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Elected FRS 1990

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Malcolm Chisholm was one of the most creative and distinguished inorganic chemists of his generation. He was particularly renowned for his chemistry of compounds containing multiple metal–metal bonds and for showing how they could give insights into catalysis or be used in functional materials. Very early in his independent career he reported the remarkable compounds $\text{M}_2\text{X}_6$, with $\text{M} =$ molybdenum or tungsten and $\text{X} =$ alkoxide or dialkylamide, which contain metal–metal triple bonds, and his group showed how they could activate organic compounds in unusual ways, often with changes in the metal–metal bond order. He was a master of synthetic chemistry, but he also made notable discoveries in theory, spectroscopy and catalysis. Personally, he was outgoing, friendly and fun-loving. He was faithful and supportive of his family, students, colleagues and his many friends around the globe, and took great pleasure in their successes.

1. EARLY LIFE AND INTERESTS

Malcolm was born in 1945 in Bombay (now Mumbai), India, to Scottish parents, Angus and Gweneth Chisholm, at the end of the Second World War. Angus was a career officer in the British Army, and had been involved in military intelligence operations in the war against Japan in Burma, while Gweneth was a primary school teacher, but was in India to contribute to code-breaking operations. The reunited family moved back to their ancestral home in Inverness, Scotland, when Malcolm was six months old and then to Dorset, in the south of England, when Malcolm was aged three. It was here that he spent his formative years, though a slight Scottish burr could always be detected in his English accent and he always cherished his Scottish heritage. He remembers being captivated by science even at the young age of four. ‘My first interests in science were meteorological, trying to predict storms,
rain, and when it would snow,’ he said (Davis, 2007). ‘Of course, that was frustrating because it doesn’t snow much in the south of England.’ By the time he was nine, Malcolm’s interests had moved on to astronomy. With his telescope, he looked at the moons of Jupiter and, in 1956, spied the Aaron Rowland comet. Malcolm retained a strong amateur interest in both meteorology and astronomy, and could often be found contemplating the sky for threatening clouds or interesting astronomical events.

In the late 1950s, Malcolm was given a chemistry set. In those days, one could buy a lot of chemicals from a chemist’s shop and, like many a schoolboy, he found materials for his experiments at the local pharmacy. He found that sodium chlorate, in combination with sugar, made good homemade rockets. His experiments took place unfettered by his parents until a particular incident drew the local fire brigade. ‘I had a bit of a fire in the garden shed,’ he said. ‘That was the end of my independent experiments.’ His parents suppressed his would-be pyromania, and he completed his school days safely (Davis, 2007), with mother Gweneth having a strong influence on his decision to go on to university.

2. STUDENT DAYS AT QUEEN MARY COLLEGE, LONDON, 1963–1969

Malcolm was admitted to Queen Mary College (QMC), London, in 1963. He now had interests in meteorology, astronomy and chemistry and had to choose the subject for his degree. He briefly considered meteorology, but then, he said, ‘I discovered you had to have a degree in math.’ So Malcolm settled on chemistry because, he said, ‘it was one of the subjects that came most easily to me.’ However, he did not envision becoming a professional chemist at that time (Davis, 2007).

As a young undergraduate, Malcolm threw himself into the social life of the university and became Social Director for the Students’ Union. He spent much of his undergraduate years booking and promoting rock concerts by rising stars from the 1960s London music scene, like Eric Clapton, The Yardbirds, The Animals and The Who. Malcolm became known as ‘Big M’, a moniker befitting his Mick Jagger style of dancing, his gold-tipped Black Russian cigarettes and his sweet-talking entrepreneurial spirit. Malcolm graduated successfully with his BSc in chemistry from QMC in 1966, an achievement that came as something of a shock to his professors, and even to himself, since he had come close to giving up university to pursue a career in music promotion. While never giving up his love of music and dancing, Malcolm shifted his abundant energy to the world of science (Anon., 2015).

A major turning point for Malcolm’s career in chemistry occurred during his final undergraduate year when he carried out a successful research project in the laboratory of a young lecturer, Alan Massey, who was later to become a distinguished professor of inorganic chemistry at Loughborough University. Malcolm found that when iron pentacarbonyl, Fe(CO)\(_5\), in a sealed, evacuated Pyrex flask was exposed to sunlight, an experiment requiring careful timing in cloudy London, crystals of di-iron enneacarbonyl, Fe\(_2\)(CO)\(_9\), were deposited on the walls of the flask. The binuclear iron carbonyl complex Fe\(_2\)(CO)\(_9\) had been known for many years, but doubt had sometimes been cast on its authenticity based on its low solubility and low volatility for a covalent compound of so low a molecular weight. Malcolm showed that Fe\(_2\)(CO)\(_9\) could be sublimed under high vacuum and that it gave a beautiful mass spectrum, which supported its proposed chemical formula. This undergraduate research garnered him his first publication, a brief communication in *Nature* (1). During his time in
Alan Massey’s laboratory, Malcolm found that he loved open-ended, curiosity-driven research and that he had a natural talent for synthetic chemistry. He began to envisage a future career in chemistry.

Malcolm stayed at QMC for his PhD studies and was initially planning to continue his research with Alan Massey. However, he finally decided to work with Don Bradley (FRS 1980), who had been appointed to the Chair of Inorganic Chemistry in 1965. Don Bradley was educated at Birkbeck College, London, and had stayed there as lecturer from 1949 to 1959, before becoming Professor of Inorganic Chemistry at the University of Western Ontario in the other London, in Canada, from 1959 to 1965. Don had promised his wife that they would one day return to the UK, and research in England was attracting more government support in the 1960s than in the immediate post-war years, so he decided to move back and to take up the offer of the chair at QMC (O’Brien, 2000). He had recently discovered that volatile molecular alkoxides of several transition metals could be obtained if bulky alkyl groups were used, to prevent oligomerization through the formation of alkoxide bridging groups. These were very early examples of transition metal compounds with low coordination numbers and their fundamental importance was quickly recognized by the growing community of inorganic chemists. Later, the volatile alkoxides became commercially important as precursors for metal oxides by chemical vapour deposition (CVD) and Don Bradley was a pioneer in that field too. While in Canada, Don Bradley had begun to study the related dialkylamide complexes of transition metals and he was keen to bring this interesting field of research with him to QMC. Malcolm joined this endeavour and made several key discoveries. The synthetic strategy was very simple. It involved an anion exchange reaction of a transition metal chloride with a lithium dialkylamide, according to scheme 1.

However, the actual synthesis was difficult at that time because most of the products were very easily hydrolysed or oxidized, and equipment, such as the modern dry box needed to handle such sensitive compounds, was not yet available. The students used vacuum lines and did most of their own glass blowing. Similarly, characterization of the new compounds was challenging. X-ray crystallography was very slow and by no means routine and, because most of the compounds were paramagnetic, the developing technique of nuclear magnetic resonance (NMR) spectroscopy was not usually helpful. A further complication was that the reactions often took place with partial reduction of the transition metal compounds. For example, the molybdenum(V) chloride MoCl₅ gave the purple diamagnetic molybdenum(IV) dimethylamide, Mo(NMe₂)₄, and NbCl₅ gave paramagnetic Nb(NEt₂)₄. Chromium(III) chloride, CrCl₃, initially gave Cr(NEt₂)₃, but this disproportionated easily to chromium(II) and chromium(IV) and the volatile compound Cr(NEt₂)₄ was then obtained as a green, paramagnetic liquid. Malcolm was fascinated by the structures, colours and magnetic properties and he taught himself ligand field theory to account for the unusual physical properties, his first of several forays into the world of theory. He developed some of the early bonding theories involved in π-donor complexes. Thus, he could explain why a four-coordinate d² ion could be diamagnetic, as was seen for Mo(NMe₂)₄. He also studied the reactivity of his new compounds. For example, Cr(NEt₂)₄ reacted easily with t-butanol to give the chromium(IV) t-butoxide Cr(O-t-Bu)₄ as a volatile royal-blue solid, as Malcolm was
able to demonstrate to the Queen Mother when she opened the new chemistry building at QMC in 1967.

A reaction that seemed at the time to go as planned was that between tungsten hexachloride and lithium dimethylamide to give tungsten hexa(dimethylamide), W(NMe$_2$)$_6$, a six-coordinate compound. Malcolm took a flask containing his precious sample to a crystallographer, who promptly dropped it on the bench. Surprisingly, nothing happened and Malcolm just scraped up the sample, redissolved it and re-used it. It turned out that steric crowding by the 12 methyl groups protected this compound from the normal easy hydrolysis of metal amides. Several years later, when Malcolm was at Princeton, he found that his original sample of W(NMe$_2$)$_6$ had been prepared as a mixture with the tungsten(III) compound W$_2$(NMe$_2$)$_6$. The compounds had similar solubility and volatility so they were not separated in his PhD studies. At Princeton, he found that W$_2$(NMe$_2$)$_6$ could be hydrolysed by t-butanol to give W$_2$(O-t-Bu)$_6$ while W(NMe$_2$)$_6$ was inert. The resulting mixture of W$_2$(O-t-Bu)$_6$ and W(NMe$_2$)$_6$ could be separated, so finally giving a pure sample of W(NMe$_2$)$_6$. Don Bradley and Malcolm Chisholm later wrote a review of these early adventures in transition metal dialkylamide chemistry (3).

Malcolm Chisholm considered his advisor, Don Bradley, a very influential man in his life and a fine role model, both as a mentor and as a person. Of course, Malcolm was still a great socializer and among his many initiatives was to introduce group meetings at the local pub. Don noted that the level of excitement, both inside and outside the lab, decreased markedly after Malcolm graduated in 1969. The year before he graduated with his PhD, Malcolm married Susan Sage, who graduated with a BA(Hons) in English from QMC. Together in 1969, they moved to London, Ontario, for further studies.


After graduation, Malcolm and Sue moved to the University of Western Ontario (UWO) in London, Canada, where Malcolm took up a teaching postdoctoral fellowship and Sue enrolled in the PhD programme in English. Malcolm had arranged to do his postdoctoral research with Howard Clark, a New Zealander who had completed a second PhD with Harry Emeleus (FRS 1946) in Cambridge before taking up his first academic position at the University of British Columbia in Vancouver, Canada, in 1957. Coincidentally, Howard Clark had then replaced Don Bradley as professor of inorganic chemistry at UWO in 1965 and he had also taken on the role as head of the chemistry department. By 1969, the Clark group was well established at UWO and his main research theme was now in transition metal chemistry. In platinum chemistry, the discovery of the cationic carbonyl complex, [PtCl(CO)(PR$_3$)$_2$]$^+$, often known as ‘Clark’s cation’, was one of several notable achievements. Research in alkylplatinum chemistry had recently been initiated by postdoctoral fellows Dave Ruddick, who was already expert from his PhD research in organoplatinum chemistry with Bernard Shaw (FRS 1978), and Dick Puddephatt, the author, who had completed his PhD the previous year with Alwyn Davies (FRS 1989) and Robin Clark (FRS 1990). Malcolm’s project was to study the chemistry of cationic alkene and alkyne complexes of platinum, analogous to the carbonyl derivative, ‘Clark’s cation’. The project in Malcolm’s talented hands turned out brilliantly. He found the synthetic chemistry very easy compared to metal amide chemistry.
and he made important discoveries very quickly (scheme 2). Now NMR spectroscopy was the main day-to-day tool for determining the structures of his organoplatinum compounds and he was not accustomed to using this technique. For the first month or two he would come by the author’s lab with his spectra to check his interpretation, but he soon became expert and the roles were then often reversed. Later, Malcolm did some state-of-the-art research with Howard Clark and Jake Stothers on 13C NMR of organoplatinum compounds, and he continued to use NMR spectroscopy creatively through his career. Shortly after Malcolm started at UWO, a young graduate student, Leo Manzer, and an Australian postdoctoral fellow, Trevor Appleton, joined the group, along with Kenji Itoh (Nagoya) and John Ward (UBC), all working on organoplatinum chemistry. This was a tremendous team and they often worked collaboratively, spurring each other on to even greater efforts. Leo went on to a distinguished career in industry at DuPont, later leading their efforts to develop environmentally benign aerosols and refrigerant gases, while Trevor often worked with platinum compounds from a bioinorganic chemistry perspective during his academic career at the University of Queensland.

The most important concept to emerge from Malcolm’s time at UWO was that cationic complexes of platinum with alkenes and alkynes could be considered as metal-stabilized carbocations and that their high reactivity could be interpreted in these terms. The cations were generated by abstraction of a chloride ion from a neutral organoplatinum complex, such as 1 in scheme 2, in the presence of an alkene or alkyne. Terminal alkynes gave the alkyne complex 2, which could undergo a hydride shift to give an isomeric vinylidene complex 3, as a reactive intermediate, which could then react with alcohols such as methanol to give stable...
alkylidene complexes such as 4. Stronger nucleophiles, such as dimethylamine, could displace the methanol from 4 to give new alkylidene complexes 5. Internal alkynes gave the cationic complexes 6 and some of these could be isolated as stable compounds, but several underwent intramolecular insertion to give 7 or attack by external nucleophiles to give 8. Both 7 and 8 are vinylplatinum complexes, but with different stereochemistry. The concept of metal-stabilized carbocations has proved to be valuable for both fundamental chemistry and applied catalysis. Similarly, the alkyne route to alkylidene complexes was a landmark discovery that has been exploited by many other research groups. Malcolm and Howard Clark published 19 papers together, including an influential review article (2). Malcolm valued his time at UWO and especially the mentorship and support from Howard Clark, a wise man who later moved to the University of Guelph as Provost and then to Dalhousie University as President. Malcolm also benefited greatly by interacting with distinguished visiting professors who visited UWO to give several research lectures and to interact informally with department members, often including Malcolm’s group meetings in the nearest pub. Malcolm recognized what it would take for him to join them at the top and realized that he would have to substantially raise the level of his game. He left UWO in 1972 determined to do so.

4. FIRST FACULTY POSITION AT PRINCETON, 1972–1978

When Malcolm Chisholm was seeking his first faculty position in 1972, there were few openings in either Canada or the UK, so he broadened his horizons to look at opportunities in the USA. Having arranged a second postdoctoral position with F. Albert (Al) Cotton (ForMemRS 1994), who was then at MIT, Malcolm was offered a position as Assistant Professor at Princeton University. He decided to drive to Boston to discuss the situation personally, whereupon Cotton generously advised him to take the Princeton appointment, thus beginning a close friendship. Princeton was to become a centre of excellence for inorganic and organometallic chemistry in the 1970s since Jeff Schwartz, of hydrozirconation fame, and a regular opponent at squash, was recruited a little before, and Jack Norton, with interests in organometallic reaction mechanisms, osmium carbonyls and metal hydrides, soon after Malcolm’s arrival. In beginning his independent research, Malcolm was interested in pursuing either of his interests in organoplatinum chemistry or metal amide and alkoxide chemistry, but the granting agencies made the decision for him and he soon focused his efforts on the amides and alkoxides of molybdenum and tungsten in lower oxidation states. One challenge was that Princeton did not have an X-ray structure determination facility and Malcolm’s chemistry could not be successful without access to one. He soon realized that his new compounds contained metal–metal bonds, and so he reached out to his new friend, Al Cotton, who had now moved to Texas A&M University and who had both state-of-the-art X-ray equipment and the expertise for studying sensitive compounds. Thus began a long and fruitful collaboration and friendship, in which Malcolm pursued the synthesis and reactivity of metal–metal bonded dialkylamides and alkoxides of molybdenum and tungsten, Al Cotton looked after the single crystal structure determinations, and they combined expertise in interpreting the bonding properties. Later, Chisholm and Cotton exchanged students to enhance their collaboration and to give the students a wider perspective. So, Malcolm’s student, Mike Extine, went from Princeton to Texas A&M and Carlos Murillo graduated from the Cotton group to become Malcolm’s first postdoctoral fellow and lifelong friend (Murillo, 2016).
Scheme 3. Early chemistry of metal–metal multiple bonds and selected structures.

The Chisholm group at Princeton soon found that reaction of MoCl₃ with LiNMe₂ gave a good route to the compound Mo₂(NMe₂)₆ and, with greater difficulty, that reaction of WCl₄ with LiNMe₂ gave a route to W₂(NMe₂)₆ that was free of the W(NMe₂)₆ that Malcolm had studied a few years earlier at QMC. These new binuclear compounds were shown to contain metal–metal triple bonds and to have staggered conformations analogous to ethane, as expected for compounds with σ²π⁴ electron configurations that could be considered as transition metal analogues of acetylene. The first such compound, W₂(CH₂SiMe₃)₆, had already been reported a few years earlier by Geoffrey Wilkinson (FRS 1965), but its chemistry had not been developed (Huq, 1971). Malcolm quickly recognized that his compounds should have an extensive chemistry, by exploiting the reactivity of both the metal nitrogen bonds and the metal–metal triple bonds, and his group proceeded to pursue this in brilliant fashion (scheme 3). For example, dimethylamide groups in 9 could be substituted by reaction with bulky alcohols to give M₂(OR)₆, 10, or with trimethylchlorosilane to give M₂Cl₂(NMe₂)₄, 11. Then the chloride groups in 11 could be replaced by alkyl groups to give M₂R₂(NMe₂)₄, 12, and Malcolm showed that these unsymmetrical compounds 11 or 12 could exist as anti or gauche conformers. Carbon dioxide could insert into some or all of the M–NMe₂ bonds to give carbamate complexes, such as W₂(O₂CNMe₂)₆, 13. All of these reactions took place with retention of the metal–metal triple bond, even while the coordination number at tungsten or molybdenum could vary between four and seven. However, W₂Et₂(NMe₂)₄ reacted with CO₂, with loss of the ethyl groups, to give W₂(O₂CNMe₂)₄, 15, which contains a metal–metal quadruple bond, and unsaturated reagents such as CO₂ could add to give products, such as 14, in which the metal–metal bond order was decreased or the bond was completely broken. A comparison of the reactivity of Malcolm’s triply bonded compounds M₂X₆, with π-donor ligands, with that of the compound Mo₂(η⁵-C₅H₅)₂(CO)₄ revealed interesting differences. For example, simple ligands L could add to M₂X₆ to give M₂X₆L₂ in which the triple bond is
retained, but the corresponding adducts \( \text{Mo}_2(\eta^5\text{-C}_5\text{H}_5)_2(\text{CO})_4\text{L}_2 \) contain only a metal–metal single bond. The Chisholm–Cotton collaboration led to over 40 papers, defining a new area of inorganic chemistry, and some of this was reviewed towards the end of Malcolm’s stay at Princeton (4).

Malcolm was immersed in his research, but found time to make new friends and to maintain contact with old ones. Leo Manzer was at DuPont in Wilmington, not too far from Princeton, and the Chisholms and Manzers often met at weekends. Malcolm liked to entertain and he and Sue warmly welcomed and supported new students and postdoctoral fellows. A particular joy was the birth of their son, Calum, on 11 May 1973. Among all these activities, Sue found time to work on her thesis and graduated with her PhD from UWO (Chisholm, 1978). However, there were strains in the marriage and Malcolm and Sue separated and later divorced. It was a very difficult and sad time for both of them. Sue moved to the University of Texas at Austin, where she has made a successful academic career in teaching, scholarly activity and service as Director of the Center for Women’s and Gender Studies. Meanwhile, Malcolm was organizing his next career move to the Indiana University. To acknowledge his gratitude to Princeton, he later endowed a scholarship there, the *Malcolm H. Chisholm Thesis Award*, for outstanding undergraduate senior achievement in inorganic chemistry and always took time to congratulate the honoured student personally.


After considering a number of offers of faculty positions, Malcolm Chisholm accepted a position at Indiana University (IU). He planned to continue his work on metal–metal bonded compounds, and IU had the great advantage of having an excellent X-ray structure service, with John Huffman in control. The Chisholm–Cotton collaboration was therefore phased out, though their strong friendship continued. At IU, Ken Caulton, with broad interests in reactivity in inorganic and organometallic chemistry, had been appointed to the faculty in 1969, and George Christou, with interests in molecular magnets, was appointed several years after Malcolm arrived. Together, they created a stimulating environment for research in inorganic chemistry, often organizing symposia with students from neighbouring universities.

A joyful event occurred on 1 May 1982, when Malcolm and Cynthia (Cyndy) Truax were married. At that time Cyndy was also Malcolm’s secretary and she was soon to take on the role of editorial assistant as Malcolm took on his first editorial position with the journal *Polyhedron*. Before long, in November 1983, Cyndy gave birth to twin boys, Derek and Selby, so a busy family life was guaranteed. The family liked to travel together, sometimes combining science and pleasure. On one occasion, while Malcolm was visiting UWO, Cyndy took the twins to a local park, where the brake on the twins’ stroller was somehow released and the stroller and twins rolled gently into the Thames River, with Cyndy in hot pursuit, fortunately with no harm done. Figure 1 shows the Chisholms on a later holiday, with the Loch Ness monster in the background. When at home, Malcolm and Cyndy were gracious and generous hosts and loved to entertain friends, colleagues and students. Malcolm was in charge of the synthesis of margaritas at these events and, at their annual Christmas parties, his renowned Artillery Punch. Malcolm owned a house in Cambridge, which he considered a second home, and he went there in the summers to escape the mid-west humidity, to relax, visit UK friends and to catch up on writing projects. Al Cotton often passed through Cambridge on his summer
trips, and they sometimes had the opportunity to meet up with their close friend Jack Lewis, Lord Lewis of Newnham (figure 2) (10).

Towards the end of his time at Princeton, Malcolm had switched the emphasis of his research from the synthesis of compounds with metal–metal triple bonds to studies of their chemical reactivity, and this was to become the main theme of his research throughout the 1980s. The reactivity was limited in part by steric effects and the dialkylamides and tertiary butoxides, which had been the first M$_2$X$_6$ compounds prepared, proved to be somewhat less versatile than the alkoxides with smaller alkyl groups, such as the isopropoxides. On the other hand, if the alkoxide groups were too small, the compounds formed polymers, so Malcolm’s trademark attention to detail was essential in finding the perfect Goldilocks systems. His research plan was to compare the properties of his triple bonds with those of alkynes. Both have $\sigma^2 \pi^4$ electron configurations, but the use of d-orbitals in M$_2$X$_6$ allows a more diverse set of reactions. Addition reactions across the triple bond gave compounds with double or single bonds, analogous to similar reactions of alkynes. For example, reaction of Mo$_2$(O-i-Pr)$_6$ with di-isopropyl peroxide or bromine gave a Mo=Mo double bond in Mo$_2$(O-i-Pr)$_8$ or a Mo–Mo single bond in Mo$_2$Br$_4$(O-i-Pr)$_6$, respectively. Reactions with nitric oxide and a ligand such as pyridine could completely cleave the triple bond to give products such as W(O-t-Bu)$_3$(NO)(pyridine) from W$_2$(O-t-Bu)$_6$. There can be no analogy for this in organic chemistry, and some other reactions which differ from those of alkynes are shown, in simplified form, in scheme 4 (6, 7). Remarkably, carbon–carbon or carbon–nitrogen triple bonds could be broken to give carbyne complexes and nitride complexes such as W(CR)(O-t-Bu)$_3$, 16, and W(N)(O-t-Bu)$_3$, 17. In some cases, the compounds could equilibrate with dimers, as in the reaction of W$_2$(O-i-Pr)$_6$ to give W$_4$(O-i-Pr)$_{12}$, 18, or react with oxo or carbyne complexes to give W$_3(\mu_3$-O)(O-i-Pr)$_9$, 19, or W$_3(\mu_3$-CR)(O-i-Pr)$_9$, 20, respectively. From a compound analogous to 14, carbon monoxide could be reduced to carbide and oxide.
Figure 2. Jack Lewis, Malcolm Chisholm and Al Cotton in Cambridge.

Scheme 4. Some unprecedented reactions of the metal–metal triple bonds in $M_2(OR)_6$ ($M = Mo$ or $W$, alkoxide groups are omitted for clarity).

To place the chemistry on a firm basis of theory, Malcolm supported his student, David Clark, to work with Bruce Bursten, then a young assistant professor at Ohio State University. The collaboration was very successful, and Malcolm and David were awarded the American Chemical Society (ACS) Nobel Laureate Signature Award on the basis of his superb PhD thesis. Malcolm loved to celebrate the successes of his students, so this award gave him particular pleasure (figure 3). This is but one example of how Malcolm enjoyed spotlighting the accomplishments of his associates throughout his career, while also giving them abundant career advice. The beauty of the Chisholm chemistry with metal–metal multiple bonds was internationally recognized and attracted many other major awards from the ACS and Royal Society of Chemistry. He was delighted by his election as FRS in 1990, at the age of 44, and by the later award of the Davy Medal by the Royal Society.
During his long stay at IU, Malcolm was developing an interest in materials chemistry, at first through a recognition that his metal alkoxides could act as models for reactions proposed to occur at the surface of metal oxides during bond activation and catalysis (5, 8, 13). Later, in collaboration with his colleague Ken Caulton, Malcolm used his volatile tungsten compounds as precursors to tungsten carbide, tungsten nitride or even tungsten metal. They also devised routes to volatile compounds of barium and copper and used them as precursors of materials such as barium oxide and metallic copper. Independently, Malcolm began to develop a major research project on the use of metal alkoxides for polymerization of dilactides, oxiranes and other ring compounds to create environmentally benign polymers from renewable resources. He was also becoming intrigued with another new project on spectroscopy of compounds with metal–metal multiple bonds, with the idea of developing photonic materials. He considered, but did not accept, a number of attractive offers to relocate from Indiana during his stay there, but finally received an offer from Ohio State University in 1999 that he could not refuse. His friend and collaborator, Bruce Bursten, had risen through the ranks there and was chair of the chemistry department, the department had excellent facilities and expertise to support his growing interest in materials science, they made a most generous offer and, critically, it was close enough to Cyndy’s mid-west roots to be attractive to her too.

6. The Ohio State University, 2000–2015

In January 2000 Malcolm made his final move from Bloomington, Indiana, to The Ohio State University (OSU) as Distinguished Professor of Mathematical & Physical Sciences.
The negotiations had been protracted and the first indication that Bruce Bursten had that the offer had finally been accepted was when Malcolm phoned to invite him to visit the new Chisholm family home in Worthington, Ohio. Soon the research was again in full flow, stimulated by interactions and collaborations with new colleagues and, with his prodigious energy, continued unabated as he served as department chair from 2007 to 2011 and as associate director of Ohio State’s Institute for Materials Research. He was involved in early planning for the award-winning new Chemical and Biomolecular Engineering and Chemistry Building, which opened in 2015. In 2006, he was named Distinguished University Professor, the highest honour at OSU. External awards continued to be showered upon him, including election as a member of the National Academy of Sciences in 2005, and as a Fellow of the American Academy of Arts and Sciences, of Die Deutsche Akademie der Naturforscher—Leopoldina, and of the American Chemical Society. Warming his Scottish heart, he was also elected as Corresponding Fellow of the Royal Society of Edinburgh. One of Malcolm’s idiosyncrasies was that he made permanent molecular models of his more interesting molecules, which he kept in a display cabinet in his office (figure 4). He was much in demand as a seminar and conference speaker and would sometimes send a parcel of these models on ahead for dramatic effect in his lectures. A lifelong vegetarian, he continued to enjoy cigars, Scotch whisky and Jaguar cars, to write with a fountain pen long after it became challenging to find either the pen or the ink, and to make new friends wherever he travelled.

In research at OSU, Malcolm switched his emphasis to the so-called ‘paddlewheel’ compounds with quadruple bonds having the $\sigma^2 \pi^4 \delta^2$ electronic configuration. Earlier, he had developed routes to these compounds, such as 15 (scheme 3), by reductive elimination from compounds with triple bonds. Now he wanted to link two or more of these quadruply bonded centres to make dimers (such as the oxalate-bridged dimer 21 in scheme 5), oligomers or
polymers and liquid crystals, by using either covalent linkers or supramolecular self-assembly, to produce interesting properties of materials (11, 12, 14, 15).

To probe the electronic properties of these new compounds, he used his own expertise in spectroscopy and theory and, in this interdisciplinary area of science, he also collaborated with Robin Clark in resonance Raman spectroscopy; with his young colleague Jeff Zaleski at IU in low temperature electronic spectroscopy; and with his new colleagues at OSU: Bruce Bursten and Christopher Hadad in theory, Pat Woodward in structure determination, Art Epstein in electroluminescence and electron paramagnetic resonance (EPR), and Terry Gustafson and Claudia Turro in studies of excited states by ultrafast absorption and emission spectroscopy. During this period, he discovered intimate electronic fine structure and new charge-transfer excited states, and developed a new understanding of the intervalence charge transfer in dinuclear units.

Malcolm’s second major theme at OSU was in the general area of green chemistry, in particular in the synthesis of oxygen-containing, biodegradable polymers from sustainable sources. His main emphasis was on the polymerization of dilactide, which is made from corn and readily available, to make polyesters, but he also worked on polymerization of epoxides to polyethers and copolymerization of epoxides with carbon dioxide to make polycarbonates. Most conventional catalysts for these processes were heterogeneous and not very selective, and Malcolm’s contribution was to design well-defined single-site catalysts that were both immortal, so as to make living polymers, and stereoselective, so as to optimize the functional properties of the polymers. His most active catalysts were based on complexes of magnesium, calcium and zinc, with one alkoxide group and with a bulky anionic ligand to discourage formation of alkoxide bridging groups. Compound 22 in scheme 5 was one successful catalyst design. He found that organotin alkoxides were less active as catalysts, but allowed a study of the mechanism of polymerization. In his typical thorough approach, he worked to optimize reactivity and selectivity based on his studies of the mechanisms of polymerization (9).

For the first 10 years or so of the Chisholm tenure at OSU, the family flourished. The twins became independent and Malcolm and Cyndy made plans for more extensive travels. Malcolm’s chemistry continued to excel and he attracted more awards, such as the DSc, honoris causa, from UWO (figure 5), where he had a last reunion with Howard Clark. However, tragedy was soon to strike when both Malcolm and Cyndy became ill. Cyndy passed away in August of 2012, leaving Malcolm bereft, but he took solace in his family, happily welcoming his first granddaughter, Fleur, in November 2012. Malcolm himself had
been diagnosed with cancer and, for the last five years or so of his life, underwent regular chemotherapy sessions, which he suffered bravely and cheerfully. He grew a beard, refused to quit, and continued with his teaching, research and social life until very near the end. This included throwing an ‘8-to-8’ party for Christmas 2013, when he invited his whole group, family and friends over to party and danced through the night. Still travelling extensively, and usually first class, he took memorable tours of Scotland: in 2013 with Calum, Erica and Fleur, and in 2014 with old friends Cliff and Pam Kubiak and George and Kim Christou (figure 6). He also treated himself to a new Jaguar sports coupe that year (his 510 hp ‘touring’ Jag), to encourage him to take road trips to see old friends, often with his canine companion, Butters (figure 7). The end came on 20 November 2015, when he passed away peacefully at home at age 70, in the arms of son Selby. He is survived by his sons Calum (daughter-in-law, Erica, and granddaughters, Fleur and Soleil), Selby (daughter-in-law, Soobin, and granddaughter, Oona) and Derek (daughter-in-law, Lauren). A day or two before the end, Calum asked if he was frightened, to which he replied ‘Oh, not at all. I have had a wonderful life’, thanks to all the friends and family who had given him so many happy memories.
Figure 6. Malcolm, Cliff Kubiak and George Christou in Dunvegan Castle Gardens, Scotland. (Online version in colour.)

Figure 7. Malcolm with Butters and Jag. (Online version in colour.)

7. Honours and awards

1976–78  Alfred P. Sloan Fellow
1979–84  Henry and Camille Dreyfus Teacher-Scholar
1979 Cordy-Morgan Medal and Prize of the Royal Society of Chemistry
1985–86 Guggenheim Fellow
1986 Visiting Fellow, Clare Hall, Cambridge
1987 Fellow, American Association for the Advancement of Science
1987 Chairman, Division of Inorganic Chemistry, American Chemical Society
1987 Royal Society of Chemistry Award for the Chemistry and Electrochemistry of Transition Metals
1988 Alexander von Humboldt Senior Scientist Award
1988 (With David L. Clark) ACS Nobel Laureate Signature Award
1989 American Chemical Society Award in Inorganic Chemistry
1990 Fellow of the Royal Society, FRS
1994 Centenary Prize, Royal Society of Chemistry
1997 Indiana University, College of Arts and Sciences Distinguished Faculty Award for Research
1999 American Chemical Society Award for Distinguished Service in the Advancement of Inorganic Chemistry
1999 Davy Medal of The Royal Society
2001 Royal Society of Chemistry Ludwig Mond Lectureship
2004 Fellow, American Academy of Arts and Sciences
2004 Fellow, Die Deutsche Akademie der Naturforscher—Leopoldina
2004 Basolo Medal, Chicago ACS and Northwestern University
2005 Member, US National Academy of Sciences
2005 Corresponding Fellow, Royal Society of Edinburgh
2006 Bailar Medal, University of Illinois
2008 Doctor of Science, honoris causa, The University of Western Ontario
2009 Fellow of the American Chemical Society
2010 Nyholm Prize of the Royal Society of Chemistry
2012 Morley Medal, Cleveland ACS

EDITORIAL DUTIES

1982–97 American Editor, Polyhedron
1996–99 Editor, Chemical Communications
1998–2002 Associate Editor, Dalton Transactions

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Dick Puddephatt is Distinguished University Professor of Chemistry at the University of Western Ontario in Canada. He completed his PhD in chemistry with Alwyn Davies and Robin Clark at University College London in 1968. He then took up a teaching postdoctoral fellow with Howard Clark at the University of Western Ontario from 1968–1970, where he was a colleague of Malcolm Chisholm from 1969–1970. He was lecturer and then senior lecturer at the University of Liverpool from 1970, before returning to the University of Western Ontario in 1978. His scientific interests are in organometallic chemistry, catalysis and molecular materials.

REFERENCES TO OTHER AUTHORS

BIBLIOGRAPHY
The following publications are those referred to directly in the text. A full bibliography is available as electronic supplementary material via http://dx.doi.org/10.1098/rsbm.2016.0025 or via https://dx.doi.org/10.6084/m9.figshare.c.3585116.

Biographical Memoirs


