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Hans Adolph Buchdahl 1919–2010

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Hans Buchdahl, who died in Adelaide on 7 January 2010 at the age of 90, contributed extensively to three fields of theoretical physics: geometric optics, general relativity and thermodynamics. His early work on optical aberration coefficients was motivated by a wartime need; through this work he rejuvenated a field that had been moribund for close to a century. The methods he developed underlie some of the modern analytic and numerical approaches to the design of optical instruments. He contributed to the general theory of relativity during what was known as its 'Golden Age', and he made pedagogic contributions to the discipline of thermodynamics.

Early Life

Hans Adolf Buchdahl was born on 7 September 1919 in Mainz, Germany, the second of two sons of Moritz Buchdahl and his wife, Emmy (née Bendix) from Hameln. Hans' brother, Gerd, was five years his senior. The family was close, happy, stable, secure and prosperous. As a young boy, Hans accumulated an impressive stamp collection, liked to ride around the district on his bicycle, and delighted in scaring his aunts by connecting batteries and wires to door handles.

Hans was well aware of the general atmosphere of anti-Semitism but, in later life, he did not discuss any acts of anti-Semitic hostility from other boys towards him although he did recall overt unkindness from his English teacher. Hubert Goenner (University of Göttingen), who exchanged scientific and personal correspondence (and mutual visits) with Hans from 1975 to 1992, commented: 'Hans Buchdahl seems to have had a happy youth in Mainz until 1933. He was made aware of the historical background of this city of 2000 years: once as a boy he had found a Roman coin on the ground. He never expressed resentment about his and his family's having being driven away from his home town by the German Nazi authorities.'

Gerd did experience anti-Semitism: he matriculated from the Realgymnasium Mainz in March 1933, two months after Hitler came to power, and an offer of a job in Berlin was withdrawn because of his race (Woodhouse 1988). He moved to England and persuaded their parents to allow Hans to finish his education there, arranging for Hans to attend the Highfield College, a small boarding school in Leigh-on-Sea, Essex. Hans arrived there on 16 October 1933, with essentially no English. A school report for the Summer term (three months) 1934, when he was aged 14 years and 10 months, shows him coming fifth in a class of 25. He detested the school so much that he left and enrolled himself at the Regent Street Polytechnic in London.

In January 1936 Hans passed the Matriculation examination for entry as a science student to the Royal College of Science (later absorbed into Imperial College), University of London, where he commenced in October 1936 at the age of 17. He completed his degree in June 1939 with first-class honours, sharing, with one other student, the final-year Governor's Prize for most outstanding student in Physics. A testimonial from Herbert Dingle (Professor of Natural Philosophy at Imperial College) states that 'but for the war he would have been employed as a demonstrator here, with opportunities for research, for which he appears to have great capacity'. Another from Sir George Thompson (Professor of Physics) says: 'he is quite one of the ablest and most intelligent students I ever had...'.

During his time as a student in London, Hans used to smuggle money out of Germany on occasional brief visits home, in the valves for wireless sets he made. (Gerd hid money in his shoes.) Money was tight but Hans was frugal—every day his lunch consisted of an apple and a Mars bar—and he saved enough to buy a grand piano at the remarkably cheap price of 10 shillings, apparently from an elderly person who could no longer use it. Besides his love of classical music, Hans developed an interest in reading the legal arguments and summaries of prominent cases before the Law Lords of the House of Lords as reported in *The Times*.

Moritz and Emmy remained in Germany until June 1939 when they moved to London. Emmy claimed to have saved Moritz' life three times during the Nazi period: first, getting him to hide in the forest on Kristallnacht; second, bribing an SS officer (their accountant) to have him released from Buchenwald; and third, insisting that they leave for England. The SS officer took over the Buchdahl family business (Mainzer Bettenhaus) in retail bedding and furniture (Woodhouse 1988), which is still a going concern today (Goenner, private communication 2012).

Transported to Australia

In mid-1940, Hans and Gerd were interned, along with many other refugees from Nazism, and deported to Australia. The story of the decision to inter and deport internees is well documented (Bartrop 1990), has been told in detail in a book (Pearl 1985) and was the subject of a 1985, four-part television series and associated movie *The Dunera Boys*, written and directed by Ben Lewin.

After war was declared, 'enemy aliens' in Britain were classified as 'A', 'B' and 'C', with 'C' being 'refugees from Nazi oppression' who (64,000 of them) were initially left free. A change in policy led to 13,000 class 'C' men, including Gerd and Hans, being interned over a three-week period in June-July 1940, and plans were made to deport them to Canada and Australia. (Moritz was interned at the Isle of Man for a short time; Emmy took in boarders in their rented house in London.) The initial lot of 1,500 internees were on *Arandora Star*, being deported to Canada, when it was torpedoed and sunk by a U-boat off the coast of Ireland on 3 July, with heavy loss of life. On 10 July the second (and, as it turned out, last) lot of internees were put on the HMT ('Hired Military Transport') *Dunera* to be deported to Australia. The *Dunera*, despite having a maximum rated capacity of 1,600, was carrying 2,543 German and Austrian refugees, including many survivors from *Arandora Star*, and also 451 class 'A' German and Italian prisoners of war (Pearl 1985). The hardships of the voyage were severe due to the overcrowding, the poor sanitary conditions, the lack of change of clothing, and the contemptuousness of the guards towards the transportees. The attitude of the guards came from the top: the commander of the escort troop wrote in a postscript to a wireless message sent when *Dunera* was in Australian waters that his 'personal views ... on German and Austrian Jews' was that they 'Can only be described as subversive liars, demanding and arrogant, and I have taken steps to bring them into my line of thought' (Pearl 1985). The more dangerous prisoners were disembarked when *Dunera* reached Melbourne, and the remaining 1,984 transportees were disembarked in Sydney on 6 September 1940 (Pearl 1985). In later life, Hans commented little on this episode in his life, except for the dysentery and the dramatic difference in attitude of the Australian guards to those on the *Dunera*.

The friendly and respectful reception the internees received on arrival made a deep impression on Hans: some servicemen on duty on the dock saluted them as they disembarked. Hans spent his 21st birthday on the train between Sydney and an internment camp at Hay, New South Wales. The internees had been given a piece of fresh fruit each, the first fruit they had had for a very long time. Gerd gave his orange to Hans as a 21st birthday present. Hans later recalled his delight at the shimmering sunshine, the sunsets, even the dust storms. ‘This is the country I am going to live in’, he decided (Pearl 1985).

The internees were later moved to Tatura in Victoria, where they set up an unofficial ‘university’ to pass the time. There were experts to lecture on politics, art, philosophy, anthropology, inorganic chemistry, German poetry and film making (Pearl 1985). It is not recorded what part Hans took in this. He may have been interested in the mathematics, physics, chemistry and medicine classes given by Felix Behrend (Cross 1993). Hans loved the isolation and the absence of people, and he continued his own research on general relativity, writing on the only available paper—the back of jam-tin labels (Pearl 1985, Sandeman 2010). Many of the internees remained in Australia after the war and became prominent members of society in a wide range of different occupations (Pearl 1985). Included in various lists of these prominent ‘Dunera Boys’ is: Hans Buchdahl, theoretical physicist.

As part of the Australian war effort, a government Optical Munitions Panel was set up, with T.H. Laby (Professor of Natural Philosophy, University of Melbourne) as Chairman (Mellor 1958). All Australian universities were asked to contribute (Fenton 2005, p. 61). Leicester McAulay (Professor of Physics, University of Tasmania) after visiting Laby’s laboratory in Melbourne, is reported to have said: ‘Laby’s going to develop camera lenses in Melbourne and we are not to do anything about them. But I don’t think Laby will do it. My hunch is that somebody will scream one day for camera lenses for the RAAF. Therefore, we’re going to start immediately and look into the problem’ (Cassidy 1990). On his return to Hobart he recruited F.D. Cruickshank and others to work on the project in the Optics Annexe, designed and built under the direction of Mr Eric Waterworth, for the manufacture of prisms and test plates (Mellor 1958, Cassidy 1990, Fenton 2005). The Director of the Commonwealth Solar Observatory (CSO) at Mt Stromlo, R. v.d.R. Woolley, who was a member of the Optical Munitions Panel, decided to convert the CSO into an optical munitions factory, and had the inspiration of screening the ‘Dunera Boys’ to identify those trained in optics (McCrea 1987). Woolley identified seven and wrote to the Government seeking their release to assist in the work of the Optical Munitions Panel.

In May 1941, the Australian Government decided to release some internees and allow them to live in the community under a guarantor arrangement. Following Woolley’s initiative, five internees were released to work at CSO, under the condition that they not leave the Australian Capital Territory (Sherratt & Condé 1994). Hans was released ‘on parole’ on 28 October 1941, with Leicester McAulay as his guarantor. Hans was initially employed to lighten the teaching load of those on the staff involved in Optical Munitions work in McAulay’s department (Fenton 2005).

Gerd was released to work as a civil engineer, which he did until 1947. He also studied Philosophy at the University of Melbourne, graduating BA in 1946. In 1947 Gerd took up, at the University of Melbourne, one of the earliest appointments anywhere in the new field of History and Philosophy of Science.

Hans lived in a bush hut behind the McAulays’ house (‘Longway’, at the top of Manning Avenue, Sandy Bay) for about nine years. Leicester’s wife Joanne was a gregarious and considerate person who loved socializing. Whereas Leicester rarely mixed with Joanne’s party comers, Hans was considered a social asset and was frequently invited to Sandy Bay dinner parties. He got good meals and they got an intelligent dining companion. He enjoyed socializing with judges, artists, politicians and many cultured people. He also occasionally gave lectures on classical music and the great composers. Hans had grown up in a musical family and had a lifelong love of classical music. His great loves were J. S. Bach, Mahler and Bruckner. He developed a love for the Tasmanian wilderness and became a keen bushwalker. The serene calm of Hobart and the enthralling beauty of the Tasmanian bush provided his ideal haven.

Family Life

In 1950, Hans Buchdahl married Pamela Wann; they had met in Melbourne at the wedding of Gerd and Pam’s sister, Nancy. Hans’ and Gerd’s parents arrived from London to settle in Melbourne in the same year. Gerd and Nancy and their family moved to England when Gerd was appointed Lecturer in Philosophy of Science at Cambridge University in 1957. Emmy joined them there later; Moritz had died in 1955. Hans

Figure 1. The Buchdahls at Hans' and Pam's Churchill College flat in 1980. Front row: Nancy, Joe, Kit, Hans, Kate; back row: Nick, Pam, Gerd, Tanya. (Roger, Gerd's and Nancy's eldest son, is absent.)

and Pam initially had difficulty finding acceptable accommodation in Hobart; later they had their own home in Lipscome Avenue, Sandy Bay. The two elder children, Tanya and Nicholas, were born during their time in Tasmania and Catriona (known as Kate) after they moved to Canberra.

Pam commented that Hans was somewhat in awe of his children, preferring to stand back and allow them to forge their own way and make their own mistakes, as he had had to do from the age of 14 when he permanently left the parental home in Germany to finish his education in England. He provided the intellectual and cultural environment, the rest was up to them. He was tremendously proud of how each succeeded in their own field of interest. The only family rule Hans imposed was that there should not be any unnecessary noise while he was trying to work in his almost-soundproof study.

Tanya developed a career as a writer and music critic, including a biography (Buchdahl Tintner 2011) of her husband, the prominent orchestral conductor Georg Tintner. Nick became a mathematician, currently at the University of Adelaide. He and Hans were co-authors of one paper [106], published in 1977. Kate was a brilliant violinist; after graduating from the Canberra School of Music, she went on to attend the Juilliard School in New York 1983–87, and then studied at the Mozarteum in Salzburg. Kate developed Hodgkin's lymphoma and returned to the family home in Canberra, where her health declined slowly; she died aged 28 on 10 December 1992. The Australian National University created the Kate Buchdahl Memorial Prize, for the graduand who had made the most progress during their course and intended continuing further study in performance. Hubert Goenner commented that Hans 'ascribed his inability to write a single letter in 1991 to the ongoing indeterminacy of her state of health. He suffered with Kate.' After Kate's death Hans fell into clinical depression and found it difficult to continue his work. Hans and Pam moved to Adelaide in 2001 to be near Nick and his family.

Hans' experiences as a child in Nazi Germany left him with a pessimistic predisposition to life in general. This was partly reflected in his love of Ecclesiastes and in his choice of reading. One of his favourite authors was Louis-Ferdinand Céline, a nihilist and anti-Semite—two of whose books, *Journey to the End of the Night* and *Death on the Instalment Plan,* he regarded as outstanding literary works, impressive and influential. Another book that loomed large in his reading was *The Brothers Karamazov*.

Pam commented that, despite this ever-present gloom, he had the gift of laughter, often telling 'shaggy dog' stories that only he found amusing. He loved Australia and Australians but needed to refresh his contact with European culture from time to time. He missed the deep resonance of the Sunday cathedral bells. Tanya added: the sound of the Sunday bells meant so much to him because he was allowed to crawl into his parents' bed on Sundays, and from there he listened to the bells, and that sound represented deep security to him—something of which he was very short for most of his life.

Tanya recalled that one of her father's favourite sayings, when settling family disputes, was 'Don't you add your Senf ', which is an anglicised version of 'Musst du deinen Senf auch noch dazu geben?' (Will you also add your mustard?). She added that he was interested in music virtually unknown outside Europe forty or fifty years ago, and not even very widely known within Europe, yet now often heard and performed—he was ahead of his time, as it were: the music of Anton Bruckner, the piano sonatas of Schubert, the music of Leos Janacek (notably Tagebuch eines Verschollenen—Diary of One Who Disappeared).

Tanya provided two anecdotes: 'One of the best lessons I learned from him was about the need to be clear and precise. When I was around six, Dad asked me to give him the definition of a circle. I tried 'Like the top of the bathroom stool' and he wasn't having any of it. In the end I came up with the definition, a line in which every point on it is equidistant from a single given point, but not before a lot of frustrating alternative tries. There was a similar episode when I was 10, when Dad described something that had happened to him on an early morning walk along the lake (in Canberra). He said that if I could come up with the explanation by the time I was 15 he would pay me a reward of money. He said that he had heard a loud bang rather like a car backfiring, followed shortly afterwards by a type of grinding noise. This happened a couple of times. The answer to me was obvious right away – the original noise was being reflected off the concrete slabs on a nearby building. So I offered this explanation but Dad wasn't having any of it. I was in fact correct, as I heard much later, but I had only offered a 'something like' solution, unsupported by any scientific description or calculation (speed of sound, and distance from point of origin to the point of reflection etc. etc.). These events taught me a good lesson about precision and clarity, and I've always been grateful—though considerably more grateful for the first event than the second (I never did get that reward).'

Tanya also related a story when her father was uncharacteristically careless. He had promised her—from the days before the Sydney Opera House was even finished—that if ever Bach's Mass in B Minor (a work he loved) were to be performed at the Opera House, he would take her to Sydney to hear it. Her story continues: 'Dad booked tickets, plane tickets, and two rooms at the (then) Wentworth Hotel. When we arrived at the hotel they had never heard of us, but [nevertheless gave us] palatial suites on the 18th and 19th floors. Thinking to save time, he had decided to walk down the fire escape from 19 to 18, but hadn't bothered to check if the doors were locked from the stairwell, and indeed they were. He'd had to walk all the way down to the basement and out via the kitchens. We ran all the way to the Opera House, arriving just after the start of the performance, and were (after some pleading) allowed in only as far as some horrible seats at the very side of the hall.'

Nick provided an anecdote: 'I recall a conversation with my father, when I was 12 or 13, in which the question arose as to what would happen to a helium balloon held on a string in a car as the car accelerated. My father predicted that the balloon would move forward, and I thought that it would have to move backward (relative to the car), the result of inertia. A few months later I came across a black balloon that had been in the sun, warmed to such an extent that it acted like a helium balloon. So we got into Dad's Fiat

500 and proceeded to do the test in the street just behind the house (Garsia Street). In spite of the rather pathetic acceleration of the Fiat, the result was exactly as my father had predicted: the balloon did indeed move forward relative to the car as it accelerated. When I asked him how he knew, his response was that as far as the balloon was concerned, it felt that gravity was pulling it towards the back of the car as the car accelerated, and so its natural inclination would be to move forward [due to buoyancy]. I think the thing that struck me as much as the result itself was my father's statement that if the balloon had not moved forward, he would have resigned his position at the university.'

Hubert Goenner added an anecdote about a cemetery and a ladder: 'While in Göttingen [in 1975] he [and Tanya] visited the grave of his grandparents in nearby Hameln. The (Jewish) cemetery was walled and closed.' Tanya recalled the incident, and commented: 'The cemetery had a high wall around it and padlocked gates, as Jewish cemeteries generally do in Germany and Austria (to guard against anti-Semitic vandalism). A man who lived next to the side boundary saw us walking around trying to find a way in and came out to offer the use of his ladder. [This was a time] when there was still much denial, failure to confront the past, and residual anti-Semitism [and] such kindnesses were not always to be expected. We were touched by the gesture beyond simple gratitude for a favour done.'

Bushwalking

Hans' love for the Australian wilderness began in his early years in Hobart. He was introduced to the bush by Geoff Hood, a member of a group that had built a hut near the ski fields in the Mount Field National Park. Hans discovered the joys of bushwalking in the South-West Tasmanian wilderness. Over the Christmas break every summer, he walked for up to two weeks to Port Davey, Lake Pedder and elsewhere. In later years he talked of the button-grass plains and the horizontal scrub. He expressed anger and disappointment at the later flooding of Lake Pedder, as part of a hydro-electric project, as desecration of the wilderness he loved. Tanya commented: 'I actually think that part of Dad never recovered from the drowning of Lake Pedder [and that] it contributed to his depression.'

Peter Ford, Hans' first PhD student and a bushwalking companion from the late 1950s and early 1960s, recalled walking with Hans over at least four summers. 'Hans trained for several weeks by walking from home to university with a backpack filled with bricks. We started our walks by being driven as far as possible into the south-west, sometimes to a deserted hermit's house. We headed west for the first week, in areas with no trails, camping overnight by rivers, and sometimes being blocked by impenetrable tea-tree scrub. After a week we turned around, and walked back during the second week.'

Hans continued to be an active walker later in his life. Pam recalled that after they moved to Canberra: 'Every day before breakfast without fail he drove his Fiat 500 to the foot of Mt Ainslie behind the War Memorial in Canberra from where he walked to the top, very often with a Bach cantata playing on his tranny [transistor radio]. After breakfast he then walked the 3 or 4 km to his office on the university campus.'

University of Tasmania

When Hans Buchdahl began teaching at the University of Tasmania in 1942, he was only a year or so older than the local third-year students and recent graduates who were building up the Optical Munitions project (Fenton 2005, p. 68). Although he was officially at 'arms' length' from the Optical Munitions project, due to the conditions of his release from internment, he began developing the theory of optical aberration coefficients. There is no record of how he got started in the field, but he would have had contact with both Leicester McAulay and Fletcher Cruickshank, who were active in the Optical Munitions project; between them, McAulay and Cruickshank published three papers in *Proceedings of the Physical Society of London* on optics, including aberrations, in 1945. Cruickshank later produced a sequence of short monographs on paraxial optics that were used for teaching purposes for several decades, and that included details of the lowest-order aberration coefficients. In Buchdahl's first paper [1], published in the same journal in 1946, he gave only two references, both to books (dated 1929 and 1932) that expressed the then prevailing view that 'the algebraic determination of the aberrations of lens systems other than the primary involves computations of such magnitude as to make such analysis useless from a practical point of view'. He proceeded to calculate the coefficients to higher orders in a systematic way. Quoting a report on research in 1947 (Fenton 2005 p. 119): 'The algebraic methods developed by H. A. Buchdahl for analysis of the higher order aberrations of optical systems have been ... extended (i) to the case of arbitrary skew rays passing through the system, and (ii) to include ... aspherical refracting surfaces'. The generalization to non-spherical surfaces [3] was later to become important in applications based on his work. Greg Forbes commented on Hans' later emphasis on Hamiltonian methods in geometric optics (Forbes 2010): 'Interestingly, McAulay's father had worked on Hamilton's quaternions, but I do not know if this seeded Hans' interest in Hamilton's methods.'

In the 1940s, he continued his research in general relativity, publishing two papers [2, 4] in the field in 1948. The latter was published in the *Proceedings of the National Academy of Science U.S.A.* When the editor (Edwin B. Wilson) sent Hans the proofs, he informed him that his paper had been referred to Albert Einstein for comment (which was favourable). Hans took advantage of this by using it as an opportunity to write to Einstein (letter dated 8 February 1949) to ask (in English) several questions of a technical nature concerning general relativity, quoting several times (in German) from Einstein's original paper on the subject. Einstein replied (in German) in a lengthy letter dated 9 March 1949, and the correspondence continued with a later letter from Einstein dated 18 August 1949. For Hans, working in isolation in Tasmania, this correspondence with Einstein must have been a major fillip.

At about this time, Hans published his first papers [6, 7, 8] on thermodynamics in the teaching-orientated *American Journal of Physics*.

In 1949 the University of Tasmania awarded him a DSc for his research in general relativity, geometrical optics and classical thermodynamics. Higher degrees were relatively uncommon there: in the period 1942–62, there were 1 DSc, 9 PhD (plus 4 in 1963) and 4 MSc in Physics (Fenton 2005). His appointments at the University of Tasmania were as Honorary Assistant Lecturer, 1943–45, Research Physicist, 1946, and Lecturer part-time and Research Physicist from 1947. He was promoted to Senior Lecturer in 1951 and to Reader in 1956, the same year in which he was awarded a DSc by Imperial College, London. In the mid-1950s he declined an invitation to apply for a chair in London, confirming his earlier decision that he would spend the rest of his life in Australia.

Hans was committed to his teaching. He wrote detailed lecture notes. His lecture notes on quantum mechanics continued to be used many years after he left Tasmania (McPhedran, private communication, 2012). There was little opportunity for supervising graduate students. Three of the Honours students whose research projects he supervised became Rhodes scholars for Tasmania: David Brink (1951), Graeme Salmon (1955) and Don Melrose (1962).

After Leicester McAulay retired, G.R.A. ('Bill') Ellis took up the position of Professor in 1959, while Hans was on study leave at the Princeton Institute for Advanced Study. Although there were no overt signs of friction between Buchdahl and Ellis, it was evident that Hans did not see a long-term future for himself at the University of Tasmania. Despite his love for Tasmania, it was time to move on.

Australian National University

In 1963 Hans was appointed to the inaugural Chair of Theoretical Physics in the School of General Studies, later renamed the Faculties, at the ANU. There was already a Department of Theoretical Physics in the Research School of Physical Sciences, led by Professor Kenneth Le Couteur. The decision to make a professorial-level appointment in the teaching part of the university could be effected only by creating a new department: the rules of the ANU at that time required that a professor be head of a department, and that a department have a minimum of three academics. Buchdahl's appointment was supported strongly by (Professor Sir) Fred Hoyle, a leading astrophysicist, who was visiting the ANU at the time. The other two positions in the department were filled by Lindsay Tassie (replaced by Don Melrose in 1969, and by Brian Davies in 1979) and Mark Andrews.

Teaching in theoretical physics was restricted to second- and third-year courses, plus supervision of Honours and postgraduate students. The undergraduate classes in Theoretical Physics covered a broad range of theoretical

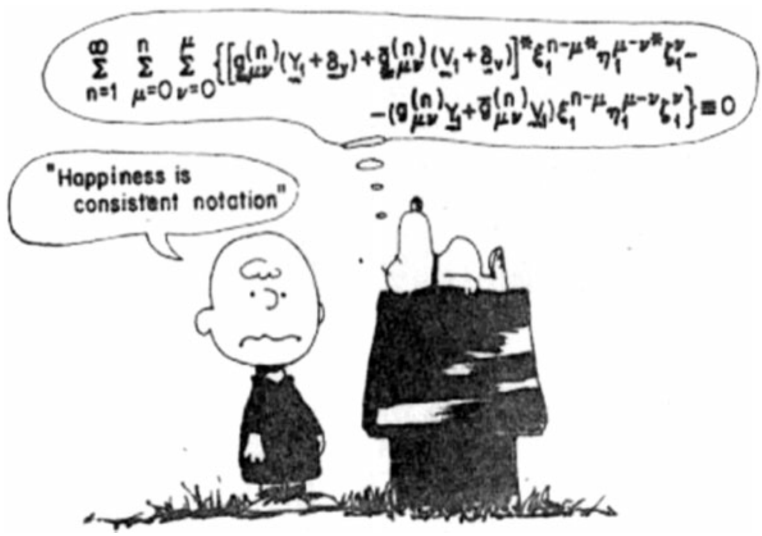

Figure 2. Hans kept a framed copy of the Snoopy cartoon presented to him by his students in 1969.

physics, with Hans regularly teaching his favourite courses, including tensor analysis, relativity and orthogonal polynomials. Although the classes were small, Theoretical Physics regularly attracted outstanding students. Hans' intellectual rigour (in research, in teaching, and in general) made a strong impression on everyone who knew him, including the students, and although some of the students found his courses very tough, the brightest also found them very rewarding. Hans encouraged the brightest of the Honours students to pursue graduate studies overseas.

Hans supervised two PhD students during his time at the ANU: Peter Sands (PhD 1967) and Greg Forbes (PhD 1984), both in optics.

Hans was memorable to his students for his attention to detail, whether in mathematical notation, physical interpretation or the use of language. In 1969, when 'Peanuts' cartoons were in vogue, his students at Rochester University presented Hans with a cartoon (Figure 2) of Snoopy asleep on top of his kennel dreaming of one of Hans' equations with multiple superscripts and subscripts, and with Charlie Brown saying 'Happiness is consistent notation'.

Hans was a perfectionist in the use of words. Greg Forbes recalls Hans writing to him: 'I should have been much harder on you when you first came to Canberra so that garbled English, repellent terminology and inappropriate symbolism might have been eradicated once and for all.' Greg recalls being told that he surely knew the difference between 'recursion' and 'recurrence', how to pronounce 'exquisite', and that 'however' is not a conjunction. Peter Sands commented that Hans' insistence on 'rigour, clear notation [and the] importance of language [became] very much a part of my personal and intellectual heritage, and one of Hans' legacy to me. I remember us often looking things up in Fowlers English Usage.' At the time Australia adopted the metric system, Hans insisted on the correct pronunciation of kilometre as Kil-o-mee-t:Jr and not the 'americanism' ki-LOM-i-t:Jr.

Hans was well respected within the ANU community, but he avoided anything that involved university politics except where it directly impinged on him or his department. On one occasion when he was sounded out about standing for the position of chair of the Academic Board he remarked that he would find the politics intolerable and would soon be 'pushing up the daisies'.

Post-retirement

Hans retired in 1985, after which he became Emeritus Professor. The Theoretical Physics Department and the Physics Department were combined. His connection with the ANU continued, initially as a University Fellow and later as a Visiting Fellow, until he and Pam moved to Adelaide in 2001. He published his last paper [165] in 1996.

His initial appointment as a University Fellow required that he give a public lecture. His lecture, entitled ‘Second Culture, Second Law’, developed his ideas on C. P. Snow’s two cultures (Snow 1959). During the retirement period, Hans continued to correspond with colleagues on his earlier work. Three examples illustrate Hans’ attitudes and opinions:

Hans had been a consultant for the Lockheed Company, and in a letter to Hans in 1987, Dr Paul Robb of Lockheed made an aside comment on a session entitled ‘Aberration Theory Made Simple’ at the 1987 annual meeting of the Optical Society of America. Hans responded: ‘there is only one simple way to present aberration theory, namely via Hamiltonian methods. Alas I failed to put the message across.’

In a snippet of self-assessment, Hans wrote in a 1993 letter to Professor I. W. Roxburgh, Queen Mary College, London, relating to citing one of his papers on general relativity: ‘You see, throughout my life I have “got into trouble” over the way I speak: I am seen as too outspoken, too aggressive. . . . I am apt to be abrupt, often saying “oh, but such and such is complete nonsense”, and so on. . . . Perhaps it is because my “upbringing” was interrupted before its proper time, . . . and it may be related to the fact that I’ve always had to discuss things with myself, having no-one else to talk [shop] with. . . . and when I talk to myself I am very outspoken! Therefore should I appear to be unnecessarily blunt, please don’t be offended!’

A rather lengthy and inconclusive correspondence arose from an article written by Dr Clive Coogan in the Trans Australian Airlines magazine, *Australian Way*, suggesting that Boeing had made $8 billion from the sale of supercameras for aerial reconnaissance, and that the design was based on Buchdahl’s work without any recognition. Hans’ initial correspondence with Coogan became sidetracked by recollections of an earlier meeting, about which they did not agree. Hans wanted to contact Boeing, seemingly with the intention of asking for a financial contribution towards the Kate Buchdahl Memorial Foundation Prize (this was the year after Kate’s death), but did not get any reply. He finally made contact with a relevant Boeing representative through his friend (Professor E. M.) Margaret Burbidge. The outcome of the correspondence was that Boeing denied (letter dated March 1994) any involvement with supercameras. It was never clarified whether Coogan’s story was incorrect, or whether he had identified the wrong company.

During Buchdahl’s career, Australian academics were expected to spend sabbatical years abroad. Buchdahl spent time at Imperial College, London 1950–51, the Institute for Advanced Studies, Princeton 1959–60, the University of Rochester 1968, the Weizmann Institute of Science, Rehovot 1975, Churchill College, Cambridge 1979, and the University of Göttingen 1975, 1986.

Geometric Optics

Buchdahl’s initial work on aberration coefficients set the pattern for his work in the field over subsequent decades; this work underlies a modern approach to the design of optical instruments. The analysis of optical aberrations in terms of coefficients of a power series had a long history, starting with Seidel in the mid-nineteenth century, and optical designers made extensive use of Seidel’s theory, which was restricted to third order in the expansion. The design of optical instruments at the time was based on experience and a trial-and-error approach, and could be described as more of an art than a science. Buchdahl’s work provided a systematic approach that allowed optimization of the optical system to satisfy specified criteria. Even in the 1947 research report cited above, when Buchdahl had published only his initial paper [1], there is mention of interest in industrial applications of his results from Kodak Ltd, England. The recognition of the importance of his first two papers in the field [1, 3] is reflected by the award of a Nuffield Fellowship for a year (1950–51) at Imperial College, London, to allow him to write up his work in a monograph. The book *Optical Aberration Coefficients* was published by Oxford University Press in 1954 (republished by Dover in 1968). It was only after the publication of this book that he began a sequence of fourteen papers entitled ‘Optical aberration coefficients’ starting with paper I [20] in 1958 and ending with paper XIV [67] in 1969. During a year as New York State Professor of Optics at the

University of Rochester in 1968/1969, Buchdahl wrote his second monograph, *An Introduction to Hamiltonian Optics*. It is described as providing a detailed account of the Hamiltonian treatment of aberration theory in geometrical optics that is important for design of laser cavities, electron optics and crystal physics.

Buchdahl's extraordinary ability to simplify and manipulate calculational schemes and devise and use concise notation is evident in these monographs and research papers. How to make practical use of the results was not so clear to those involved with the design of optical instruments. Buchdahl's students played a role in communicating the significance of the theory to those in North America who wanted to use it. Peter Ford, Peter Sands and Greg Forbes all contributed in this way. The great advantage of the approach is its generality, allowing for aspherical optical surfaces. Another important generalization that Buchdahl introduced in Part II of *Optical Aberration Coefficients* is what he called a chromatic coordinate. This involves only a simple change of variable from wavelength, and it enables a power series to account for colour dependence across the full visible spectrum with far fewer terms than when the wavelength itself is used. In a letter to Hans in 1983, Paul Robb of Lockheed wrote that 'having the chromatic coordinate turned out to be exactly like having the key to a room full of gold'.

Peter Sands commented on two other innovative contributions included in Buchdahl's 1954 monograph. The first relates to the Appendix, 'Symmetrical systems with continuously varying refractive index'. 'This was was way ahead of it's time! I took that work up in 1968, and although still restricted to third order, it did stimulate thought on the practical use of such media in optical systems. Nowadays, as with homogeneous systems, everything is done via ray tracing. However, many optical design programs still include Hans' 5th order aberration coefficients as study of these does provide understanding of why a design works, or doesn't.' The second comment is that 'the tabular computational schemes developed by Hans and others in Hobart for analysis of optical systems represent pre-computer spreadsheet applications. Also, the process of optical design was, as I understand, performed by a group of mainly women on mechanical computing machines analysing optical systems that differed slightly from one another: a prescient example of parallel computing!'

Technical developments in the 1990s made the accurate finishing of aspherical optical surfaces commercially viable, by employing magneto-rheological fluids. Buchdahl's general methods enabled a systematic design of optical instruments by optimizing the aberrations without being restricted to spherical surfaces. Thus his work relates to many modern-day applications, including familiar ones such as cameras in mobile phones.

In the mid-1980s Buchdahl published a series of five papers on 'Power series of geometrical optics' [135, 136, 137, 141, 143] in which he explored the generic properties of the point characteristic function of a refracting plane. He noted that the aberration coefficients are the coefficients of a Taylor series expansion of this function, and that essentially nothing was known about the generic properties of the function itself, including the radius of convergence of the power series. Through this series of papers he put the theory of optical aberrations on a sound mathematical footing. In another series of papers on 'Invariant aberrations' [146, 147, 148, 149] he identified invariants of the characteristic function. In his final paper [165], he noted that the conventional aberration coefficients are defined by a Taylor expansion, and when the Taylor expansion does not converge, one can define 'aberration coefficients of the second kind' through a Laurent series.

Buchdahl's name is associated with 'Buchdahl–Rimmer coefficients' (Rosete-Aguilar & Rayces 1995), 'Mercado–Robb–Buchdahl coefficients' (Bolser 2002), and 'Buchdahl's glass dispersion coefficients' (Reardon & Chipman 1989), testifying to the importance of his work in geometric optics.

General Relativity

Buchdahl's interest in general relativity predated that in geometric optics, and continued throughout his career. His scientific reputation in the field was established by his early work on relativistic fluid spheres. In a paper [37] published in 1959, he found solutions of Einstein's field equations for the interior of a (perfect-fluid, spherically symmetric, non-rotating) star that is more physically realistic than Schwarzschild's interior solution, which assumes that the density of the sphere is constant. In this paper he proved ('Buchdahl's theorem') that the inequality, $GM/c^2R \leq 4/9$, derived by Schwarzschild on the ratio of the gravitational mass, M, to the radius, R, of the sphere, is valid for any equation of state provided (a) the pressure and density are everywhere non-negative, (b) the density is non-increasing outward, and (c) there exists a boundary where the pressure is zero. In the same paper [37] he derived another important result, that the total energy emitted in radiation during the symmetrical gravitational contraction of an amount of matter cannot exceed the initial (rest) energy, when the matter was completely dispersed. He later returned to the problem of self-gravitating fluid spheres to refine the inequalities imposed by physical constraints [61, 62].

In his work on alternative theories of gravity and their application to cosmology [74], Buchdahl placed physical constraints on theories derived from higher-order Lagrangians. He concluded that theories with quadratic Lagrangians, or $f(R)$-theories as they are sometimes called, are unphysical. He showed [116] that Palatini's device (an independent variation of metric and affine connection within Riemannian geometry) applied to quadratic Lagrangians leads, with only a few exceptions, to field equations with solutions exhibiting unacceptable ambiguities. Decades later, Buchdahl's results became relevant to alternative theories of gravity explored in connection with dark energy, but his results have been overlooked in some more recent applications to cosmological models (Goenner 2010).

Buchdahl recognised the possibility of cross-fertilization between optics and gravitation. He discussed the world functions of Robertson-Walker-, Schwarzschild- and Gödel-metrics [86, 113, 122], developing the analogy between this function and the point characteristic of geometric optics. The world function contains complete information about all geodesics, just as the point characteristic contains complete information about all ray paths. However, for practical use in general relativity, the world function needs to be approximated [119, 138, 160], and the analogy did not prove as fruitful as he must have hoped. The importance of this cross-fertilization has been recognised in the past few years in the field of metamaterials: 'tranformation optics' is explicitly based on the correspondence between general relativity and optical propagation (Leonhardt & Philbin 2012).

When Einstein was still alive, Buchdahl like many other theorists could not escape the lure of the famous scientist's 'unified field theory' of gravitation and electricity. Buchdahl was attracted by the possibility of the more general geometries that these theories provided, rather than by the physical motivation of unification. As shown in his monograph *Seventeen Simple Lectures*, his understanding of general relativity made him avoid (and criticize) the language adopted by the main stream, following J. A. Wheeler (with whom he corresponded in 1960). In particular, he avoided the term 'black hole', preferring 'occluded star' or 'frozen star' (Goenner 2010).

Tensors, Spinors and Wave Equations

Buchdahl had a particular attraction to tensor analysis, clearly related to the pleasure he got from calculational manipulations. Early in his career, he published papers on solutions of various gravitational field equations [2, 4, 14, 16, 19], on variational methods [5, 12, 13, 21] in gravitational and related field theories, on constructing the Lagrangian and the field equations from the metric [11], and on gauge invariance of these theories [22, 28]. His paper [11] arose while he was working with Weyl's theory and quadratic Lagrangians; he presented the Euler-Lagrange derivative of the most general Lagrangian built from the metric, the curvature tensor and its derivatives to arbitrary order. This paper, in a respected mathematical journal, was written in German and is little known, although it covers all later rederivations of field equations with higher-order Lagrangian (Goenner 2010). He returned to some of these interests throughout his career, e.g. [121, 132], and developed related interests, e.g., a calculus reflecting the group $SO(3, 2) \sim Sp(2, R)$ [94]. In his teaching of tensor analysis, he made a particular point of emphasising the difference between tensors and tensor densities [78], and the 'weight' associated with a tensor density.

His interest in tensor analysis led naturally to an interest in spinor analysis [25]. Initially this interest was associated with wave equations of higher spin [30, 48] and of transformation of spinors [31]. Later he devised a new 'rotor' calculus [59, 60] for self-dual bivectors in a complex three-dimensional space, and used it to prove that a certain curvature invariant is a divergence. He also published on the calculus of four-spinors [66, 68]. However, he did not follow those using spinors as a tool in general relativity, for example, for the study of gravitational radiation (Penrose & Rindler 1984). He continued to publish on spinor analysis well after his retirement [157, 161].

Another of Buchdahl's interests was the compatibility of wave equations for particles with higher spin ($\geq 3/2$) in a space with curvature.
By dropping the conventional non-minimal coupling, he showed that one can write down a consistent wave equation [115]. He published on this topic relatively early in his career [30, 48], later in his career [124, 125, 132] and post-retirement [145, 153, 158].

Thermodynamics

Buchdahl's interest in thermodynamics was teaching-orientated, with a strong pedagogic theme. He adopted an axiomatic approach to thermodynamics, based on Carathéodory's Principle and Carathéodory's Theorem.

In his first three papers in this field, he first [6] explained the formulation of the Second Law of Thermodynamics in terms of Carathéodory's Principle:

> *In the neighbourhood of any arbitrary initial state J_0 of a physical system there exist neighbouring states J which are not accessible from J_0 along adiabatic paths*; then [7] proved Carathéodory's Theorem for three variables:
>
> *In the neighbourhood of any arbitrary point G_0 there are points G which are not accessible from G_0 along solution curves of the equation*
>
> $$P(x, y, z)dx + Q(x, y, z)dy + R(x, y, z)dz = 0,$$
>
> *if, and only if, the equation is integrable*;

and finally [8] generalized this to an arbitrary number of variables and applied it to thermodynamics. The important step [15, 17] involves introducing an integrating factor, interpreting this in terms of an absolute temperature function, and interpreting the (perfect) differential in terms of the absolute entropy function.

He developed this approach in a number of papers [41, 50, 51, 88, 98, 144], and expounded it in two books: *The Concepts of Classical Thermodynamics* (1966, 2009) and *Twenty Lectures on Thermodynamics* (1975). In the preface of the latter he described his approach as an endeavour to allow 'physical intuition to take precedence over mathematical niceties'. His paper [41] 'The concepts of classical thermodynamics' was included as one of the memorable papers from the *American Journal of Physics* 1933–1990.

He had an interest in the relation between thermodynamics and statistical mechanics [96, 120], and a particular interest in the Fermi-Dirac gas. Based on numerical calculations he aimed to approximate the parametric form of the equation of state for a Fermi-Dirac gas by a form involving elementary algebraic functions [18, 32, 49].

His interest in teaching the concepts in theoretical physics more generally is shown by his papers in the *American Journal of Physics* on angular momentum [52, 53], the harmonic oscillator [63, 95], general relativity [70, 76, 126], thermodynamics [102], statistical mechanics [96] and other topics [108, 152].

Awards

Hans Buchdahl was honoured by grants, prizes, medals, and memberships, including: Nuffield Fellowship (1950), Fellow of the Australian Academy of Science (1968), Thomas Rankin Lyle Medal (Australian Academy of Science) (1972), Member of the Optical Society of America (1974), Overseas Fellow of Churchill College, Cambridge (1979), Walter Burfitt Medal (Royal Society of New South Wales) (1980), C.E.K. Mees Medal (Optical Society of America) (1993), A. E. Conrady Award (International Society for Optical Engineering) (1997).

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