh): in this volume Ludgate's 1914 paper "*Automatic Calculating Machines*" on Charles Babbage's machines [4] ended with a brief paragraph on Ludgate's own analytical machine that provided a direct references to his 1909 paper, followed by a somewhat lengthier paragraph on Ludgate's unpublished work on a difference engine.

> I myself have designed an analytical machine, on different lines from Babbage's, to work with 192 variables of 20 figures each. A short account of it appeared in the Scientific Proceedings of the Royal Dublin Society, April 1909.

1914: A review of the *Handbook of the Napier Tercentenary Celebration* (ed. E.M. Horsburgh) by C.V.Boys in *Nature* [81] simply states "*The further chapters are as follows : "Calculating Machines," by F. J. Whipple, but including special articles by P. E. Ludgate and ..., by a number of specialists. As this chapter includes such varied and elaborate instruments … it will be evident that this is one of the most technically difficult and illuminating in the book.*" This implies Ludgate did not attend or present but was asked to provide his article.

1926: David Baxandall's 1926 catalogue of the Collection in the London Science Museum [18], which was for many years the primary source for information on contemporary and earlier calculating machines, contained the earliest known mention of Ludgate's work. It stated: "*Other difference engines were designed and made by Martin Wiberg (1863) in Sweden, G. B. Grant in the United States; others were designed by Léon Bollée in France, and Percy E. Ludgate in Ireland, which, however, were never constructed.*" This only referred to Ludgate's unpublished work on a difference engine; no mention was made of Ludgate's "*analytical machine*". The text did not include any citation.

1936: Vannevar Bush's 1936 Gibbs Lecture "*Instrumental Analysis*" [19] included a passage "*It is comparatively recently that such [four-function calculating] machines can be built at moderate cost, and sufficiently reliable and rugged to withstand continuous hard usage. The combination of such machines with punched cards [4], [5] has made arithmetic into an entirely new affair*". Bush's citation "*[4]*" referred to:

> E. M. Horsburgh, editor, Napier Tercentenary Celebration. Handbook of the Exhibition of Napier relics and of books, instruments and devices for facilitating calculation. Royal Society of Edinburgh, 1914, pp. 27, 124-127.

Here pages "*124-127*" referred to Ludgate's 1914 paper, curiously without naming him or giving its title, and so constituting an extremely obscure but definitive reference to Ludgate.

1937: Howard Aiken's PhD thesis submission, "*proposed automatic calculating machine*"[20], simply stated "*Then followed several other difference engines constructed and designed by Martin Wiberg in Sweden, G. B. Grant in the United States, Leon Bollée in France, and Percy Ludgate in Ireland. The last two, however, were never constructed.*" This was probably derived from the almost identical text in Baxandall above, and similarly lacked any citation.

1938: Irven Travis created a "*Bibliography of literature on calculating machines*" in 1938 [21], in which Ludgate's 1909 paper was cited, but merely as the full bibliographic reference (but missing the leading "On" in the title) with no details of its contents:

> Ludgate, P. E., A Proposed Analytical Machine, Dublin, Sci.Proc.R.Soc. 12, pp.77-91, 1909.

Given Travis' very close interactions with Vannevar Bush, who in 1936 obscurely cited Ludgate, it is very possible he learned of Ludgate from Bush. In Travis' evidence more than 30 years later to the ENIAC patent litigation[5] he said of his 1938 Bibliography, that students "*did all the leg work, and I directed them to sources and compiled this document*", so it is quite likely that he was already familiar with the contents of Ludgate's paper.[6] In any event, Travis' clear, direct and complete citation of Ludgate's 1909 paper is the earliest post-1914 citations we have yet found.

1946: Howard Aiken and Grace Hopper published a description of the Automatic Sequence Controlled Calculator [22], with two citations to Ludgates 1914 paper. The first was within the sentence: "*In spite of being unable to complete the difference engine, Babbage embarked upon the creation of a far more ambitious concept, an "analytical engine.*[16,18,17]", where citation "*17*" referred to Ludgate's 1914 paper:

> Automatic Calculating Machines, P. E. Ludgate, Modern Instruments and Methods of Calculation, edited by E. M. Horsburgh, 1914, pages 124-7.

However, the second citation was within the sentence "*In 1906, H. P. Babbage, son of the philosopher, completed a part of the analytical engine. A table of multiples of π which it computed to 29 significant digits was published as a specimen of its work.*[20]", where citation "*20*" was to:

> Automatic Calculating Machines, P. E. Ludgate, Modern Instruments and Methods of Calculation, edited by E. M. Horsburgh, 1914, page 127.

The sentence and citation referred very obviously to paragraph 2 of page 127 of Ludgate's 1914 paper, in the very next sentence of which Ludgate stated "*I myself have designed an analytical machine, on different lines from Babbage's, to work with 192 variables of 20 figures each. A short account of it appeared in the Scientific Proceedings of the Royal Dublin Society, April 1909.*" It is hard to exclude the possibility that Aiken and/or Hopper had read that next sentence, and therefore knew of Ludgate's 1909 paper.

1948: Raymond Clare Archibald was Professor of Mathematics at Brown University, teaching the history of mathematics, and developing a magnificent mathematical library. His "*Mathematical Table Makers*" [23] included in a section on Charles Babbage:

> Modern Instruments and Methods of Calculation, ed. by E. M. Horsburgh, London, 1914, portrait facing p. 69, copy of 6 (b), reduced in size. Article by P. E. Ludgate "Automatic calculating machines," p. 124-127, refers to Babbage's machines.

This is followed by a reference to Baxandall's 1926 catalogue of the Collection in the London Science Museum (see above and [18]), but without mention of Ludgate, and then a reference to "*A Manual of Operation of the Automatic Sequence Controlled Calculator*" which included the same references to Ludgate as in Aiken and Hopper's paper (see [22] and above).

1951: Wilkes' 1951 paper in the Journal of the Royal Society of Arts "*Automatic Calculating Machines*" contained, after a detailed description of Babbage's Analytical Engine, the cursory statement "*At least one other proposal for the construction of an automatic calculating machine was made - by P. E. Ludgate in 1909 - but as far as I am aware nothing was ever built*" without any citation [24].

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5 One of the major untapped sources is the voluminous set of records of the ENIAC patent litigation (1967-1973) at the Charles Babbage Institute, the University of Pennsylvania, and the Computer History Museum (copied from Brian Randell's set of microfiche). However, these very important records (said to be 68GB in size) are not fully indexed, and not available online.

6 Travis stated in evidence to the ENIAC trial that "*[Questioned by Mr. Halladay]*:

Q: Excuse me. Did you compile that bibliography as of 1938?

A: I caused it to be compiled and I was its editor.

Q: All right.

A: I had the good fortune of having a couple of students who were supported by the relief programs that were going on in the mid-thirties to work with me.

Q: The N.Y.A.? *[National Youth Administration, a New Deal agency to provide work to those aged 16-25 years]*

A: That's right.

Q: I know about that one.

A: And these two very young assistants assisted me in doing this. They did all the leg work, and I directed them to sources and compiled this document." [52]

1956: Maurice Wilkes' book "*Automatic Digital Computers*" [25] contained a lengthy historical introduction, based closely on his 1951 paper - and repeated verbatim the above single sentence about Ludgate without citation, however Ludgate's 1909 paper <u>was</u> then listed (later in the book) in the bibliography as item 59:

> LUDGATE, P. E., On a Proposed Analytical Machine. Sci. Proc. R. Dublin Soc. v. 12, p. 77 (1909).

This one of only two clear and direct post-1914 references yet found to this date (the other by Travis in 1938).

1957: David W. Taylor of the Naval Ship Research and Development Center, Bethesda, Maryland, USA, mentioned Ludgate in a report [26] as follows: "I*n 1909 P. E. Ludgate proposed the construction of an automatic calculating machine, but without any tangible results*". Although there was no direct citation, earlier on the same page there was a citation to Wilkes 1956.

1959: Jiří Klír (George Klir), then a PhD student (aspirant) at Czech Academy of Sciences (later Professor of Systems Sciences at Binghamton University, New York), wrote an article (in the Czech language) for Prague school children that mentioned Ludgate: "*Roku 1909 se setkáváme po Babbageovi s dalším projektem samočinného počitače, který vymyslil P. E. Ludgate. Ke stavbě stroje však nedošlo.*" (i.e. "*In 1909, after Babbage, we meet another project on an automatic computer, invented by P. E. Ludgate. However, the construction of the machine did not take place.*") [27]. The text did not include any citation.

1960: Gerhard B. Hagen, a patent attorney engaged by Triumph-Werke (with IBM support), cited Ludgate's 1909 paper in his objections to Konrad Zuse's Z3 computer patent until the litigation concluded in 1967 [83][84]:

> P.E. Ludgate "On a proposed analytical machine", published in the journal "Scientific Proceedings Royal Dublin Society", 1909, Volume XII, Issue IX, Pages 77-91.

1961: Paul A.V.Thomas' "Design Philosophy Small Electronic Automatic Digital Computer" PhD thesis at Univ.Glasgow, in 1961 [28] stated: "*In 1909, P.E. Ludgate proposed the construction of an automatic calculating machine, but it appears that nothing was ever built*[W15]" His "*W15*" referred to Wilkes' 1956 book p.15, which did not provide a citation, but its bibliography item 59 referred to Ludgate's 1909 paper.

1962: Walter Hoffmann provided a citation to Ludgate's 1909 paper in his book *Digitale Informationswandler* [29]:

> LUDGATE, P. E.: On a Proposed Analytical Machine. Sci. Proc. Royal Dublin Soc. **12** N. S. (1909) No.9, S. 77-91.

To summarise, Table 1 shows a list of the known direct and indirect mentions of Percy Ludgate's work relevant to computing over the period up to the introduction of Randell's 1971 paper [9].

Year	Source	Mentioned?	Referred To?	Citation?	References
		1909			
1909	Percy E. Ludgate, Sci.Proc.Royal Dublin Society, pp.77-91, No.9, Vol.12, 28th April 1909				[3]
1909	IEE Science Abstracts	Directly	Ludgate 1909	Ludgate 1909	[12]
1909	C.V. Boys *Nature* review	Directly	Ludgate 1909	Ludgate 1909	[13][30]
1909	English Mechanic and World of Science	Directly	Ludgate 1909	—	[31]
1909	Engineering	Directly	Ludgate 1909	—	[32]
1909	German astronomical yearbook	Directly	Ludgate 1909	Ludgate 1909	[16]
		After 1909			
1913	Deutsche Seewart library catalogue	Directly	Ludgate 1909	Ludgate 1909	[17]
1914	Percy Ludgate	Directly	Ludgate 1909	Ludgate 1909	[4]
1914	C.V. Boys *Nature* review	Indirectly	Ludgate 1914	Horsburgh 1914	[81][30]
1926	David Baxandall	Indirectly	*difference engines*	Horsburgh 1914	[18][33]
1936	Vannevar Bush	Indirectly	Ludgate 1914	Horsburgh 1914	[19]
1937	Howard Aiken	Indirectly	*difference engines*	—	[20]
1938	Irven Travis	Directly	Ludgate 1909	Ludgate 1909	[21]
1946	Howard Aiken and Grace Hopper	Directly	Ludgate 1914	Ludgate 1914	[22]
1948	Raymond Clare Archibald	Directly	Ludgate 1914	Ludgate 1914	[23]
1951	Maurice Wilkes	Directly	Ludgate 1909	—	[24]
1956	Maurice Wilkes	Directly	Ludgate 1909	Ludgate 1909	[25]
1957	David W. Taylor	Directly	Ludgate 1909	Wilkes 1956	[26]

1959	Jiří Klír (George Klir)	Directly	Ludgate 1909	—	[27]
1960	Gerhard B. Hagen	Directly	Ludgate 1909	Ludgate 1909	[83][84]
1961	Paul A.V.Thomas	Directly	Ludgate 1909	Wilkes 1956	[28]
1962	Walter Hoffmann	Directly	Ludgate 1909	Ludgate 1909	[29][34]
1971					

Table 1: Currently known direct and indirect mentions of Percy Ludgate's work between 1909 and 1971

How else was Ludgate's 1909 paper disseminated?

Were there secondary sources of dissemination? From the above very few primary facts one may deduce:

(a) In 1909, there were two widely distributed reviews (*Nature*, *IEE Science Abstracts*) of Ludgate's 1909 paper;
(b) After 1909, the earliest source, the unexplained accession of an offprint of Ludgate's 1909 paper into the 1913 catalogue of the library of the Deutsche Seewarte in Hamburg, may be somewhat of an outlier;
(c) Ludgate's 1914 paper cites his 1909 paper, and is cited by Baxandall, Bush, Aiken & Hopper, and Archibald;
(d) Of the remainder, Vannevar Bush's 1936 obscure but definitive reference to Ludgate is the earliest yet found;
(e) After 1914, the 1938 citation by Travis (who closely collaborated with Bush) is the earliest complete reference yet found to Ludgate's 1909 paper.

Travis had enquiries worldwide for copies of his Bibliography[7]. Although he gave a lecture "*The History of Computing Devices*" at the famous 1946 Moore School Lectures[8], thus far no evidence has been found that his Bibliography was provided to the attendees. In the subsequent ENIAC litigation, the first item in the Plaintiff's huge list of exhibits was a copy of Charles Babbage's "*Passages from the Life of a Philospher*" (1864), followed by over a hundred items predating Travis' Bibliography. From Rosen:

> *'Honeywell lawyers submitted 30,000 documents, and Sperry Rand lawyers submitted 6000 documents. The transcript of the trial was 50,000 pages long. The verdict that was handed down on October 19, 1973 was 319 pages long. The trial record has become a major source of information about the early history of electronic computing.' [35] page 6*

Despite this focus on related early literature, thus far it appears that the ENIAC trial and its extensive discovery process did not find either Ludgate's 1909 or 1914 papers, Horsburgh [4] or Baxandall [18]. The trial record does include Travis' Bibliography, and the trial transcript includes exchanges about his Bibliography, but the name Ludgate does not appear in any of the indexes or finding aids to the trial archives, and no mention has been discovered thus far in the very limited searches of the transcript. Moreover, Travis' Bibliography does not seem to have been included with the sets of lecture notes that were distributed some time after the Moore School Lectures. However over this period, there are several prominent scientists in particular who had access to early electronic computing material, and might have disseminated Ludgate's work:

(1) Sir Charles Vernon Boys F.R.S. was a Professor at Imperial College London who from the 1890s until the late 1920s was considered an expert on calculating machines. He reviewed Ludgate's 1909 paper (entering into correspondence with Ludgate), and reviewed the volume containing Ludgate's 1914 paper, and so was very well informed about it's content and significance.
(2) Vannevar Bush was a renowned Professor at MIT who in the 1930s created the first differential analyzer, a mechanical analog computer for solving differential equations. He subsequently promoted digital solutions.
(3) Irven Travis was a Professor of Electrical Engineering at Moore School, Pennsylvania, who based his PhD on Bush's differential analyzer and over the 1930s had close interactions with Vannevar Bush, leading in 1938 to an army contract for Travis to build two differential analyzers (from Bush's engineering drawings but with

[7] Travis stated in evidence to the ENIAC trial that "[Questioned by Mr. Halladay]:
Q: Was that document itself part of the official files of Moore School, or available in the library, or was it or was it accessible to others?
A: I was amazed at the attention this thing gathered. I got enquiries from all over the world for copies of it. I had it mimeographed, and copies were distributed to anybody who wanted them." [52]

[8] A by-invitation-only series of lectures held in Moore School of Engineering, where the details of ENIAC were first disclosed and which appears to have spawned all of the very next computer developments except Turing's ACE.

improved torque amplification), one for the army's nearby ballistics laboratory[9], the other for Moore School [36]. This expertise led to consulting work to solve electric power grid issues for General Electric, resulting in two 1938 reports for G.E., one on electronic analog computing, the other on electronic digital computing [37][38].[10] Also in 1938 he created his "*Bibliography of literature on calculating machines*". Subsequently (in 1940) Travis submitted a proposal for Moore School to build an electronic differential analyzer [39](p.10)[40](pp.10-11)[41][11], but spent from 1941-45 in the US Navy, John Mauchly taking his post at Moore School. Mauchly wrote to Atanasoff about using some of Atanasoff's Laplaciometer-like ideas, who in reply raised patent issues [42][43](extracts pp.64-65). The subsequent 1942[12] Mauchly report *The Use of High Speed Vacuum Tube Devices for Calculating* [44](p.26)[45] and 1943[13] Eckert and Mauchly *Report on an Electronic Difference Analyzer* [44](p.26)[46] bore a strong overall resemblance to the digital version of the differential analyzer that Irven Travis had described in 1940 [38][47](pp.181-193)[44](page 26), including a block diagram similar to those drawn by Travis [44](page 29). After the end of World War II, as Director of Research at Moore School, Travis strongly opposed Eckert and Mauchly's plan to patent ENIAC independently of the School (whereupon they resigned and did so, the patents ultimately owned by Remington Rand, but licence-free to IBM under an IP exchange). Given the above, it has been argued that the ENIAC designed and built at Moore School may have inherited its architecture from Travis' 1938 reports for G.E. and his 1942 proposal to Moore School [47][43][44].

(4) Douglas Hartree F.R.S. was a Professor of Mathematics at Manchester, and later Cambridge. In 1933 he visited Vannevar Bush and on his return built a Meccano demonstrator, then a full copy of Bush's differential analyzer. In 1945 he visited ENIAC, visiting again in mid-1946, when with assistance from Kay McNulty he became the first civilian to program ENIAC.[14] Early in 1946 Hartree briefed Wilkes on American computing efforts. After Wilkes received an invitation to the Moore School lectures, Hartree briefed him on ENIAC. Then Hartree, his Manchester colleague David Rees, and Wilkes attended the Moore School lectures in 1946, where Hartree actually lectured (and Wilkes did later cite Ludgate). Subsequently Hartree helped Wilkes in developing the usage of EDSAC.

(5) Leslie J. Comrie F.R.S., Director of the Scientific Computing Service (SCS), visited the U.S. in 1946. One of the very few copies we have found of Travis's Bibliography in the U.K., that held by Manchester University's John Rylands Library, is marked on the cover as having come from the SCS (a company set up by Comrie to produce scientific tables, see [48], and led by him from 1936, after serving since 1925 initially as Deputy Director then as Superintendent of the Nautical Office). From [48]: "*At this time the British Tabulating Machine Company, Limited (BTM), manufacturer of the Hollerith line of tabulating machines, and a subsidiary of IBM,[15] operated punched-card service bureaus for commercial rather than scientific applications all over England. Comrie maintained a consulting relationship with BTM for many years and*

9 Ballistic Research Laboratory (BRL) of the Ordnance Department at the Aberdeen Proving Ground, Maryland.

10 Travis stated in evidence to the ENIAC trial that "My doctors thesis had to do with work that was closely related to the differential analyzer … it was of fundamental practical importance to the General Electric company. GE sent their engineers down to the Moore School … we at the Moore School worked with the GE Engineers to solve that problem on the differential analyzer and it was solved and indeed I think it saved the GE capacitor business … led to me becoming a consultant", and also "Plaintiff's Exhibit 201.3 … a copy of one of these two consulting reports to which you have previously referred dated August 30 1935 … This is the document in which I suggested the possibility of building an electronic differential analyzer" [52]

11 This proposal for an electronic naval fire control system was sent to Warren Weaver, Section D-2, NDRC (National Defense Research Committee, established by Vannevar Bush to coordinate science in support of the war effort), but was not funded.

12 Brainerd [70](p.487) stated "*Mauchly drew up a proposal, without any technical details or mention of the reliability problem, and gave it to Brainerd in March 1943. Although it was dated August 1942, no document bearing that date was ever found.*"

13 Brainerd [70](p.487) stated "*In April 1943 Goldstine asked Brainerd to meet Simon of BRL. Brainerd wrote out by hand a proposal after consultation with the others who might be on the project. He chose Mauchly (because of his original memorandum) and Eckert (because of his well-demonstrated electronic circuit ability) to go to BRL with him.*"

14 Douglas Hartree F.R.S. (1897-1958), received his PhD in physics at Cambridge in 1926, supervised by Ernest Rutherford, on calculations of the structure of Niels Bohr's atomic model, but his notable expertise was in numerical anlaysis. His first ENIAC program was to calculate supersonic airflow around an aircraft wing [53] p.190].

15 Until 1949 BTM had an exclusive licence to make and sell IBM products in the Commonwealth (except Canada); thereafter it had a free non-exclusive licence, but competed with the new IBM UK Ltd [71](p.243)[72].

earned commissions on referrals." During his 1946 trip he had visited the Moore School, from where he brought a copy of the now-famous 1945 EDVAC Report. He was an avid collector of literature on computation, which he shared with anyone showing an interest, and is known to have been familiar with the Handbook of the Napier Tercentenary Celebration [49] in which Ludgate's 1914 paper was published. It seems very likely that he was aware of both Ludgate's paper and the Travis Bibliography, and passed this information on, but this is unproven.

(6) By 1946 the mathematician Cuthbert C. Hurd was Dean of Allegheny College, Pennsylvania. Although he and Jay Forrester (MIT) were not invited, they attended some of the Moore School lectures. In 1949 he was hired by IBM President Thomas Watson Sr., only the second IBM employee with a PhD, and became a highly influential staff member, eventually Director of its Electronic Data Processing Machines Division, retiring in 1962. It is possible he was aware of and a source of information about Ludgate's work.

(7) Jay Forrester was not invited (although his MIT colleague Robert Everett was) but attended some of the Moore School lectures. Forrester subsequently led MIT's Whirlwind project (and invented core memory), the basis for IBM's AN/FSQ-7 SAGE strategic air defense computers, and advised the military and IBM on these interconnected real-time systems.

(8) Howard H. Aiken was Professor of Applied Mathematics at Harvard University, and conceived the *Automatic Sequence Controlled Calculator* (ASCC, funded and built by IBM, first operational in 1944, later renamed the *Harvard Mark I* computer).[16] He cited Ludgate in 1937 and 1948 (see above), and actually lectured at the Moore School lectures. He is said to have been a generous disseminator, and may have been another source.

(9) Professor Maurice Wilkes F.R.S., Director of the Mathematical Laboratory (later 'Computer Laboratory'), University of Cambridge, was by 1937 responsible for its meccano differential analyzer (built by Lennard-Jones). Wilkes' book "*Memoirs of a Computer Pioneer*" [50] describes how while Leslie Comrie was in Cambridge overnight in May 1946, he had lent the EDVAC Report to Wilkes for the night. Early in 1946 Hartree briefed Wilkes on American computing efforts, then after receiving an invitation to the Moore School lectures, Hartree briefed him on ENIAC. Wilkes, Douglas Hartree and David Rees attended the Moore School lectures in 1946. Wilkes then initiated and led the development of EDSAC, and in subsequent publications cited Ludgate's 1909 paper.

(10) Professor Eduard Stiefel of ETH Zürich, and his PhD students Heinz Rutishauser and Ambros Speiser (who later founded and led IBM Research, Rüschlikon, Zürich) visited IBM New York, von Neumann, Howard Aiken, ENIAC and Dahlgren's MARK II over 1948-49[17], and then rented and operated Zuse's Z4 at ETH for five years. Any one of these three, especially Speiser, may have also known of Ludgate's 1909 paper. ETH Zürich library [51] holds issues of the Sci.Proc.Royal Dublin Society volume containing Ludgate's 1909 paper, as well as the *Nature* and *IEE Science Abstracts* volumes containing reviews of the paper.

(11) Dr. Gerhard B. Hagen, a physicist with a PhD in quantum mechanics, was a Munich patent attorney engaged by Triumph-Werke (with IBM support), who cited Ludgate's 1909 paper in his objection to Konrad Zuse's Z3 computer patent, just in time, as it was about to be granted, repeating this citation until this patent litigation concluded (rejecting the patent) in 1967 [34][83][84].

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16 In 1937 Howard Aiken approached Bryce, who persuaded IBM to spend $1M to develop what became the Harvard Mark I. When Aiken published a press release announcing the machine, Bryce was the only IBM person mentioned.

17 Professor Eduard Steifel, Head of Mathematics and Physics (1946-48) at ETH Zürich, founded ETH's Institute for Applied Mathematics in 1948. Bruderer describes in [60] how Stiefel arranged an extended visit to America with his PhD students Heinz Rutishauser and Ambros Speiser (the latter inspired by visiting Wilkes in Cambridge in 1947 [82]) "*The stay began with training at the Watson Laboratory for Scientific Computation at Columbia University in New York, where numerical work was carried out on IBM punched card machines. In March 1949 Stiefel returned to Switzerland. At that time Rutishauser was working with John von Neumann at the Institute for Advanced Study in Princeton, where the fastest electronic machine (IAS computer) was built. Speiser worked with Howard Aiken at Harvard University in Cambridge (Massachusetts) on the construction of the large Harvard Mark 3 vacuum tube computer. Stiefel's employees remained in the United States until the end of 1949.*" They also visited a number of other computer installations, including the ENIAC at Aberdeen and the MARK II at Dahlgren. From 1949 Steifel arranged that ETH Zürich rented Zuse's only machine that survived World War II, the Z4, then the only working computer in Europe, for five years, with Rutishauser and Speiser working with Zuse in Bavaria to learn about and extend Z4, then operating Z4 while it was at ETH.

(12) Walter Hoffman, a physicist from Munich, then head of IBM's Patent Department at Rüschlikon, Zürich, provided a 697-entry bibliography in his 1962 book *Digitale Informationswandler* [29] including Babbage, Lovelace, Ludgate, Torres y Quevedo, Couffignal, Turing, Zuse, Schreyer, Stibitz, Aiken, Hartree, Comrie, Eckert & Mauchly, Wilkes, Williams & Kilburn, etc.. Walter Proebster said that Hoffmann "*helped quite a bit in getting literature and in getting literature spread around.*" [18] Hoffmann most probably supported Hagen in the Zuse Z3 patent litigation [34][84].

(13) Max Newman was Alan Turing's mentor, and understood the importance of Turing's work. After creating and directing the Bletchley Park "Newmanry" (where ten Colossus and 30 other machines were installed), Newman became F.R.S. and Professor of Mathematics at Manchester University. He instigated the creation of the SSEM (Manchester Baby, the first stored-program computer to run a program). Manchester became one of the locii of British computing research. Newman had strong links with von Neumann at Princeton.

(14) In 1946 Max Newman bought David Rees, a pure mathematician at Bletchley Park's Hut 6 and Newmanry, to Manchester University. Rees, Hartree and Wilkes attended the Moore School lectures[19]. On their way home Rees and Hartree sketched out what would become the SSEM. Rees was an avid collector of books on mathematics, and became Professor of Pure Mathematics at the University of Exeter and an F.R.S..

(15) Patrick Blackett F.R.S. and Nobel, Professor of Physics, Manchester University, an ex-Cambridge colleague and close friend of Douglas Hartree and Max Newman, was best man at Newman's wedding, very political, recruited Newman to Bletchley Park and Manchester University, with strong links in the UK and USA.

Table 2 lists these prominent scientists and their correlation to dissemination of Ludgate's work.

Prominent Scientist	**Cited Ludgate?**	**Attended Moore School lectures?**	**Notes**	**References**
C.V. Boys	1909 Directly 1914 Indirectly	—	Reviewer of Ludgate's 1909 paper, and reviewer of the volume containing Ludgate's 1914 paper.	[13][30][81]
Vannevar Bush	1936 Indirectly	—	Created MIT differential analyzer, created NDRC	[19]
Irven Travis	1938 Directly	Yes	Moore School staff, built two differential analyzers, 1938 Bibliography, managed EDVAC completion	[21][36] [37-41][52]
Douglas Hartree	—	Yes	Visited ENIAC, built differential analyzer	[53][54]
Leslie Comrie	—	—	Visited ENIAC, had a copy of Travis' Bibliography	[48][55]
Cuthbert Hurd	—	Yes	IBM, Director Electronic Data Processing Machines	[56]
Jay Forrester	—	Yes	Visited ENIAC, led MIT's Whirlwind, core memory	[57]
Howard Aiken	1946 Directly	Yes	Created Harvard Mk.I, II, III	[20][22]
Maurice Wilkes	1956 Directly	Yes	Visited ENIAC, created EDSAC	[50][58]
Ambros Speiser	—	—	Visited ENIAC, ran ETH Z4, then led IBM Zürich lab	[59][82]
Eduard Stiefel	—	—	ETH, employed Speiser/Rutishauser, rented Zuse Z4	[60][61]
Heinz Rutishauser	—	—	Visited ENIAC, ran Z4 at ETH, colleague of Speiser	[62]
Gerhard B. Hagen	1960 Directly	—	Cited Ludgate 1909 in objections to Zuse's Z3 patent	[34][83][84]
Walter Hoffmann	1962 Directly	—	Head of IBM Zürich's Patent Department	[29][34][84]
Max Newman	—	—	Bletchley Park, then instigated Manchester Baby	[63][64]
David Rees	—	Yes	Bletchley Park, then Manchester with Newman	[65]
Patrick Blackett	—	—	Scientific/political advocate of electronic computing	[66][67]

Table 2: List of prominent scientists in particular who might have disseminated Ludgate's work.

[18] From [73]: "*One man who should be mentioned in this connection is Walter Hoffman, who was at this time an assistant of Professor Walther in Darmstadt. Walter Hoffman engaged in literature search and literature collection. Later he became a patent lawyer and worked for many, many years with IBM in one of the patent departments. ... He has a wealth of historical information on developments of this type and also how they eventually led to the state of the art which we have now. He helped quite a bit in getting literature and in getting literature spread around.*"

[19] From [74]: "*Finally consider the case of David Rees of Manchester University. He must have had a uniquely interesting and frustrating experience at the Moore school in 1946. He had been sent by Max Neumann from Manchester University to the lectures as a "student" and yet he was the only person present who had first hand knowledge of Bletchley Park – the largest computing facility in the world, but, in the interests of British national security he was not allowed to talk about it.*"

Which institutions hold Ludgate's 1909 paper and its Nature and IEE Science Abstracts reviews?

Finally, given the *Scientific Proceedings of the Royal Dublin Society* were distributed so widely (to 375 important scientific institutions in the world in 1899, 474 in 1915, and 567 in 1953 [7][8]), and knowing that *Nature* was widely distributed, and that the *IEE Science Abstracts* were widely circulated in the UK, USA and Italy, we have asked and are asking institutions (and would be delighted if other institutions proactively contact us to report their holdings) whether they hold copies of the following volumes and pages within, and if so, when they were received:

(a) *Proc.Sci.Royal Dublin Society*, pp.77–91, No.9, Vol.12, 28th April 1909 [3]
(b) *Nature*, pp.14-15, No.2070, Vol.81, July 1909 [13]
(c) *IEE Science Abstracts, Section A.—Physics,* Vol.XII, June 1909 [12]

In addition we have searched for:

(d) *Napier Tercentenary Celebration: Handbook of the Exhibition (also published as Modern instruments and methods of calculation)*, 1914 [4]
(e) Irven Travis, *Bibliography of Literature on Calculating Machines*, pp.1-16, ISBN: B0008BAXBM, Moore School of Eleclrical Engineering, Univ.Pennsylvania, Philadelphia, 1938 [21].
(f) Maurice V. Wilkes, *Automatic Digital Computers*, Methuen, London, 1956 [25].
(g) The 1956 DFG Bibliography that references Maurice V. Wilkes, *Automatic Digital Computers*, 1956 [25].
(h) *Engineering*, August 1909 [14]
(i) *English Mechanic and World of Science*, May 1909 and September 1909 [11][15]

Below are the results thus far in chronological order of discovery:

(1) From ETH Library Zürich [51]:

Proc.Sci.Royal Dublin Society, No.9, Vol.12, 1909: markings on the bound volume indicate that it found its way into our collection in the year 1909 (with small reservations); and the binding of the volume corresponds to the usual bindings of the time of the ETH Library, so this would be consistent.
Nature, No.2070, Vol.81, 1909: marks on our volume 81 (1909) of Nature indicates that it was acquired in 1909 and the binding of the volume is consistent with that.
IEE Science Abstracts, Vol.XII, 1909: The volume was acquired by the ETH Library in the year 1935, according to a marking in the volume.

(2) From Library of the German Patent and Trade Mark Office [68]:

Proc.Sci.Royal Dublin Society, No.9, Vol.12, 1909: not part of our collection.
Nature, No.2070, Vol.81, 1909: The accession date for this specific issue was July 10, 1909.
IEE Science Abstracts, Vol.XII, 1909: not part of our collection.
Napier Tercentenary Exhibition, 1914: not part of our collection **ALSO** there isn't any appearance of the "Scientific Proceedings of the Royal Dublin Society" in neither the 1954 volume nor the 1955 or 1956 one
Irven Travis, "Bibliography of Literature on Calculating Machines": not part of our collection.
Maurice Wilkes "Automatic digital computers"(1956): in 1956 edition of DFG Bibliography https://ld.zdb-services.de/resource/244327-2.
"A proposed analytical machine", Engineering, pp.256-257, No.2277, Vol.88, 20-Aug-1909: Accession was on August 28, 1909.

(3) From Bayerische Staatsbibliothek [69]:

Proc.Sci.Royal Dublin Society, No.9, Vol.12, 1909: does hold the publication … cannot give you any information on when the issue arrived
Nature, No.2070, Vol.81, 1909: does hold the publication … cannot give you any information on when the issue arrived
IEE Science Abstracts, Vol.XII, 1909: not in our collection.

(4) From the ZDB-Katalog, *Proc.Sci.Royal Dublin Society*, No.9, Vol.12, 1909, is held by at least 17 German libraries [75].

(5) From the ZDB-Katalog, *Nature*, No.2070, Vol.81, 1909, is held by at least 20 (but probably many more) German libraries [76].

(6) From the ZDB-Katalog, *IEE Science Abstracts: Section A.—Physics*, Vol.XII, 1909, is held by at least 12 German libraries [21].

(7) *Napier Tercentenary Celebration: Handbook of the Exhibition (also published as Modern instruments and methods of calculation)*, 1914, is held by no German libraries [78]. It is rare in Germany. One reason may be the sad fact that it was published during World War I. The ETH Library have a copy that was acquired in 1963.

(8) Irven Travis, *Bibliography of Literature on Calculating Machines*, pp.1-16, ISBN: B0008BAXBM, Moore School of Electrical Engineering, Univ.Pennsylvania, Philadelphia, 1938 [21] is not known to be held by any German libraries or the ETH Library.

(9) Maurice V. Wilkes, *Automatic Digital Computers*, Methuen, London, 1956 [25] is not known to be held by any German libraries or the ETH Library, but the Library of the German Patent and Trade Mark Office have confirmed that it is listed in the 1956 DFG Bibliography. The ETH Library has a 1957 print of the 1956 edition that was acquired in 1984.

(10) The 1956 DFG Bibliography that references Maurice V. Wilkes, *Automatic Digital Computers*, 1956 [25] is held by at least the Library of the German Patent and Trade Mark Office.

(11) From the ZDB-Katalog, *Engineering*, August 1909 (which includes the thus far only known diagram of Ludgate's machine), is held by at least thirty German libraries [79]. The "Publication History" for [79] includes "1.1866 - 210.1970/71", confirming that this is indeed *Engineering*, a London-based monthly magazine founded in 1865, that actually continues to this day, (but now only electronically).

(12) From the ZDB-Katalog, *English Mechanic and World of Science*, May 1909 and September 1909 (the latter also includes the thus far only known diagram of Ludgate's machine), are held by at least two German libraries [80].

It seems then that the April 1909 issue of Sci.Proc.RDS was able to be found in over eighty locations in Germany, either directly or via the July 1909 issue of *Nature*, the June 1909 *IEE Science Abstracts: Section A.—Physics* (where Ludgate's 1909 paper [3] is listed on the first page), or the August 1909 issue of *Engineering*. In addition, anyone interested in historical calculation/computation would be led to the 1914 *Napier Tercentenary Handbook* (although rare in Germany) containing Ludgate's 1914 paper on *Automatic Calculating Machines* [4] and thence from there to Ludgate's 1909 paper [3].

An important result for this investigation was provided by the Library of the German Patent and Trade Mark Office, which was able to confirm that the *Scientific Proceedings of the Royal Dublin Society* is not listed in the 1954, 1955 or 1956 editions of the DFG Bibliography, but that pre-1954 entries were listed in that 1954 first edition of that bibliography, although none that would lead to Ludgate's 1909 paper:

> The very short preface to the first list of the bibliography states that titles of newly published and older literature on computing systems are listed. We also found entries for older titles, e.g. from 1864 or 1898.
> It appears that the **Scientific Proceedings of the Royal Dublin Society** simply were not evaluated for this list.
> **IEE Science Abstracts** do not appear in the bibliography. **Nature** does appear, but only vol. 163, 169, 174, 175.

Table 3 summarises the institutions known to hold Ludgate's 1909 paper and its *Nature* and *IEE Science Abstracts* reviews, as well as the *Napier Tercentenary Handbook* and Travis *Bibliography of Literature on Calculating Machines*.

Institution	Sci.Proc.RDS April 1909		Nature July 1909		IEE Science Abstracts June 1909		Napier Tercentenary Handbook 1914		Travis Biblio 1938	Wilkes 1956
	Held?	*Deposit*	*Held?*	*Deposit*	*Held?*	*Deposit*	*Held?*	*Deposit*	*Held?*	*Held?*
ETH Zürich Library	✓	1909	✓	1909	✓	1935	✓	1963	—	1984 [20]
DPMA Library (Munich Patent Office)	—	—	✓	1909	—	—	—	—	—	
München BSB (Bayerische Staatsbibliothek)	✓		✓		—	—	reprint	1982	—	
Deutsches Museum			✓							
Bamberg SB	✓									
Berlin AdW Bib	✓									
Berlin SBB Haus Unter d.Linden	✓		✓		✓					
Berlin UBHU Grimm-Zentrum	✓									
Bochum UB					✓					
Bonn ULB AbtBib MNL	✓		✓							
Erlangen-Nürnberg UB	✓		✓							
Frankfurt/M UB/ZB	✓		✓							
Freiburg UB	✓		✓							
Halle/S Dt. Akad. Naturfor	✓		✓							
Heidelberg UB	✓		✓							
Jena ThULB	✓		✓							
Karlsruhe KIT-Bibliothek			✓		✓					
Konstanz Universität KIM					✓					
Leipzig UB	✓		✓							
München UBTU					✓					
Neubiberg UniBundeswehr			✓		✓					
Osnabrück UB					✓					
Potsdam Astrophysik	✓		✓							
Potsdam UB	✓									
Siegen UB			✓		✓					
Tübingen UB	✓		✓		✓					
Wien Öster. Akad. Wiss			✓		✓					
Wien UB/ÖZB-Physik			✓		✓					
Wiesbaden HLB Rheinstr.	✓									
Wuppertal UB					✓					
Manchester University John Rylands Library									✓ (x2)	
Trinity College Dublin Library										
John Gabriel Byrne Computer Science Collection	✓[21]		✓				✓			✓

Table 3: List of institutions known to hold Ludgate's 1909 paper and its Nature and IEE Science Abstracts reviews, as well as the Napier Tercentenary Handbook, Travis Bibliography and Wilkes 1956 book.

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