BIOGRAPHICAL MEMOIRS

William Thomas Tutte. 14 May 1917 –– 2 May 2002

D. H. Younger

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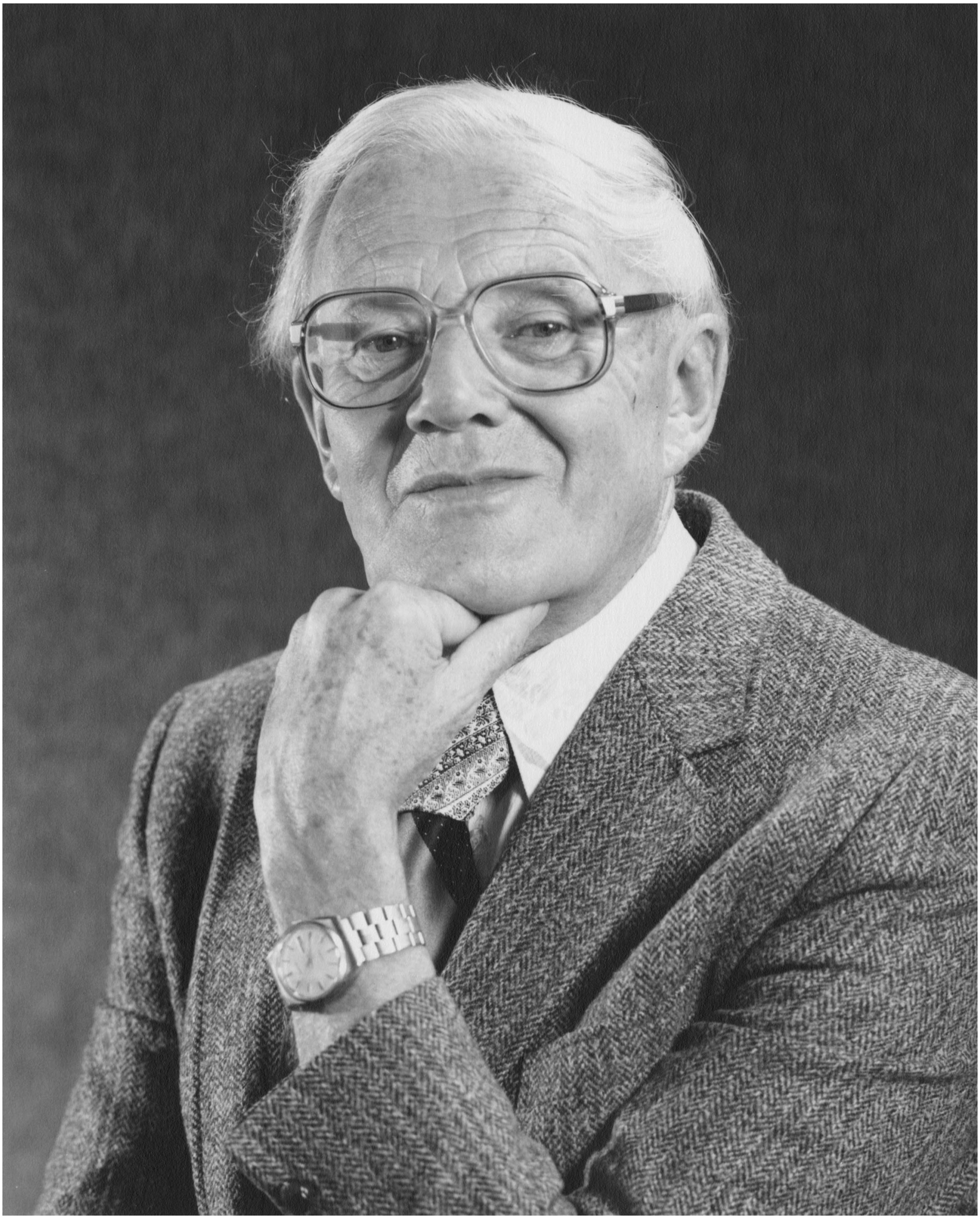

W T Tutte

WILLIAM THOMAS TUTTE

14 May 1917 — 2 May 2002

Elected FRS 1987

By D. H. Younger

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William Tutte, born in Newmarket, completed a master's degree in chemistry at Cambridge at the end of 1940, whereupon he was recruited to work at Bletchley Park as a cryptographer. He became the primary person responsible for breaking the Fish code used for high-level Army communication. After the war he returned to Cambridge as a Fellow of Trinity College, for three years of study for a PhD in mathematics. On completing his degree in 1948, he joined the Faculty of the University of Toronto, where he rose to pre-eminence in combinatorics. In 1962 he moved to the University of Waterloo, where he had a significant role in the development of the university and its Faculty of Mathematics.

Jeanne Youlden, the niece of William Tutte, received the letter shown in figure 1 concerning Tutte's codebreaking work from the Prime Minister, David Cameron.

Family

William Tutte was born on 17 May 1917 at Fitzroy House, Newmarket, Sussex. His father, William John Tutte, was the gardener at that House; his mother, Annie Newell, was the housekeeper. They had just one other child, Joseph, 16 years older than Bill. Joseph and his wife, Lola, had two children, Joseph and Jeanne. Bill's grandparents lived in Burnham Beeches, Buckingham: his paternal grandfather, Thomas Tutte, was a policeman; his maternal grandfather, Joseph Newell, was, as known to Bill, an 'exploder of tree stumps'.

Early years

In Bill's early years, the family moved several times: they lived for a while at Englefield Green, not far from Burnham Beeches. They then moved to Croft Spa, Durham, where Lewis

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10 DOWNING STREET
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THE PRIME MINISTER

30 March 2012

Dear Mrs. Youlden,

I am writing to you to express my personal thanks and the United Kingdom's gratitude for the work of Professor William 'Bill' Tutte.

The success of the cryptographers at Bletchley Park was an iconic British triumph of the Second World War and their achievements represent one of history's greatest intelligence successes.

We should never forget how lucky we were to have men like Professor Tutte in our darkest hour and the extent to which their work not only helped protect Britain itself but also shorten the war by an estimated two years, saving countless lives.

I know that Bill's contribution to the cryptanalysis of the Lorenz cipher, which allowed the Allies unparalleled access to the intercepted high level German communications, was of enormous value to the war effort.

I understand that, partly owing to the secrecy of his work, Professor Tutte was never honoured officially in his lifetime, although he undoubtedly held the respect of those in his field. Whilst the only honours that can be awarded posthumously are those for gallantry I can say without a doubt that Bill Tutte deserves the thanks of the British people.

Yours sincerely,

David Cameron

Mrs Jeanne Youlden

Figure 1. Letter from the Prime Minister to Jeanne Youlden.

Carroll had lived as a boy; as an adult, Tutte loved Carroll's playful wit and mathematics-based imagery. When Bill was about four years old, the family moved to Yorkshire, where his parents became caretakers of a house called 'Moorend' in the village of Aislaby, about three miles inland from Whitby. Tutte later referred to this as his Garden of Eden. He loved the bracken and gorse, the wild bilberries, the heather and the buttercups. There was from the moor's edge a sweeping view of the Esk valley far below. He 'loved the sandy beaches at Whitby and the hundred and ninety-nine steps, and the Church and Abbey ruins to which they led.'

It was at Aislaby that he began school. Vivid in his memories were observations of nature, of geology and of plant life. And there were psychological conundrums: 'Sometimes we went to Aislaby Church. I firmly believed that the inside of that building was bigger than the outside.' When Bill was about age seven years, his family returned to the Newmarket area, to the village of Cheveley, located about three miles southeast of Newmarket, but across the county line, in Cambridgeshire. The family lived in a flint cottage, the far half of a duplex, reached by a footpath from the end of Church Lane. His father worked as a gardener at Banstead Manor in Cheveley, and later at the Rutland Arms Hotel in Newmarket. The family lived in that cottage until his father's death in 1944.

Bill attended the local school, directed by the Church of England, located near the 600-year-old church that dominated Cheveley. There were lessons in the Bible, Church history, and the history of Great Britain; in each of those areas he would grow to be learned. His favourite subjects were the sciences and mathematics. One of these sciences was geology—he looked 'for fossils in the chalk pits around Cheveley: they were mostly lamp-shells, other bivalves, and sea urchins.' Other special interests were astronomy and evolution. He pursued these interests by voracious reading in the volumes of *The children's encyclopedia* (Mee 1912), which the school possessed.

Concerning his early experiences in mathematics, Bill had this to say: 'At some time during my early schooling I was introduced to the prime numbers, and I was much fascinated by them. I learned how to find the highest common factor of two integers, using what I was later to call Euclid's Algorithm. Later I was introduced to ruler and compass constructions. I learned how to bisect segments and angles, how to divide an angle into four equal parts, and how to partition a segment into any desired number of equal parts. But I was much perplexed because my little text-book entirely ignored the related problem of dissecting an angle into three equal parts.' He later wondered what his text-book should have said about this intractable problem.

In May 1927, as Bill was reaching age 10 years, he took the scholarship examinations for secondary school. He won a scholarship, as did another boy, a success so notable that the headmaster at Cheveley declared a half-day school holiday in celebration. The high school in the city of Cambridge was 18 miles distant. There was another closer secondary school in Cambridgeshire that Bill could have gone to, but apparently the headmaster felt that the central school would offer greater prospects. Too distant, his parents judged, and he was kept at home. A year later, he took the same examinations, was successful once again, and this time his parents permitted him to attend the Cambridge and County High School for Boys. It involved a long daily commute each way, by bike and by train.

Bill Tutte continued his successful academic ascent in the new school: 'I remember with pleasure my courses in English history. But I was chiefly interested in the scientific subjects, including mathematics. One stimulus that seems to me supremely important came from outside the regular curriculum. In the school library I came upon a copy of Rouse Ball's *Mathematical Recreations and Essays* [Ball 1892]. There I found much information about graph theory and more general combinatorics. I read the basic theory of the Four Colour Problem and a discussion, without proofs, of Petersen's work on cubic graphs. This was my first encounter with the subject in which I was later to specialize.'

'In 1933, at the age of sixteen, I had to decide whether to leave school or to stay on for another two years, preparing for University. I stayed on, my scholarship continuing.'

Here is a snapshot from his experiences in mathematics at that time: 'There was a course on algebra in which I learned to solve quadratic equations, to sum arithmetical and geometric series and to manipulate simple determinants. I was sufficiently aroused by my series-summing to look around for other series to experiment with. I dreamed up a series which had first term 0 and second term 1 and in which each term thereafter was the sum of the two preceding. Some years later I learned that this was called the Fibonacci series. I spent much of my spare time trying to find a formula for its sum to *n* terms. At last I noticed that there were two geometric series with the same additive property and that my series was but a linear combination of the two. I then got my formula. The episode stands out in my memory as an early occasion in which I practiced real mathematical research.'

Trinity College

In October 1935, Bill Tutte entered Trinity College, Cambridge: 'I was adequately supported financially by a State Scholarship, a College Scholarship, and a grant from the County.' His field was the natural sciences, with specialization in chemistry. However, from his first days, he attended the lectures of the Trinity Mathematical Society. 'As time went on, I yielded more and more to the seductions of Mathematics.'

In his first three months, Tutte came to know three other members of the Trinity Mathematical Society: these were R. Leonard Brooks, Cedric A. B. Smith and Arthur H. Stone. Like Bill, they were in their first year; unlike him, they each majored in mathematics. They spent many hours together discussing mathematical problems. One of the first, proposed by Bill, concerned an exponential function. Soon 'we switched to another problem, the geometrical one of dissecting a square into smaller squares, no two of the same size.' It came from a puzzle book by H. E. Dudeney, *The Canterbury puzzles* (Dudeney 1907). One puzzle is about a Lady Isabel's casket: it asks for a tiling of the lid, with given dimensions, that uses wooden squares of different sizes. The answer in the back of the book mentions, as an aside, that the tiling given there is unique. This led Arthur Stone to observe that uniqueness would be possible only if a square could not be divided into unequal smaller squares. Stone could not verify that, and turned to his three mathematical friends for help. 'This led us deeply into graph theory. That is how we became graph theorists.'

The Four went on to develop a theory of squared rectangles, from which they eventually constructed a square divided into unequal smaller squares. They described their theory in a paper of far-reaching significance, published in the *Duke Mathematical Journal* (3)*.

Tutte completed his undergraduate degree in chemistry in 1938 with first-class honours, and continued in physical chemistry as a graduate student. He worked in the renowned Cavendish Laboratory, first with G. B. B. McI. Sutherland (FRS 1949) on infrared spectroscopy (1), and then with W. C. Price (FRS 1959) on ultraviolet spectroscopy (2). Journal articles describing each of these experiments were the first of Tutte's publications. This work also convinced him that he would not succeed as an experimenter. He asked his tutor, Patrick Duff, to arrange his transfer from natural sciences to mathematics. This transfer took place at the end of 1940.

The friendship of the Four forged by their intense collaboration as undergraduates remained strong throughout their lives. They corresponded frequently, and met when they could. Leonard Brooks, after graduating from Trinity College in 1938, enlisted in the Royal Air Force. After the war he joined the Civil Service and worked as an income tax inspector. He is remembered for Brooks' Theorem on graph colourings. Cedric Smith, on graduation, continued study in statistics, obtaining a PhD after three years of study. On the basis of his Quaker religious beliefs, he was

* Numbers in this form refer to the bibliography at the end of the text.

a conscientious objector to active military participation. On completing his degree he worked for three years during the war as a hospital porter, and for some time after as a relief aid worker. When he resumed academic life, he rose through the ranks to professor in the Galton Laboratory of Genetics at University College, London. Arthur Stone studied and then worked during the war in the USA. He then returned to a fellowship at Trinity College, followed by a lectureship at Manchester University. This led to a professorship in Mathematics at Rochester University in New York State. Each of the Four married and, except for Bill, each had one or two children.

Bletchley Park

At that time of transition to mathematics, with Britain at war, Patrick Duff also arranged for an interview for Tutte with a mysterious government agency. The result of that interview was that Tutte was enrolled in the Government Code and Cipher School, located at 54 Broadway, London. At the School they were told about World War I ciphers. On the basis of his solutions to problems based on these, he was chosen to work at Bletchley Park, the legendary organization of code-breakers. He arrived there in May 1941 as a member of the Research Section. To that section came codes that had not yet been broken. Tutte worked at Bletchley Park until the autumn of 1945.

When Tutte arrived, the Research Section was concerned with an Italian naval cipher, which used a Hagelin machine, of Swedish manufacture. Like Enigma, the Hagelin machine itself was known to Bletchley. The deciphering of that code was reduced to routine by the late summer of 1941.

Bletchley Park was set up as a centre for code-breaking in 1939. Its initial purpose was the analysis and decipherment of Enigma morse codes. A leader of this work was Alan Turing (FRS 1951). Breaking Enigma was particularly vital in the early stages of the war: in that period, German submarines, using Enigma, were sinking North Atlantic supply ships at a devastating rate.

This story is not about Enigma. In 1940, British radio receiving stations began to detect a new type of signal. They soon recognized this to be high-speed output originating from a teletypewriter. Bletchley gave the general name Fish to codes used for teletype data and the specific name Tunny to the code used by the German Army. It was learned after the war that the Tunny ciphers were produced by a heavy 3-cubic-foot apparatus manufactured by Lorenz. Attached to the output of a teletypewriter, it converted messages into cipher by adding key, a teletype signal of the same format as the message. The machines could be big because they were located in secure places: the messages were top secret communications between the Army High Command, located in and near Berlin, and field headquarters, mainly in Russia, the Middle East and, later, in France.

In the early use of this machine in 1941, an operator in Athens made an error in procedure: a message of some 4000 letters was sent, and then, against protocol, sent again with the same code setting. The problem was that the re-sent message differed slightly from the original. When this pair of cipher tapes reached the desk of the chief Bletchley cryptographer John Tiltman, he was able to exploit the near but not exact repetition to separate message and key from this cipher text. This gave Bletchley a string of 4000 letters produced by the Lorenz machine.

A tape of this string was passed around to several cryptographers without anyone coming up with a way to use it. It was a couple of months later, after Tutte had completed work on the Italian naval cipher, that he was presented with the tape. Could he make any sense of it?

After pondering the 4000-letter string, and other bits of information that were known of these signals, Tutte began to determine the structure of the machine that produced the string: that it had twelve encoding wheels, two of which were associated with each of the five positions of punched holes on a teletype tape; and that the remaining two had an executive function affecting all the other wheels. For the first wheel, he deduced from the tape that it must have 41 spokes, and for the second 43 spokes. After he explained how he had made these deductions, others joined the effort, and after a few weeks the complete structure of the machine was worked out. In effect, they recreated a Lorenz machine, as real as though it were physically there. So the error in procedure made by the operator gave away not just the message, it gave away the machine that enciphered it. This was Tutte's first great discovery.

Knowing the structure of the Tunny machine was essential, but that in itself did not give any way to decipher codes it produced. Nevertheless, Bletchley was able sometimes to exploit special circumstances to decipher codes. Because of the importance of the messages, that occasional deciphering had an important role in the war. One characteristic that Bletchley made use of was the fact that the beginning of each cipher text specified the setting by a string of 12 German letters, from which the receiver of an enciphered message could set the initial positions of the 12 wheels. The wheel settings that could be specified by a letter were called wheel patterns. There came a time, at the beginning of 1943, when the wheel patterns were no longer given before the cipher: they were instead to be looked up in code books that were sent to each receiving station. How many possible patterns were there? A pattern consisted of 12 letters, each chosen from 25. One wheel had 23 spokes, the others more. So the number of patterns was 23×25^{11}, that is, more than 5 followed by 16 zeros, an astronomical number. Without being given the pattern, 'we had met with disaster. In spiritual metaphor, we shouldered our pencils and squared paper and trudged glumly out of Eden.'

How did they cope with this harsh cipher world that they then faced? It was the period, at the start of 1943, that Tutte called 'the Winter of our Discontent.' During that period, they were able to decipher Tunny only rarely. After much thought, Tutte came up with 'The Statistical Method'. Here is the idea. When the international teletype system was set up, years before, letters that occurred frequently in ordinary language were represented with fewer punched holes than those that occurred infrequently. For example, E has a punched hole in just one of the five positions, whereas Q has four holes. This was done to minimize repair and maintenance of the teletype machine. If one is given a cipher text and a setting of the Tunny machine—that is, its key string—then adding that key string to the cipher text might give a message that, when read, makes good linguistic sense, in which case it is the true message. Now if it gives a message that has more blanks than punched holes, for example more E's than Q's, then it is likely, but not certain, to be the true message. However, one cannot simply try all settings: there are too many. Tutte then reasoned that this bias toward blanks would hold, over the course of a message, even if one looked at only one of the five teletype positions. The cipher for the first position of the five was determined, for the most part, by just two wheels, for which the number of settings was $41 \times 43 = 1763$. The most likely settings of those two wheels for this position would be those that gave a bias towards blanks rather than holes. Shifting attention to a second position involves a similar number of cases. Altogether, the number considered is in the thousands. Tutte reasoned that this many possibilities could in principle be tested by a machine, namely a computer. However, no such computer existed.

It is true that Bletchley was already using an electromechanical computing machine—called a 'bombe'—in the breaking of Enigma codes. More to the point, Tommy Flowers, an engineer with the British Postal Service, in the Research Department at Dollis Hill, had been urging Bletchley to support the development of a computer that used a large array of vacuum tubes. So the need—in this new world—to perform several calculations each millisecond came together with the means to do just that. In less than a year, under wartime restrictions, the giant computer Colossus was developed and built by the British Postal Service, under Tommy Flowers's leadership. The Computer Revolution had begun. Colossus was up and working, and was used to break Fish traffic before D-Day. It played an invaluable role: after that, Bletchley was able to break Tunny codes routinely for the duration of the war. That Tutte conceived of a method to employ a high-speed computer to break this Tunny code, a code otherwise unbreakable, is an achievement that still stands tall in our perspective of 70 years.

This work was secret: it was never to be revealed. 'Never' for Enigma turned out to be 30 years. For Fish, it was longer. In the 1980s and early 1990s one could see elusive references, such as a photograph of Colossus in an account otherwise about Enigma. It was a period in which historians of computer science continued to accept the claims of ENIAC as the world's first electronic computer. Nevertheless, the secret was maintained. That bothered Tony Sale, an engineer who had until 1968 worked for the Security Service, MI5. He wanted to publicize Colossus by rebuilding it. At first his entreaties to do so were turned down by British Security. Finally, in 1993, and more fully in 1996, he was allowed to proceed. Sale's Colossus rebuilding project and Tutte's contributions to deciphering were revealed in *New Scientist* (Fox 1997), just four days before Tutte's 80th birthday. There Sale characterized Tutte's exploits as the 'greatest intellectual feat of the whole war'. The vow of silence was broken. It persuaded Tutte that he could himself describe his work at Bletchley. His first article was 'Fish and I' (14). Gradually, long repressed memories came back in a fuller way, and in August 2000 he wrote the manuscript 'At Bletchley Park' (15). It appeared as an appendix to the book *Colossus* in 2006. The BBC documentary *Bletchley Park's Lost Heroes* (BBC 2011) made this story known to a wide audience when it was broadcast in October 2011.

One positive consequence of his code-breaking work was Tutte's becoming a Fellow of Trinity College in 1942. 'It seemed to me that the election might be criticized as a breach of security, but no harm came of it.'

In the autumn of 1945 Tutte returned to Cambridge: he had rooms in Neville's Court and, as a Fellow of Trinity, meals at the High Table. His supervisor was Shaun Wylie of Trinity Hall. Three years of research culminated in his receiving a PhD in mathematics.

Doctoral research

When Tutte began his doctoral research, he had ideas to pursue in graph theory that had originated in his study, with the Four, of squaring the square. In the early days of his PhD research, Tutte told Wylie that he had found a non-Hamiltonian planar cubic graph, assuring Wylie that it was 3-connected: it was a counterexample to Tait's conjecture. His supervisor was not impressed: 'In those days, graph theory had a low reputation in the mathematical world. So it is not surprising that Shaun Wylie, as my Ph.D. supervisor, advised me to drop graph theory and take up something respectable, such as differential equations. If one assumes that graph theory was my métier, it was just as well that I had the prestige of a Fellow of Trinity.'

In this way, it came about that Tutte's doctoral research was in the area of graph theory. He began with four papers, each of lasting significance. The first was the counterexample to Tait's conjecture (4). The second was a study of symmetry in graphs (6). The third contained what was to become the most famous of Tutte's discoveries, his 1-factor theorem (7). The last in this group, 'A ring in graph theory' (5), identifies a function that satisfies a natural product rule, which he spoke of as a V-function. In a later paper, he specializes V-function to 'dichromate': other research workers preferred 'Tutte Polynomial', the name by which this function is now known (8).

These formed only a prologue to Tutte's PhD thesis. As to the latter, he explained: 'My thesis attempted to reduce Graph Theory to Linear Algebra. It showed that many graph-theoretical results could be generalized as algebraic theorems about structures I called 'chain-groups'. Essentially, I was discussing a theory of matrices in which elementary operations could be applied to rows but not columns.' This is matroid theory.

Canada

When Tutte finished his thesis in the summer of 1948, he sought a position teaching mathematics at a university, 'but there seemed to be few openings.' No doubt his supervisor had foreseen this when suggesting he consider an area of mathematics other than graph theory. 'I remembered that Professor Coxeter [FRS 1950] of the University of Toronto had shown interest in my graph-theoretical work and I applied, through him, for a post there.' Tutte was accepted, and began his teaching career at the University of Toronto. In his 14 years at Toronto, he rose to pre-eminence in the field of combinatorics. Tutte was in that period elected a Fellow of the Royal Society of Canada.

Some time in the late 1930s, Tutte had joined the British Youth Hostels Association. He went on several expeditions, including a bicycle trip to Land's End and back. Another cycling trip took him and a friend to Mount Snowdon in North Wales. It was not surprising, then, that when he came to Canada he became a member of the Canadian Youth Hostels Association. Bill met Dorothea Geraldine Mitchell of Oakville, Ontario, through that Association. Bill and Dorothea—many of her friends called her Dorothy—were married a year later, in October 1949. For a time they lived on the upper floor of the Hostel's Great Lakes regional office, located adjacent to the campus of the University of Toronto. There they frequently hosted social events of the Association.

In 1953 the Association received an invitation to send a couple to the Coronation of Queen Elizabeth: Bill and Dorothea were chosen. They took a boat trip to England and were at Westminster Abbey—in the balcony—on that historic occasion, as witnesses to the Coronation. That trip gave Bill the chance to introduce Dorothea to his relatives and to all the precious places from his youth, to Yorkshire, Cheveley and Trinity College.

In 1962 Tutte moved to the University of Waterloo at the invitation of Ralph Stanton, who had known him at Toronto. It seemed a surprising move, given that only five years had elapsed since that university's creation. He was given the privilege of teaching only courses close to his heart, for the most part in graph theory. Tutte had a major role in the development of the university. His presence attracted combinatorialists from around the world, to visit and to teach. He was an important ingredient in the Faculty of Mathematics, which was formed in 1967. He received the title Distinguished Professor in 1968, one of only two at Waterloo ever to receive that honour in their active careers.

One attraction that Waterloo offered the Tuttes was the lovely little village of West Montrose, located on the Grand River, about a dozen miles from Waterloo. Their home was

Figure 2. Tutte on the portal of the Royal Society in May 1987, with Dorothea, Jeanne and her husband David Youlden. (Photograph courtesy of Richard Youlden.) (Online version in colour.)

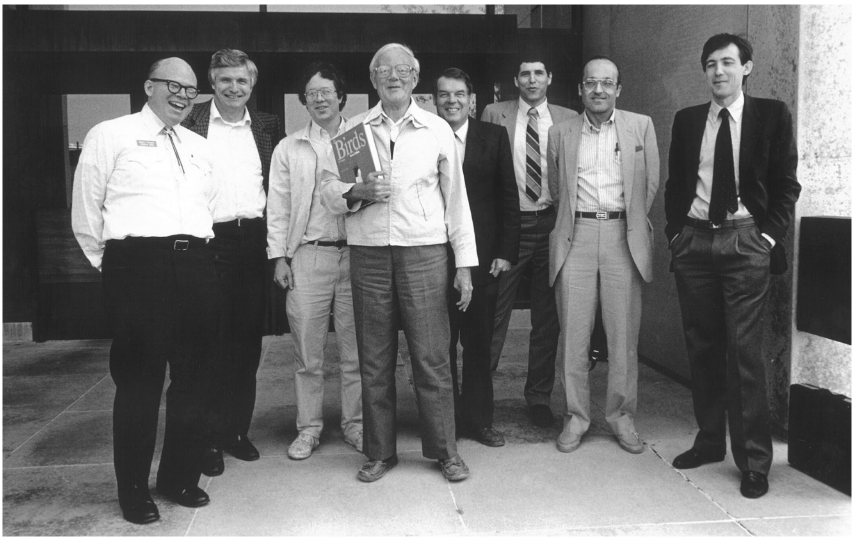

Figure 3. Tutte in June 1992, with his PhD students: Arthur Hobbs, Neil Robertson, Ken Berman, Ron Mullin, Richard Steinberg, Will Brown and Stephane Foldes. John Wilson was not present. (Photograph courtesy of the University of Waterloo.)

located on a two-acre plot on the river, next to a famous covered bridge. In warm weather, Bill and Dorothea would oft-times take a morning dip in the river. It was a great area for hiking, a pastime they both enjoyed. Bill managed a garden primarily composed of wild plants and flowers. Their house included a potter's studio for Dorothea, and an upstairs study for Bill. They lived there until Dorothea's death in 1994 (figures 2–4).

Figure 4. Tutte in May 1997, wearing his Trinity College tie, about to blow out his 80th birthday candles. U. S. R. Murty is beside him. Tutte had just learned of the article that revealed his code-breaking work. It was also the week of a major international conference at the University of Waterloo that celebrated his 80th birthday. (Photograph taken by the author.) (Online version in colour.)

Conclusion

Blanche Descartes was a pseudonym for a member of the Four, usually Smith or Tutte. An example of the latter is the following contribution to the 60th birthday celebration of the polymer chemist Manfred Gordon (Descartes 1977):

Sexagesimal

To be sixty years old, to be solemn and sage
And a fount of the wisdom that mellows with age
Esteemed by the old and revered by the young—
And to sit at a feast where one's praises are sung.

To be sixty years old, to look over one's field
And survey the knowledge oneself has revealed
In papers well-structured for learning and gain
And extending like links in a polymer chain.

How good to be sixty! Yet each may aspire
Diamond Jubilee joys for himself to acquire
What happens to Manfred can happen to thee!
I try to forget it will happen to me.
—Blanche Descartes

Tutte became the Editor-in-Chief of the *Journal of Combinatorial Theory* in 1967. Under his leadership the journal flourished. It became such a desirable place to publish significant results in combinatorics that in time it was partitioned into two, series A and B, with Tutte

Figure 5. Professor Tutte and Governor General Adrienne Clarkson in October 2001. She is presenting him with the medallion of Officer, Order of Canada. (Photograph taken by MCpl Paz Quillé of Rideau Hall.) (Copyright © Her Majesty The Queen in Right of Canada represented by the Office of the Secretary to the Governor General.) (Online version in colour.)

retaining the leadership of the latter until his retirement as professor from the University of Waterloo in 1985.

Tutte was awarded Canada's Killam Prize in 1982. He was chosen for the Order of Canada, Officer rank, in 2001; the citation for this honour included his wartime achievement of breaking the Fish code (figure 5). In 2011 the Cryptologic Research Institute in Ottawa was renamed the Tutte Institute for Mathematics and Computing.

In graph theory his footprint is large. Every graph theorist knows Tutte's Theorem, the characterization of which graphs have a 1-factor (6). Concerning connectivity, there is Tutte's Wheel Theorem (11) and its extension to matroids: Tutte's Wheels and Whirls Theorem (12). Another Tutte theorem states that every 4-connected planar graph has a Hamilton cycle (9). A major result from the thesis is his characterization of graphic matroids (10). Among polynomials associated with graphs, one of the foremost is the Tutte Polynomial (8). When asked which of his works was his personal favourite, he said the enumeration of convex polyhedra (13), adding as a reason that polyhedra had been known since antiquity. As for challenges to the next generation, there is the trio of Tutte k-flow Conjectures, $k = 3,4,5$.

A collection of his mathematical papers, with his comments about their relevance, is *Selected papers of W. T. Tutte* (McCarthy & Stanton 1979). Another good source book, one in which the reader hears his voice, is *Graph theory as I have known it*.

How could he become a leading mathematician after having taken his first and second degrees in natural sciences? Tutte's answer: 'I learned mathematical research by doing it for fun with the other members of the "Gang of Four".'

Acknowledgements

I thank Howard Cadman for sending me the Prime Minister's letter and for sharing information about Tutte. I am grateful to the Prime Minister's Office for authorizing the use of his letter in this memoir. I also thank Jeanne Youlden for approving my use of the letter. I thank Richard Youlden for his reading of a preliminary version of the memoir. Colleagues Bruce Richmond, U. S. R. Murty and William Cunningham read a draft copy; their comments led to improvements in the text.

The frontispiece photograph was taken by Godfrey Argent and is reproduced with permission. The photograph in figure 5 is reproduced with the permission of the Office of the Secretary to the Governor General of Canada.

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Author's statement

It was as a graduate student in electrical engineering at Columbia University that I first heard Professor Tutte speak, in May 1963. I had learned that he was to give a lecture at Princeton University, and I took the trip down to Princeton to attend. Tutte was already a famous name for me. I was closely familiar with his studies on planarity of a graph and knew about other parts of his work. Earlier, when I was an undergraduate, the methods we learned to find currents in an electrical network that did not go back to Kirchhoff were set out in the 1940 paper by the Four in the *Duke Mathematical Journal*. That paper begins with squared rectangles, translates the analysis to the realm of electrical networks, and then describes new methods of general application to solve for the currents. Tutte's lecture at Princeton, entitled 'How to draw a graph', was outstanding, more so than any I had previously heard about graphs, the subject of my PhD thesis. Before the lecture there was an announcement of a two-week meeting of the Canadian Mathematical Congress in Saskatoon, Saskatchewan, that August: Tutte would speak each weekday morning. When I graduated that July I gave myself, as a present, a trip to that conference. There I got to know Bill and Dorothea.

In 1964 I was a postdoctoral student at Princeton. One day that year, I chanced to meet Tutte on the streets there. Later, when I worked in Schenectady, New York, there were a few instances of written correspondence between us. In 1967 I was invited to join the new Faculty of Mathematics at the University of Waterloo, becoming a faculty colleague of Tutte's. One context for friendship was our work together on the *Journal of Combinatorial Theory*. Another was hiking on Saturday or Sunday afternoons along the rivers and other wild places near Waterloo.

In the last half year of his life, as his final illness became manifest, we had less opportunity to hike, and more to talk. This was after his war exploits had been revealed, when he was less reserved. We discussed more about his early life, his parents' personalities, what he knew of his grandparents, and the like. These conversations helped me in this and other writing about him.