



Cite this: *Chem. Soc. Rev.*, 2016, 45, 6799

Octahedral Werner complexes with substituted ethylenediamine ligands: a stereochemical primer for a historic series of compounds now emerging as a modern family of catalysts†

Andreas Ehnborn, Subrata K. Ghosh, Kyle G. Lewis and John A. Gladysz*

As reported by Alfred Werner in 1911–1912, salts of the formally D_3 symmetric $[\text{Co}(\text{en})_3]^{3+}$ (en = ethylenediamine) trication were among the first chiral inorganic compounds to be resolved into enantiomers, the absolute configurations of which are denoted Λ (left handed helix) or Δ (right handed helix). After a >100 year dormant period during which few useful reactions of these substitution inert complexes were described, carbon substituted derivatives have recently been found to be potent catalysts for enantioselective organic synthesis. This review systematically outlines the fascinating range of stereoisomers that can arise, such as conformers associated with the five membered chelate rings (λ/δ), alignment modes of the C–C bonds with the C_3 symmetry axis (lel/ob), geometric isomers (fac/mer), and configurational diastereomers (R/S) arising from carbon stereocenters. These analyses demonstrate a profound stereochemical diversity that can be applied in catalyst optimization. Efforts are made to bridge the often orthogonal nomenclature systems inorganic and organic chemists employ to describe these phenomena.

Received 9th August 2016

DOI: 10.1039/c6cs00604c

www.rsc.org/chemsocrev

Key learning points

- (1) Representations, symmetry, absolute configuration of the chiral octahedral trication $[\text{Co}(\text{en})_3]^{3+}$.
- (2) Conformations of the en ligands in $[\text{Co}(\text{en})_3]^{3+}$, and lel/ob orientations.
- (3) Stereoisomers of analogs with 1,2-propylenediamine ligands.
- (4) Stereoisomers of analogs with vicinally disubstituted ethylenediamine ligands.
- (5) Diastereomer stabilities and catalysis.

1. Introduction

Werner complexes with chelating 1,2-diamines have played prominent roles in the development of inorganic and coordination chemistry, particularly with regard to structure and stereochemistry.^{1,2} For example, octahedral cobalt(III) adducts – the most widespread family of Werner diamine complexes – were the first chiral inorganic compounds to be isolated in enantiomerically pure form.² However, until recently they have had few, if any, applications in synthetic organic chemistry, either as reagents or catalysts. One reason is that cobalt(III) complexes are, by virtue of their low spin d^6 electronic configurations, substitution inert,³

thereby preventing the coordination and activation of organic substrates at reasonable temperatures.

Recently, there have been conceptual and practical breakthroughs that have enabled chiral Werner complexes to serve as highly effective catalysts for enantioselective organic reactions.^{4–6} One has been the realization that the NH bonds associated with coordinated amines are capable of functioning as hydrogen bond donors to Lewis basic organic substrates.^{4,7} Over the last 20 years, a number of chiral organic hydrogen bond donors have been found to be effective catalysts for a multitude of enantioselective transformations.⁸ Not surprisingly, coordination compounds can function similarly, and frequently offer architectures and binding site arrays that have no counterparts in organic systems. Another has been the development of lipophilic⁴ and/or fluorophilic⁹ Werner complexes, such that catalysis can be conducted in the absence of water, which would otherwise saturate (or compete with substrate access to) the hydrogen bond donor sites.

Department of Chemistry, Texas A&M University, P.O. Box 30012, College Station, Texas 77842-3012, USA. E-mail: gladysz@mail.chem.tamu.edu

† Electronic supplementary information (ESI) available: Figures and tables representing all stereoisomers for the complexes described in Fig. 7 and 11. See DOI: 10.1039/c6cs00604c



Given this new interest in chiral Werner complexes, the authors thought it would be helpful to review the many hierarchical levels of stereochemistry that can be embodied in octahedral cobalt(III) complexes of chelating 1,2-diamines, for which ethylenediamine (en) is the archetype. This has already seen extensive analysis,¹⁰ but the literature is fragmented, and many studies present crystal structures or CD spectra with little accompanying analysis. A potential entry level stumbling block is that organic and inorganic chemists often favor different vocabularies in analyzing the same phenomena. Hence, efforts are made to employ both syntaxes side by side throughout this review.

Several conspicuous omissions deserve note at the outset. First, some cobalt *N,N,N',N'*-tetramethyl ethylenediamine (TMEDA) complexes have been reported.¹¹ However, there are questions regarding the existence of the cobalt(III) tris(chelate).¹² Dissecondary diamine chelates, which feature NHRR' donor groups, are easily accessed,¹³ but introduce additional stereocenters. The "asymmetric nitrogen atoms" rapidly invert in the free ligands, but become fixed upon coordination. This leads to a further level of stereoisomerism, which can be subject to either kinetic or thermodynamic control. Outside of efforts by Searle,^{13b-d} there have been no systematic studies of such coordination



Andreas Ehnborn

Andreas received his MSc from Lund University (LU) in 2013. His awards include the Oxford University Press Award (2009), the Dean's Summer Student Scholarship (2010) from University College London (UCL), a Ludvig Stenberg Scholarship (2014), and the American Institute of Chemists Student Award (2014). In 2012, Andreas participated in an exchange abroad program working in the lab of Prof. Suzanne Blum at UC-Irvine. Prior to that, he worked with Prof. Ebbe Nordlander (2009–

2011), collaborated with Prof. Graeme Hogarth at UCL, and researched with Prof. Sehwyn Mapolie at Stellenbosch University (2011). In 2016 he coauthored a chapter in Organic Reactions with Prof. Peter Somfai (LU). Since June 2015, he has worked for Profs. John A. Gladysz and Michael B. Hall at Texas A&M University, with the goal of developing novel Werner catalysts and studying them using computational tools.



Subrata K. Ghosh

Subrata received his MSc from Texas A&M University-Commerce in 2010 where he worked with Profs. Allan D. Headley and Bukuo Ni. He then began work on his Doctoral degree with Prof. John A. Gladysz at Texas A&M University, where his research involves the development of novel catalysts family based on Werner complexes and resulted in several papers (see citations) and a patent. His honors include a Pathways to the Doctorate Fellow-

ship (2010–2012), an A. E. Martell Graduate Student Prize (2014), an Eastman Chemical travel grant (2015), and the Derek and Christiane Barton Graduate Award for Outstanding Research (2016). On the personal side, he is married to Swagata Ghosh who is a homemaker, and he plays cricket in his spare time.



Kyle G. Lewis

Kyle received his BS in Chemistry at Baylor University in 2008 where he worked for Prof. C. M. Garner and graduated Phi Beta Kappa. He earned his PhD at Texas A&M University in 2013 with Prof. J. A. Gladysz where he developed Werner-type cobalt complexes for enantioselective hydrogen bond mediated catalysis that resulted in several papers (see citations) and a patent. He has given invited presentations at the BASF-CaRLa Winter School (Heidelberg)

and the ACS Division of Organic Chemistry Graduate Research Symposium (Boulder); the latter was assisted by an Eastman Chemical travel grant. He is currently a Senior Research Chemist at ExxonMobil Chemical Company in Houston, Texas.



John A. Gladysz

John is a native of the Kalamazoo Michigan area, and since receiving his doctoral degree (Stanford, 1974) has held academic appointments at UCLA, the University of Utah, the Universität Erlangen-Nürnberg, and Texas A&M University. He has received awards in organometallic chemistry from the ACS (1994) and the RSC (2013), and is a Fellow of the ACS (2009) and RSC (2013). From June 1984 through July 2010, he served as the Associate Editor of Chemical Reviews. He

then succeeded Dietmar Seyferth as the Editor in Chief of Organometallics, a position he held until January 2015. On the personal side, he is married to Janet Blümel, a Professor of Chemistry at Texas A&M. They live on the Crow's Nest Ranch, which consists of 137 acres (56 hectares) a few miles east of College Station, Texas.



environments, and it is left to motivated readers to derive the extensive families of stereoisomers that can result.

2. The chiral $[\text{Co}(\text{en})_3]^{3+}$ trication: cobalt stereocenter

All octahedral tris(chelate) complexes are chiral, and the enantiomers of the $[\text{Co}(\text{en})_3]^{3+}$ trication can be rendered in the “Star of David” motifs shown in Fig. 1a. These non-superimposable mirror images differ in whether the connections between the “front triangle” and “rear triangle” run in counter clockwise or clockwise directions. This constitutes an example of helical chirality, with the first motif being left handed and the second right. As detailed in many inorganic textbooks, the former is designated Λ and the latter Δ .¹⁴ In the organic literature, enantiomers that can be viewed as left or right handed helices are often designated *M* and *P*. Other common representations of the enantiomers of $[\text{Co}(\text{en})_3]^{3+}$ are given in Fig. 1b and c. Such compounds are sometimes referred to – together with non-planar complexes of formula $\text{M}(\text{A})(\text{B})(\text{C})(\text{D})$ – as “chiral at metal”. Note also that the two NH_2 protons, and the two CH_2 protons, are diastereotopic and can give different ^1H NMR signals.

In 1912, Werner reported that the enantiomers of $[\text{Co}(\text{en})_3]^{3+}$ can be separated by fractional crystallization of the diastereomeric tartrate salts.^{2e} Chloride anion exchange then afforded the resolved enantiomers, Λ - and Δ - $[\text{Co}(\text{en})_3]^{3+} 3\text{Cl}^-$. In the preceding year, Werner described analogous resolutions of cations of the formulae $[\text{Co}(\text{en})_2(\text{A})(\text{B})]^{n+}$ and $[\text{Co}(\text{en})_2(\text{A})_2]^{n+}$. As is evident from Fig. 1d, two chelating ligands are sufficient to render an octahedral complex chiral. Tricationic tris(ethylenediamine) adducts of other metals ($[\text{M}(\text{en})_3]^{3+}$, $\text{M} = \text{Cr}$,^{15,16} Rh ,^{16,17} Ir ¹⁸)

and the tetracation¹⁹ $[\text{Pt}(\text{en})_3]^{4+}$ were similarly resolved *via* salts of various chiral anions.

Despite being chiral, the $[\text{Co}(\text{en})_3]^{3+}$ trication possesses several symmetry elements. However, for reasons that become obvious in Section 3, this initial analysis approximates the chelate backbones as planar, or having identical conformations. With this proviso, there is a principal C_3 axis that runs perpendicular to the plane of the paper in Fig. 1a and exchanges each blue nitrogen atom (and each vermillion nitrogen atom). There are furthermore three C_2 axes in a perpendicular plane (the plane of the paper) that exchange blue and vermillion nitrogen atoms. This corresponds to the chiral point group D_3 . However, the authors are not aware of any crystal structures where the trication exhibits this idealized symmetry,⁷ as the counter anions (and/or solvate molecules) hydrogen bond to the NH groups in motifs that lower the symmetry.

The enantiomers of $[\text{Co}(\text{en})_3]^{3+}$ are extremely stable with respect to ligand dissociation or racemization under ambient conditions. The half-lives for the hydrolysis and racemization of $[\text{Co}(\text{en})_3]^{3+} 3\text{Cl}^-$ in 0.10 M aqueous NaOH at 25 °C have been estimated as 3.2 years (38 kcal mol⁻¹) and >3.2 years, respectively.^{3b} Other reports confirm that no racemization of $[\text{Co}(\text{en})_3]^{3+} 3\text{Cl}^-$ occurs in aqueous solution during (a) 3 months at room temperature, (b) 75 minutes at 85 °C in the presence of 100 equiv. of NaNO_2 , or (c) 15 hours at reflux in the presence of HCl .²⁰ However, when activated charcoal is added, racemization takes place within two minutes at 90 °C.²¹ The charcoal is believed to function as a redox catalyst, allowing the generation of small amounts of substitution labile cobalt(II).

Naturally, the enantiomers give mirror image CD spectra with opposite signs for $\Delta\epsilon$ or $[\theta]$.²² When additional ligand based stereocenters are introduced, such that diastereomers result, the shapes of the CD spectra remain largely a function of the cobalt configuration.^{5b,23} Hence, cobalt configurations can be reliably assigned from the sign of the Cotton effect.

3. The chiral $[\text{Co}(\text{en})_3]^{3+}$ trication: ligand conformations

In the previous section, the conformations of the ethylenediamine chelate rings were not considered. With respect to the CH_2CH_2 backbone, a *gauche* orientation of the two NH_2 groups (torsion angle *ca.* 60°) would be expected to be much more stable than an eclipsed orientation (torsion angle *ca.* 0°). Thus, as illustrated by A and B in Fig. 2, nonplanar rings would be anticipated. For each $\text{Co}(\text{en})$ fragment, two nonsuperimposable mirror images are possible. These are commonly designated with the lower case Greek letters λ and δ and correspond to left handed and right handed helices, respectively (the counterclockwise and clockwise senses are illustrated with green arrows in Fig. 2). Each NH_2 and CH_2 group features one hydrogen atom that is pseudoaxial, and one that is pseudoequatorial.

The axial and equatorial hydrogen atoms of cyclohexane rapidly exchange *via* a “ring flip”, and the same holds for the hydrogen atoms of the ethylenediamine chelate rings.

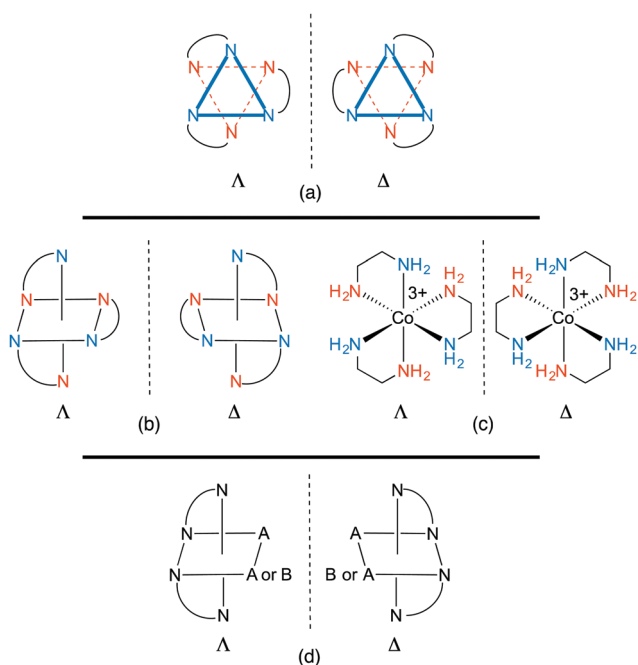


Fig. 1 Representations of the enantiomeric Λ and Δ - $[\text{Co}(\text{en})_3]^{3+}$ trications (a–c) and the related bis(chelates) $[\text{Co}(\text{en})_2(\text{A})_2]^{3+}$ and $[\text{Co}(\text{en})_2(\text{A})(\text{B})]^{n+}$ (d).



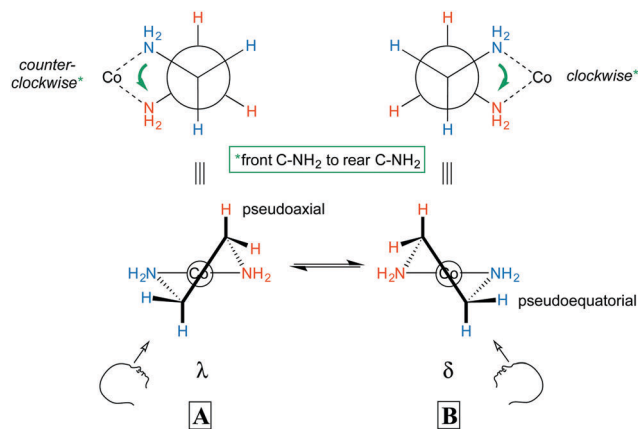


Fig. 2 Chelate conformations of ethylenediamine.

Thus, the λ and δ conformers will readily equilibrate (see Fig. 2, bottom). However, in the absence of disorder, each chelate will crystallize in one conformation or the other.

Importantly, the conformation of the chelate affects the relative orientations of the $\text{CH}_2\text{--CH}_2$ bonds and the symmetry of the $[\text{Co}(\text{en})_3]^{3+}$ trication. First, consider the “docking” of three λ ethylenediamine units to give a trication with a Δ configuration at cobalt. The initial step is shown in Fig. 3A, and when all three chelates are in place, the structure represented as $\Delta\text{--}\lambda\lambda\lambda$ results. Next, consider the docking of three δ ethylenediamine units to give a trication with the same Δ configuration at cobalt (*i.e.*, an identical spatial orientation of chelating cobalt–nitrogen bonds). The initial step is shown in Fig. 3B. In order for the cobalt–nitrogen bond locations to “match up”, the δ ethylenediamine must first be rotated by 90° . When all three chelates have been similarly put in place, the structure represented as $\Delta\text{--}\delta\delta\delta$ results.

In the first structure ($\Delta\text{--}\lambda\lambda\lambda$; Fig. 3A), the λ chelates are said to adopt *lel* orientations, so named because the three $\text{CH}_2\text{--CH}_2$ bonds are parallel to the C_3 symmetry axis.²⁴ These linkages are often incorporated into Newman type projections, as indicated by hollow circles. In the second structure ($\Delta\text{--}\delta\delta\delta$; Fig. 3B), the δ chelates are said to adopt *ob* orientations, so named because the three $\text{CH}_2\text{--CH}_2$ bonds are oblique to the C_3 axis. The designations $\Delta\text{--}\lambda\lambda\lambda$ and $\Delta\text{--}lel_3$ (Fig. 3A) are both found in the literature, and can

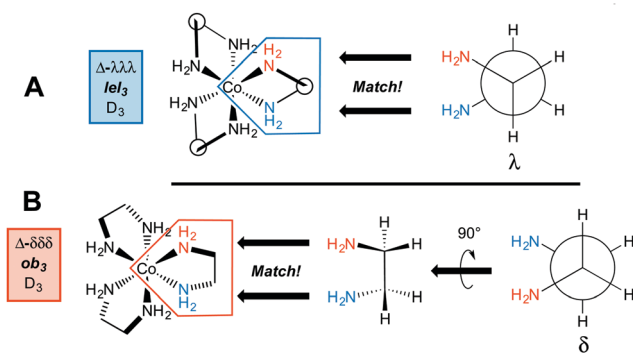


Fig. 3 Accommodation of ethylenediamine ligands with three λ or three δ conformations in the coordination sphere of an octahedral cobalt atom with a Δ configuration.

be used interchangeably, but with one important caveat that soon follows below. The same holds for $\Delta\text{--}\delta\delta\delta$ and $\Delta\text{--}ob_3$.

When the $[\text{Co}(\text{en})_3]^{3+}$ trication has a Λ configuration at cobalt, these relationships are reversed. A λ chelate leads to an *ob* orientation while a δ chelate results in a *lel* orientation. Furthermore, each of the three ethylenediamine ligands can independently adopt either an *ob* or *lel* orientation. Therefore, for a complex with a given cobalt configuration, four diastereomers exist.

All possibilities are depicted in Fig. 4. Note that the complexes analyzed in Fig. 3, and their mirror images, have D_3 symmetry. However, the new diastereomers introduced in Fig. 4, with mixed *lel* and *ob* orientations, have C_2 symmetry.

Fig. 4 also illustrates a “trap” or potential error in identifying enantiomers. Just like the descriptors *R/S* always identify enantiomers of compounds with a single tetrahedral carbon stereo-center, so will the family of descriptors consisting of upper/lower case delta/lambda identify mirror image components of the $[\text{Co}(\text{en})_3]^{3+}$ trication. In other words, the stereoisomer $\Lambda\text{--}\lambda\lambda\lambda$ can automatically be regarded as the enantiomer of $\Delta\text{--}\delta\delta\delta$.

However, this is not the case with *lel/ob*. Instead, $\Lambda\text{--}lel_3$ and $\Delta\text{--}ob_3$ are diastereomers, as is easily seen in the upper left and lower right structures in Fig. 4. Rather, it is $\Lambda\text{--}lel_3$ and $\Delta\text{--}lel_3$ that are enantiomers. Another way to look at this is as follows: if the C_3 axis is perpendicular to the plane of the paper, and one enantiomer is reflected in the plane of the paper to give the other, a “parallel” (*lel*) orientation of the $\text{CH}_2\text{--CH}_2$ bond with respect to the C_3 axis must be preserved. For these reasons, the authors generally refer to *lel/ob* as “orientations” or “perspectives”.

In practice, the conformations of the ethylenediamine chelate rings rapidly interconvert and do not have to be considered when analyzing the complexes in Fig. 1. In other words, the four diastereomers with Λ configurations in Fig. 4, as well as the four diastereomers with Δ configurations, will not normally be distinguishable in solution. However, all of these motifs can be observed in crystal structures.⁷ They also become important with certain types of substituted ethylenediamine ligands as described below.

Tris(chelate) complexes with larger rings, such as derived from 1,3-diaminopropane²⁵ and 1,4-diaminobutane²⁶ ligands, have also been reported. These similarly yield Λ and Δ enantiomers, but the additional CH_2 units give rise to larger numbers of chelate conformations. These have not yet been analyzed in comparable detail. However, parallels between chair, boat, and twist-boat cyclohexane and 1,3-diaminopropane chelate conformations have been noted.²⁵

4. Octahedral Werner complexes with monosubstituted ethylenediamine ligands

The simplest monoalkylated diamine ligand is 1,2-propylenediamine (pn).²⁷ Whereas ethylenediamine is limited to two conformational enantiomers (see Fig. 2), this ligand allows for two configurational enantiomers: (*R*)-1,2-propylenediamine ((*R*)-pn) and (*S*)-1,2-propylenediamine ((*S*)-pn). In the following



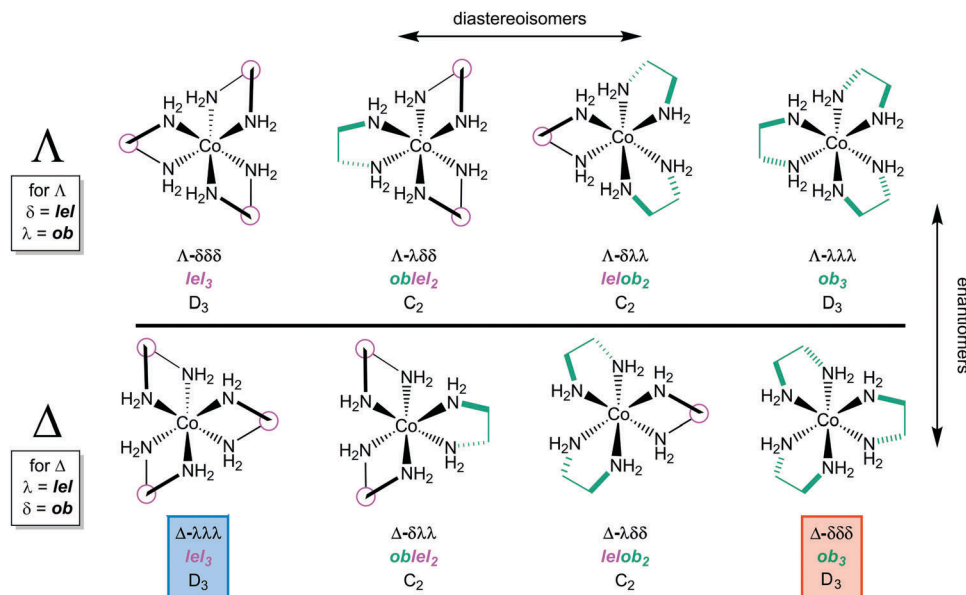


Fig. 4 All possible stereoisomers of the $[\text{Co}(\text{en})_3]^{3+}$ trication.

analysis, cobalt(III) tris(chelate) complexes with homochiral ligands (*i.e.*, all *R* or all *S*) are treated first.

4.1 Stereoisomerism at the cobalt center

As with ethylenediamine (Fig. 1), three pn ligands can chelate to give either a Λ or Δ cobalt configuration. However, the methyl group lowers the chelate symmetry from an “A–A” to an “A–B” motif. This in turn leads to *facial* (*fac*) and *meridional* (*mer*) stereoisomers, which can be viewed as counterparts to geometric isomers in organic compounds. Fig. 5 illustrates the four possible adducts of cobalt(III) and (*R*)-pn that can result (ignoring the chelate conformations). Four additional adducts can be generated with (*S*)-pn.

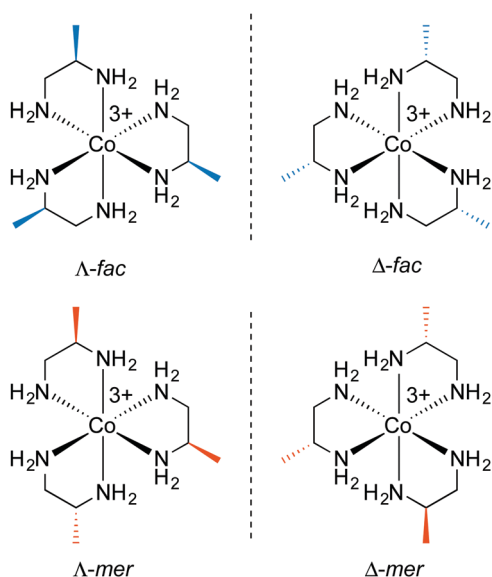


Fig. 5 The *fac/mer* isomers of the $[\text{Co}((R)\text{-pn})_3]^{3+}$ trication.

4.2 Chelate conformation

The conformation of the five membered chelate ring plays a more involved role with substituted ethylenediamine complexes than with the parent ligand. For 1,2-propylenediamine, the chelate will logically prefer conformations that place the methyl group in pseudoequatorial positions over pseudoaxial positions. Fig. 6 illustrates the pseudoequatorial and pseudoaxial versions of both (*R*)-pn and (*S*)-pn ligands.

For (*R*)-pn, the λ conformation of the chelate directs the methyl group into a pseudoequatorial position. A “ring flip” to the δ conformation is unfavorable because the methyl group must occupy a pseudoaxial position. It then follows that the tris(chelate) $[\text{Co}((R)\text{-pn})_3]^{3+}$ should, irrespective of *mer/fac* geometry, preferentially exist as either $\Lambda\text{-}\lambda\lambda\lambda$ or $\Delta\text{-}\lambda\lambda\lambda$ stereoisomers. With reference to the analyses of *ob/lel* orientations of unsubstituted ethylenediamine (Fig. 3 and 4), this means that in the Λ complex, the chelate $\text{CH}_2\text{-CHCH}_3$ linkages will all be oblique to the C_3 axis ($\Lambda\text{-ob}_3$). Similarly, in the Δ complex the chelate $\text{CH}_2\text{-CHCH}_3$ linkages will align parallel to the C_3 axis ($\Delta\text{-lel}_3$).

In contrast, the (*S*)-pn ligand will be more stable in the δ conformation (Fig. 6, right). Thus, $[\text{Co}((S)\text{-pn})_3]^{3+}$ should preferentially exist as either $\Lambda\text{-}\delta\delta\delta$ or $\Delta\text{-}\delta\delta\delta$ stereoisomers, which correspond to $\Lambda\text{-lel}_3$ and $\Delta\text{-ob}_3$. In any event, Fig. 7 summarizes the four preferred stereoisomers of $[\text{Co}((R)\text{-pn})_3]^{3+}$, considering all possible combinations of metal configurations, chelate conformations, and *fac/mer* geometries. As a side comment on nomenclature, one could ask whether the first example, labeled $\Lambda\text{-fac-}\lambda\lambda\lambda$, might equally well be represented as $\Lambda\text{-fac-RRR}$. The authors would discourage this practice, as the absolute configurations of the carbon stereocenters are already specified in the formula $[\text{Co}((R)\text{-pn})_3]^{3+}$, and the absence of the $\lambda\lambda\lambda$ designation leaves open the possibility that one of the chelate rings might display an alternative δ conformation as, for example, a consequence of crystallization.

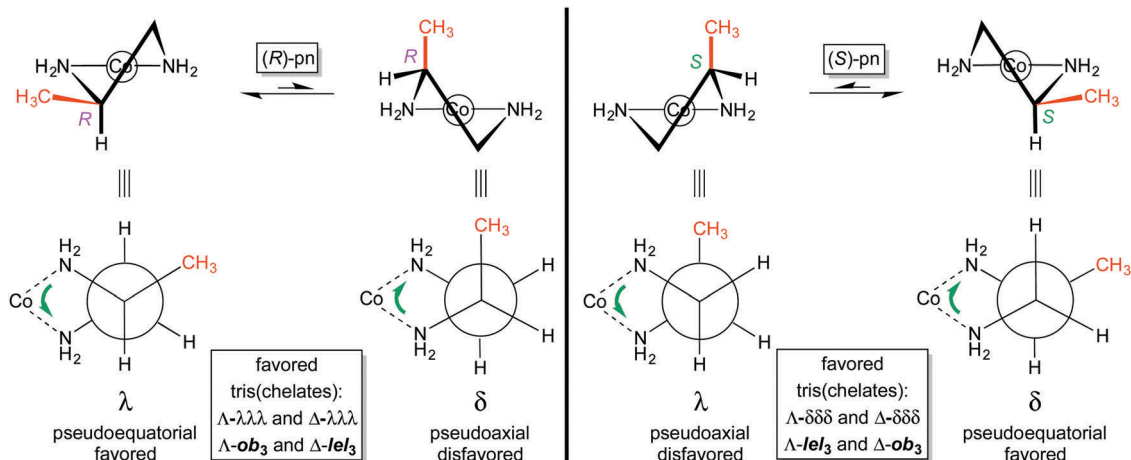


Fig. 6 Chelate conformations of (R)-pn and (S)-pn.

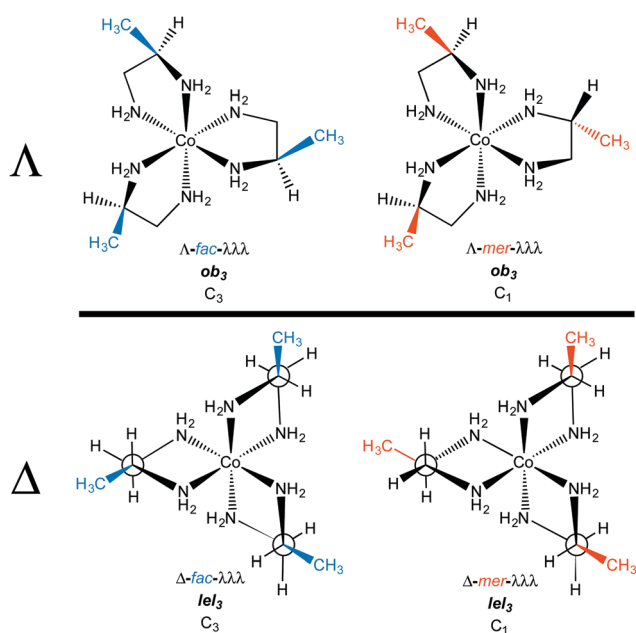


Fig. 7 Principal stereoisomers of the $[\text{Co}((R)\text{-pn})_3]^{3+}$ trication.

Alert readers will note that upon going from Fig. 1a–c to Fig. 4 to Fig. 7, structures of progressively lower symmetries are encountered (D_3 , C_3 , C_2 , C_1). Thus, it is essential to define a common reference point. Accordingly, this is taken as the “formal” or “pseudo” C_3 axis that is perpendicular to the two “Star of David” triangles (Fig. 1a), each comprised of one NH_2 group from each of the three chelate rings. This corresponds to a true C_3 axis for structures with D_3 or C_3 symmetry, and is always depicted perpendicular to the plane of the paper.

4.3 Stereoisomers allowing all possible combinations of ligand configurations

Cobalt(III) complexes of racemic pn are also chiral. This leads to a series of stereoisomers consisting of 2 : 1 or 1 : 2 (heterochiral) mixtures of (R)-pn and (S)-pn ligands, in addition to those enumerated above. Table 1 summarizes these various isomers,

which were originally enumerated by Harnung.²⁷ However, drawing the new structures is left as an exercise for the reader – one that would be very appropriate for a graduate student take-home exam. The answers are supplied in Fig. S2 of the ESI.†

5. Octahedral Werner complexes with symmetrically disubstituted ethylenediamine ligands

Many Werner complexes have been prepared from ethylenediamine ligands with two identical vicinal substituents. Examples include 2,3-butanediamine (1,2-dimethylethylenediamine),²⁸ 1,2-cyclohexanediamine (chxn),^{29,30} and 1,2-diphenylethylenediamine (dpn).^{23,31,32} In all cases, three ligand stereoisomers are possible, as depicted for chxn in Fig. 8. The first two are chiral and constitute the familiar “rac” pair, whereas the last is the achiral *meso* diastereomer.

Due to the metal centered chirality, *meso* ligands can yield chiral adducts, and enantiopure complexes have in fact been isolated.^{28a,30a} Since chxn complexes have received the most attention in the literature, these are treated first.

5.1 Stereoisomerism at the cobalt center

Consider first the chelation of three identical ligands of any of the preceding types to cobalt. As with the other cases above, either Λ or Δ configurations can result. As a general rule, disubstituted ethylenediamine ligands that have C_2 symmetry, such as *trans*-chxn or (*S,S*)- or (*R,R*)-dpn, do not lead to *fac/mer* isomers. For *cis* or *meso* (*R,S*)-chxn or (*R,S*)-dpn, which are not C_2 symmetric, *fac/mer* isomers result. In a *fac* isomer, the three Co– NH_2 bonds that connect to carbon atoms with *R* configurations would all have bond angles of ca. 90° . In a *mer* isomer, one of these angles would be ca. 180° .

5.2 Ligand conformation: *trans*-1,2-cyclohexanediamine (*trans*-chxn)²⁹

As shown in Fig. 9, the chelation of *trans*-chxn requires that both NH_2 groups occupy equatorial positions (a single atom cannot span axial substituents that have 1,2 relationships).



Table 1 Stereoisomers of $[\text{Co}(\text{pn})_3]^{3+}$ trications comprised of all combinations of (*R*)-pn and (*S*)-pn ligands (rows in bold are for tris(*RR*)-pn adducts as analyzed in Fig. 7)

Cobalt configuration	Ligand configuration	Preferred chelate conformation	Perspective down the C_3 axis ^a	Geometric type isomers	Number of stereoisomers
Λ	<i>SSS</i>	$\delta\delta\delta$	<i>lel</i> ₃	<i>fac</i> (1), <i>mer</i> (1)	2
Δ	<i>RRR</i>	$\lambda\lambda\lambda$		<i>fac</i> (1), <i>mer</i> (1)	2
Λ	<i>RSS</i>	$\lambda\delta\delta$	<i>oblel</i> ₂	<i>fac</i> (1), <i>mer</i> (3)	4
Δ	<i>SRR</i>	$\delta\lambda\lambda$		<i>fac</i> (1), <i>mer</i> (3)	4
Λ	<i>SRR</i>	$\delta\lambda\lambda$	<i>lelob</i> ₂	<i>fac</i> (1), <i>mer</i> (3)	4
Δ	<i>RSS</i>	$\lambda\delta\delta$		<i>fac</i> (1), <i>mer</i> (3)	4
Λ	<i>RRR</i>	$\lambda\lambda\lambda$	<i>ob</i>₃	<i>fac</i> (1), <i>mer</i> (1)	2
Δ	<i>SSS</i>	$\delta\delta\delta$		<i>fac</i> (1), <i>mer</i> (1)	2

Number of stereoisomers

24^b

^a Or an equivalent axis as defined in the text. ^b This increases if chelate conformations that have pseudoaxial methyl groups are allowed (see Fig. 6).

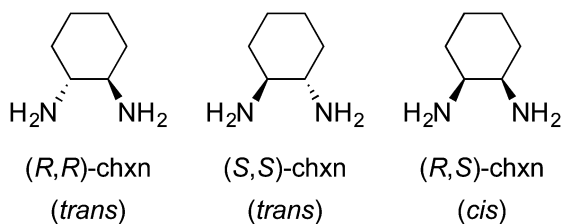


Fig. 8 Configurational stereoisomers of 1,2-cyclohexanediamine.

With (*R,R*)-chxn (top left), this in turn requires a λ chelate conformation. Thus, for the tris(chelate) $[\text{Co}((\text{R,R})\text{-chxn})_3]^{3+}$, only $\Lambda\text{-}\lambda\lambda\lambda$ ($\Lambda\text{-ob}_3$) and $\Delta\text{-}\lambda\lambda\lambda$ ($\Delta\text{-lel}_3$) stereoisomers are possible (bottom left). In contrast, (*S,S*)-chxn requires a δ chelate conformation (Fig. 9, top right). For the tris(chelate) $[\text{Co}((\text{S,S})\text{-chxn})_3]^{3+}$, only $\Lambda\text{-}\delta\delta\delta$ ($\Lambda\text{-lel}_3$) and $\Delta\text{-}\delta\delta\delta$ ($\Delta\text{-ob}_3$) stereoisomers are possible (bottom right), each enantiomeric with one of the isomers of $[\text{Co}((\text{R,R})\text{-chxn})_3]^{3+}$. There are no other stereoisomers for tris(chelates) in which the *trans*-chxn ligands are homochiral.

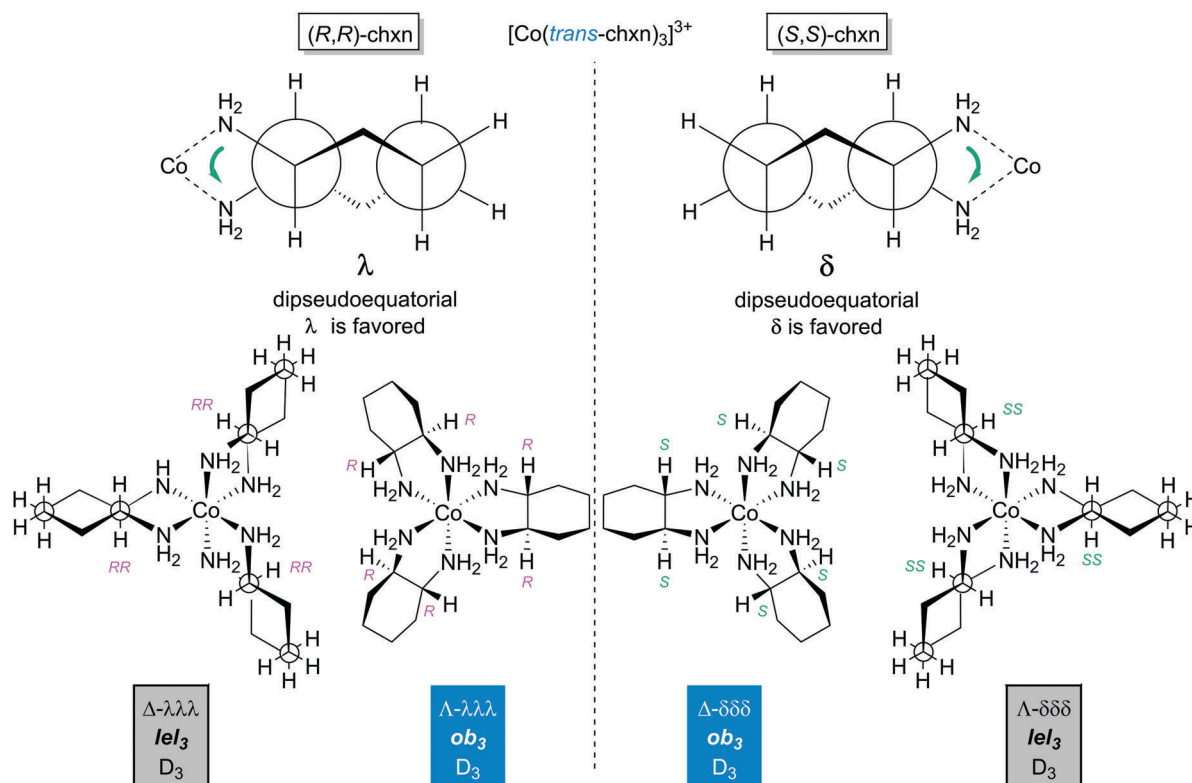


Fig. 9 Diamine chelate conformations and principal stereoisomers of the $[\text{Co}(\text{trans-chxn})_3]^{3+}$ trication with homochiral (all *S,S* or all *R,R*) ligands.



Next, consider the complexes possible when the *trans*-chxn ligands are no longer restricted to be homochiral (as with syntheses carried out with racemic diamine).²⁹ This is reminiscent of the scenario entertained for pn in Table 1, but more tractable due to the higher ligand symmetry and constraints imposed by the cyclohexane ring. The eight possible stereoisomers are depicted in Fig. 10, four with a Λ cobalt configuration (top), and four with a Δ configuration (bottom). Each set of four contains a complex derived from (i) three (*R,R*)-chxn ligands (depicted in fuller form in Fig. 9), (ii) two (*R,R*)-chxn ligands and one (*S,S*)-chxn ligand, (iii) one (*R,R*)-chxn ligand and two (*S,S*)-chxn ligands, and (iv) three (*S,S*)-chxn ligands (depicted in Fig. 9).

Enantiomeric relationships are color coded in Fig. 10. Here, designations such as Λ - $\lambda\lambda\lambda$ and Λ -*RR/RR/RR* would be fully equivalent, given the inability of *trans*-chxn to chelate when the amino groups occupy axial positions. The latter expression may be more intuitive for organic chemists.

5.3 Ligand conformation: *cis*-1,2-cyclohexanediamine (*cis*-chxn)³⁰

As illustrated in Fig. 11, the chelation of the *meso* ligand, *cis*- or (*R,S*)-chxn, requires that one amino group occupy an equatorial position on the cyclohexane ring, and the other an axial position. With respect to the five membered chelate ring, one CCH_2 substituent must occupy a pseudoequatorial position, and the

other a pseudoaxial position. The partial structures in Fig. 11 (top) can be interconverted by a cyclohexane “ring flip”, analogous to those of related bicyclic molecules such as *cis*-perhydroindane and *cis*-decalin.

Four representative stereoisomeric cobalt tris(chelates) are shown in Fig. 11 (bottom). These have cobalt and chelate configurations as well as *lel/ob* orientations and enantiomeric relationships analogous to those of $[\text{Co}(\text{trans-chxn})_3]^{3+}$ in Fig. 9. However, additional *fac/mer* descriptors are required; all of those illustrated are *fac* isomers (as is easily derived from the *R/S* labels).

As one generates all possible permutations of cobalt and chelate configurations and *fac/mer* arrays, a plethora of stereoisomers proves possible. Only by simultaneously building molecular models of each (to ensure no duplicates and optimally test for mirror images) were the authors able to convince themselves of the existence of 24 stereoisomers (12 pairs of enantiomers). Given this somewhat overwhelming set of data, the structures are depicted in the ESI† (Fig. S3) and summarized in Table S1. However, many of them can be interconverted by a cyclohexane “ring flip”, and when this is applied to all three chelates only four distinct families of isomers remain. These consist of Λ -*fac* and Δ -*fac* groupings (enantiomeric, four members each), and Λ -*mer* and Δ -*mer* groupings (enantiomeric, eight members each).

Interestingly, although all four types of stereoisomers have been isolated in enantiopure form, they have not been extensively analyzed.³⁰ Given the low barriers for most cyclohexane “ring flips”, these likely exist as mixtures of conformers in solution. In any case, Fig. S3 (ESI†) testifies as to the incredible stereochemical diversity associated with the title compounds.

5.4 Ligand conformation: (*S,S*)- and (*R,R*)-1,2-diphenylethylenediamine (dpn)

As illustrated in Fig. 12, the chelation of either enantiomer of dpn requires that both phenyl groups occupy either pseudo-equatorial or pseudoaxial positions. Naturally the former will be greatly favored. This results in a λ chelate conformation for (*R,R*)-dpn and a δ conformation for (*S,S*)-dpn. It then follows that for the tris(chelate) $[\text{Co}((\text{R,R})\text{-dpn})_3]^{3+}$, the stereoisomers Λ - $\lambda\lambda\lambda$ (Λ -*ob₃*) and Δ - $\lambda\lambda\lambda$ (Δ -*lel₃*) should be the more stable (Fig. 12, bottom left). Similarly, for $[\text{Co}((\text{S,S})\text{-dpn})_3]^{3+}$, the stereoisomers Λ - $\delta\delta\delta$ (Λ -*lel₃*) or Δ - $\delta\delta\delta$ (Δ -*ob₃*) will be the more stable (Fig. 12, bottom right; mirror images of the bottom left structures). All of these are analogous to the isomers given for *trans*- or (*S,S*)- and (*R,R*)-chxn in Fig. 9 (in which the CCH_2 substituents on the chelate ring are constrained to occupy pseudoequatorial positions).

As was analyzed for other chiral chelate ligands above, tris(chelate) complexes of dpn can be generated from a racemate. As shown in Fig. 13, eight stereoisomers are possible, four with a Λ configuration at cobalt and four with a Δ configuration. Half of these feature combinations of heterochiral (*R,R*)-chxn and (*S,S*)-chxn ligands. The situation is closely related to that for $[\text{Co}(\text{trans-chxn})_3]^{3+}$ in Fig. 10.

A similar analysis for the *meso* ligand (*R,S*)-dpn leads to a set of isomers analogous to those of $[\text{Co}(\text{cis-chxn})_3]^{3+}$ in Fig. 11 and Fig. S3 (ESI†). However, reports to date indicate that such

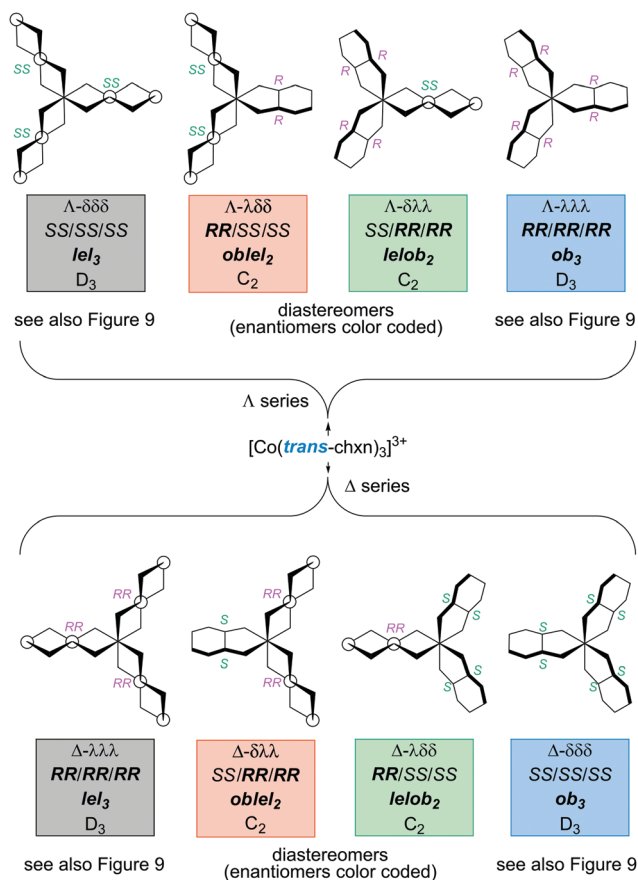


Fig. 10 Stereoisomers of the $[\text{Co}(\text{trans-chxn})_3]^{3+}$ trication with all possible combinations of (*R,R*)-chxn and (*S,S*)-chxn ligands.



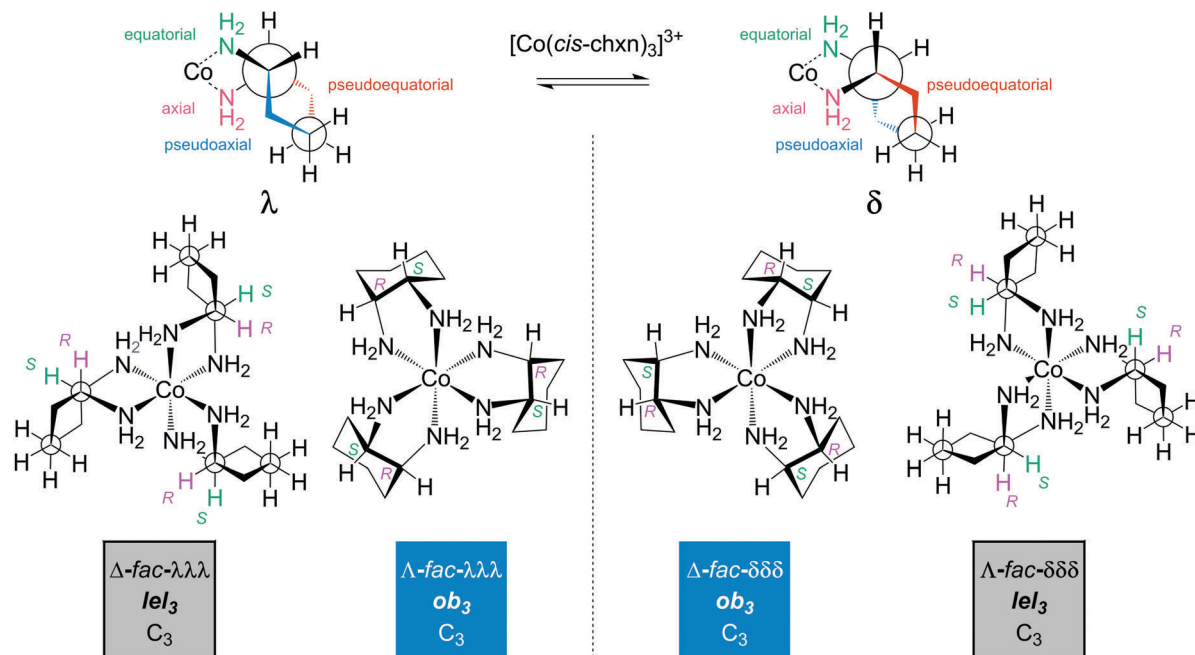


Fig. 11 Diamine chelate conformations and representative stereoisomers of the $[\text{Co}(\text{cis-chxn})_3]^{3+}$ trication; axial and equatorial are used to designate C–N bond positions on the cyclohexane ring, and pseudoaxial and pseudoequatorial are used to designate C– CH_2 bond positions on the chelate ring.

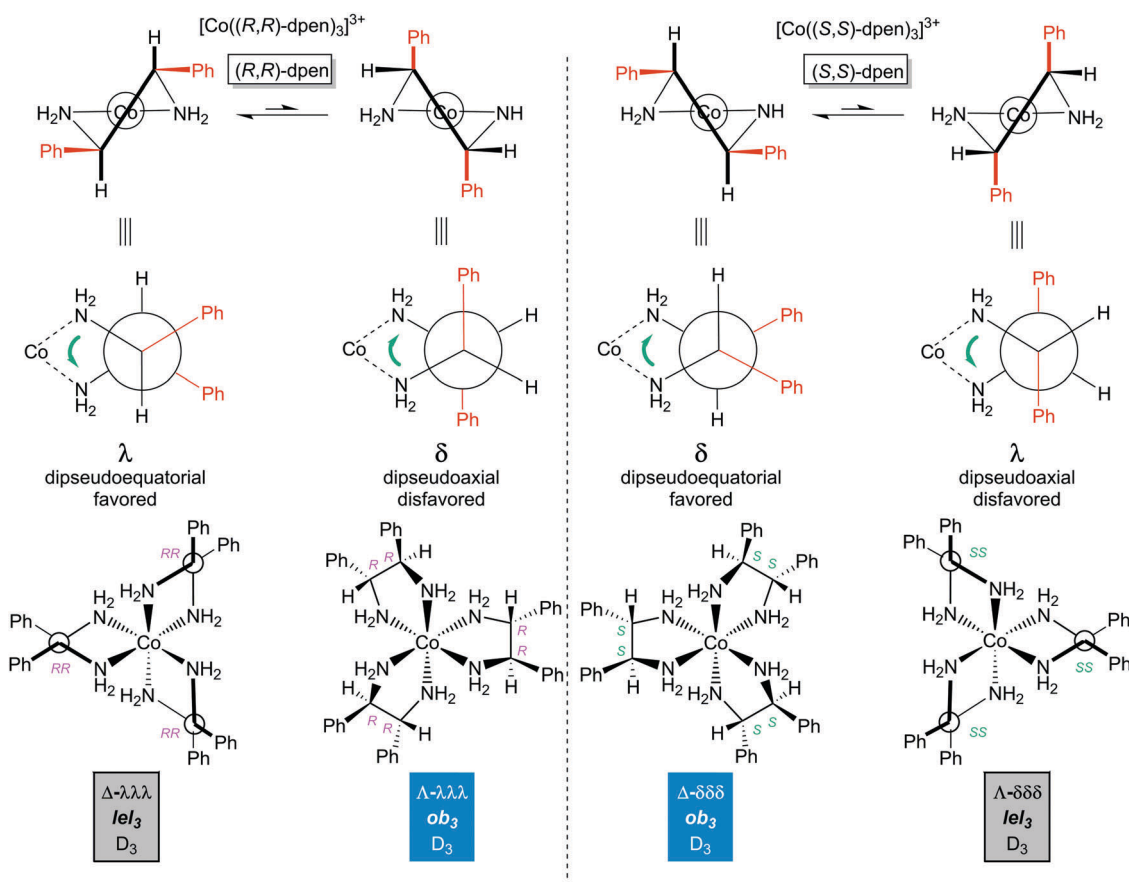


Fig. 12 Diamine chelate conformations and principal configurational stereoisomers of the $[\text{Co}(\text{dpen})_3]^{3+}$ trication with homochiral (all S,S or all R,R) ligands.



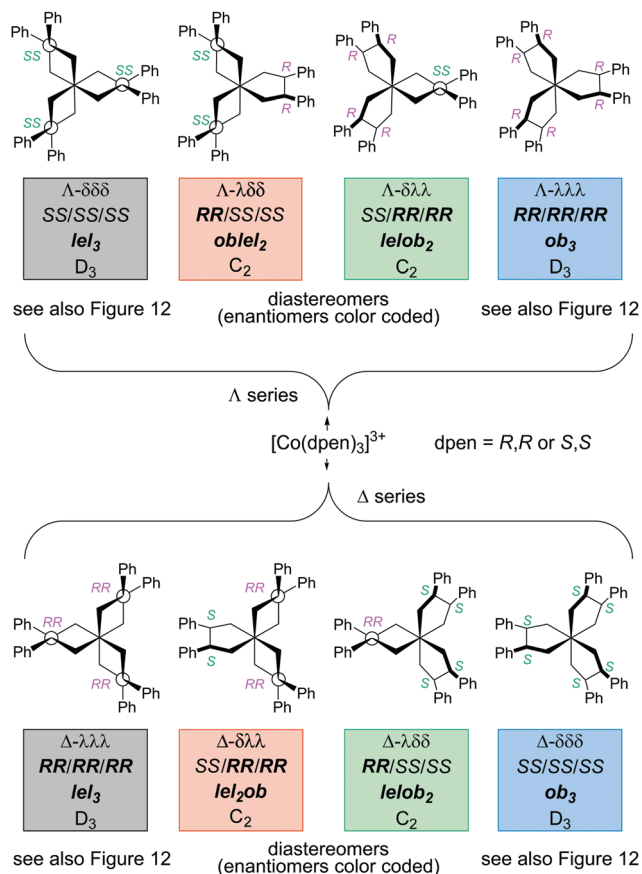


Fig. 13 Stereoisomers of the $[\text{Co}(\text{dpen})_3]^{3+}$ trication with all possible combinations of (R,R) -dpen and (S,S) -dpen ligands.

adducts are labile, presumably due to steric interactions resulting from the phenyl group that must occupy a pseudoaxial position on the chelate ring.³² Several isomeric tris(chelate) cobalt(III) complexes of the *meso* ligand (R,S) -2,3-butanediamine have been isolated.^{28a,b}

6. Diastereomer stabilities

A detailed discussion or analysis of the relative stabilities of the preceding types of diastereomers would be beyond the scope of

this review. Indeed, there is strong evidence that interactions with anions can affect stability orders in solution,^{5a,26b} and this issue is currently being probed in the authors' laboratory. Nonetheless, available literature is briefly summarized.

In their seminal study of the $[\text{Co}(\text{en})_3]^{3+}$ trication, Corey and Bailar estimated $\Delta\text{-}\lambda\lambda\lambda\text{-}[\text{Co}(\text{en})_3]^{3+}$ (which has a *lel*₃ orientation per Fig. 3) to be more stable than $\Delta\text{-}\delta\delta\delta\text{-}[\text{Co}(\text{en})_3]^{3+}$ (which has an *ob*₃ orientation) by 1.8 kcal mol⁻¹.²⁴ This was based upon intramolecular carbon–hydrogen and hydrogen–hydrogen interactions, a treatment the authors admitted was a rough approximation. Isomers with *oblel*₂ and *lelob*₂ orientations were thought to have intermediate stabilities. More recent DFT results suggest that $\Delta\text{-}\lambda\lambda\lambda\text{-}[\text{Co}(\text{en})_3]^{3+}$ is 1.5 kcal mol⁻¹ more stable than $\Delta\text{-}\delta\delta\delta\text{-}[\text{Co}(\text{en})_3]^{3+}$ in water.^{22a}

In another study, Harnung was able to equilibrate diastereomers of the trichloride salt $[\text{Co}(\text{trans-chxn})_3]^{3+} 3\text{Cl}^-$.²⁹ As shown in Fig. 14, an aqueous solution of the racemate, both enantiomers of which have *lel*₃ orientations (Fig. 10), was refluxed over charcoal²¹ in the presence of added racemic *trans*-chxn. All of the stereoisomers depicted in Fig. 10 were generated, and the ratios (determined after chromatographic separation) showed a distinct trend. Namely, the original stereoisomers with *lel*₃ orientations dominated, and quantities monotonically decreased as the proportion of *ob* orientations increased.

In a follow up experiment shown in Fig. 15,²⁷ an aqueous solution of enantiopure $\Delta\text{-}[\text{Co}((R,R)\text{-chxn})_3]^{3+} 3\text{Cl}^-$ (which has an *lel*₃ orientation) was refluxed over charcoal in the presence of enantiopure (R,R) -chxn. After the same time, only 7% of a new stereoisomer had been generated, $\Delta\text{-}[\text{Co}((R,R)\text{-chxn})_3]^{3+} 3\text{Cl}^-$ (which per Fig. 10 has an *ob*₃ orientation).

An experiment analogous to that in Fig. 14 was conducted with the salt $[\text{Co}(\text{pn})_3]^{3+} 3\text{Cl}^-$ that had been generated from racemic pn and an achiral cobalt(II) precursor.²⁷ The many possible isomers of this trication were analyzed in Table 1. Chromatography gave separate fractions for the *lel*₃, *oblel*₂, *lelob*₂, and *ob*₃ structures (each fraction a mixture of stereoisomers) in a 35.0:41.1:18.0:4.0 ratio with excellent mass balance. Additional background regarding the often surprisingly efficient chromatographic separation of isomeric (even enantiomeric) tris(diamine) cobalt(III) complexes is provided elsewhere.³³

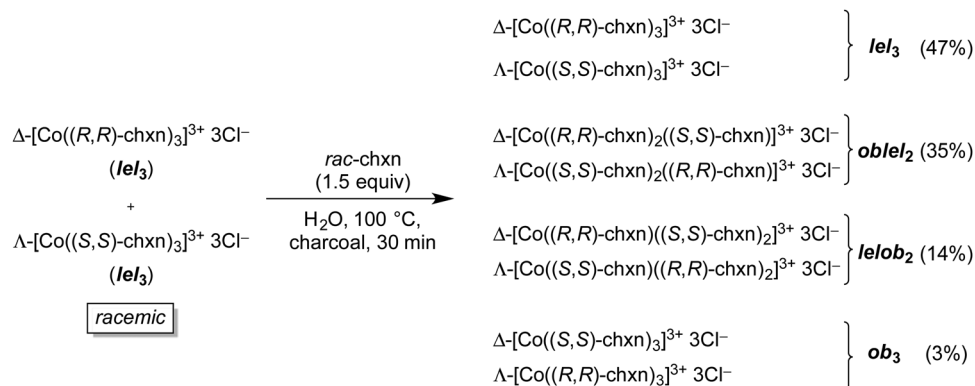


Fig. 14 Thermal equilibration of racemic $[\text{Co}(\text{trans-chxn})_3]^{3+} 3\text{Cl}^-$ in the presence of excess ligand.



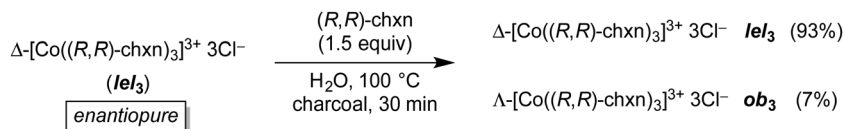


Fig. 15 Thermal equilibration of enantiopure Δ -[Co((*R,R*)-dpn) $_3$] $^{3+}$ 3Cl $^-$ in the presence of excess ligand.

A version of this experiment with non racemic [Co(pn) $_3$] $^{3+}$ 3X $^-$ has also been reported.³⁴ An equilibration similar to that in Fig. 14 but with the *meso* or *cis* chxn adduct [Co((*R,S*)-chxn) $_3$] $^{3+}$ 3X $^-$ has been mentioned, but the isomer ratios were not given.^{30a}

Thus, a clear bias for isomers with *lel* rich orientations is observed in the preceding experiments. However, it should be noted that in Fig. 14 and 15, reactants already possessing *lel* $_3$ orientations were employed. Also, the authors did not

definitively establish that equilibrium had been attained. Perhaps longer reaction times would have resulted in greater proportions of products with *ob*-rich orientations. Furthermore, the counter anion, chloride, is a strong hydrogen bond acceptor and may influence equilibrium ratios. Nonetheless, the aggregate data strongly suggest a trend, which is furthermore consistent with preliminary DFT computational results obtained by the authors.

7. Catalysis

A detailed treatment of the catalytic properties of the preceding types of complexes will be deferred until additional results from the authors' laboratory are published. However, applications reported to date are summarized in Fig. 16.^{4–6} These include Michael additions of malonate esters to α,β -unsaturated nitro compounds (top) and ketones, additions of 1,3-dicarbonyl compounds to di(*t*-butyl) azodicarboxylate, yielding amino acid precursors (middle), and ring opening polymerizations of lactide (bottom).

With the first reaction, a bifunctional catalyst that incorporates a tertiary amine proves somewhat more effective than a monofunctional catalyst with dpn ligands that is used in conjunction with Et $_3$ N. With the last reaction, another type of chelating nitrogen donor ligand, in which the activating NH groups are found in the chelate backbone, proves to be especially effective (see C). Although the polymerizations have yet to be conducted with an enantiopure catalyst, the other reactions have and under optimum conditions deliver products of >90% ee. Many mechanistic questions surrounding these processes remain extant.

8. Summary and recommendations

Although all of the examples cited in this survey involve cobalt, the principles and conclusions can clearly be extrapolated to all octahedral tris(chelate) metal complexes of ethylenediamines. Also, most types of carbon substituted ethylenediamine ligands should be closely modeled by one of the examples analyzed. For instance, pn can be viewed as representative of all mono-substituted diamines. For geminally disubstituted analogs such as H $_2$ NCR $_2$ CH $_2$ NH $_2$, the larger R/R' group would prefer a pseudoequatorial position in the chelate ring, leading to stereoisomers analogous to those of pn. The chxn and dpn complexes define the stereoisomer space for ethylenediamines with identical vicinal substituents. In cases where the substituents are rendered unequal (*e.g.*, H $_2$ NCHRCHR'/NH $_2$), what were formerly *rac* type ligands will now have an added layer of *fac/mer* isomerism. However, such cobalt tris(chelate) complexes remain, to the authors' knowledge, unknown.

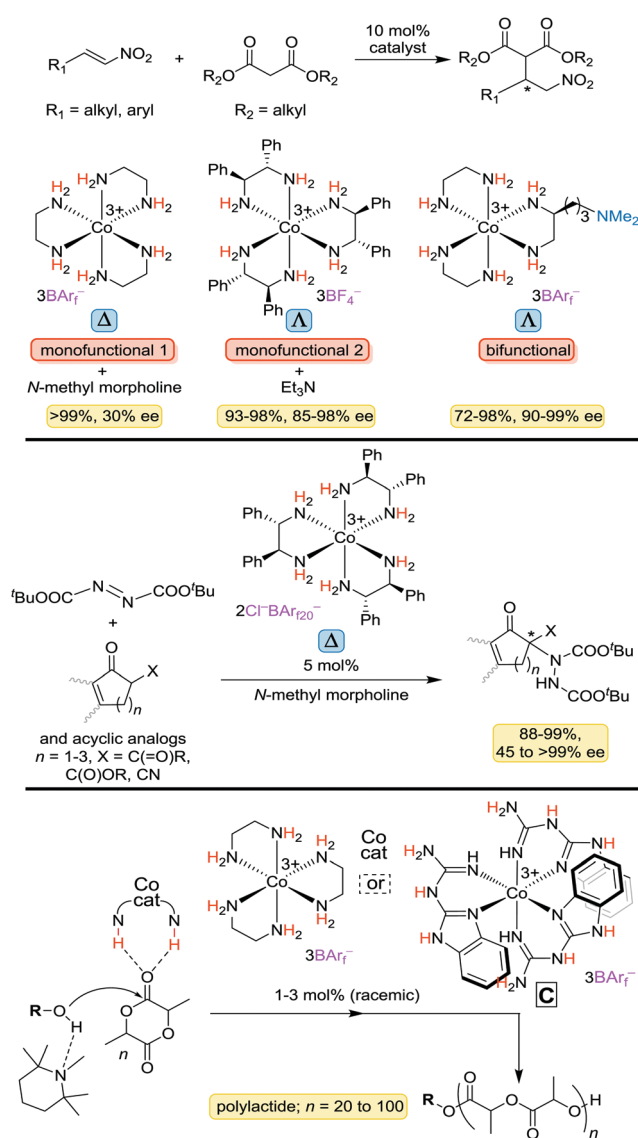


Fig. 16 Organic transformations that can be catalyzed by cobalt(III) complexes with ethylenediamine or substituted ethylenediamine ligands (BArF $^-$ = B(3,5-C $_6$ H $_3$ (CF $_3$) $_2$) $_4$ $^-$; BArF $_{20}$ $^-$ = B(C $_6$ F $_5$) $_4$ $^-$).



Underneath the many structures given above can be found a variety of types of “names”. In the authors’ view, the most appropriate one will be situational. If one wishes to specify a reactant or product, representations of the type in Fig. 14 and 15 are sufficient. If one wishes to denote a specific three dimensional structure, all of the descriptors Λ/Δ , R/S , λ/δ , and (for diamines without C_2 symmetry) *fac/mer* will generally be necessary. With certain conformationally restricted diamines (e.g., chxn), the R/S and λ/δ designations may be formally redundant, but both are recommended nonetheless. The authors consider it a disservice to the reader to replace the configuration of a ligand, such as (*R,R*)-chxn in Fig. 14 and 15, with the sign of the optical rotation, such as (–)-chxn. However, the sign of the optical rotation of the complex may be added at the front of the name if desired.

In the authors’ opinion, the descriptors *lel* and *ob* do not represent primary stereochemical phenomena but rather chelate orientations or perspectives that are enforced by fundamental stereochemical variables. Hence, these designations are given separately. However, they are clearly valuable for purposes of geometric classification. Furthermore, as noted in the previous section, this feature appears to be a major determinant with respect to chromatographic retention times and thermodynamic stabilities. Efforts to drill down deeper on this relationship are underway.

These are exciting times for Werner complexes. They have always been a classroom favorite, but most often for illustrating tried and true physical principles established long ago. Now they have contemporary applications in enantioselective catalysis,^{4–6,35,36} and the literature and new analyses summarized above should help to better understand the underlying phenomena and more methodically mine this emerging field.

Acknowledgements

The authors thank the Welch Foundation (Grant A-1656) for support.

Notes and references

- General treatments of inorganic stereochemistry that include introductions to Werner complexes of 1,2-diamines: (a) A. von Zelewsky, *Stereochemistry of Coordination Compounds*, John Wiley & Sons, Chichester, 1996; (b) H. Amouri and M. Gruselle, *Chirality in Transition Metal Chemistry*, John Wiley & Sons, Chichester, 2008; (c) C. J. Hawkins, *Absolute Configuration of Metal Complexes*, Wiley-Interscience, New York, 1971; (d) See also G. B. Kauffman, *Coord. Chem. Rev.*, 1974, **12**, 105–149.
- (a) A. Werner, *Chem. Ber.*, 1911, **44**, 1887–1898. V. L. King is listed as an author for the Experimental section; (b) A. Werner, *Chem. Ber.*, 1911, **44**, 2445–2455; (c) A. Werner, *Chem. Ber.*, 1911, **44**, 3272–3278; (d) A. Werner, *Chem. Ber.*, 1911, **44**, 3279–3284; (e) A. Werner, *Chem. Ber.*, 1912, **45**, 121–130.
- (a) H. Taube, *Chem. Rev.*, 1952, **50**, 69–126; (b) Data for $[\text{Co}(\text{en})_3]^{3+}$: J. A. Friend and E. K. Nunn, *J. Chem. Soc.*, 1958, 1567–1571; (c) For an entry level rationale, see W. U. Malik, G. D. Tuli and R. D. Madan, *Selected Topics in Inorganic Chemistry*, S. Chand & Company, New Delhi, 2002, ch. 14.
- C. Ganzmann and J. A. Gladysz, *Chem. – Eur. J.*, 2008, **14**, 5397–5400.
- (a) K. G. Lewis, S. K. Ghosh, N. Bhuvanesh and J. A. Gladysz, *ACS Cent. Sci.*, 2015, **1**, 50–56; (b) S. K. Ghosh, C. Ganzmann, N. Bhuvanesh and J. A. Gladysz, *Angew. Chem., Int. Ed.*, 2016, **55**, 4356–4360 (*Angew. Chem.*, 2016, **128**, 4429–4433); (c) A. Kumar, S. K. Ghosh and J. A. Gladysz, *Org. Lett.*, 2016, **18**, 760–763.
- See also C. Thomas and J. A. Gladysz, *ACS Catal.*, 2014, **4**, 1134–1138.
- S. K. Ghosh, A. Ehnborn, K. G. Lewis and J. A. Gladysz, review in preparation.
- (a) M. S. Taylor and E. N. Jacobsen, *Angew. Chem., Int. Ed.*, 2006, **45**, 1520–1543 (*Angew. Chem.*, 2006, **118**, 1550–1573); (b) A. G. Doyle and E. N. Jacobsen, *Chem. Rev.*, 2007, **107**, 5713–5743; (c) X. Yu and W. Wang, *Chem. – Asian J.*, 2008, **3**, 516–532.
- S. K. Ghosh, A. S. Ojeda, J. Guerrero-Leal, N. Bhuvanesh and J. A. Gladysz, *Inorg. Chem.*, 2013, **52**, 9369–9378.
- (a) A recent review that is complementary to this one: Y. Liu, Y. Liu and M. G. B. Drew, *Coord. Chem. Rev.*, 2014, **260**, 37–64; (b) Y. Saito, in *Topics in Stereochemistry*, ed. E. L. Eliel and N. L. Alinger, 1978, vol. 10, pp. 95–174.
- (a) C. Comuzzi, A. Melchior, P. Polese, R. Portanova and M. Tolazzi, *Eur. J. Inorg. Chem.*, 2002, 2194–2201; (b) A. Johansson, E. Wingstrand and M. Håkansson, *Inorg. Chim. Acta*, 2005, **358**, 3293–3302.
- (a) P. Hendry and A. Ludi, *J. Chem. Soc., Chem. Commun.*, 1987, 891–892; (b) When a Sci-Finder search was conducted for the tris(TMEDA) trication $[\text{Co}(\text{Me}_2\text{NCH}_2\text{CH}_2\text{NMe}_2)_3]^{3+}$, the previous reference was obtained. However, there are no structural or line formulae given in this article, and a key phrase “producing 2,3-methyl-2,3-diaminobutane or tetramethylethylenediamine (tmen)” can be construed to mean two separate compounds or the same compound (the title and abstract of the article are ambiguous). As can be inferred from subsequent papers in this series involving other metals, the authors must intend tmen to be 2,3-methyl-2,3-diaminobutane, meaning that instead salts of $[\text{Co}(\text{NH}_2\text{CMe}_2\text{CMe}_2\text{NH}_2)_3]^{3+}$ have been synthesized: S. Brönnimann, A. Zilian, H. U. Güdel and A. Ludi, *Inorg. Chim. Acta*, 1990, **173**, 159–162; (c) A Sci-Finder search for $[\text{Co}(\text{NH}_2\text{CMe}_2\text{CMe}_2\text{NH}_2)_3]^{3+}$ does not afford ref. 12a. However, it does yield a corresponding full paper: P. Hendry and A. Ludi, *Helv. Chim. Acta*, 1988, **71**, 1966–1970.
- (a) J. A. Hearson, S. F. Mason and R. H. Seal, *J. Chem. Soc., Dalton Trans.*, 1977, 1026–1034; (b) G. H. Searle and F. R. Keene, *Inorg. Chim. Acta*, 1989, **155**, 125–138; (c) G. H. Searle and E. R. T. Tiekink, *Inorg. Chim. Acta*, 1989, **156**, 57–63; (d) I. M. Atkinson, F. R. Keene and G. H. Searle, *J. Chem. Soc., Dalton Trans.*, 1991, 45–51.
- T. S. Piper, *J. Am. Chem. Soc.*, 1961, **83**, 3908–3909.
- A. Werner, *Ber. Dtsch. Chem. Ges.*, 1912, **45**, 865–869.
- F. Galsbøl in *Inorganic Syntheses*, ed. R. W. Parry, McGraw-Hill, New York, 1970, pp. 269–280.
- A. Werner, *Chem. Ber.*, 1912, **45**, 1228–1236.



- 18 (a) A. Werner and A. P. Smirnoff, *Helv. Chim. Acta*, 1920, **3**, 472–486; (b) F. Galsbøl and B. S. Rasmussen, *Acta Chem. Scand.*, 1982, **A36**, 83–87.
- 19 A. Werner, *Vierteljahresschr. Naturforsch. Ges. Zürich*, 1917, **62**, 553–564.
- 20 W. G. Gehman and W. C. Fernelius, *J. Inorg. Nucl. Chem.*, 1957, **9**, 71–81.
- 21 (a) B. D. Douglas, *J. Am. Chem. Soc.*, 1954, **76**, 1020–1021; (b) For interesting observations regarding differences between types of charcoals and their catalyst lifetimes, see the final paragraph of the Experimental section of ref. 27.
- 22 (a) F. E. Jorge, J. Autschbach and T. Ziegler, *J. Am. Chem. Soc.*, 2005, **127**, 975–985; (b) C. F. Bell, *Syntheses and Physical Studies of Inorganic Compounds*, Pergamon, New York, 1972, ch. 22.
- 23 B. Bosnich and J. MacB. Harrowfield, *J. Am. Chem. Soc.*, 1972, **94**, 3425–3437.
- 24 E. J. Corey and J. C. Bailar Jr., *J. Am. Chem. Soc.*, 1959, **81**, 2620–2628.
- 25 (a) T. Nomura, F. Marumo and Y. Saito, *Bull. Chem. Soc. Jpn.*, 1969, **42**, 1016–1020; (b) Y. Sunatsuki, S. Miyahara, T. Suzuki, M. Kojima, T. Nakashima, N. Matsumoto and F. Galsbøl, *New J. Chem.*, 2010, **34**, 2777–2784.
- 26 (a) J. Fujita and H. Ogino, *Chem. Lett.*, 1974, 57–58; (b) S. Sato, Y. Saito, J. Fujita and H. Ogino, *Inorg. Nucl. Chem.*, 1974, **10**, 669–673.
- 27 S. E. Harnung, S. Kallesøe, A. M. Sargeson and C. E. Schäffer, *Acta Chem. Scand.*, 1974, **A28**, 385–398.
- 28 (a) M. Kojima, H. Funaki, Y. Yoshikawa and K. Yamasaki, *Bull. Chem. Soc. Jpn.*, 1975, **48**, 2801–2804; (b) C. J. Hilleary, T. F. Them and R. E. Tapscott, *Inorg. Chem.*, 1980, **19**, 102–107; (c) M. F. Gargallo, L. Lechuga, M. C. Puerta, F. González-Vílchez and R. Vilaplana, *J. Chem. Educ.*, 1988, **65**, 1018–1019.
- 29 S. E. Harnung, B. S. Sørensen, I. Creaser, H. Maegaard, U. Pfenninger and C. E. Schäffer, *Inorg. Chem.*, 1976, **15**, 2123–2126.
- 30 (a) H. Toftlund and T. Laier, *Acta Chem. Scand.*, 1977, **31**, 651–656; (b) T. Mizuta, K. Toshitani and K. Miyoshi, *Bull. Chem. Soc. Jpn.*, 1991, **64**, 1183–1191.
- 31 R. Kuroda and S. F. Mason, *J. Chem. Soc., Dalton Trans.*, 1977, 1016–1020.
- 32 For the isolation of racemic $[\text{Co}((R,S)\text{-dpen})_3]^{3+} 3\text{Cl}^-$, which slowly decomposes in solution, see M. Kojima, M. Ishiguro and J. Fujita, *Bull. Chem. Soc. Jpn.*, 1978, **51**, 3651–3652.
- 33 Y. Yoshikawa and K. Yamasaki, *Coord. Chem. Rev.*, 1979, **28**, 205–229. See in particular sections F-v and F-vi.
- 34 F. P. Dwyer, F. L. Garvan and A. Shulman, *J. Am. Chem. Soc.*, 1959, **81**, 290–294.
- 35 See also (a) L. Gong, L.-A. Chen and E. Meggers, *Angew. Chem., Int. Ed.*, 2014, **53**, 10868–10874 (*Angew. Chem.*, 2014, **126**, 11046–11053); (b) J. Ma, X. Ding, Y. Hu, Y. Huang, L. Gong and E. Meggers, *Nat. Commun.*, 2014, **5**, 4531; (c) H. Huo, C. Fu, C. Wang, K. Harms and E. Meggers, *Chem. Commun.*, 2014, **50**, 10409–10411; (d) J. Liu, L. Gong and E. Meggers, *Tetrahedron Lett.*, 2015, **56**, 4653–4656; (e) Y. Hu, Z. Zhou, L. Gong and E. Meggers, *Org. Chem. Front.*, 2015, **2**, 968–972.
- 36 V. I. Maleev, M. North, V. A. Larionov, I. V. Fedyanin, T. F. Savel'yeva, M. A. Moscalenko, A. F. Smolyakov and Y. N. Belokon, *Adv. Synth. Catal.*, 2014, **356**, 1803–1810.

