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Charles Angas Hurst 1923–2011

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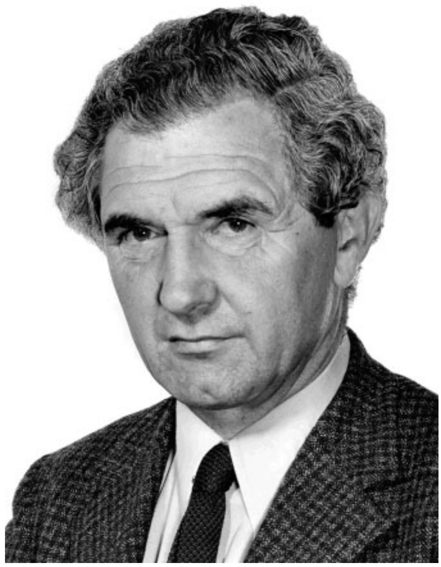
Charles Angas Hurst was born in Adelaide, South Australia, on 22 September 1923 and died in Adelaide on 19 October 2011. He was internationally renowned as a mathematical physicist, making seminal contributions to the understanding of perturbation expansions in quantum field theory, to statistical mechanical models, and other topics in mathematical physics. He was a fine ambassador for his country and for Australian science. His commitment extended beyond physics and mathematical physics, for he was always interested in fostering links across disciplines and with science internationally, especially in the Asia-Pacific region.

Family Background



Charles Angas Hurst was born in the Adelaide suburb of Unley Park, South Australia, on 22 September 1923, as the second child of Walter William Hurst (1897–1983) and Audrey Carrie Alexandra Morris (1897–1983). The other children were Valwyn (born 1920) and Neville (born 1933).

Walter Hurst was the second of nine children living at Paracombe (a small town near Adelaide), where his father (Reuben Mark Hurst) was an apple orchardist. At the age of seven Walter Hurst contracted 'infantile paralysis', so he was not able to work in the orchard, but attended the Houghton school, then Adelaide High School, and subsequently the University of Adelaide. There he did well, graduating with honours in chemistry (1916). He intended to take a job in Indiana, and was married (in 1919) to Audrey Morris, just before departure. The married couple went to Sydney but there was a lengthy shipping strike, so they decided instead to go to England. Walter Hurst had letters of introduction to Sir William Bragg,[1] who suggested taking a PhD at Cambridge in surface chemistry. Walter Hurst followed this advice and completed his PhD in 1923 under Sir Eric Rideal. He was the first South Australian and the third Australian to get a Cambridge PhD.

The maternal grandfather of Angas, Charles Richard Morris (1863–1918), left school when he was 14 and worked in the timber yard known as Robin and Hack, in Port Adelaide. Following a fire, the firm was taken over in 1886 by Theophilus John Walter and Charles Morris, to be known as Walter and Morris Limited. Angas said of Charles Morris:

> The trouble with him was that he was an 'Edwardian' father. He insisted that the eldest daughter, who was very scholastic, should stay home and help her mother; the eldest son, who was very musical, should run the business; and the youngest son, who was very smart and businesslike, should become a medico. He got everything wrong. The worst thing of all was that he insisted that my mother come to the University of Adelaide to do botany, and she

managed to fail every subject. But whilst at Adelaide University she met my father, who was assisting Kerr Grant[2] as a lecturer in physics. Kerr Grant and my father were the entire physics department back in 1919.[3]

The Hurst family returned from Cambridge to Adelaide in 1923 and six months after the birth of Angas they moved to Melbourne where Walter Hurst had accepted a position as a biochemist at the Commonwealth Serum Laboratories. So Angas grew up in Hawthorn, Victoria, where he attended Scotch College from 1930 to 1940 as a member of Monash House, and was dux of the Preparatory (Junior) School in 1935, and Dux of the Senior School in 1940. Angas said of his schooling:

> There was a whole string of first-class people, and it was because of Ross's inspirational teaching in mathematics. I was really torn between mathematics and chemistry, as a result of having two outstanding schoolteachers.[4]

Angas began a Bachelor of Arts/Science at the University of Melbourne as a resident student at Ormond College but after one year this was interrupted by the war. Angas describes his interests and experiences at school, and then at university where he was inspired by the mathematics lectures of Professor T. M. (Tom) Cherry. From 1941 to 1942 Angas served as a private in the army, and in 1942 enlisted with the Royal Australian Air Force. Angas completed a radio physics course at the University of Sydney, and a radar course at Richmond (as part of Bailey's radar courses).[5] Angas recalled:

> Each day we would be marched across to the physics department at the university and there we started on the six-months pressure cooker course on radio physics. After about a month at STT (School of Technical Training) we were moved to the Deaf, Dumb and Blind Institute in Darlington, just opposite the university. This institute was a school for handicapped children before the RAAF took it over. We were all intrigued by the notices on the walls of the dormitories which said 'If you want a mistress, please ring the bell'.[6]

Following officer training at Bradfield Park, the 19-year-old Pilot Officer Hurst was stationed first on Normanby Island, off the eastern tip of Papua New Guinea.[7] Angas described his experiences regarding his enlistment, his training in radio physics, and life on the island in his recollections '304 Radar Station'. In one incident Angas recalled:

> One day in April I was called down to the radar to see an echo right up to saturation at a range of well over 100 miles. It just sat there, moving slowly towards us, without any need to change the bearing. From the strength of the echo it could be estimated to contain at least 100 aircraft, and eventually we saw them flying almost directly over us. They were in tight formation together with circling Zero fighters, and making the characteristic drumming sound of a large raid. It was a massive Japanese air raid intended for Milne Bay. Goodenough, being over 100 miles to the north of us had picked up the same echo long before, so that Fighter Command had well over an hour's warning of the raid. This meant that they were able to bring squadrons of Kittyhawks, Lightnings and Aerocobras down from Port Moresby and Buna in time to meet the incoming Japanese. About an hour later we saw the remnants coming back, no longer neatly aligned and much nearer the sea. Just as they were passing us a Hudson aircraft turned up, clearly unaware of the enemy aircraft and on one of its regular patrols. The Zeros, obviously very miffed at being beaten up at Milne Bay, tried to take it out on the Hudson, and we were treated to a dogfight on our doorstep. The Hudson pilot dived down almost to sea level and the rear gunners opened up on the Zeros. The latter were greatly hampered because they had to pull out of their dives well short of the target, and so were not able to shoot it down. The Hudson headed back thankfully to Milne Bay, having had a bit more excitement than usual, and probably not very pleased at not being warned. The following day we received a congratulatory signal from headquarters, which boosted our morale.[8]

Angas expressed his amazement and frustration at the RAAF's incompetence in organization and support ('the RAAF's almost unequalled ability to mess things up'), but made the best of his life on the island. He described one incident in camp life:

> The platoon used to hold their morning parade in the clearing outside my office. One morning I heard the sound of a rifle shot followed by sharp exclamations. Apparently that morning they were practising the drill of present arms, which requires one to operate the rifle bolt several times and then pull the trigger once the rifle is emptied. However on this occasion one soldier got the order of the commands mixed up and pulled the trigger before clearing the rifle.

> The bullet passed through the hat of the man alongside, who nearly collapsed with fright.

At the end of 1944 Angas was posted to 331 Radar Station on Tami Island and later to Manus Island, Papua New Guinea, where he was commander of the 347 Radar Station with the rank of flight lieutenant. Again, Angas wrote of his experiences in the entertaining account 'Back to New Guinea'. Fundamental physics was not entirely forgotten:

> After the nuclear bomb was dropped, Padre Michell asked me if I would talk about it to the airmen at the RAAF base in Finschhafen. This was not going to be easy for me because I had enlisted after finishing only first year physics, and my radar training had nothing of fundamental atomic physics. I spent a lot of time trying to find some sources which would augment my only basic knowledge, and looking back I shudder to remember how ignorant I was. To embellish the story I always say that the airmen had the choice of coming to hear me or cleaning the latrines. So there was a large audience and I can recall some very good questions to which I did not really have any answer. One in particular asked how they could be sure that an atom bomb would not set off an atmospheric chain reaction. That was a question which the Manhattan Project people had taken seriously and did calculations to check that it could not happen. Fred Hoyle was another who also assured himself that it was safe.[9]

In subsequent years Angas rose to the rank of Wing Commander through the University of Adelaide Squadron of the RAAF.

Following his return in 1945 to civilian life in Sydney, Angas became reacquainted with his friend Barbara Leigh Stevens, whom he knew from his time in Melbourne. Barbara was the daughter of Evelyn Alice (Hender) and the Congregational minister, the Rev. Aubrey Clement Stevens, who had previously completed an MA at the University of Adelaide with Sir William Mitchell.[10] Aubrey Stevens entered Theological College at Medindie (Adelaide) and became the first student of Parkin College under the Principal Dr Bevan. As a Congregational minister he moved to Melbourne, where Angas first met Barbara, the second-youngest of nine children. Angas greatly admired Rev. Stevens, describing him as 'a fine sportsman, a man of great intelligence and compassion.' In 1943, Rev. Stevens moved to Sydney to work in Redfern and Waterloo and Angas, having returned from New Guinea, again met up with Barbara. On 15 December 1945, Angas and Barbara married at Redfern Congregational Church. There were three children, Angas John, Elinor Mary and Rachel Louise (Fig. 1).

Figure 1. Hurst family portrait, Adelaide, 1960. L–R: John, Angas, Rachel, Barbara and Elinor.

Cambridge

Angas resumed his studies at the University of Melbourne in 1945, completing his BA with first class honours (1947) and BSc (1948), and was awarded the Aitchison Travelling Scholarship from the University of Melbourne that allowed him to travel in 1950 to the University of Cambridge for his PhD studies. Once in Cambridge, as a member of Trinity College in the Faculty of Mathematics, he was able to gain a scholarship from the Australian National University (March 1950), which provided for an adequate living for his family. His first thesis advisor was C. J. Eliezer, who had completed his PhD at Cambridge under Dirac in 1945. Eliezer left shortly after one term, leaving Angas to 'pick my own problem at the end of the first year and work on that for the remaining two years of my PhD'.[11] A later supervisor was the physicist James Hamilton, who was appointed Lecturer in the Faculty of Mathematics in January 1950. Angas expresses in his PhD thesis 'gratitude to Dr C. J. Eliezer for suggesting the subject of the first part of this dissertation' and also thanks Mr J. Hamilton 'for the helpful discussions and encouragement given during the latter part of this dissertation'. The two parts of the dissertation are entitled 'The Self-energy of a Dirac Particle with an

Anomalous Magnetic Moment', and 'The perturbation Expansion of ϕ^3-theory'. Hamilton's 1952 paper 'Real and Virtual Processes in Quantum Electrodynamics',[12] acknowledges discussions with Angas and refers to two of his papers.[13]

On the staff at that time were: the Professor of Mathematical Physics, Douglas Hartree; in theoretical physics, Professors Paul Dirac and Nicholas Kemmer; and in the Cavendish, Lawrence Bragg. Among Angas' contemporaries as students were Paul Matthews (under Dirac), Abdus Salam (under Kemmer), John Polkinghorne (under Kemmer), John C. Taylor (under Eden), Denys Sciama (Dirac's last postgraduate student) and Roger Phillips (possibly under Hamilton's supervision), John Carver (in nuclear physics), also J. S. Roy Chisholm (under Kemmer and Hamilton) and Behram Kurşunŏglu. A description of the development of quantum field theory within the Cambridge circle, in particular the problems of divergences and how they might be resolved, appears in the book by Kaiser.[14] Angas found himself in the midst of a group of very active students (Chisholm, Salam, Matthews) who were coming to grips with the meaning and properties of Feynman diagrams as developed by Dyson. Angas was later fond of telling the story of his conversations with a seriously discouraged Salam,[15] who possibly contemplated abandoning theoretical physics at that time.

Angas was active in many spheres while at Cambridge, as described in the interview with Bob Crompton,[16] including the position of treasurer with the Delta Squared V Club, a theoretical science club, and membership of the Trinity College tennis team. In his studies Angas clearly enjoyed the vigorous and fruitful interactions between mathematics and physics, and was fully aware that fundamental physics was at a very interesting stage. Already in those early years, Angas saw his role as bringing the broad mathematical and physical communities into closer communication. Even before he completed his PhD he was the Australian representative at the inaugural International Mathematical Union general assembly that was held in the Palace of Farnesina (Rome) in March 1952.

Angas published three papers while at Cambridge,[17] and also completed a Trinity College dissertation entitled 'Analytic Behavior of the S-matrix of the Field of Three Scalar Particles with Scalar Interaction as a Function of the Coupling Constant',[18] which contained several original sections. His PhD thesis 'Perturbation Expansion in Field Theory and other Topics', submitted in 1952, completed his PhD studies at Cambridge. Before completion, however, Angas was offered a position in the Mathematics Department in Melbourne, by Professor Tom Cherry.

Melbourne

Angas returned to Australia in 1952 as Senior Lecturer in the Department of Mathematics, University of Melbourne, a position he retained until his departure for Adelaide in 1957. Angas enjoyed his time in Mathematics, particularly with staff such as Cherry, Love, Behrend and Schwerdtfeger. He maintained an interest in physics, however, and 'used to go across to physics to have afternoon tea and keep in touch with them',[19] but missed the developments in modern particle physics that were taking place in Cambridge and elsewhere. Of the Melbourne association there is a remarkable parallel of Angas' path with that of Tom Cherry. Both had been Dux of Scotch college, undergraduates in Ormond College, served in the air branch of the Australian armed services, received PhDs in mathematics from the University of Cambridge (within Trinity College), had loyal students, collaborators and colleagues, and eventually saw their departments change in directions not to their liking. These parallels occurred just over twenty years apart.[20]

Before leaving Melbourne, Angas assisted in the formation of the Australian Mathematical Society, particularly in support of Cherry who convened meetings to organize the inaugural meeting of the Australian Mathematical Society in August, 1956, in Melbourne.[21] The second general meeting was held at the University of Adelaide in August 1958, where the joint secretaries were Maurice Brearley and Angas.

Adelaide Years

In 1957, Angas accepted the position of senior lecturer in the Department of Mathematical Physics at the University of Adelaide. Initially there was some confusion as to whether Angas' position was tenured or not because the previous incumbents (H. Messel and J. C. Ward) had each lasted less than a year. Angas recalled:

> Both of these people only stayed nine months, and the University came to believe that the position was a short-term contract post rather than tenured. This led to a problem for me when I arrived in Adelaide, because the University Council decided that the post did not warrant long-term support such as housing loans and superannuation. The Registrar put the question as to whether it was my intention to stay longer than a year. I actually stayed until my retirement thirty-one years later![22]

Some colleagues have attributed these early departures to difficulties experienced with communicating with the founding Professor of Mathematical Physics, Bert Green. While there may be some evidence for this, Angas, alone among those who worked with Bert at this time, had the personal characteristics needed to forge a partnership that benefited Adelaide and Australian science generally. Angas quickly acquired a reputation for his intellectual prowess and for uncompromisingly challenging lectures and exams.[23] Peter Szekeres, who was later appointed to the Department, does not remember managing to solve a single problem in the exam paper when he took Angas' course in classical mechanics. Peter, previously a student in pure mathematics, encountered a lecture by Angas:

> My first memory of him was an evening lecture my father took me to in the physics department (probably for the Institute of Physics), on the topic of the clock paradox. It was my first introduction to the theory of relativity, and kindled an interest which was eventually to define my working life. I totally blame Angas for it. In my third year he gave a course on classical mechanics for Applied Maths III, which I can say unhesitatingly was the most difficult course I ever did in my undergraduate years. It was also the most fascinating.[24]

Returning to Cambridge interests, Angus worked on fundamental problems in quantum electrodynamics, looking for a rigorous basis. He later said of this work: 'It is not new particles and it is not new laws of physics, but it puts things on a solid foundation. I am very proud of that.'[25] The staff of the Department grew to three in 1960 with the appointment of Dr I. E. McCarthy and this was followed by the appointment of Dr Lindsay R. Dodd in 1968, and then Dr Peter Szekeres (1971) (Fig. 2). Following the promotion of Angas to Reader in 1961, and to Professor in 1964, he and Bert Green shared the duties of Head of Department. Angas held the position of Professor from 1964 until his

Figure 2. Staff and students in the Department of Mathematical Physics (1971). L–R: Angas Hurst, Bert Green, Peter Bell, Denis O'Brien, Jim McGuire, Tony Bracken, Janice Gaffney, Geoff Anstis, Max Lohe, Peter Szekeres, Doug Gray, Henry Krips, Lindsay Dodd.

retirement in 1988, when he became Emeritus Professor of Physics and Mathematical Physics.

Angas was always interested in fostering links across disciplines and did so particularly with connections between physics and mathematics as a founding member (1956) of the Australian Mathematical Society. This interest extended to regional scientific activities including the appointment of Chair of the Australian National Committee for Physics in 1980. Angas delivered an invited paper at the International Conference on Physics and Technology in Kuala Lumpur in September 1980, in which he described the 'State of Physics in Australia'.[26] In his concluding comments he referred to the proposal for the formation of an Australasian Physical Society (AAPS) in order to increase cooperation on a regional scale. Angas also delivered papers in Seoul in 1985,[27] Bangalore 1986,[28] Hong Kong 1988,[29] Seoul 1990,[30] and then in Brisbane 1994 for the 6th Asia Pacific Physics Conference.[31]

Other examples of his interest in communicating physics events to both the physics and broader community were the obituary he wrote for Julian Schwinger in the *Australian* newspaper in 1994,[32] and his summary of John Bell's visit to Australia in 1983.[33]

Angas took advantage of the study leave program at Adelaide to travel to Edinburgh in 1961, where Kemmer had taken over from Born. Angas recalled:

> I actually shared an office with a chap by the name of Peter Higgs. Peter Higgs was chugging away most of the time trying to organise 'ban the bomb' marches and things like that. Every now and then I would get rung up by the police: 'Police here; can you give us some information on the 'ban the bomb' march?', and I would say, 'Wait until Dr Higgs comes in.' He went on study leave two or three years later and wrote a paper. In that paper he invented what is called the 'Higgs boson'.[34]

Angas also benefited from his holding visiting positions in Mathematics (University of Toronto, 1964); the Center for Theoretical Studies (University of Miami, 1966 and 1967–8); Mathematics (Indiana University, 1977–8); Centre de Physique Théorique, Luminy, France (1981); Institut für Theoretische Physik (Universität Wien, 1981) as Schrödinger lecturer; and Canterbury (University of Kent, 1986). For his own department Angas organized visits by such distinguished scientists as Paul Dirac, Freeman Dyson, Murray Gell-Mann, Rudolph Peierls, Ed Salpetre, Bob Geroch, Arthur Wightman, Arthur Jaffe, A. O. Barut, John Bell, Jim McGuire and others. Jim recalled:

> I met Angas in 1968 when he was in Miami with Behram Kurşunŏglu at Behram's Institute. In those days there was a lot of money and a lot of people, Onsager, Dirac, Salam for example. I had a little grant from the Research Corp, so I invited Angas to Boca Raton. We conversed at considerable length and Angas said he wanted to write a proposal to ARGC for me to come to Australia. I didn't hear much, and in fact kind of forgot about the whole thing until suddenly in late 1969 I got a telegram from Angas saying the grant was approved for 1970–71. Thus I arrived in Adelaide in March of 1970, family in tow. What followed was an absolutely remarkable 15 months. Mathematical Physics at Adelaide was a wonderful place. Janice Gaffney and I talked a lot about it later. Her observation was that if you were there, you just thought it was normal, that every place was like that. It isn't and it wasn't.

Contributions to Administration

Angas served for many years as an Associate Editor for the *Australian Mathematical Society Journal (Series B)*, and also for the *ANZIAM* journal. Through his work as a member during 1981–7 of the International Union of Pure and Applied Physics, Commission C18, Mathematical Physics, and Executive of the International Association of Mathematical Physics from 1986 to 1990, Australia became recognized as an influential participant in the international scene. It was largely through this early groundwork that his successors were able to mount a successful Australian bid to hold the International Congress in Mathematical Physics in 1997, the first time this triennial meeting had been held outside Europe or North America. Angas, by accepting a leadership role in these organisations, was able to strengthen not only mathematical physics but Australian science generally.

Angas held many senior positions during his career; he was elected a Fellow of the Australian Academy of Science in 1972, and was awarded an honorary DSc by the University of Melbourne in 1991. He was a member of the Council of the Australian Academy of Science (1983–6) and Vice President 1984–5; also a Fellow of the Australian Institute of Physics and of the

Australian Mathematical Society, and Chairman, National Committee for Physics 1979–87. He was a member of the University of Adelaide (student) Union House Committee from 1964 to 1967, a member of the Union Council from 1964 to 1973, and chair of the Union Planning Committee from 1965 to 1973. He was concerned with the welfare of postgraduate students and was one of the prime movers for establishing the first Graduate College of the University of Adelaide (Kathleen Lumley College). He served on its Council from its inception in 1971 until 1974, and in 1974 chaired the Council.

Angas chaired the senior Committee of the University Education Committee from 1973 to 1976, and served as a member of the Council of the University from 1975 to 1978. He established and led the Animal Ethics Committee of the University during a period when animal experimentation was an extraordinarily sensitive issue. He was Pro-Vice-Chancellor (1986–8), and Acting Vice-Chancellor on several occasions. In the Australia Day Honours list 2003 he was awarded Member in the General Division (AM) for service to science, particularly in the field of mathematical physics as an educator, researcher and administrator.

Scientific Accomplishments

Angas' PhD at Cambridge was a seminal work on quantum field theory, showing the divergence of perturbation expansions for any value of the coupling constant. Quantum field theory originated in the 1920s from the problem of creating a quantum mechanical theory of the electromagnetic field. Basic physical quantities, such as the energy shift of electron states due to the presence of the electromagnetic field, gave infinite, divergent contributions when computed using the perturbative techniques available in the 1930s and most of the 1940s. This 'divergence problem' was solved, in the sense that physically meaningful answers could be extracted, in the case of quantum electrodynamics during the late 1940s and early 1950s by Bethe, Tomonaga, Schwinger, Feynman and Dyson through the procedure known as renormalization, by which infinities were removed order-by-order in the perturbation series.

In his papers[35] Angas showed that the perturbation series could never converge, essentially because the number of terms in such expansions grew so quickly that convergence was impossible; this naturally raised the question as to what if any meaning could be ascribed to such expansions. It later emerged that W. Thirring, who at that time (1951–2) was assistant to Wolfgang Pauli at ETH in Zurich, was working on similar problems. According to Thirring's book *Cosmic Impressions* (2007), Pauli came in to his office one day to announce '…Angas Hurst, an Australian who's now working in England, has made the same calculations and has arrived at the same conclusion …'. Hurst and Thirring later became good friends, and Angas wrote a typically humorous and anecdotal tribute for Thirring's 80th birthday in 2007.[36] It appears that Pauli was an examiner for Angas' PhD thesis; according to Kaiser, 'Pauli had to admit to a younger colleague in the summer of 1952, 'I myself am not enough of an expert in 'graphs' to be able to check the details' of a recent diagram-filled dissertation he had just received', this being Angas' thesis.[37]

Angas' best known result is probably the Griffiths-Hurst-Sherman inequalities, which established the concavity of magnetisation for Ising ferromagnets. With his students Angas was active in a wide variety of other research topics that included relativistic wave equations, representations of classical Lie algebras, C*-algebra approaches to quantum field theory, infinite-dimensional algebras, and topics in statistical mechanics.

During his career Angas produced over 90 publications, most of them advanced research publications in academic journals, including two books.[38]

Research

First a brief word on the distinction between mathematical physics and theoretical physics (further confused in recent years by the use of the term 'physical mathematics'). Over time this distinction has deepened, but it did not exist when Angas began his career. Today they are overlapping but distinctive subdisciplines. The former aims to meet the standards of proof that prevail in mathematics and focuses on mathematical questions inspired by physical theory. The latter is concerned with explaining experimental physics in a consistent framework only some of which is formulated in terms that a mathematician would understand. Angas always viewed his work in terms of being mathematically precise and he understood when his work did not meet the proof standards of mathematics itself. He knew that in studying physical theory one had to sometimes make intuitive leaps and, as long as these were clearly explained, progress could be made if one did not get bogged down by technical mathematical difficulties. On the other hand he was well aware of the traps that imprecise reasoning could lead one into and thus regarded the interaction of physics with mathematics as essential for reducing these dangers. Angas always maintained links with scholars in Mathematics Departments and encouraged joint seminars between Mathematics and Mathematical Physics.

Upon retirement he was part of a discussion group in the philosophy department, the 'Space-Time Group', whose members were interested in understanding fundamental topics such as general relativity from a philosophical perspective, in which Angas had become very interested. The topics were often wide-ranging and included aspects of quantum theory, particularly its interpretation.

Angas moved easily between statistical mechanics and quantum field theory and retained a long-term interest in physical problems where it was clear that existing mathematical theory was inadequate. For example he recognized that gauge theories required an understanding of infinite-dimensional Lie groups and Lie algebras well before the theory of Kac-Moody algebras had been introduced. He recognized also that the theory of Banach Lie algebras as it existed in the 1960s was not the way to approach gauge symmetries in physical theory. He was of course absolutely prescient and the development of conformal field theory and Yang-Mills theory in the late 1970s and 1980s through the use of new mathematical tools was entirely consistent with the ideas he had around 1970.

Statistical Mechanics

Angas began his work in statistical mechanics with an investigation of the Ising model. Initially solved in the two-dimensional case by Onsager in 1944, in a remarkable contribution to mathematical physics, this simple model of a magnetic material consisting of a rectangular array of elementary magnets that can point only up or down, has become the 'model T Ford' of the field. Onsager gave an exact description of an interacting many particle system that exhibits a phase transition at a particular temperature, the so called critical temperature. At this temperature the system changes from an ordered phase in which the elementary magnets are aligned to one in which complete disorder prevails. In other words it describes a change in the material from a state of being magnetized to one in which it is not. It has been used, particularly in computer experiments, to provide insight into physical phenomena such as melting, evaporation, magnetization and quark-gluon plasmas.

Onsager's solution is an exceptional piece of mathematical reasoning, but his exposition was not the best and there was a need for a simpler treatment. The first to provide this were Mark Kac and John Ward who used a combinatorial approach. Angas constructed a graphical picture that seemed to capture their method, although Bert Green observed that it would not work in all cases. Despite Bert's urging that Angas' idea should be published, Angas did nothing about it. Eventually Bert produced a complete manuscript describing a new solution to the Ising problem using the mathematical formalism of Pfaffians introduced in Angas' notes but not fully exploited. This Pfaffian approach, as a substitute for the determinants of Kac-Ward led to a complete solution, as described in the publications of Bert and Angas (1960)[39] and a subsequent monograph (1964).[40] Angas published further results in the years 1963–7.[41] Today we understand Pfaffians as arising from real Clifford algebras and determinants from complex fermionic systems and as such are closely related.

The work of Angas and Bert motivated the first solution of the complete dimer problem by Temperley, Fisher and Kasteleyn.[42] Eventually their approach became known as the free fermionic field approach. Angas wrote, in his obituary of Bert Green, that it 'simplified the solution of the two-dimensional Ising model so much that it could easily be given in an undergraduate course.' Angas also added some further insight into this story:

> Ilya Prigogine asked Green to prepare a review article, and this he started to do in collaboration with me, at a time when I was on sabbatical leave

> in Edinburgh. In the course of preparing this article, which soon turned into the book already mentioned, all the Ising models that had been solved up till that time were found to be particular cases of the free fermion model. No further essential progress was made in this field until 1967 when Elliott Lieb solved the six vertex model, leading on to Rodney Baxter's solution of the eight vertex model and the enormously significant Yang-Baxter relations.[43]

Despite Angas' feeling that his work on the Ising model had not received sufficient recognition, it was nevertheless a benchmark against which future work, not only that of Angas and Bert Green, but also contributions to Australian statistical mechanics more generally, was measured. Eventually of course Baxter's contributions over-shadowed it.

Another unappreciated work was that of Angas and Jim McGuire that began in during the latter's time in Adelaide and only partially succeeded.[44] These two papers approach the problem of 'what happens when the Yang-Baxter equations are not satisfied?' The first of these papers deals with impenetrable point particles in one dimension and the second with penetrable particles. Both situations result in finite difference equations that cannot be rendered algebraic by the Bethe ansatz, the primary consequence of the Yang-Baxter equations. In the impenetrable case the difference equations are of the *r*-function type, involving only rational functions and can be said to be 'solvable'. The penetrable case involves algebraic functions and the resulting problem has not been solved, or rendered algebraic. Even in partial failure these investigations show that the boundary between regimes of solvability and insolvability, if it exists, is not determined by the satisfaction of the Yang-Baxter equations.

Angas' best known and most widely appreciated contribution is the proof of the Griffiths, Hurst, Sherman (GHS) inequalities. These establish that the magnetization for Ising ferromagnets is a concave function of a positive external magnetic field.[45] The result was later picked up by researchers in constructive quantum field theory after the advent of the Euclidean field theory approach and used quite extensively.[46] The GHS inequalities, though initially only proved for Ising systems were later generalized to other models in statistical mechanics. Many authors have written on them, seeking new and shorter proofs (the original argument was a complicated combinatorial one). The GHS inequalities have some surprising links to other parts of mathematics, involving even the Riemann hypothesis.[47]

Quantum Field Theory

Angas wrote about his interactions with the problem of the perturbation expansions in quantum field theory in a small memoir (2006).[48] This memoir does not completely capture the insights that he had before the advent of constructive quantum field theory. In his PhD thesis he investigated the perturbation theory approach to calculating the matrix elements of the scattering operator. He showed that a subsequence of the perturbation expansion diverged. He introduced the notion that the series was an asymptotic expansion that was Borel summable, a fact not proved until decades later. As described above, his work predated that of Walter Thirring, later a close friend but at that time (1951–2) was a scientific assistant to W. Pauli at ETH Zurich, and also A. Petermann, both of whom were working on similar problems. In their comprehensive review of the question, Kazakov and Shirkov credit Angas with the first results.[49]

Reflecting his understanding of mathematical subtleties, Angas explained in the introduction to his article that it was conceivable that miraculous cancellations might occur as a result of the terms he did not consider and thus eliminate the divergence.[50] However, he did not really believe this was possible and he held the view throughout his working life that quantum field theory was mathematically incomplete and would never be consistently formulated in a fashion that would satisfy mathematicians. This belief did not deter him from investigating low-dimensional quantum field theories where the work of James Glimm and Arthur Jaffe (whom Angas knew well, having met him in Hercegnovi in the 1960s) had shown that the problems of four-dimensional theories like quantum electrodynamics did not occur in dimension two.

The divergences in perturbation theory occur for Feynman diagrams containing closed loops. There is an anecdote that Angas casually mentioned once over lunch. Angas discusses closed loop diagrams in his 1952 paper,[51] in particular figure 2 of this paper shows diagrams that are now uniformly referred to as 'tadpoles', consisting of a closed circle with an attached tail, sometimes referred to at that time as 'balloons'. The term 'tadpoles' was in fact invented by Angas, although it is widely believed to have been first used by Coleman in an influential paper dated 1964.[52] There is also, however, mention of tadpole graphs in an earlier 1962 paper by Goldstone, Salam and Weinberg.[53] It seems that Salam picked up the term from Angas, as a fellow student at Cambridge. Angas indeed refers to 'tadpole' graphs on page 95 of his 1952 PhD thesis,[54] in the context of ϕ^3 field theory, not knowing how deeply entrenched this terminology was to become! More significantly, Angas understood the importance of such diagrams.

Angas revisited the mathematical problems that had been posed by quantum electrodynamics in the late 1960s and early 1970s. He absorbed Dirac's theory of constrained dynamical systems, appreciating that quantum electrodynamics was possibly Dirac's motivation. The conventional approach to a mathematical formulation of quantum electrodynamics at that time was provided by the Gupta-Bleuler method where the linear space of states was equipped with a Lorentz invariant bilinear form (the 'indefinite metric') that was not positive definite. This meant that the usual Hilbert space approach to quantum mechanics was abandoned and only reinstated later after the imposition of constraints (in the sense of Dirac). Angas focussed on Fermi's quantization method as a more palatable mathematical alternative. With his PhD student Janice Gaffney he developed an approach using the von Neumann algebras generated by the Weyl C*-algebras modelling the electromagnetic vector potential fields. It was realised however that one could not impose the gauge constraint on the electromagnetic potential in this framework. A solution of this problem was found (with Carey) by recognizing that gauge conditions on the electromagnetic potential could only be imposed if one used the stronger C*-topology of the underlying Weyl C*-algebras. This idea was further generalized in the 1980s and 1990s into a full blown mathematical theory of quantised constrained dynamical systems by Angas and his student Hendrik Grundling that is discussed below.

A second direction that Angas developed was the understanding of the peculiar features of quantum field theories in two dimensions. With his collaborators Alan Carey and Denis O'Brien he developed the representation theory of gauge symmetries before the appreciation by other researchers that Kac-Moody theory was relevant to these questions. They also showed that the superselection theory ideas of Doplicher-Haag-Roberts were realized in two-dimensional quantum field theories using a Fredholm index approach to the gauge symmetries (which were thought of as Bogoliubov automorphisms of fermionic systems). This work led to a mathematically precise formulation of Coleman and Mandelstam's 'boson-fermion' correspondence that connected it directly to Angas' older passion, the representation theory of infinite-dimensional groups.

In field theories, implementability of Bogoliubov transformations as unitary transformations on a Hilbert space is not always possible, neither is the construction of a vacuum representation of the C*-algebra of observables. With his PhD student Phil Broadbridge, Angas developed a simple approach, evident even in finite degrees of freedom, to resolve the problem that was studied in parallel by I. E. Segal and his student S. Paneitz, namely to determine for which systems such a vacuum representation was possible by complexification of a real symplectic space. During this period (the late 1970s to early 1980s), there was an active group around Angas, the students Broadbridge and Grundling, and research fellows Carey, Lohe and O'Brien. All benefited greatly from the many overseas visitors that Angas attracted to the department.[55]

Angas' research on infinite-dimensional Lie groups also pre-dated that of Pressley and Segal and in fact extended it by also considering the 'non-compact' case (Pressley and Segal compactify space into a circle). It was also incorporated into the approach of Alan Carey and Angas to the Schwinger model.

Anomalies

Very early on Angas understood the significance of the 'Schwinger term' in two-dimensional quantum electrodynamics. This term arises because the representation of U(1) gauge symmetries is inconsistent with positivity of the energy unless one allows projective representations as predicted by Wigner in 1939. The Schwinger term is, mathematically phrased, a Lie algebra expression for a group two-cocycle exactly as arises in Wigner's work. The Schwinger term played a role in the earlier mentioned work on the boson-fermion correspondence and the Schwinger model. Angas later returned to this question in connection with the Dirac monopole and anomalies in quantum chromodynamics.[56] In this work the anomaly is seen to again be a consequence of asking for the fields of the theory to satisfy algebraic relations inconsistent with other features of the theory.

Quantum Constraints

Angas understood the importance of quantum constraints, given that all gauge theories need the application of constraints. Unlike the classical theory where the Dirac constraint method is a systematic method of enforcing constraints (since made rigorous by Mark Gotay and others), quantum constraints were treated on a case by case basis. Those constraints involving gauge theory even included the ill-understood use of indefinite metric representations in the Gupta-Bleuler approach. The problem was therefore to determine a systematic approach for dealing with quantum constraints similar to the Dirac constraint method. Such a method should be immediately applicable to the C*-algebra formulation of quantum electromagnetism, and give correct results. This was developed by Hendrik Grundling in his PhD studies, supervised by Angas.

The quantum constraint method developed by Angas and Hendrik (called the T-procedure) is defined at the abstract C*-algebra level, and hence avoids the analytic difficulties involved with specific representations, such as continuous spectrum problems. It imposes a constraint condition on the full state space of the field C*-algebra, obtaining the subset of Dirac states, and then analyzes the algebraic structures produced by restriction of the field algebra to the Dirac states. This is immediately applicable to all versions (gauges) of quantum electromagnetism in a C*-framework, and produces the correct final algebra of physical observables. In fact, it also avoids the indefinite inner product of the Gupta-Bleuler method. There is a theorem by Strocchi (in the Wightman framework) that shows that an indefinite metric is unavoidable if one requires a vector potential that is relativistically covariant, has a vacuum vector and satisfies the Maxwell equations. The apparent clash with Strocchi's theorem is resolved by observing that the Dirac states are all nonregular, hence the fields cannot be defined in their GNS representations (hence there is no vector potential to apply Strocchi's theorem to). However, after reduction to the algebra of physical observables, the representations become regular again. This was one of Angas' favourite results (he called it Reinfelds' problem, after an Honours student who asked the question about continuity of constraint reduction in a seminar).[57]

The method was subsequently extended by Angas and Hendrik to also include a quantum version of second-class constraints, which was believed to connect with quantum anomalies. If the given dynamics was not compatible with the constraint, it needed to be adjusted consistently together with the constraints to obtain a stable system (as in the classical Dirac method). This turned out to be a very hard problem. In the limited case (finite-dimensional) of a quantum particle dynamics given by a Schrödinger equation, restricted to a lower dimensional submanifold, an answer was found by Angas and Hendrik;[58] however, the answer to the full question, that includes QFT, remains unresolved.

Angas also collaborated with Mark Gotay and Hendrik on the problem of analyzing obstructions to quantization maps. In particular, they extended the well-known Groenewold-Van Hove obstruction from the Poisson algebra of R^{2n} to that of the two-sphere.[59]

Students and Other Collaborators

Despite his reputation for challenging lectures and exams Angas related well to his students and 'tended to put all the problems to my students rather than to work on them myself'.[60] The research topics were highly varied, as were those of Bert Green's students, and included upper-air meteors (Logan Francey, MSc), underwater submarine detection,[61] Ising models (Bob Irvine, Bob Gibberd and Graeme Mills),[62] problems in group theory and wave equations (Geoff Iverson, Doug Gray, Max Lohe, Tony Cant),[63] tachyons (Chris Ey),[64] quantum field theory, quantization and C*-algebras (Janice Gaffney, Phil Broadbridge, Hendrik Grundling),

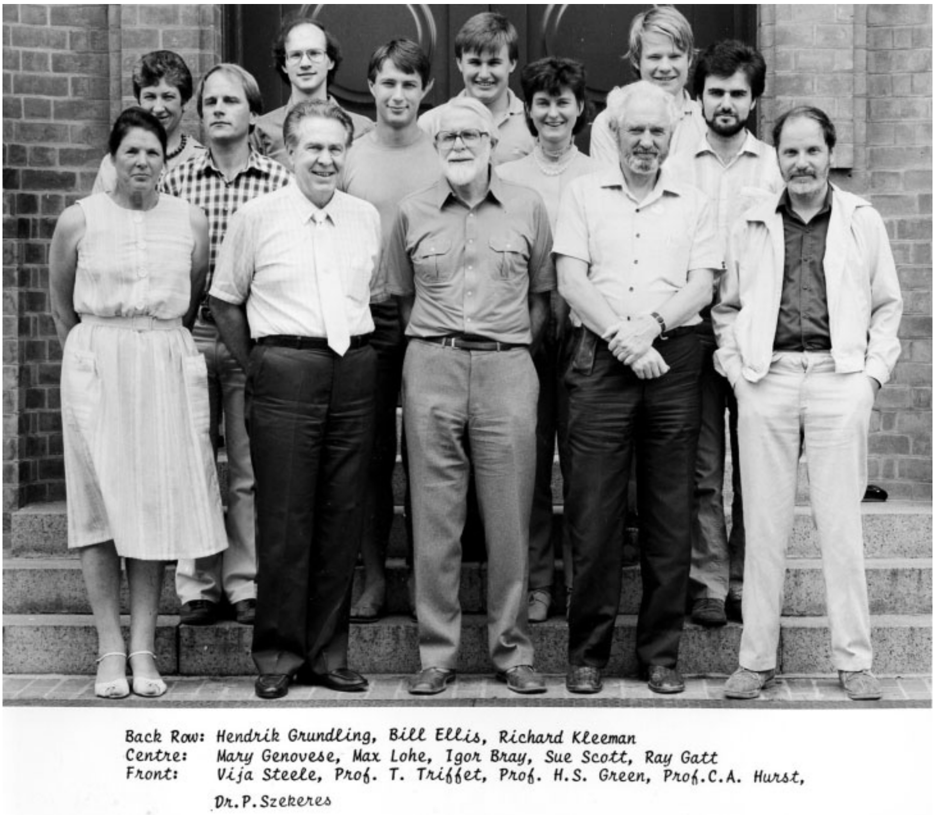


Figure 3. Staff and students in the Department of Mathematical Physics, 1985.

but there were many other students such as Henry Krips (axiomatic approach to measurement theory), Henry Tuckwell, Jill Wright (MSc students in field theory), Jim Evans (cooperative adsorption-desorption models)[65] who researched a wide variety of topics for Honours and postgraduate degrees.[66] Other collaborators in diverse topics were Huxley (on distributions of electrons and ions),[67] John Corbett (on fundamental questions in quantum mechanics),[68] and David Kerr (on physiology and nerve membranes) (Fig. 3).[69]

In 1969, Angas returned from a period of leave in Miami enthusiastic with new ideas and research topics, including problems in quantum field theory, which were investigated by Janice Gaffney and later Hendrik Grundling and Alan Carey; Alan began his collaboration with Angas in 1976 when there appeared to be a problem in the thesis of Janice. The solution was not too hard to find. This interaction led to a series of papers with Janice, Denis O'Brien and Brian Keck on representations of gauge groups in quantum field theory over the next 10 years.[70] Much later, in 1995, they worked together again, this time with Edwin Langmann and Hendrik on anomalies in gauge theories (see above).

Another initiative Angas brought back from Miami was the investigation of Lie groups and their representations with applications to modern physics, a 'hot topic' of those days, which became part of a very active program in the Department involving also students of Bert Green. This program has been described and summarized by Tony Bracken.[71] One suggestion of Angas was to generalize to all classical Lie algebras the very successful algebraic approach of Schwinger (1952)[72] to angular momentum, in particular to the orthogonal and symplectic groups, which was undertaken with Max Lohe;[73] this work later found application to the five and six-dimensional harmonic oscillator models used in nuclear physics because of their relevance to the Bohr-Mottelson-Frankfurt collective models and to the interacting boson model.[74]

Latter Years

After his retirement in 1988, Angas continued his research and also used his much greater freedom from administration to pursue his interests in philosophy and other areas of human endeavour. As always he was fascinated by the interplay of ideas from different disciplines.

He received many career awards beginning with an honorary DSc from The University of Melbourne in 1991, and in the Australia Day Honours list 2003 he was Made a Member (AM) in the General Division for service to science, particularly in the field of mathematical physics as an educator, researcher and administrator. He was deeply disappointed by the gradual dissolution after his retirement of the mathematical tradition that he and Bert had established in Adelaide, as is particularly clear in his interview with Alastair Blake in 2011.[75] However, this cannot be separated from the general decline in the support for the teaching of the enabling sciences in Australia that began in the 1980s but reached a peak in the 1990s and early years of the new century. The culture of universities has changed in Australia and funding has become formulaic so that initiatives like the setting up of the Department of Mathematical Physics at Adelaide in 1951 are now possible only with the injection of external funds (as for Centres of Excellence for example).

Confronting the Infinite

In 1994 Alan Carey, Bill Ellis, Paul Pearce and Tony Thomas organized a special meeting, with conference proceedings entitled ‘Confronting the Infinite’, to commemorate the contributions of Bert Green and Angas Hurst to Mathematical Physics and to celebrate their passing the milestone of ‘three score years and ten’.[76] Initially conceived as two days of informal talks, this meeting expanded into a four-day conference with 74 participants. The scientific program was intended to cover the full breadth of research in Mathematical Physics since the founding of the Department in 1951, together with original contributions. The conference proceedings[71] display the influence of Bert Green and Angas on their students and collaborators and the breadth of their research. A typical tribute, from John Corbett, reads:

> Their examples as scientists and teachers have been and continue to be an inspiration to us who were lucky enough to study under them and work with them. We have been ‘entered into their labours.

Scenes from a Life

Angas was involved in community service in both church and political life. He was treasurer of the Clayton-Wesley Uniting Church, and was greatly admired for his compassion and wisdom in the service of the church. He was a member of the Council of Parkin-Wesley College in 1979–80. He served as treasurer of the Norwood Branch of the Australian Labor Party (ALP), and was active in campaigning for the ALP at election times. His membership of the ALP was one way in which he tried to influence the world and express his concern for the society in which he lived. He wrote letters in support of individuals as identified by Amnesty International. He was passionate in combating injustice at all levels, and there have been many who have been touched by his goodwill and compassion. His community spirit is reflected in his extensive work for the South Australian Council of Social Service (SACOSS) (the peak body for social services in South Australia). Angas served for a decade from 1960 until 1970 in this not-for-profit independent organization that works towards the elimination of poverty and discrimination and a just and equitable distribution of resources and improved services to support individuals and families.

Angas was an inspiration and role model to his students, colleagues and friends. He was survived by his wife Barbara,[77] their children John, Elinor and Rachel and four grandchildren.

Endnotes

1. Elder Professor at the University of Adelaide 1885 to 1908, and Nobel Laureate in Physics, 1915.
2. Professor Kerr Grant occupied the Elder Chair of Physics from 1911 until his retirement in 1948.

3. Australian Academy of Science, Interviews with Australian Scientists, Professor Angas Hurst, Mathematical physicist (interviewed by Professor Bob Crompton in 2010).
4. As above. The two school teachers were A. D. Ross (mathematics) and W. R. Jamieson (chemistry).
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