

# The Foundation of the Sydney School of Coordination Chemistry

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**ABSTRACT.** The so-called 'Sydney School of Coordination Chemistry' has had an immense, even definitive, influence on Australian inorganic chemistry. Australian coordination chemists have been at the forefront of developments in the area and the international influence of many of the key figures (eg. Dwyer and Nyholm) has been widely acknowledged.

The founders of the 'School' were E.E. Turner, an Englishman who briefly held an appointment at the University of Sydney (1919-1921) and George Joseph Burrows, who after Turner's return to England influenced colleagues and research students toward careers in coordination chemistry. The scientific backgrounds of the founders and the state of inorganic chemistry at the time of foundation have been considered in detail. World War I significantly changed university education and the attitude of governments to scientific research. The timing of these influences ensured that the new foundation would become firmly established.

## INTRODUCTION

It is generally agreed that the first research in coordination chemistry in Australia was carried out at the University of Melbourne (Baker & Livingstone, 1985; Mellor, 1976). The legendary professor of chemistry, David Orme Masson and Bertram Dillon Steele, later to be professor of chemistry at the University of Queensland, demonstrated that copper was present as a cupritartrate anion in Fehling's solution (Masson & Steele, 1899). This work was revisited by Packer and Wark at Masson's suggestion some twenty years later (Packer & Wark, 1921). After this initial foray Masson did no further work in coordination chemistry (Weickhardt, 1989) and Steele also did no further work in this area, concentrating his energies on the development of a unique design of microbalance (Hardman-Knight, no date; Chiswell, 1986).

The leadership in coordination chemistry in Australia passed to the University of Sydney in the late 1910s and a 'school', as it is generally understood, was founded that was extremely influential in defining inorganic chemistry in this country, as well as having a significant impact on world chemistry. This school is often referred to as the Sydney School of Coordination Chemistry (Craig, 1987).

## BACKGROUND TO FOUNDATION

Coordination chemistry was a relatively young and active field of chemistry in the 1910s. The development of the field had occurred mainly through the efforts of Alfred Werner in Zürich. In his work Werner contributed significantly to the understanding of valency through introducing the concept of auxiliary valencies (German: *Nebervalenzen*) to explain the binding in coordination compounds (Werner, 1911a, p.57):

1. Principal valencies are manifestations of affinity, which permit their saturation capacities to be measured in terms of hydrogen atoms or groups equivalent to the latter.

2. Auxiliary valencies are manifestations of affinity which bring about stable union of radicles; the latter being able themselves to exist as independent molecules.

Werner went on to point out that for sodium nitroprusside it is practically impossible to decide to which class of valency the NO groups belongs. Having explained that the bonding can be represented similarly for both types of valency, he continued "Nevertheless, it appears desirable to preserve for the present the difference between principal and auxiliary valencies, for to-day the doctrine of valency is in a transition state, and hence it is judicious to construct sharply defined conceptions....." (Werner, 1911a, p.66). Werner's ideas were first published in the 1890s but it was only on the publication of his book *Neuere Anschauungen auf dem Gebiete der Anorganischen Chemie* in 1905 that significant attention was paid to his ideas. This work went through five editions in German [1905, 1909, 1913, 1920 (edited by P. Karrer) and 1923 (edited by P. Pfeiffer)] (Kauffman, 1966, p. 120). The second edition was translated into English (Werner, 1911a) with the title 'New Ideas on Inorganic Chemistry' by Edgar Percy Hedley, a Lecturer in Chemistry at the University of Birmingham. It is noted on the title page that the work is "translated, with the author's sanction, from the second German edition". This publication must have significantly assisted in bringing Werner's work to the attention of English-speaking scientists.

Werner was able to determine the structure of six-coordinate complexes by considering what isomers were possible for various combinations of ligands. This approach was an extension of the reasoning by Van't Hoff and Le Bel that led to the proposal of the tetrahedral arrangement of bonds for carbon (Jaques, 1993).

For six-coordinate complexes, four structures were considered possible: (i) hexagonal pyramidal, in which the metal atom sits above the plane of the six donor atoms which are arranged in a regular hexagon; (ii) hexagonal planar, in which the metal atom sits at the centre of a regular hexagon defined by the donor atoms; (iii) trigonal prismatic, in which the metal atom is at the centre of a trigonal prism defined by the donor atoms; and (iv) octahedral, with the metal atom sitting at the centre of a regular octahedron defined by the donor atoms. The first structure, hexagonal pyramidal, can be considered a special case of hexagonal planar (or *vice versa*) so only three structures need be considered.

For systems with only monodentate ligands only one isomer is possible for each of  $MA_6$  and  $MA_5B$  for all structures. For  $MA_4B_2$ , the hexagonal planar and trigonal prismatic configurations would each result in three possible geometric isomers, whereas the octahedral configuration would result in only two possible geometric isomers (*cis* and *trans*). Again, for  $MA_3B_3$ , the octahedral configuration would yield two geometric isomers whereas for the other configurations three isomers would exist. Werner directed synthetic efforts at complexes of these formulae ( $MA_4B_2$  and  $MA_3B_3$ ) and other complexes containing bidentate ligands. His results strongly support the octahedral configuration but it was realised that failure to produce a third isomer was negative evidence and may have only reflected the inability to achieve the synthesis. Werner recognised that the resolution of optical isomers would confirm the octahedral configuration.

Werner wrote to his friend and fellow student Arturo Miolati on 20 February 1897 explaining that they were engaged in attempts to resolve cobalt complexes and in a paper published in 1899 on oxalato bis(ethylenediamine)cobalt(III) salts Werner discussed the possibility of the formation of asymmetric isomers, which he carefully distinguished from the optical isomerism displayed by carbon compounds in which one carbon atom has four

different groups attached (Kauffman, 1981, p.122). Werner realised that complexes containing bidentate ligands would, for certain stoichiometries, yield resolvable optical isomers. Victor L. King spent a year trying unsuccessfully to resolve  $[\text{Co}(\text{en})_2\text{CO}_3]\text{Br}$  (en = ethylenediamine) and reasoned that working on a related compound  $[\text{Co}(\text{en})_2(\text{NH}_3)\text{Cl}]\text{Cl}_2$  might be more successful (Kauffman, 1981, p.125). The successful resolution was eventually achieved in June 1911 and the paper was dispatched that month for publication (Werner, 1911b). In what now would be considered an unusual convention, Werner was the sole author of the critical paper but at the head of the experimental section was "(Von V. L. King)". Werner's assistant, E. Scholze, was also acknowledged for collaboration on this paper (Werner, 1911b). Werner summarised (Werner, 1911b, translated in Kauffman, 1968, p.163) the importance of the results of this work as follows:

(1) the proof that metal atoms can act as central atoms of stable, asymmetrically constructed molecules and thereby lead to phenomena which agree with those produced by the asymmetric carbon atom; (2) the proof that pure molecular compounds can also occur as stable mirror-image isomers, whereby the difference between valence compounds and molecular compounds, which is still frequently maintained, disappears entirely, and (3) the confirmation of one of the most far-reaching conclusions from the octahedral formula, by which the latter has found a new, important confirmation.

Subsequent to this important work, Werner was able to resolve further optical isomers of various complexes. The complexes contained ligands that included carbon atoms and it has been surmised that detractors suggested that the optical activity arose from asymmetric carbon atoms (Kauffman, 1966, p.37). Werner resolved the optical isomers of the carbon-free complex ion tris[tetrammine- $\mu$ -dihydroxocobalt(III)]cobalt(III), isolated as the bromide:  $[\text{Co}\{(\mu\text{-OH})_2\text{Co}(\text{NH}_3)_4\}_3]\text{Br}_6$ , which dispelled these doubts (Werner, 1914). This remarkable achievement of a completely carbon free optically-active octahedral complex has only been repeated on a few occasions since (Kauffman, 1981, p.134).

Werner was awarded the Nobel Prize for Chemistry in 1913. In the presentation speech, Nordström, the President of the Royal Swedish Academy of Sciences stated (Nordström, 1913):

By far the greatest interest in the field attaches also to the discovery he made in the last few years, that certain cobalt, chromium, iron and radium compounds with an asymmetrical metal atom in the complex radical can be divided into two forms which behave like mirror images and show differences of the same kind as those in organic mirror-image isomers, i.e. they are optical antipodes of each other. This discovery is a splendid support for Werner's theory. It has been called the most important discovery in chemistry in recent times, and his stereochemical work makes him the founder of inorganic stereochemistry.

Read, who completed his doctorate with Werner at Zürich (1907) and subsequently was Professor of Organic Chemistry at the University of Sydney (1916-1923), remarked later that the resolution of the salts of  $[\text{Co}(\text{en})_2(\text{NH}_3)\text{Cl}]^{2+}$  into optically active isomers "was a stereochemical achievement of the first order, confirming the octahedral environment of the central metallic atom" (Read, 1947, p.264).

Optical isomerism thus had a central role in the establishment of the structure of coordination compounds and the resolution of optical isomers of octahedral complexes has been a continuing theme in the history of coordination chemistry.

## FOUNDATION

Credit for the founding of the Sydney School must go to Eustace Ebenezer Turner (1893-1966), who briefly held an appointment as lecturer at the University of Sydney from 1919-1921. Though Turner's time in Sydney was short, his influence was immense, particularly on George Joseph Burrows (1888-1950). It is through Burrows that the Sydney School was established.

Turner studied chemistry at East London College (now Queen Mary College), supported by an exhibition from the Drapers' Company, graduating B.Sc. in 1913 with first-class honours in chemistry. He found the professor of chemistry, J.T. Hewitt, a stimulating teacher who presented all areas of chemistry as equally interesting. After his B.Sc. Turner stayed one year at East London College, where he started a course on practical physical chemistry. In 1914 he was appointed as an Assistant Lecturer in Goldsmiths' College but spent most of World War I in war work. He worked on medicinals at Boots' Laboratories, Nottingham and Huddersfield Technical College for a few months at each location. Subsequently he worked on arsenicals as assistant to W.J. Pope at Cambridge. Interestingly, he published several papers in this period, including preliminary work on the structure of the biphenyls, an area in which he subsequently made a substantial contribution (Ingold, 1968).

Prior to his appointment at the University of Sydney, Turner had made some contribution to inorganic chemistry. His first publication (Bennett & Turner, 1914) opens with the statement: "The object of this investigation was to obtain organo-metallic derivatives of chromium." Anhydrous chromium(III) chloride was reacted with "the Grignard reagent" (phenyl magnesium bromide). The expectation was that  $\text{Cr}(\text{C}_6\text{H}_5)_3$  (or perhaps  $\text{CrCl}(\text{C}_6\text{H}_5)_2$  or even  $\text{CrCl}_2(\text{C}_6\text{H}_5)$ ) would be obtained. The reaction was found to yield diphenyl ( $\text{C}_6\text{H}_5\cdot\text{C}_6\text{H}_5$ ). The reaction was extended using other Grignard reagents to prepare  $\alpha,\alpha$ -dinaphthyl, dibenzyl and 4,4'-dimethyldiphenyl. Attempts to obtain asymmetric products (eg 4-methylphenyl- $\alpha$ -naphthalene) and products from aliphatic halides were not successful. Turner subsequently showed that copper(II) chloride could also be used as a coupling reagent, giving diphenyl from phenyl magnesium bromide (Krizewsky & Turner, 1919) and yielding 2,2'-dimethyldiphenyl from the appropriate Grignard reagent (Turner, 1920). It is to be noted that Turner's interest in the structure of diphenyl and related compounds was one of the principal lines of research that he pursued for many years. R.J.W. Le Fèvre worked with Turner at East London College in the 1920s and they co-authored eleven papers on the structures of diphenyl in 1926-8. It can be argued that Turner exerted an immense influence on chemistry at the University of Sydney, directly through his own time there (1919-1921) and indirectly through his student being appointed to a chair there from 1946-1970.

Turner's work on Grignard reagents and their reactions with transition metal compounds was only tangentially related to inorganic chemistry and was more in the sphere of organometallic chemistry rather than coordination chemistry. From his war work with Pope, he gained great experience in arsenic chemistry (Pope & Turner, 1920). In the paper it is acknowledged that "permission for its publication has been given by the General Staff."

Turner had made a strong contribution to the understanding of the structure of coordination compounds by a vigorous defence of Werner's theories. John Albert Newton

Friend published a series of papers (Friend, 1908a, 1908b & 1916) in which he proposed a cyclic theory for the structure of complexes. Friend was concerned that the “dissociable chlorine atoms hover in an indefinite manner” around the complex ion as a whole. He was also concerned that the valency (of six) proposed for cobalt was too high (Friend, 1916). Friend suggested that the chloride ions were attached directly to the cobalt atom thus exhibiting a valency of three and that the other groups were bound together in a hexagonal planar arrangement of donor atoms (in  $[\text{Co}(\text{NH}_3)_6]\text{Cl}_3$ , nitrogen would display a valency of five because it was bound to three hydrogen atoms and two adjacent nitrogen atoms). In his terms, “the cobalt atom lies in the ring from which it cannot easily escape for purely physical reasons”. In the case of  $[\text{Co}(\text{NH}_3)_5\text{Cl}]\text{Cl}_2$ , one of the chlorine atoms would be in the ring, as well as bound to the cobalt, and the other two would be bound directly linked to the cobalt atom.

In his response to Friend’s proposals, Turner demonstrated an understanding of the importance of optical isomerism in establishing the octahedral structure of six-coordinate complexes (Turner, 1916):

The strong point of Werner’s theory is the definite proof that the six-coordinated atoms or groups have a more or less well-defined octahedral orientation. Unless Friend’s “shell” is identical with Werner’s octahedral structure, there is no explanation on the cyclic theory of the existence of optical activity among certain types of compounds.

Clearly, Friend’s proposal had, as an essential element, a tendency of nitrogen compounds to form ring structures. He suggested that the ammonia molecules can combine in the same way as “atmospheres” of water molecules surrounding ions as had been proposed by Kohlrausch to explain ion mobility in solutions (Friend, 1916). In modern terms, the formation of such “atmospheres” would depend on hydrogen bonding rather than a direct O-O bond as Friend claimed. Turner dismissed Friend’s suggestion by reference to current understandings of nitrogen chemistry (Turner, 1916):

Friend refers to the analogy between metalamines and ring compounds of carbon, but he seems to overlook the fact that unless some strong salt-forming influence is at work, nitrogen atoms do not combine together in the way that is so characteristic of carbon.

In the 1910s, Turner, coming from the synthetic tradition, had worked with Grignard reagents, in an attempt to prepare organometallic compounds, had gained experience in the chemistry of arsenic compounds and also had acquired a significant appreciation of the current theories of coordination compounds.

At the University of Sydney, he had the opportunity for sustained research. The work that he chose to do reflected his background and experience in that he worked on compounds of fundamental importance to the debate on bonding in coordination compounds and pursued further work on arsenic compounds. In this work on the constitution of coordination compounds and new organic arsenicals, Turner collaborated with Burrows. One of their principal triumphs was to demonstrate optical activity in an arsonium salt even though the racemisation was extremely rapid. The cation isolated was the phenyl- $\alpha$ -naphthylbenzylmethylarsonium ion, ie with an arsenic atom bound to four different groups. They also were able to clarify a controversy over the correct formulation of the nitroprussides by conductivity and cryoscopic measurements.

Turner returned to England to take up a research appointment at the Royal Arsenal, Woolwich and re-joined East London College as a Senior Lecturer in 1923. Eventually he

retired in 1960 as the Professor and Head of Chemistry at Bedford College, having moved there in 1928. He was elected to the Fellowship of the Royal Society in 1939 (Ingold, 1968).

#### INTERLUDE: DEVELOPMENTS IN RESEARCH AND THE UNIVERSITY OF SYDNEY

World War I proved to be a great spur to scientific research in the British Empire as a means of supporting the development of technology-based industries. At the outbreak of the war Britain found that Germany was far in advance in the production of many goods relevant to the war effort (Currie & Graham, 1966, p.11):

Great Britain was rudely awakened to the fact that she had been far too dependent on Germany for her supplies of manufactured articles, chemicals and raw materials. Optical glass, magnetos, drugs and pharmaceutical preparations, tungsten and zinc smelted from ores mined in the British Empire were among the many items processed in Germany and later imported by pre-war Britain.

Remarkably, Britain was paying royalties to Krupps for fuses in shells until 1915 and the stocks of chemical glassware were so low that a national inventory was established in case there was a need to commandeer university and other supplies (Rose & Rose, 1970, p.36).

The dyestuffs industry is particularly illuminating in emphasising the lead that Germany had taken in chemical manufacture. The aniline dyes had been discovered by the British chemist, W.H. Perkin, as a young man in 1856, and his family established a company to manufacture these dyes (Edelstein, 1961). The commercial potential of the discovery was realised by German manufacturers and there was a ready supply of well-trained chemists to support their endeavours. The German developments in the area were so effective that "by 1879, Germany was producing some £2 million-worth of coal-tar products and Britain only £450,000-worth of the dyes which had been invented in Britain by a British scientist." (Rose & Rose, 1970, p.28). A critical point was a technically-trained workforce, Britain's science in the nineteenth century had been largely in the hands of "amateurs and gentlemen" (Rose & Rose, 1970) but technical education in Germany was much better organised (Turner, J.W., 1909). Four German chemical concerns involved in the dyestuffs industry employed over 1000 chemists each in 1914, whereas the whole British industry employed only 1500 chemists (Currie & Graham, 1966, p.11).

As a result of concern expressed by the Royal Society, the British government established an advisory committee for scientific research. Australians were quick to realise the importance of this move with Professor Orme Masson expressing his relief that politicians had realised the parlous state of British science after much urging by scientists (Currie & Graham, 1966, p.12). These developments led in Britain to the establishment of the Department of Scientific and Industrial Research (Rose & Rose, 1970, p.40) and to the formation of an Advisory Council of Science and Industry in Australia in 1916, this body being the forerunner of the CSIRO (Currie & Graham, 1966, pp.43-56). In the discussions surrounding the formation of the Advisory Council, universities were strongly consulted and it was recognised that the stimulation and coordination of research in universities was an important aim. Some of the advice received in founding the Advisory Council had strongly urged that funding and organisation of research in universities should be the principal aim of the Advisory Council (Branagan & Holland, 1985, p.18), so scientific research in universities was very much 'on the agenda'.

There were parallel developments at this time at the University of Sydney that secured the future of research within the university. In the British tradition of science referred to above, workers often pursued their interests as a lone worker, for example Archibald Liversidge was the sole author on almost all of his many publications (Baker, 1997). In order to incorporate further research training in the science degree a four-year Honours degree was introduced in 1922 and the Master of Science degree was introduced in 1923 (Turney, Bygott and Chippendale, 1991, p.527). The other pressure which probably helped in the establishment of a research culture was the huge growth in numbers of students studying the sciences, possibly as a response to the important role science and technology played in World War I. First year Chemistry classes with an enrolment of 222 in 1909 had more than doubled by 1919 (Branagan & Holland, 1985, p.19). There was a sharp post-war increase in enrolments with the student enrolment jumping by 700 to a total of 2,764 (including 748 women) at the start of the 1919 academic year (Turney, Bygott and Chippendale, 1991, p.431). Because of the introduction of the Honours year and the research degree (M.Sc.), academic staff were able to pursue research in collaboration with research students. This probably led to an increase in output and the opportunity to disseminate influence through appointment of graduates to other institutions. Certainly, most of Burrows' publications after the early 1920s had a research student as a co-author (see Appendix).

## ESTABLISHMENT

George Joseph Burrows graduated in science at the University of Sydney in 1910 with a double university medal in chemistry and in geology & mineralogy (Branagan & Holland, 1985). As an undergraduate he had undertaken a study of the water supply of Goulburn and made recommendations for the clarification of the supply (Burrows, 1909). There was a later publication on the analysis of natural waters (Burrows, 1926b) but the samples had been collected by Dr. W.G. Woolnough in 1911 and the analyses were also performed that year. He was appointed a lecturer at the University of Sydney and collaborated with Charles Edward Fawsitt, the professor from 1909 to 1946 (Branagan & Holland, 1985), on the corrosion of steel (Burrows & Fawsitt, 1911) and the decomposition of carbamide (Burrows & Fawsitt, 1914).

In his independent work Burrows appears to have shown a strong orientation toward physical chemistry, with several publications on the rates of reactions eg. inversion of sucrose (Burrows, 1914), hydrolysis of methyl acetate (Burrows, 1919b and 1921). The study of the hydrolysis of esters included a later paper on the equilibrium in such systems (Burrows, 1925). He also worked extensively on determining the volume changes associated with dissolution of solutes, eg. (Burrows, 1919a, Burrows & James, 1925 and Burrows, 1926a).

Burrows was appointed to a temporary lectureship in chemistry at the Royal Military College, Duntroon from August 1915 to April 1919. He was depressed about his academic prospects and considered resigning from his post at the University of Sydney (Mellor, 1976). Fortunately Turner arrived in 1919 and Burrows collaborated with him on coordination chemistry projects.

Their first work together was to study the composition of the nitroprussides. Turner had indicated that he intended to do some experimental work on these compounds in his response to Friend's theories of the structures of coordination compounds (Turner, 1916):

In the case of the nitroprussides, Friend suggests a double formula. A molecular-weight determination or, better, a determination of the number of ions by the conductivity method, is necessary before such a formula can be accepted. The author hopes to examine these points when time is available for experimental work.

Presumably Burrows' skills as a physical chemist were of significant use in this initial study as there is no indication of such experience in Turner's background. Their experimental work confirmed that the nitroprussides were salts of an acid with the formula  $H_2[Fe(CN)_5NO]$  as had been earlier assigned by Hofmann rather than salts of  $H_4[Fe_2(CN)_{10}(NO)_2]$ , as had been suggested by Friend. Rather archly the authors stated "Friend, apparently without further experimental work, proposed for potassium nitroprusside the formula ...." (Burrows and Turner, 1919). In subsequent work, they managed to isolate nitroprussic acid and alkyl derivatives of the acid (Burrows and Turner, 1921c). This work was of considerable significance and was still referenced in the major inorganic chemistry text-book in the early 1950s (Sidgwick, 1950).

As has been mentioned Turner had worked on arsenic compounds in the years of World War I and the collaborators now turned their attention to compounds of arsenic. In their first paper on arsenic compounds (Burrows and Turner, 1920) they reported work on the deeply-coloured "additive compounds" that are formed when tertiary arsines ( $RR'R''As$ ) are reacted with diiodomethylarsine ( $CH_3AsI_2$ ).

Burrows and Turner reasoned that the As-oxide of 1-methyl-1,2,3,4-tetrahydroarsenoline (the arsenic analogue of reduced quinoline) should be capable of resolution into its optical isomers. They prepared the compound but not in sufficient quantity to attempt the resolution of the isomers (Burrows and Turner, 1921a). They reported the successful resolution of a salt of the phenyl- $\alpha$ -naphthylbenzylmethylarsonium cation in the same paper. In these salts the arsenic atom is asymmetric in the same way that a carbon atom is considered asymmetric if all four groups attached are different. It was noted that racemisation was very rapid and only small molecular rotations were recorded (Burrows and Turner, 1921a). This was an important result and represented the first successful resolution for an arsenic compound. Burrows and Turner were too modest to make such a claim but mentioned that previous attempts were unsuccessful.

They also worked on additive compounds formed between tertiary arsines and the iodides of arsenic, bismuth, mercury, lead, tin, antimony and cadmium (Burrows and Turner, 1921b). The subject of their last collaboration was the preparation of certain tris(oxalato)ferrate(III) salts. They attempted to resolve the anion into its optical isomers through isolation of the cinchonine and strychnine salts but were unsuccessful (Burrows and Turner, 1921d). They noted that the resolution of tris(oxalato)ferrates had been achieved during the course of their study by Thomas.

Turner returned to England in 1921. Burrows, remaining at the University of Sydney, had been fired with enthusiasm to continue research in coordination chemistry but had not entirely lost interest in the physical chemistry of solutions he had pursued prior to Turner's arrival (Burrows & Eastwood, 1923; Burrows & James, 1925 and Burrows, 1926a). His first work in coordination chemistry, in the absence of Turner, was to study the



dissociation of cyano complexes (Burrows, 1923) and oxalato complexes (Burrows & Walker, 1923) by conductimetric and cryoscopic methods.

The intention of this paper is to focus on the foundation of the Sydney School of Coordination Chemistry, so a detailed review of the subsequent work published by Burrows will not be attempted. A sense of this work will be gained from considering the full list of his publications included as an Appendix and through his Liversidge Lecture to the Royal Society of New South Wales (Burrows, 1940).

## CONCLUSION

The Sydney School of Coordination Chemistry was founded because coordination chemistry was clearly a very active area in the 1910s. This claim can be substantiated by considering the activity of Werner's school in the 1910s and their marvellous achievements in elucidating the stereochemistry of coordination compounds. This work culminated in the award of the Nobel Prize in Chemistry to Alfred Werner in 1913. The importance of this decade in the development of coordination chemistry was summarised by Lawrence Bass in his preface to a book on coordination chemistry (Schwarz, 1923):

So far as the writer is aware, there is only one monograph in English on the subject, viz., Hedley's translation (Longman's, 1911) of the Second Edition (1908) of Werner's "Neuere Anschauungen." Since the publication of this translation many fundamental contributions to the theory have been made which should be included in any study of the complex compounds.

Turner came from the synthetic tradition in chemistry and was clearly well aware of Werner's theory of bonding in coordination compounds as is demonstrated by his effective rebuttal of Friend's ideas (Turner, 1916). His expressed interest in the nitroprussides was pursued in Sydney and his collaboration with a chemist from the physical chemistry tradition was fortuitous, given that conductimetric and cryoscopic methods were used to confirm the formula of the nitroprussides. Turner's wartime experience with arsenic compounds provided initial synthetic problems to pursue. Burrows and Turner had an early success in resolving the optical isomers of an arsonium salt, in which the cation has four different substituents (Burrows & Turner, 1921a). Having had experience in polarimetry Burrows was able to contribute to the work on the resolution of optical isomers. The study of arsenic compounds as ligands in metal complexes was a continuing theme in the Sydney School (Craig, 1972; Burrows, 1940).

Burrows had been pursuing independent research in physical chemistry until Turner's arrival in Sydney. As has been mentioned, his independent work included studying rates of reaction of hydrolysis of esters and inversion of sugars. After Turner's brief stay, and a few further physical chemistry papers, the character of Burrows' work changed to focus on the synthesis of coordination compounds. The matter of resolving optical isomers of coordination complexes that was pursued by Burrows has been a continuing theme in the 'Sydney School' with the work on complexes of sexadentate ligands by Dwyer and Lions being a highpoint (Baker, Xiao, Craig & Baker, 1999; Baker, 1999). Given that Burrows had no preparative experience in his research work, had little or no contact with coordination chemistry and had not previously dealt with arsenic compounds, Turner's influence was absolutely critical in recruiting Burrows to coordination chemistry. Burrows

clearly learnt well and, as a proselyte, was effective in promoting coordination chemistry to students and colleagues.

Part of the reason for the vast influence of this school in Australian inorganic chemistry is that coordination chemistry itself was experiencing a vast resurgence on a world scale in the 1950s. Coordination chemistry was actively pursued in Australian chemistry departments after that time, so coordination chemists were in plentiful supply to take up academic appointments in the period of expansion in Australian universities in the 1950s and 1960s. An important conference on coordination chemistry was held in Sydney on 25th and 26th May, 1953. Sir Ian Wark opened the conference and his remarks serve as an excellent summary of the influence of Burrows (Wark, 1954):

Sydney's proud position in coordination chemistry has sprung from the efforts of one man, G.J. Burrows, now dead. Probably, in the first instance, he owed something to E.E. Turner, but Turner returned to England after a short stay in Australia, and thereafter, for 25 years, Burrows devoted his whole working life to coordination chemistry. I collaborated with Burrows on a small piece of research on the aluminium salicylato complexes. One of us had expected to get salts of an acid  $H[Al(C_7H_4O_3)_2]$ , the other  $H_3[Al(C_7H_4O_3)_3]$ . Instead we got  $H_2[Al(C_7H_4O_3)_2(OH)(H_2O)]$ . Burrows was delighted that here was something new and unexpected.

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## APPENDIX

Following is a complete listing of the publications of George Joseph Burrows. All papers have been sighted in the original journal and confirmed through Chemical Abstracts.

1. G.J. Burrows, Notes on Goulburn water with some experiments on its clarification. *Journal and Proceedings of the Royal Society of New South Wales*, **43**, 394-8 (1909).
2. G.J. Burrows and C.E. Fawsitt, Observations on the corrosion of steel in water. *Journal and Proceedings of the Royal Society of New South Wales*, **45**, 67-75 (1911).
3. G.J. Burrows and C.E. Fawsitt, Decomposition of carbamide. *Journal of the Chemical Society*, **105**, 609-23 (1914).
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5. G.J. Burrows, Volume changes in the process of solution. *Journal and Proceedings of the Royal Society of New South Wales*, **53**, 74-99 (1919).
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8. G.J. Burrows, The hydrolysis of urea hydrochloride. *Journal and Proceedings of the Royal Society of New South Wales*, **53**, 125-35 (1919).
9. G.J. Burrows and E.E. Turner, A new type of compound containing arsenic. *Journal of the Chemical Society*, **117**, 1373-83 (1920).
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18. G.J. Burrows and F. Eastwood, Molecular solution volumes in ethyl alcohol. *Journal and Proceedings of the Royal Society of New South Wales*, **57**, 118-25 (1923).
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