The Development of the Electron Microscope at the University of Toronto

Mike Sutherland
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(416) 929-0661
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In Commendation of ye Microscope

Of all the Inventions none there is Surpasses
The Noble Florentine's Dioptrick Glasses
For what a better, fitter guift Could bee
in this World's Aged Luciosity.
To help our Blindnesse so as to devize
a paire of new and Artificial eyes
By whose augmenting power wee now see more
than all the world Has even doun Before

Henry Powers 1664
The electron microscope has had a profound impact on science in the 20th century. It has aided us in our drive to develop new technologies, yielded us ammunition for our war against disease, and provided us unique and powerful insights into the natural world. One of the key milestones in the development of this instrument was the pioneering work performed by two young graduate students at the University of Toronto. Their accomplishments showed the world that such a machine was not only possible but practical, and paved the way for the commercial production that has made the electron microscope so ubiquitous a tool in the modern scientific laboratory.


The field of physics was a turbulent one in the early decades of our century. The careful experimentation and insightful theoretical work of Max Planck, Albert Einstein and Erwin Schrodinger had eroded the classical framework of Newtonian mechanics upon which physicists had formulated their theories for centuries. Their new ideas were fervently debated and eventually most scientists began to accept that the universe we live in was not as well understood as previously thought. A key point in the formulation of the new 'quantum theory' of nature was forwarded by Albert Einstein in 1905. Investigating the previously unexplained photoelectric effect, he proposed that light could both be described as a wave and as a particle. This wave-particle duality of light confounded other physicists of the day as they struggled to comprehend how the boundary separating the regimes of wave theory and particle behavior could be so blurred. Einstein's pioneering work provided inspiration for many others in the field. In 1923 a young French scientist named Louis de Broglie published his Ph.D. thesis, a paper which was the theoretical starting point for the development of electron optics.[1] He considered the ambiguity of light, as Einstein had suggested, and came to the clever realization that such a crisis of identity could be applied to particles as well. He argued that if a wave could exhibit particle properties, then a particle should exhibit wave properties also. As a test, de Broglie proposed that experimentalists look for signs of particles exhibiting diffraction, a distinctly wave like characteristic. Curiously his challenge went unmet for several years until Davisson and Germer of Bell labs in New York attempted to observe such a phenomenon using rapidly moving electrons incident on a nickel sample. After little more than a year of trying they were rewarded in 1927 with images that unequivocally demonstrated the diffraction of electrons [2]. This
experiment ushered the wave theory of matter from the abstract pages of deBroglie's thesis to physical reality. What was exciting from a practical standpoint was that images obtained with electrons would, in theory, be of higher resolution than those possible with an optical microscope. The so called 'optical limit' that places restrictions on the magnification of a light microscope results from the fact that light has a wavelength on the order of $1\mu m$, and any detail smaller than a single wavelength is impossible to image. Electrons on the other hand typically have much shorter wavelengths, so that the hypothetical resolution of an electron based instrument is many times greater than that of its optical counterpart. This fact was realized almost immediately after the thesis of deBroglie and its subsequent verification in New York. At this point, several German theoreticians quickly began to develop electron analogies of the lenses which form the basis of the light microscope. One of the key problems was figuring out how to bend and focus electrons with the accuracy that glass lenses were able to do to normal light. The solution was proposed by E.Busch [3] and later improved upon by Ernst Ruska and his colleagues at the Berlin Technische Hochschule. Their approach was to use pole pieces to concentrate a magnetic field, which could be adjusted in strength and symmetry.[4] The field served to interact with an incident stream of electrons, bending it in exactly the same way that a glass lenses bends a ray of light. This theory marked the birth of the field of geometrical electron optics.

The first ever images obtained with this technique were captured by E. Bruche and H. Johansen in 1932.[5] Their microscope was very crude, and served more to demonstrate the feasibility of electron optics than to produce any real images of notable quality. A year later Ruska and his team succeeded in increasing the power of his microscope to provide the first tentative glances at the world beyond the barrier imposed by light. Their efforts, however, yielded only a few scattered images whose quality was poor. Indeed some American physicists discounted the German results as fakes, and seriously doubted whether any useful images could ever be obtained with such an apparatus.[6] There was also a prevailing belief that the magnitude of any electron beam needed to provide sufficient illumination for the image would be detectable to the human eye would burn any conceivable sample into oblivion. Other attempts at capitalizing on the theoretical success of the Germans were also ill fated. Experimental models were developed in the mid 1930's in Brussels by Marton, in England by Martin, Whelpton and Parnum and in Japan by Sugata and Hibi. Despite the effort and credentials of these researchers, none were able to obtain images that were adequate for any practical use. There remained problems with chronic astigmatism and aberration of the lenses, which tended to blur the images almost beyond recognition. It is perhaps the struggles and
skepticism of the researchers in the world's scientific powerhouses that casts the accomplishments of two young graduate students from Canada in such a favorable light.

II The University of Toronto Physics Department in the 1930's

The 1930's treated Canada in very much the same way as it treated the rest of the industrialized world. Mass unemployment fueled by crop failures and detrimental economic policies caused a great financial strain on many of Canada's universities and research institutions. In 1932 and 1933 the chief bursar at the University of Toronto issued a notice that staff salaries were to be severely cut, [7] and women who were married were under pressure from the administration to resign from their positions as a cost saving measure[8]. By the end of the 1930's things had begun to improve slightly, as Canada began to recover from the depths of the Depression. The physics department at U of T during this period was under the direction of Prof. Eli F. Burton, the 'oddball' member of the Burton family that owned the Simpsons department store chain. Burton obtained his B.A. in Math and Physics from the University of Toronto in 1901, and quickly accepted a position as a lecture assistant there. In 1902 he was awarded an Exhibition scholarship to study at the Cavendish laboratory at Cambridge University in England, where he worked under the discoverer of the electron, Sir J.J. Thompson. His interests in physics appear to be highly diversified, as his topics of research included everything from colloids (liquid suspensions of fine particles) to dielectrics. It may also be worthwhile to note that Burton was a diabetic, and perhaps as a result, he was active in the field of medical technology research for the greater part of his career. This interest was likely what provided the catalyst for maintaining a lifelong friendship with Sir Frederick Banting, the co-discoverer of insulin and head of the Banting Institute at the University of Toronto.

His interest in medical matters even extended to his academic career. In the mid 1920's Burton worked with A.H. Hendrick, a local doctor, on a proposal to use colloidal suspensions of arsenic for the treatment of cancer [9]. His work on colloids was likely what led him to be interested in microscopy. In 1926, he gave a lecture to the
Mayo Foundation on the latest generation of light microscope (the so-called ultramicroscope) and its usefulness in the biological sciences. Ironically, he expressed dismay at the limit on resolution imposed by the wavelength of light remarking in frustration "In many respects we must be disappointed with the ultramicroscope. While it enables us to become aware of the presence of small particles, the veil is only half withdrawn."[10]

The organizational structure of the physics department in the 1930's was much different than that which exists today. The head of the department exercised a virtually unilateral control over the direction of research and played a dominant role in most decisions made in departmental matters. The credibility of the department rested heavily on the shoulders of the chair, and consequently he had to have a superior ability at steering research and garnering funds to support it. When Burton took over as head of physics in 1932, he inherited a department that had already established a reputation as a creditable research institution. Under the direction of John Cunningham McLennan (1907-1932) the department made many notable contributions to the fields of spectroscopy, atomic physics and low temperature physics. Probably the most important accomplishment was the liquefaction of helium in 1923, which made Toronto the second laboratory in the world to do so. There were a few other noteworthy members of the department that would play important roles in the development of the electron microscope in the years to come. Under Burton was Dr. Ireton, who held the position of assistant head of the department during most of the 1930's. He was described by students as a "curmudgeon" in the fullest sense of the word [11], but was a successful physicist and sometimes aided graduate students in choosing fields of research.

In what could hardly be described as coincidence, a German expert in electron physics maintained a position at the department. Walter H. Kohl was a guest lecturer during the 1930's, at the invitation of Burton he provided regular lectures and seminars on many areas of experimental physics. Schooled in Dresden Germany, Kohl accepted a position with Rogers Radio Tubes in Toronto after completing his doctorate in engineering physics in 1930. His work with Rogers centered on the development of the television set, which necessitated a great deal of working knowledge in the field of electron physics. He studied extensively the works of Knoll, Ruska, Bruche and others and in doing so "derived great benefit from the facilities of the University of Toronto library."[12] Occasionally, he would build special tubes at Rogers to repeat the work of the German pioneers. When he was successful, he would use these tubes in the special
lectures at the university, and is believed to be first person to demonstrate electron optics of any sort in Canada.

III Cecil Hall's Preliminary Electron Microscope

It has been suggested that Burton's medical condition was a factor that guided the direction that he chose to take his department. [13] In 1935 Burton returned from a trip to Germany, where he attended a lecture in Berlin on "Possible Areas for the Application of the Electron Microscope". Inspired, he desired to find a student that would undertake a similar project at the University of Toronto. Although the reaction to his plans among other graduate students was lukewarm at best, he managed to catch the interest of a new student, Cecil E. Hall, who had graduated with a B.A. from the University of Alberta the previous year. Hall's first step was to develop a simple electrostatic emission electron microscope. This was a device that did not use a rapidly moving electron beam to image specimens, and consequently did not provide the same resolution that later magnetic electron microscopes would. An image of the cathode (electron emitter) taken from Hall's 1936 M.A. thesis is shown at left. Under the supervision of Kohl, Hall's work progressed rapidly, and he obtained a National Research Council grant to continue his project in 1936-1937. After completion of the electrostatic microscope, he used the $800 NRC allowance to purchase equipment to construct a more advanced two-stage microscope with magnetic lenses. He achieved a fair amount of success, obtaining images of the cathode of the instrument at a magnification of about 3000. Excited by the prospect of continuing the development further, Burton returned to the National Research Council to request more funds. "The next step in this research is to take electron pictures of sections of some substance placed in the electron stream" he wrote in his application. "For the purpose of carrying out this extension ... it is now necessary to purchase a condenser for use with the tubes that will stand up to 50,000 or 100,000 volts." [14] Burton requested $724.50 to cover both the expense of the condenser and Hall's salary for the coming year. Unfortunately, in what could be described as a lack of foresight, the NRC declined this request on the grounds that it was work more suitable to a scholarship holder. Hall collected his M.A, and was forced to move on. He accepted a position at Kodiak under Dr. C.E.K. Meeks (a good friend of Burton's), but even after the first
successful high resolution electron micrographs were produced some years later, Kodak remained uninterested in his work. In 1941 he joined the faculty at M.I.T. and worked on electron microscopy in biology. Burton was left with no other option than shelving the project indefinitely, and research in electron microscopy at the University of Toronto ground to a premature halt.

IV James Hiller and Albert Prebus

Albert Prebus received his undergraduate education at the University of Alberta, the same institution as Cecil Hall. He excelled in his studies, and obtained an M.Sc. in the field of atomic spectroscopy. His ability earned him a National Research Council fellowship which supported him for the years to come. He was excited about the prospects of working underneath the eminent researcher M.F. Crawford, who headed Toronto's reputable spectroscopy laboratory. Upon arriving in Toronto in September of 1937, Prebus first met with the head of physics to discuss the direction his Ph.D. work would take. The failure to retain Hall through lack of funding must have been on Burton's mind, and the fact that Prebus held an NRC scholarship likely caught his eye. The combination of Burton's persuasive manner and dynamic personality proved to be too formidable a foe for the young graduate student's reservations, and he left his office with his plans to study under Crawford forgotten. Prebus recounted this experience in a 1978 address.

"In my first meeting with Professor E.F. Burton, then head of the Physics Department, my plans to continue in this field were seriously perturbed. He suggested that a new field would broaden my outlook. The particular field he had in mind was revealed somewhat later in the conversation. It was, of course, electron optics, an area he had found intensely exciting during a recent European trip he had made sometime earlier. His enthusiasm rapidly overcame my initial reluctance to switch from work that I had enjoyed to a field about which I knew very little, but which did offer many exciting possibilities." [15]

Hoping to pick up where Hall had left off, Burton had already decided that work would progress faster if he assigned another student to work with Prebus, James Hillier.

James Hillier was born in 1915 in Brantford Ontario. As a child he gained an interest in microscopy at an early age, a result of a telescope purchased for him by his father. The telescope, which he used to watch planes taking off and landing at a nearby barnstorming outfit had an eyepiece that when reversed, served as a crude light
microscope. As with many young children, his curiosity was unbounded and he recalls spending much time looking at just about everything. He later attended Brantford collegiate, where he studied physics, chemistry, geometry, algebra and trigonometry in order to fulfill the requirements of matriculation. Although he developed an interest in physics during these years, he never intended to pursue it as a career. He instead pictured himself as an artist, and excelled as a painter during his time at the school. Hillier recalls that it was a geography teacher at the collegiate that led him onto the path of physics. The teacher, who was a W.W.I veteran, had been involved with radio while in the army and had started a small HAM radio club at the school. Hillier decided to join, and gained a good deal of experience in the building and operating of these radios. A class mate attested that Hillier "excelled at electronics" [16], and perhaps this is the reason that the geography teacher took such a liking to the would be artist. Believing that Hillier would make a better technical student than artist, the teacher managed to arrange for a scholarship at the University of Toronto provided he study math and physics there. Being from a fairly large family, Hillier thought that the strain of sending all four of his siblings to college would have been beyond the financial capabilities of his parents. He accepted the award without much hesitation. A self professed workaholic, Hillier maintained the first class honours he needed to keep his scholarship and graduated with a B.A. Hon in Math and Physics in 1937. In his third year of his undergraduate studies Hillier married Florence Bell, an acquaintance from high school whom he had met up with in university. Florence became pregnant almost immediately, to the severe disapproval of the administration at Victoria college, who threatened her with expulsion. After some expert diplomacy Florence was allowed to continue her studies and their son, Robert, was born in Hillier's fourth year. Upon graduation the financial responsibility of supporting a new family weighed heavily on Hillier's shoulders. Ireton called him into his office near the time of his graduation to sell him on the prospects of graduate school. Since jobs were scarce and he had no other promising alternatives, Hillier agreed to continue at the university as a graduate student, picking up a small stipend of $631.00 for his first year. Ireton tried to entice him with many of the current graduate projects that were in vogue in the department at the time, but Hillier was hesitant about getting involved in ventures that he thought were in danger of becoming stagnant. Despite the fact that his undergraduate education had covered all the basic fields of physics, and that both Kohl and Hall were active at the time Hillier was a student at the university, he had never heard of the concept of the electron microscope.
"Ireton called me into his office to sell me on the idea of going on to graduate studies, saying there would be a stipend for me. I knew I was going to do that because it was the middle of the depression and I didn't really have anything else to do, and I was very interested by then. Then he went through a list of the research that I could do, and he listed all of these projects that I knew were over the hill. There was spectroscopy and optics and a certain amount of radio and electronic projects, as well as plain thermodynamics. I wasn't showing much enthusiasm and he got literally annoyed at me, exasperated is a better word. So he threw out at me that the chairmen had a pet project, the electron microscope. Up until then I had never heard those two words together." [17]

Intrigued at the prospects of combining two childhood interests, microscopes and electronics, Hillier began searching the scientific literature of the day. He claimed that at the time he couldn't figure out for the life of him how electrons had anything to do with the brass tubes and glass lenses he had experimented with as a child. He discovered quickly that although the theory of electron optics was well formed, there was little relevant practical information available to aid him. In the fall of 1937, Hillier and Prebus met and set about the task of designing their electron microscope.

V. North America's first Transmission Electron Microscope

For the first few months Hillier and Prebus busied themselves with dusting off and reviving Hall's emission microscopes. At this point Hillier also had teaching responsibilities that took up much of time, but Prebus insisted that he more than made up for this with an abundance of enthusiasm. After careful consideration, the two students agreed that the only way to achieve resolution greater than that of the light microscope was to build a high voltage transmission microscope as Knoll and Ruska had attempted. Big plans however, called for big money. This is where the administrative skills of Burton, who as Hillier has attested "didn't know a damn thing about the electron microscope" came into play [18]. There was considerable opposition to Burton's obsession with the microscope within the department itself, some thought he was 'a little off his rocker' about the whole project. It has even been suggested that there was more than a little animosity over Burton's habit of
steering would be spectroscopists into the field of electron optics [19]. On top of this, the prevailing opinion at the time was that even if the apparatus could be built successfully, the whole field of electron optics would only be suitable to the development of commercial television and therefore didn't have much academic merit. Hillier was always amazed at the wisdom and foresight that Ireton and Burton demonstrated in letting two young and completely inexperienced graduate students undertake such a major endeavor. Burton managed to secure enough funds to cover much of the cost of construction, and between the three of them they managed to beg, borrow and scrounge the rest of the materials and components, including essential high-voltage capacitors from the University of Alberta, and a 40,000KV step up transformer loaned from the x-ray department of a local hospital.

Prebus moved in with Hiller and his wife shortly into the semester, and they would spend much of their time planning and discussing aspects of the design at their apartment. At the end of the 1937 Christmas vacation, which was filled with 18 hour work days and many lively debates, they submitted their plans to Burton for approval. The general design followed that which was sketched out by Knoll and Ruska, but the details of the engineering were unique. As a testament to their skill, the design was tweaked over the next few months, but the column support, specimen chamber, objective lens and projection lens never needed any major overhaul. With Burton's approval the construction began in January of 1938. The shop facilities at the department of Physics were poor at the time, as the lack of available funds during the Depression prevented the purchase of the highest quality machines. To compound the problem, the two were assigned the help of the new part time machinist Fred, whose only previous experience had been at a locomotive repair shop. "Fred was a delight at precision machining of very large pieces," Hillier later explained, "but anything that needed more than one part per inch completely confounded him." [20] Since neither of the two had taken little more than elementary carpentry in high school, they were left with no other option than to learn the skills necessary to complete the detailed machining themselves. The manager of the machine shop gave them lessons and, somewhat reluctantly, allowed them after hours access to the shop provided they work together. Machining until 4 am, and sometimes until the day shift showed up for work, Hillier and Prebus made rapid progress on the smaller components. Remarkably, with no previous machining experience and Fred the locomotive repairmen as their professional help, the electron microscope evolved from the blueprints to completed form in 4 short months.
Once the construction was finished, the long and arduous task of working out the many bugs began. A constant source of frustration for the two graduate students was the vacuum system itself. The entire central column of the apparatus had to be under very low pressure, since the stream of quickly moving electrons would spread out in the presence of air making imaging impossible. This task was accomplished by first pumping the central chamber with a small mechanical pump, then pumping with a more elaborate mercury diffusion pump specially constructed by the shop's resident glassblower. The pump, which was intricate for its day, worked slowly and even though much effort was made to keep the joints tightly sealed, there were leaks. The central column consisted of a stack of lenses and tubes, with an electron source perched on top and the camera system at the base. The electrons would be emitted at the cathode, then pass through the various magnetic lenses and through a thin sample, where they would strike a screen. The screen, provided by Kohl, was coated with phosphor, which glowed brightly when bombarded with electrons. A photograph of the instrument is shown at left. Since the instrument took so long to prepare for use, they had originally hoped to place an entire roll of film in the camera so that they would not have to re-pump the microscope for each and every image. To their dismay, the film became extremely brittle under the vacuum, and winding the next exposure into the camera usually fragmented the entire roll of film into thin plastic shards. The sections of the column were allowed to slide transversely relative to each other for alignment, with the seal being created by a homemade gelatinous mixture of gum rubber and Vaseline. The current supply to the lenses consisted of nothing more than a collection of car batteries, and by keen foresight, a water based cooling system was installed and served to protect the lenses from thermal fluctuations caused by internal heating. The high voltage system for the electron gun itself was a curious collection of scavenged equipment, aluminum foil and spare pieces found around the physics department. The almost sinister looking jumble of apparatus later prompted Hillier to comment "the only place where one could possibly see anything comparable today would be in a very old Frankenstein movie."[21]
Almost unbelievably, the apparatus conceptualized and constructed in less than a year by two inexperienced Canadian graduate students began to offer tantalizing glimpses into realms previously unseen by human eyes. The first successful image taken with the equipment was of a piece of platinum foil at 800 magnification, in April 1938. The act of improving the machine which Hillier admitted "literally must have had a hundred bugs"[22] was made exceedingly difficult by the fact that the only output of the machine was a single blurred image, whose poor resolution could have been a result of any number of contributing factors. In these early days only about one out of every 50 pictures was clear enough to be of worth. Over the course of the next few months the pole pieces in the magnetic lens were redesigned, and gradually the quality of the images improved and the resolution increased from 140 Å to 60 Å1. The original electron source was a cold cathode emitter, which proved to be a hindrance. It was soon replaced by a V shaped tungsten tip, which has become the standard in today's instruments. Word of their accomplishments finally attracted the eye of the National Research Council, who granted Hillier and Prebus a small amount of money to continue work over the summer vacation of 1938. Burton immediately began wondering if the increase in resolution might lead to information helpful to cancer research, or aid in the studies of the lung disease Silicosis that frequently plagued Ontario miners of the day. In December of that year Burton wrote an article for the Canadian magazine Saturday Night entitled "The Electron Microscope." [23] In it, he expressed his excitement at the early achievements of his graduate students. He included a picture of a small shell plant known as a diatom, with a magnification of 8000. In a characteristic flourish he ended his article with "So we have made a breech in the impassable [light] barrier and have opened up great possibilities for the future of human vision. Who will occupy the new field?" Prebus later admitted to a colleague that both he and Hillier were somewhat surprised at their early success, but the machine managed to operate without major overhaul for the next 6 years.

1One Å = 10^-10 m, roughly the size of a hydrogen atom.
Money was still a constant worry for the two, who did not want to suffer the same fate as Hall. Hillier was unable to obtain government support for students since he was married, but once again Burton managed to pull some strings to obtain funds. Approaching his old colleague Sir Frederick Banting, Burton attempted to entice the medical researcher into allocating some of his budget towards the microscope project. On Nov.1 1939 Banting wrote in his diary

"Burton over had talk concerning electron microscope - application to medicine. I would like to have a setup such as the above to investigate cell division as well as virus, bacteria, blood cells, platelets. Burton would like to build a couple more machines and increase the workers and publish results. He would like to plan a five year program and keep a lead on the rest of the world."[24]

Unfortunately, Burton's 5 year plan was never realized since the war interrupted his research efforts. He did however manage to obtain sufficient funding from Sir Frederick to allow Hillier to continue his work for the next few years. Almost immediately, a close collaboration between the Banting institute and the department of physics arose, with Burton occasionally bringing Banting images to let him know how work was progressing. A good deal of the early work done of the microscope involved the imaging of bacterium and viruses.

The media seemed to be taken with the work being performed at the university. Articles appeared in the Toronto Star, the Globe and Mail and the Montreal Standard over the next few years. The writers seemed to enjoy the fact that cutting edge science was being performed in the basement of a building in downtown Toronto, and seemed taken with publishing images that had never before been attainable. Perhaps the most significant article of the day appeared in the April 1, 1939 issue of Maclean's magazine. A full three pages long, the article boasted that the microscope would "magnify a grain of sand so as to seem bigger than the Royal York hotel." [25] The author also seemed to take delight in the fact that the Canadian model outperformed others in Germany, noting that the two young graduate students were "matching strides with the most brilliant physicists in Europe." It was about this time that Ruska'a team published the
results of his team's microscope, which managed to achieve only 100 Å resolution. Hillier was awarded his M.A. at the end of 1938, and Prebus finished his Ph.D. requirements in 1939. Their results were published in their classic article in the April 1939 Canadian Journal of Research [26] and following on the heels of the media, the academic and industrial communities suddenly became interested in electron microscopy.

VI. What Followed

Buoyed by their successes, the two toyed with the idea of creating their own company to manufacture and sell the instruments. They quickly realized that this would have been a doomed venture for two young and inexperienced physics majors, and instead opted to share their expertise with American commercial organizations. In hindsight it seems that their choice to go south was unavoidable. The decision is indicative of a Canadian scientific community that at the time was either unable or unwilling to see such an innovative idea to fruition. In a letter responding to the Maclean's article, a reader expressed concern on the issue.

"The editorial gives some detail of the incomes of the two young scientists. They are not details that will bring any glow of pride to the average Canadian. We are in whole hearted agreement with their [Maclean's] suggestion that Canada should not leave itself open to the loss of two young men who are almost certain to become distinguished scientists."[26]

Without the industrial infrastructure or available capital, Canada lost its brief edge on electron microscopy to the corporate giants of the south. Hillier later recalled their decision quite clearly.

"At first we decided we ought to set up a company to build it. Thank God we had enough sense not to do that, because there was no way we could have built the right kind of company in Canada because of the numbers of different disciplines you needed to make the damn instrument. We finally decided, correctly, that the only people who could possibly make it would be a company like GE or RCA."[27]

The two sent their ideas off to a few potential employers, and both General Electric and the Radio Corporation of America responded by sending interviewers to Toronto. Hillier and Prebus were unimpressed with the people from GE since they wouldn't commit to developing a model for production, which is what Hillier and Prebus were really
interested in. RCA only had the money to hire one of the pair, and Hillier was chosen over Prebus. Hillier claimed that this fact bothered him for almost 20 years, since in his opinion the two were virtually equal. Finally it was revealed to him that someone had told the interviewer from RCA that he had better eyesight than Prebus, and to break the tie the interviewer chose Hillier. Prebus went on to work at Ohio State, attaining the rank of full professor, and in the following years he produced his own electron microscope.

VI. The Next Generation

With the practicality of the microscope finally demonstrated, Burton desired to expand his program. He was able to obtain funding for more graduate students, and for the construction of newer, improved instruments. In 1939 Bill Ladd from the University of Toronto, and John Watson from McMaster University were paired with Hillier and Prebus to continue work in the field. Faced with a choice as to what path to follow for his graduate work, Watson recalls:

"I happened to read the Maclean's story in the spring of 1939, when I was in my graduating year in Mathematics and Physics at McMaster University in Hamilton, Ontario. I was intrigued by the description of a new type of microscope which used a magnetic field instead of glass as a lens, and electrons instead of light as radiation, and wishing, in any case, to continue with university life, I wrote to Professor Burton asking if I could be considered for a situation as a graduate student in Physics under his direction"[28]

To his surprise and delight he was accepted, and Watson and Ladd began work in the fall of 1939. Through Burton a contract with the Columbia Carbon Company of Brooklyn was arranged to finance the construction of a second microscope, which was based on the design of the original. The process was sped up considerably, as Hillier claimed that when he and Prebus were developing their first instrument, they were always making notes of possible design improvements. Through the foresight of Dr.W.B. Wiegard, who was the director of research for Columbia Carbon at the time (and himself a University of Toronto graduate and close friend of Burton) one of the first applications of the new technology to industry was made.
In conjunction with the development of the new microscope, active research was still being conducted with the original version, whose resolution eventually approached 20 Å. Studies were done of lubricating greases, diatoms, viruses and various biological samples from the Banting institute. A good example of such projects can be seen in the micrograph at right, which was used to examine the internal structures of the bacteria for tuberculosis research. The direction of research changed drastically with the onset of World War II. In the early years of the war, the Toronto microscope was the only instrument available to the Allies in operating condition, and it spent the next few years almost exclusively devoted to classified military-related research. The scientific output of the Toronto group suffered immensely in these years and a great percentage of their work was never published in journals. In 1940, the second microscope left for Brooklyn with Ladd, and two more graduate students undertook wartime research, Beatrice Deacon and Lorne T. Newman. An interesting collaboration resulted two years later, when Watson and the others received an urgent project from the National Research Council asking them to investigate various screens for an unknown purpose. Burton was not informed as to the purpose of this research, and quickly grew bored with the mindless nature of the work. He instead encouraged the students to investigate other specimens that seemed more engaging to him, such as the wings of flies. When the stream of reports on the screens began to dwindle, a 'friendly visit' to the Toronto labs was paid by two physicists involved with the war effort, G.P. Thompson and Dr. Simon. The students were never officially told what the project was for, but as it turns out Watson recalls in later years seeing the names Thompson and Simon affixed to documents associated with the Manhattan project. It seems quite likely then that the results of the work on sub microscopic screens were applied to the purifying and processing of uranium for the first atomic bombs [29].
In 1944 a third microscope was designed and built at the university, and regular work was reinitiated. Several more graduate students completed their theses on this apparatus in topics as diverse as the study of insect wings to diffraction measurements of microcrystals. With the death of Burton in 1948, much of the research in electron optics was dropped. The original microscope that Hillier and Prebus had constructed was phased out of use, and was eventually donated to the Ontario Science Center for display.

VII. In Conclusion

The real value of the Toronto electron microscope was that it served as a model for later production instruments. RCA invested $10,000 1939 dollars (roughly $200,000 US as the modern equivalent) in James Hillier's project, and quickly obtained results. With better shop facilities and a good budget he was able to complete the first prototype in under 4 months. The microscopes developed by C.E. Hall at Kodak, and by Albert Prebus at Ohio State also followed directly from the 1938 Toronto instrument. Hillier continued on at RCA for over 30 years, helping to develop the electron microscope to the precision instrument that is so invaluable to scientists today. In a few short decades the apparatus became a standard in a wide number of fields. Its full impact on medical and biological research is likely too great to be measured, but it would not be an exaggeration to suggest that our understanding of the mechanisms and structures of life would be severely reduced without the electron microscope. Thomas Edison claimed that the act of invention was more perspiration than inspiration. The work performed at the University of Toronto by the early microscopists seems to have included a generous amount of each. It seems remarkable today, in a society where the development of ground breaking technology is almost solely the domain of the large corporation, that they were as successful as they were. The success of the electron microscope and its subsequent impact on our understanding of nature stands as a testament to the hard work and innovation of these Canadian pioneers.
Endnotes

7. University of Toronto bursar memo, 1933.
10. The Clinic Bulletin April 22, 1926 Vol.7 No.223
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