Planes and pacifism: Activities and attitudes of British mathematicians during WWI

Dr June Barrow-Green

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I would like to begin by thanking Gresham College, especially Barbara Anderson, and also the British Society for the History of Mathematics for their joint invitation to speak here this evening. It is a great honour to give a talk at Gresham, an institution both unparalleled in its list of distinguished professors and unrivalled in its history of public lectures.

The aim of my lecture is to tell you what British mathematicians did during the First World War. Now one of the things that distinguished this War from all others that had gone before was that it was the first to be fought in the air. The Wright brothers had made their first flight in 1903 and by the time War broke out in August 1914 considerable advances had been made but aeronautical theory was still in its infancy. For example, at the beginning of the war aircraft were being used only for reconnaissance - it had hardly been imagined that they could be used for anything else - and at that time the British Air Services possessed only 272 planes but by October 1918 the RAF possessed more than 22,000 planes and bombing was a matter of course.

The first part of the talk, which is concerned with two pioneers in aeronautical theory, FW Lanchester and GH Bryan, will include some prehistory. Having progressed with them into the wartime period, the discussion will move to two centres of aeronautical activity: the Royal Aircraft Factory and the National Physical Laboratory; and then on to the question of Anti-Aircraft Gunnery, and the work of Hill's Brigands and Pearson's human computers.

Finally, the locus will move to Cambridge where there were mathematicians not working on anything to do with the War. Some were under no compunction to do so - they were too old to be called up - but others were very deliberately not doing so: the pacifists and they will be the subject of the last part of the talk.

1) Two Pioneers: Lanchester and Bryan

My two pioneers, Lanchester and Bryan, both brilliant men, were from rather different backgrounds and had very different characters. Lanchester was not at all easy to deal with:

But for defects of character - quarrelsome nature etc - he would have been recognised for what he is as a very great man. His scientific intuition foresaw many of the developments and applications of aircraft... he has been one of the prophets - but unfortunately a very truculent and unreasonable one...

Bryan, on the other hand,

...was a friendly, kindly, very eccentric individual with a keenness for ' unsolved problems' .

FW Lanchester (1868-1946)

Lanchester studied at the Normal School of Science, a forerunner of Imperial College and concomitant with this, and despite the title of my talk, was not a mathematician. Nevertheless, his theories were crucial for the development of aeronautics and provided a basis from which mathematicians could work. It was in 1894 that he first put forward his fundamental circulation theory of lift in a paper (before the Birmingham Natural History and Philosophical Society) entitled ' The Soaring of Birds and the Possibilities of Mechanical Flight.'

But the paper was not understood and three years later when Lanchester tried to get it published, his efforts came to nothing. After that Lanchester rather lost interest in flight, becoming fully absorbed in his work on the design of motor cars, and it was not until 1905 that he really began working on aerodynamics again.

The result was his two volume Aerial Flight, published in 1907 and 1908, which contained his pioneering vortex theory of lift and although it was difficult to comprehend and was not accepted by other theorists, he began to be noticed. The first volume ' Aerodynamics' , included a discussion on propellers, while the second ' Aerodonetics' included a study of the motions of aircraft under aerodynamic forces and gravity, and investigated questions of stability. However, it was not a mathematical text, as Lanchester made clear in the introduction. Although little real notice was taken of Lanchester's ideas at the time, the book was well reviewed, although reviewers often conspicuously skated over his vortex theory. Later Lanchester said it had only excited interest when it was published due to the interest in flying generated by the activities of the Wright brothers. That said, it did run to four editions (1909, 1911, 1918) and it was the reason that in 1909 that Lanchester was invited to join the newly formed Advisory Committee for Aeronautics, an influential government body for whom he wrote several reports before and during the War.

Of Lanchester's contributions during the War, I will mention just one, hisAircraft in Warfare which was originally published in 15 weekly articles during 1914, and which contains one of Lanchester's most famous results: his N-square Law.

It was the scientific statement of a truth which had been used in the past but for the first time stated in figures and logically proved. And amongst the examples he included to demonstrate its validity was that of Nelson's victory at Trafalgar, when the British fleet of 40 ships triumphed over the combined French and Spanish fleet of 46 ships. [322 + 82 = 1088 (402 = 1600); 232 + 232 = 1058 (462 = 2116)].

GH Bryan (1864-1928)

Moving on to GH Bryan. Having studied at Cambridge, Bryan spent almost all his career as the Professor of Pure & Applied Mathematics at University College of North Wales, Bangor. In 1904 (together with WS Williams), he wrote a pioneering paper on the 'Longitudinal Stability of Aerial Gliders', and indeed the question of stability of aircraft was one that dominated his research. In this first paper he showed that the longitudinal stability was capable of mathematical investigation, and indeed the importance of mathematics for aeronautics was something that he continually stressed, often to the point of exasperation.

Typical in this regard were the two lectures on Aerial flight in theory and practice he gave to the Royal Institution in 1909, where an attendee reported:

... One thing which must have been noticed was the lecturer's repeated references to the necessity of mathematical knowledge on the part of those who undertook research work connected with aerial navigation. It was a remarkable fact, he said, that with very few exceptions those who had experimented with aeroplanes and airships did not possess a large amount of mathematical knowledge or knowledge of experimental physics. It was a pity that the practical and theoretical men had not worked side by side. Few of the experimenters knew what a biquadratic equation was, and the sooner they did the better it would be for them.

And in 1911 Bryan published his most famous work Stability in Aviation. In it he essentially developed the modern mathematical theory of the motion of an airplane in flight. Except for minor differences in notation, Bryan's equations are the same as those used today.

During the War Bryan continued his campaign on behalf of mathematics. In his Wilbur Wright Memorial Lecture on The Rigid Dynamics of Circling Flight given in 1915, the message was clear. The lecture had been introduced by Lanchester and it is interesting to note Bryan's opinion that Lanchester had reached the end of the line as far as managing without algebra was concerned

As the War waged on, Bryan pressed for mathematicians to get stuck in to aeronautical problems; and for engineers and mathematicians to work together. The pages of Nature are full of his appeals. One person who responded was Selig Brodetsky, then a lecturer at Bristol, who began work with Bryan at the end of 1915, and this example comes from Bryan's description of their work:

While we are making a fresh start in the study of the rigid dynamics of aeroplane motions, more recruits are needed if we are to arrive at anything approaching a clear understanding of the subject before the end of the war. In the meantime every aeroplane is to be regarded as a collection of unsolved mathematical problems. I have seen no reference to aeroplanes in connection with Section A of the British Association; and this in war-time!

Nature, January 1916

2) Aeronautics

Moving now to where the aeroplanes were being tested and theories refined: the Royal Aircraft Factory at Aldershot and the National Physical Laboratory at Teddington in Middlesex.

The Royal Aircraft Factory

The Royal Aircraft Factory, which started life in 1892 as the Royal Balloon Factory, was responsible for generating aircraft designs. These were mostly research aircraft but a few went into mass production, especially during the War. The Factory built some of the aircraft itself but the majority were built by private companies.

The personnel were largely drawn from Cambridge (in contrast to the Natioanl Physical Laboratory which tended to look to Imperial College). Among those who worked there were GI Taylor, the celebrated physicist and engineer; DH Pinsent a brilliant mathematician and a close friend of Wittgenstein but who died in an aircraft accident in 1918. There was also GP Thomson, who in 1919 published a textbook on Applied Aerodynamics which brought together much of the work that had been done at the Royal Aircraft Factory, and who later (1937) who won a Nobel prize for physics. And then there was Hermann Glauert, mathematically the most talented.

Glauert, described as ' a mathematician with quite unusual powers of verbal exposition'

had been a b* wrangler at Cambridge in 1913 (that is in the first class of the first class of the Mathematical Tripos) and was engaged in postgraduate research in astronomy and optics when he went to the Royal Aircraft Factory in 1916. He was one of the few of the theoreticians who did not want to get into the air himself, most of the others, such as GI Taylor, were desperate to do so.

During the war Glauert wrote a number of ACA reports, several of which concerned one of the most pressing problems of the time, the spin of an aeroplane, and on which very little work had been done. Given that stalling and spinning were a major cause of accidents and fatalities (eg in one month in 1918 of 106 flying accidents, 41 were attributed to spinning), Glauert's work in this connection was particularly important.

By all accounts Glauert was one of the most popular men at Chudleigh, the large house run as a private mess where practically everyone of note in aeronautics stayed at some time during the war, including Pinsent, Taylor and Thomson.

Amongst the aircraft developed at the Royal Aircraft Factory was the B.E.2c, which came into service in 1914. It was the first plane to be successful in intercepting and destroying German Zeppelins, and it:

... [the B.E.2c] showed conclusively that the line of argument developed by Bryan could be used to calculate the degree of stability of an aeroplane and so paved the way for the design of aeroplanes with the desired characteristics of indifference or stability as required for fighting or bombing.

National Physical Laboratory

The National Physical Laboratory (NPL) was founded in 1900, with the Department of Aerodynamics being founded nine years later. The latter was overseen by the Advisory Committee for Aeronautics (ACA) which itself had been founded in response to Bleriot's crossing of the channel which had demonstrated Britain's vulnerability to attack in wartime. The ACA's purpose was to give advice on the scientific problems arising in connection with the Admiralty and War Office in aerial construction and navigation; and it provided the link between the NPL, Royal Aircraft Factory, the universities and with industry.

Of the people working at the NPL, one of the most important was Leonard Bairstow who ran the Aerodynamics Department from its inception in 1909 until 1917. Other members of staff included Robert Jones and Dan Williams, two of Bryan's outstanding mathematics students.

Bairstow, like Lanchester, had been educated at a predecessor of Imperial College and, like Lanchester, he cannot be classified as a mathematician. He was an aeronautical engineer. Nevertheless, he made significant and important contributions to the relevant mathematical theory. He wrote 35 ACA Reports and became a member of the ACA Aerodynamics Committee in 1918.

One of Bairstow's main contributions to aeronautics concerned the theory of stability. In this he extended Bryan's investigations; putting Bryan's mathematics into more convenient form; and applying Bryan's theory by taking measurements in wind tunnels. And one of his ACA Reports included a long appendix showing how to find the numerical solution of the 8th order equations required by the theory.

Bairstow was involved in two great controversies in his career, both of which had a profound effect on the development of aeronautical research. One of these involved the discrepancies between measurements in wind tunnels and measurements made in an aeroplane in flight, i.e. the measurements made at the NPL versus the measurements made at the RAF respectively. These discrepancies were eventually traced to the difference in turbulence between wind tunnels and free air. As GI Taylor later remarked ' Models could be made geometrically similar to full-scale planes, model experiments could not be carried out under conditions of dynamical similarity.'

The other controversy, which I don't have time to go into here, involved the theory of the boundary layer of airflow round an aeroplane which had been proposed by the German physicist and engineer Ludwig Prandtl in 1904.

3) Anti-Aircraft Gunnery

Having discussed getting and keeping aeroplanes in the air, it is now time to discuss the activities of those engaged in is getting aeroplanes out of the air, i.e. the work on anti-aircraft gunnery.

Once the Zeppelin raids started in earnest, the pressing need for effective anti-aircraft gunnery became abundantly clear. On the 9th September 1915 Adelaide Davin, a member of Karl's Pearson's computing staff, wrote to Pearson to describe the Zeppelin raid over central London that she had witnessed the night before. This was in fact the worst Zeppelin raid in London during 1915 - 20 people killed and 86 injured, and it was estimated that over ½ million pounds worth of property damage had been inflicted on the area - and Davin concluded her account by observing that the anti-aircraft guns ' all went very wide of the mark.'

However, it must be remembered that since this was the first war to involve combat in the air, the theory and practice of anti-aircraft gunnery was only just being developed. But with increasing numbers of Zeppelin raids - the first had occurred over Norfolk in January 1915 - the improvement of anti-aircraft systems had become a matter of urgency.

The development of air defences was part of the brief of The Ministry of Munitions - the ministry created in the aftermath of the artillery shell crisis of 1915 which had helped to bring down the Liberal Government. The Ministry, initially headed by Lloyd George, had various divisions, one of which was the Munitions Inventions Department (MID).

When the MID was formed in August 1915, an Advisory Panel was assembled. This was a group of scientists the members of which included Horace Darwin, the fifth son of Charles Darwin, and founder of the Cambridge Scientific Instruments Company, and the electrical engineer Sir Alexander Kennedy. One of the principal functions of the MID was ' to investigate and experiment upon means for dealing with aircraft attack.' Thus they assumed direct responsibility for the group entitled the Anti-Aircraft Experimental Section or AAES.

The AAES had different sections, according to the type of work being done and its location. The two sections I shall be discussing are Ballistics based at HMS Excellent and computing based at UCL.

The story of the AAES began in early 1916 when Darwin and Kennedy, appreciating the need for training anti-aircraft gunners, had persuaded the MID to form a new section with a brief to deal with height and range finding. Charged with the task of finding someone to run the AAES, they sought out AV Hill, a physiologist from Cambridge, who had graduated as 3rd wrangler in 1907, then serving as a Brigade Musketry Instructor in the Infantry. Hill's priority was to find staff and so he went to Cambridge to consult with GH Hardy, with whom he had studied as an undergraduate, hoping that Hardy might be willing to come himself. Hardy was indignant in his response, saying that '... although he was ready to go off and have his body shot at he was not prepared to prostitute his brains for the purposes for war.'

However, Hardy did not seem to have any qualms about prostituting other people's brains because he recommended EA Milne, then a second year undergraduate, and RH Fowler, who had been a research student in pure mathematics when war broke out who was convalescing after having been badly wounded in the shoulder at Gallipoli.

Hill's Brigands

In assembling his staff, Hill met with considerable resistance from the recruiting authorities who had other ideas for their employment and without the ongoing support from Horace Darwin the entire enterprise might have collapsed. Shortly after Fowler and Milne were engaged, HW Richmond, a geometry don of some 30 years standing from King's, volunteered his services; and it was these three, Fowler, Milne and Richmond, who became the mathematical mainstay of the AAES. Other mathematicians and electrical engineers, old and young, were recruited or volunteered - the main requirement being an ability to calculate trajectories and fuze curves. As well as being a sound mathematician, Hill was an inspirational and good humoured leader - collectively the group became known as Hill's Brigands. Hill was also blessed with natural tact and diplomacy, attributes which would stand him in good stead as the war developed.

After a couple of false starts, the main part of the AAES finally settled at the Royal Navy's firing ground at HMS Excellent, near Portsmouth. They were officially assisted in their activities by Karl Pearson and his group of human computers at the Biometric Laboratory at UCL, as well as mathematicians working at the NPL.

This is probably a good moment to point out that there was no structured mobilisation of mathematicians during the War. Of the mathematicians who did contribute their skills to the war effort, the majority, like Richmond, did so on their own initiative, although it was not always easy for them to find an outlet for their talents especially if (as in the case of the group theorist William Burnside) they wanted to make a contribution but were not naturally drawn to ballistics.

So what did the AAES actually do? Their remit was pretty extensive - it included such things as investigating the dynamics of shell flight and the effectiveness of various instruments, and it involved ordinary as well as anti-aircraft gunnery. Two things in particular worked on by the mathematicians were the construction of range tables and the construction of fuze curves.

Those based at HMS Excellent were employed in making observations and developing the theory. There was much to do since different guns and different shells each required their own tests and observations.

The work was quite unlike anything that had been done in a military arena before and completely new theories had to be developed. Where previously the target had effectively been stationary, the target was now moving and moving in three dimensions. With flat fire only the point of fall is of paramount importance, whereas with AA gunnery, every point of the trajectory needs to be known and since the fuze needs to be set the flight time is critical. In addition there were factors such as wind speed; air density; aircraft speed, height, and rapidity of manoeuvre; as well as lack of visibility of the aircraft (there was of course no radar).

Now the problem that needs to be solved is what is known as the external ballistic problem. The problem breaks down into two parts: the primary ballistic problem which is the determination of the plane trajectory of a given shell in still air, assuming certain relations between resistance and velocity, and between density and height, and neglecting all effects of curvature and rotation of the earth. And secondary ballistic problemswhich involve corrections for errors caused by assumptions as to the shell and the types of air forces acting on it.

What adds substantially to the complications for anti-aircraft gunnery is that the density of air, since it varies with height, needs to be taken into account - for flat fire it can be considered as constant.

The primary ballistic problem requires the solution of differential equations. However these equations cannot be solved exactly, so an approximate method of solution must be used to calculate any given trajectory. Essentially there are three methods of solution: One involves calculating each point on the trajectory independently but this is not suitable for high angle fire since there are too many points to calculate, although it has the advantage that an undetected error affects only one point. A second involves integrating the equations numerically using a step-by-step process ('small arcs') but the calculations at end of one step affect those at the beginning of the next. And the third involves calculating the trajectory by interpolation with previously calculated trajectories, although the interpolations need to be performed on quantities that vary slowly over a small range. And of these methods, the AAES used the latter two.

As far as the activities of the AAES are concerned, a good source of information is the correspondence between Milne and his younger brother Geoffrey who was still at school, as they are informative both about life as a member of the AAES, and about the public attitude to AA defence. On the 19th October 1917 there had been a particularly bad Zeppelin raid, in which 11 Zeppelins had attacked London, and not only had a single one not been shot down, no shots were even fired. This caused an outrage in the popular press and questions were asked in the House. What made matters worse was the fact that the Zeppelins had then flown over France and the French had managed to down the majority of them. The English public was not at all happy. But as Milne explained to his brother, the outrage was based on complete ignorance of the situation. The raid took place on a cloudy night, so it would have been impossible for the anti-aircraft gunners to even see the Zeppelins, so there was no point shooting. Moreover, not only were the Zeppelins over France in daylight but also due to the strong wind, they would not have realised that that was there they were until it was too late. So the point was that the French should not be congratulated for shooting down 4 or 5 of the Zeppelins which were easy targets, but that they should be castigated for not shooting down the lot.

Later in the same letter, Milne explained the role of the AAES: 'designing new guns, new fuzes, new methods of fire' and 'pointing out faults' in the current weaponry. And he made the point that whatever improvements or devices they invented, there was inevitably a time lag, sometimes of almost a year, before they could be implemented. He also drew attention to the barrage system being employed in London at night:

Pearson and his human computers

The other half of the work of the AAES - the computational half was done in the Biometric Laboratory at UCL under the leadership of Karl Pearson. Pearson had begun his career at UCL as Professor of Applied Mathematics but in 1910 had changed his position to become Professor of Applied Statistics.

From the outbreak of the War Pearson had been involved in war-related work. He worked for the Board of Trade producing unemployment charts and import tonnage charts, for the Royal Aircraft Factory calculating the torsional strain in the blades of airplane propellers, and for the Admiralty Air Department calculating elastic constants of wood and bomb trajectories. But then at the end of 1916 he offered to help Hill with his calculations. And in December 1916 Hill wrote to Pearson jumping at the offer.

Somewhere else where ballistics calculations were being done, and which was also keen to use Pearson and his computers, was Woolwich where JE Littlewood was working, as Hill pointed out to Pearson.

An idea of the number of staff working for Pearson and the conditions under which they worked is evident in this letter from the MID to the Provost of UCL, written in July 1917, which singled out three men and three women as being particularly valuable to the enterprise. Women were an important constituent of Pearson's staff. Not only was Pearson supportive of women per se but the escalating demands of conscription meant that with respect to his male staff he, like Hill, had ever increasing difficulties in keeping the recruiting sergeants at bay.

We can get a good idea of how hard and how quickly Pearson and his team worked from the fortnightly reports prepared by Hill. In the Reports Hill describes the activities of the Section, listing the personnel, their achievements, and what he hopes they will achieve. The work of the Laboratory more than fulfilled Hill's expectations. In March 1917 he considered their diagrams and tables 'to represent the highest accuracy ever attained in the ballistics of High Angle Gunnery, both from the accuracy of the experimental data, the exactness of the drawing, and the care expended in the calculation.'

Typical of their work was the calculation of fuze curves. The time fuze is a device intended to explode a shell at a specific moment after firing but since there is no significant chance of a direct hit, the aim is to burst the shell close to target, and hence it is necessary to know (accurately) the behaviour of the time fuze.

This is part of a graphic range table for a particular gun, shell and fuze. Curves of constant quadrant elevation, constant fuze, and constant time are plotted with horizontal ranges and heights as abscissa and ordinate respectively. The angles of sight are marked on a scale around the edge of the chart which are not visible here.

In order to use the table you need to know the height and the range of your target but once you know those you can read off the angle of sight, the quadrant elevation and the fuze setting required to hit it. For example:

Height of target is 11,000 ft. Horizontal range is 5,500 yds.

What is its angle of sight, and what Q.E. and fuze setting would be required to hit it?

Angle of sight is 33.80. Q.E. is 400. Fuze setting is 13.9.

The Biometric Laboratory also provided ordinary as opposed to graphic range tables. This particular one tabulates tangent elevations, fuze settings, ranges and times of flight for clear heights and angles of sight, and other tables can be constructed from it either by interpolation or drawing curves.

These tables were computed to a high degree of accuracy, e.g. the times of fuzes to 100th of a second, and at one point Pearson questioned Hill as to whether such a high degree of accuracy was really essential. Hill explained that it was purely to appease the powers that be who thought it was necessary. This exemplifies a consistent theme: the lack of understanding by the military of the work that was being done by the mathematicians. Hill was regularly annoyed by staff officers who needed to be convinced not only that it was possible to find the height of an aeroplane from the ground, but also that it was actually useful to know the height when it was found. At its most extreme, there were those who thought that there really wasn't any need to construct new range tables for anti-aircraft gunnery - surely all you needed to do was to turn the flat fire range tables through 900!

Hill was quite explicit about the difficulty of dealing with the military. Here, in a specific example of this difficulty, Hill is responding to a query from Pearson, about the possible heights reached by German planes.

With reference to your queries of the Boche flying above 21000 feet. Only freak machines have ever been to heights of 24 and 25000 and there is absolutely no reliable evidence that his machines are flying at these heights. In the recent raids they have been flying at 14000. Various incompetent people have turned long base height finders on to the whole enemy squadron and probably got the opposite ends of the base on different targets. That is the explanation of these so-called heights of 24000. They might equally (and probably do) get negativeheights by the same means but they cannot bring themselves to believe the latter so we do not hear of them. 18000 is the greatest recorded height of any German military machine.

Now it is course one thing to produce accurate range tables but how easy were they to use in the field? So far I have not managed to gather any first-hand testimonies but we can get some idea from Hill himself who went to France with the British Expeditionary Force in May 1917 and wrote to Pearson:

I think you and your people would be really gratified if you could be out here for a few hours and see how your diagrams are regarded. I have seen several [...] Officers [...] at G.H.Q. They affirm without hesitation that these diagrams are invaluable and fulfil a long felt want: that they are beautifully done and printed [...] and that people here are really grateful for these charts. They seem to spend hours every day poring over them, measuring them and reading things off them. And they want to have a dozen each so they can draw on them and use them generally. Please tell your people of this.

Now of course not all this calculation that was being done by Pearson and his human computers was being done by hand. Pearson had nine mechanical calculators that were constantly in use - in fact so constantly, that they were beginning to wear out. The trouble was that it was virtually impossible to get them repaired, not least because they mostly originated from the Continent, e.g. the ubiquitous Brunsviga, from Germany. In July 1917 in an effort to try to make up the shortfall, Pearson appealed through the columns of Nature for calculating machines to be bought 'at a reasonable price'.

And the appeal met with at least one offer. This was from Arthur Schuster, erstwhile Professor of Physics at Manchester, who was retired but keeping himself active as Secretary for the Royal Society. Schuster having been born in Germany of German parents had rather a difficult time in the War but nonetheless was fervently patriotic to Britain. Thus to offer the use of his calculating machine was an entirely characteristic gesture.

But not all was sweetness and light between Pearson and those at HMS Excellent. And in the autumn of 1917, there was a significant difference of opinion between him and Richmond. Richmond, quite innocently, had queried some calculations which did not seem to him to correspond with the data. Pearson took immediate umbrage. He considered a slur had been cast on the ability of his computers, and decided to resign from the project. While Richmond might have gone about things slightly differently, it was nonetheless a reaction out of all proportion to the event. And it meant that Hill had to bring all his diplomatic skills in to play to keep Pearson on board, even going right to the top of the administrative tree, and writing to Colonel Goold Adams, Comptroller of the MID, concerning what became known as 'the Richmond incident'. The Richmond incident reverberated around the staff of the AAES, and it transpired that some time earlier Milne too had had a not dissimilar incident with Pearson.

Nevertheless, the truth of the matter was probably that Pearson, who had been working for the AAES non-stop for almost a year while at the same time trying to keep his other research going, was exhausted and looking for an excuse to leave. Pearson and his staff had worked tirelessly on ballistics problems for the whole of 1917 almost without a break. Apart from one week at Christmas the Biometric Laboratory was never closed. And for most of that period Pearson had a staff of eight to ten computers and draughtsmen working with him. Given the nature of the work and the long hours he spent on it, it is not perhaps surprising that he over-reacted to Richmond's remarks.

In February 1918 he wrote a Report to the Worshipful Company of Drapers, the City Livery Company that sponsored the Biometric Laboratory. While one may scent a whiff of self-congratulation in theReport, Pearson was writing for the sponsors of his Laboratory and as such it would have been important to portray his activities in the best possible light. The Report includes a concise description of the work he had undertaken during the past year as well as referring to its effectiveness in the field. As his parting salvo, he once again referred to the importance of keeping his team of computers together. To Pearson the idea of collective and/or collaborative working in the Laboratory was absolutely fundamental, irrespective of whether the country was at war or not.

Towards the end of March, Pearson finally decided to give up running the show and told Hill of his plans. Hill expressed his thanks and appreciation for all that Pearson had done, saying

If it had not been for your help a large part of the work done by the AAES could never have been done, and the present stage of development could never have been reached.

'Archie' [anti-aircraft gun] has not done much up to date, but the production of your diagrams has done more I think to educate the gunners up to the developments which will now really occur within a few months than any other one link in the chain of 'Archie's' evolution as a scientific weapon.

But what did Hill really think of Pearson? It is clear that Pearson was not an easy person to deal with. He was a perfectionist, certainly, but tolerance was not always his strong suit. Much later in life when Hill recalled his time working with Pearson, he said that he 'was not easy to instruct', that he had a 'dominating and pugnacious spirit, controlled by a passion of loyalty and desire to help, in what must have been, for him, the very distasteful role of accepting advice and instruction from people much younger and less experienced than himself'. And Hill did refer to the Richmond incident, unequivocally putting blame for the calculating error on Pearson. Nevertheless, he spoke about him as a friend and with affection.

Pearson gave up working for the AAES at the end of March 1918. He went gracefully, making pains to ensure that the handover to his successor, Arthur Doodson, went smoothly. Without Pearson, there was little reason for the work to be done in the Biometric Laboratory, and Pearson made arrangements for the team to be transferred to Woolwich, which was in many ways a more practical location than UCL, since it meant that there would be ballisticians and computers working on the same spot.

After the war was over Richmond took on the enormous task of compiling a record of the theoretical and experimental advances in which the AAES had been involved. The result, the Textbook of Anti-Aircraft Gunnery, was a 2 volume work of 1300pp to which many members of the AAES contributed and which was published in 1925. The information it contained was so comprehensive that it was still in use in the Second World War. It was a classified document which explains why copies of it are not to be found in the British Library or any other copyright library in Britain. I got my own copy from a bookshop in Winnipeg!

4) Cambridge

Moving now to Cambridge. As we have seen, several of the mathematicians involved in war-related work were recruited from Cambridge, and many of the others had Cambridge connections. And this is of course not surprising since Cambridge was the centre of mathematical activity in Britain at the time. However, what is rather more surprising is the number of Cambridge mathematicians who were either conscientious objectors or displayed pacifist sympathies. I was initially alerted to this fact by a remark made by Hill in one of his letters to Pearson 'I don't know why so many mathematicians are conscientious [objectors]: it is sad though a fact.', a remark which was re-enforced by the contents of the wartime diary of the Cambridge mathematics student and conscientious objector, FP White.

Let me begin by giving a brief rundown of events leading up to conscription. After War was declared (on the 4th August 1914), three main groups emerged which either opposed conscription or were pacifist.

The Union of Democratic Control (UDC) (formed the day after the outbreak of War), pressed for a more responsive foreign policy and was concerned with settlement after the war. It was not pacifist but it was strongly against conscription and many members became conscientious objectors. GH Hardy was Secretary of the Cambridge branch.

The No-Conscription Fellowship (NCF) (formed in November 1914) had as its first purpose the fighting of conscription by parliamentary methods; but it contemplated resistance to military service if conscription was enforced. A large proportion of members were Quakers and from other religious bodies, and almost all became conscientious objectors after conscription.

The Fellowship of Reconciliation (FOR) was a Christian pacifist organisation (formed at end of December 1914). It was largely inconspicuous during hostilities but emerged to lead pacifism after the War.

On the recruitment side, the Derby Scheme, which was a personal canvass of every man on the Electoral Register, ran between October and December 1915 - it ended because over 500,000 men had refused to fill in the form. The Military Service Act which brought in the first wave of Conscription became law on the 24th January 1916. By April 1918, after four revisions to the Act, Conscription applied to men between the ages of 17 and 51, and a network of over 2,000 Tribunals had been set up to administer the system and to hear appeals.

Meanwhile in Cambridge, the student numbers dropped dramatically - from over 3,000 in 1914 to 533 in 1918, with the numbers taking Part II of the Mathematical Tripos dropping from 59 to 4, and of the latter all three wranglers were Indian. The number of mathematics lectures declined likewise - in 1914 16 lecturers gave a total of 37 courses, while in 1917 4 lecturers gave a total of 6 courses. (Altogether some 16,000 men from Cambridge served in the War, with over 6,000 either killed or wounded.)

White's diary, which ran through the years 1915 and 1916 - the years he was doing the Tripos and beginning postgraduate work?gives a lot of information about the activities of pacifist students and their lecturers. White came from a solid middle class background in Islington - his father was a schoolmaster - and his pacifism, which caused his father great distress, was born out of a deep religious conviction. The diary which contains a wealth of detail about life at Cambridge (mathematical and otherwise), includes descriptions of meetings of the UDC, NCO and FOR, as well as descriptions of Tribunals, as well as White's thoughts about his personal situation. In total White attended five different Tribunals before eventually being given non-combatant exemption and agreeing to work for the Friends Ambulance Unit.

One thing that comes across very clearly in White's diary is the striking difference in attitude towards conscientious objectors between those within the academic confines of Cambridge and those within his home environment in London. White had many Cambridge friends who went off to fight and with whom he maintained a close contact - they understood and respected his position. Whereas in London, the attitude of his family and the neighbours was quite different - the former simply didn't understand, while the latter not only didn't understand, they didn't respect either, equating conscientious objection with cowardice.

Perhaps the most difficult to pin down in the pacifist spectrum is GH Hardy. Hardy, originally signed up under the Derby scheme but was rejected on medical grounds, but as we heard earlier, he was not prepared to do war-related research. He was certainly supportive of those with pacifist inclinations, and indeed interceded on their behalf. For example, in the case of Sydney Chapman, later renowned as a geophysicist, Hardy asked Joseph Larmor, the Lucasian Professor, if he could write a strong statement on the importance of Chapman as an applied mathematician. And while Hardy often went to Tribunals to support applicants he knew, he nevertheless bluntly stated that he 'didn't like conscientious objectors as a class.'

With respect to Hardy's general attitude, White's diary provides a revealing anecdote:

Then heard an excellent story about G.H. Hardy. He has recently published a Cambridge Mathematical Tract in conjunction with Marcel Riesz (and is awfully bucked at having produced something in collaboration with an enemy in war time). Riesz lives at Copenhagen and Hardy had occasion to write to him on some mathematical subject and the letter contained a good many mathematical symbols - also he mentioned the name of a German worker at the end. The censor got hold of the letter, determined from the German name that it must be a code message and spent hours trying to interpret the symbols as a cipher. Failing altogether he refused to let the letter through.

Arthur Eddington, the Plumian Professor of Astronomy was a Quaker, and hence a pacifist on religious grounds. Even though the University applied for exemption for Eddington on the grounds that he was essential to the work at the Observatory, Eddington also applied on his own behalf as he wanted it on record that he was a conscientious objector. On the 10thMay 1916 White reported:

Then to Guildhall for Local Tribunal. Listened to case of Milne (who got off as he is doing anti-aircraft work) and the University appeals for Pigou, Eddington etc. It was most undignified to see the V.C. and the Master of John's etc pleading to be allowed to keep these men. What is the University coming to?

Best known amongst the pacifist mathematicians is of course Bertrand Russell, who was initially very active in the UDC, having helped to found the Cambridge branch.

But before long he began to find the UDC's call for peace to be negotiated irrelevant to the pressing needs of the day, and gravitated to the NCF. His ever more vocal advocacy of NCF positions, his protests against the unjust treatment of conscientious objectors, and his criticisms of the war made him more and more unpopular in the country, but he was well connected and difficult to touch. Eventually, however, when in June 1916, after having admitted in a letter to The Times to the authorship of an NCF leaflet, he was convicted of '...making statements likely to prejudice the recruiting and discipline of His Majesty's forces', Trinity, moved against him and the College Council (made up of Fellows) voted to dismiss him from his lectureship.

The following month a number of (mostly the younger) Fellows, sent a protest to the Council against Russell's dismissal. Both non-pacifist and pacifist mathematicians signed. Amongst the former were Fowler, Littlewood, Proudman and Whitehead, while the latter included Eddington, Hardy, Barnes, Neville and Chapman.

Of the latter, Barnes, who was a friend of Russell's and an ardent pacifist, had been second wrangler in 1896 and had had a strong reputation as an analyst. But he had also been ordained as a priest in 1903, and his outspoken views were not compatible with his those of many of his Trinity colleagues and in 1915 he left to become Master of the Temple, eventually becoming Bishop of Birmingham (in 1924) a position from which he gained considerable notoriety for his unorthodox opinions, and in particular his 'gorilla sermons' supporting evolutionary theory.

Neville on the other hand is probably best known as the man who on Hardy's instructions sought out Ramanujan in Madras and persuaded him to come to Cambridge in the spring of 1914. Due to his pacifist stance, Neville's Trinity Fellowship was not renewed at the end of the War and he left Cambridge, spending the rest of his career at Reading University.

One of the staunchest pacifists was Ebenezer Cunningham, former senior wrangler, and a lecturer at St John's, who in 1914 had been the first to publish in English on relativity theory. Cunningham's pacifism, like Eddington's and White's was based on a religious conviction, and it had at its roots the horrors he had felt at the events of the Boer War. Young enough to be called up, he got exemption and spent the latter part of the war years working on a farm, before returning to Cambridge, his best mathematics behind him.

My last example is of someone who was not a through and through pacifist, nevertheless he did describe himself as conscientious objector 'more or less'. He is Max Newman, who was later to play an important role in code-breaking in World War II. Newman, who had a German father and changed his name, went up to St John's College in 1915 where he would have been in contact with Cunningham and White. After a year he left to spend some time in the Army as a paymaster before becoming a schoolteacher, which is what he was doing when in February 1918 he wrote the following in a letter to Harold Jeffreys (who incidentally was a very close friend of White's).

I have become a Conchy, more or less, skilfully welding any objections, as I call them, on to my unfortunate father's place of birth. I am seeking exemption from military service, but am not refusing Work of National Importance.

Code-breaking

Having mentioned code-breaking in connection with the Second War, this naturally raises the question of what mathematicians did in this respect during the First War. The simple answer is 'almost nothing' for it was not in general seen as a mathematical activity, as the following excerpt from a memo of March 1918 from an official in the British Embassy to the Cipher Bureau in Washington, makes clear.

Suffice it to say, code-making and code-breaking during the First World War (which relied heavily on the use of codebooks) were very different activities to those in the Second. And while it is undoubtedly the case that an education in classics, linguistics or palaeography provided a perfectly sound background for cryptography in this period, to categorically deny the usefulness of a mathematically trained mind in this context, does I would suggest appear somewhat bizarre.

Conclusion

So in conclusion, what lasting effect did the First World War have on British mathematics? Was there any way in which the mathematical landscape in Britain was irrevocably changed because of the War?

It was certainly the case that during the War there was woefully little overt recognition of the value of mathematicians or of the use of mathematics itself as an essential tool in the development of effective defence systems. But mathematics was not alone in this respect. Throughout the War the organisation of science suffered from a general lack of coherence and poor communication. In Britain scientists did not have the same reputation as their Continental counterparts and the fighting forces often resented the offering of scientific advice. Very few civil servants, let alone the military, had any scientific knowledge. The startling lack of comprehension by some senior officers of the nature of the work being done resulted in the Government's failure to support some of the most urgent and essential research

Thus while there were many mathematicians who wanted to use their abilities for the good of the country during the War, the country did little to encourage them. Without doubt the most active group was Hill's Brigands who played a vital role in the develop-ment of anti-aircraft gunnery. But the evidence shows that their success had rather more to do with their leader, Captain AV Hill, than the efforts of the official bodies. Hill, although a physiologist by inclination (and later winner of a Nobel prize for medicine), was not only a competent mathematician who understood what mathematics was required and recognised the urgency of the task, but importantly provided the social glue which kept the group together. He was also an expert when it came to dealing with officialdom and ensuring that he got what was necessary in order to get the job done.

Postwar, there was certainly a change of attitude and scientific institutions such as the NPL and the Royal Aircraft Establishment certainly benefited from an increased number of mathematicians on their staff. With regard to the subjects taught and researched in the universities, it is hard to detect much in the way of organised change as a result of the War. Nevertheless, the conflict did affect the careers of a number of mathematicians and in this way it did have an effect on the nation's mathematics.

At the outbreak of War both Fowler and Milne had been set for careers in pure mathematics but as a result of their experience with Hill, by the end of the War their interests had completely changed. Hill was later to write that 'Kaiser William and I, jointly, did good service to science in diverting both RH Fowler and EA Milne from pure mathematics to other fields'. Both Fowler and Milne had impressive careers in areas of applied mathematics: Fowler in statistical mechanics and Milne in astrophysics. Fowler became Plummer Professor of Mathematical Physics at Cambridge in 1932 and Director of the NPL in 1938. While Milne became Beyer Professor of Applied Mathematics at Manchester in 1924 and Rouse Ball Professor of Applied Mathematics in Oxford four years later.

And of course there were those whose future career was specifically defined by their work during the War. Glauert, for example, remained at the Royal Aircraft Establishment where he wrote numerous influential reports and eventually became head of the aerodynamics department in 1934, although he was tragically killed in freak accident on Fleet Common shortly afterwards. Douglas Hartree's experience in calculating trajectories for the AAES marked the beginning of his work in computation, a subject in which he later he came to be regarded as 'a world leader'. Bryan's student Dan Williams went on to have a distinguished career as an aerodynamicist at the NPL. While on the other side there was Neville who was sidelined from Cambridge and Barnes who left mathematics altogether.

And of course the war provided additional opportunities for women to become involved in mathematical and computational activities. Apart from the women working with Karl Pearson, there were also women, mostly ex-Cambridge, such as Hilda Hudson, who worked in the Admiralty Aircraft Production Department and in 1919 received an OBE for 'Aerodynamics Technical Research'; and Lorna Swain who worked at the Royal Aircraft Factory on vibration of propellers of aircraft.

The War had a different effect on the career of GH Hardy. Trinity College's wartime treatment of Russell had left him disillusioned with Cambridge and in 1920 he left for Oxford where he took up the Savilian Chair in geometry, staying there for 11 years, until in 1931 he returned to Cambridge as Sadlierian Professor of Pure Mathematics. Hardy had an enormous influence on every aspect of Oxford's mathematical life. Not only with his immense mathematical ability but also by actively promoting mathematics in many quarters, arguing for an increase in the number of college Fellows and making the case for a dedicated mathematics institute. There can be no doubt that Hardy's move to Oxford shaped the course of mathematical development there.

Then there was the tragic loss of EK Wakeford in 1916. Wakeford had been a b* wrangler in 1914 and had been quickly recognised as a young geometer of uncommon knowledge and power. He wrote a fellowship dissertation on the theory of Canonical Forms, and when he died, although not a member, the LMS exceptionally published his obituary. It closed with the haunting words 'He only needed a chance, and he never got it.'