

# Exploring the Chemistry of $\text{Re}^I$ : Physical and Theoretical Investigations

by

Philip D. Bulsink

*Thesis submitted to the  
Faculty of Graduate and Postdoctoral Studies  
In partial fulfilment of the requirements  
For the degree of*

***Master of Science  
In  
Chemistry***

*Ottawa-Carleton Chemistry Institute  
University of Ottawa*

***Supervisors:*** *Professors Darrin Richeson & Tom Woo*

© Philip D. Bulsink, Ottawa, Canada, 2014

## Abstract

The development of Rhenium I photocatalysts has been pursued since Lehn first showed the excellent performance of the  $\text{Re}^{\text{I}}$  bipyridine tricarbonyl catalyst. Since then, development has modified the organic ligand to demonstrate continued or improved activity with other  $\alpha$ -diimine bidentate geometries. Geometry has been limited to  $\kappa_2$  motifs, with *fac*-(CO)<sub>3</sub> and axial halide. This work will demonstrate the synthesis, characterization, and testing of a new  $\kappa_3(\text{L}_3)\text{-Re}^{\text{I}}\text{-mer}(\text{CO})_2\text{X}$  (X = Cl, Br, CN, OTf) family of compounds for CO<sub>2</sub> reduction, as well as computational investigations into the mechanism of the reduction,

## Acknowledgements

Thanks to the members of the Richeson and Woo research groups, both past and present, for the assistance provided and for making the time spent researching and writing this thesis enjoyable. Thanks as well to Frank and Sean in the Brusso lab, for their willingness to allow use of their characterization equipment. Thanks to Jake and the Gambarotta laboratory for use of their GC, and to the Sciano Lab, especially Janice, Charles, and Deni, for the use of their photolysis equipment.

I'd like to thank Dr. Ilia Korobkov for his work measuring and solving the x-ray crystal structures of the compounds discussed. He assisted with some paper writing as well.

Finally, I'd like to thank my fiancé Leanne, and my parents for their unending support, and understanding when I came home frustrated or exhausted from work.

# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Inorganic Chemistry . . . . .	1
1.2	Photochemistry & Catalysis . . . . .	2
1.3	Rhenium . . . . .	3
<b>2</b>	<b>New Coordination Geometries for Re<sup>I</sup></b>	<b>7</b>
2.1	Introduction . . . . .	7
2.2	Synthesis of Bidentate and Terdentate Re <sup>I</sup> Complexes . . . . .	8
2.3	Characterization . . . . .	11
2.3.1	NMR Analysis . . . . .	11
2.3.2	X-Ray Crystallography . . . . .	13
2.3.3	Spectroscopy . . . . .	13
2.3.4	Conclusions . . . . .	14
<b>3</b>	<b>Photocatalysis of CO<sub>2</sub></b>	<b>15</b>
3.1	Introduction . . . . .	15
3.2	Photocatalytic Reactions with New Compounds . . . . .	16
3.2.1	Conditions . . . . .	16
3.2.2	Experimental Results . . . . .	16
3.3	Section . . . . .	17
3.4	Section . . . . .	17
3.4.1	Subsection . . . . .	17
<b>4</b>	<b>Mechanism of CO<sub>2</sub> Reduction</b>	<b>18</b>
4.1	Introduction . . . . .	18
4.2	Literature Mechanisms . . . . .	19
4.3	Consequences From $\kappa^2$ Terpyridine Complex Inactivity . . . . .	20

4.4	Comparison Between Mechanistic Pathways . . . . .	21
4.4.1	Subsection . . . . .	21
<b>5</b>	<b>Conclusions</b>	<b>22</b>
<b>A</b>	<b>Experimental Procedures</b>	<b>23</b>
A.1	1 . . . . .	23
A.2	2 . . . . .	23
A.3	3 . . . . .	23
A.4	4 . . . . .	24
	<b>Glossary of Terms</b>	<b>25</b>

# List of Tables

# List of Figures

1.1	Two common bidentate complexes using terdentate ligands . . . . .	4
2.1	Results of TGA analysis on <b>1</b> and <b>2</b> . . . . .	9
2.2	The aromatic region of the <sup>1</sup> HNMR spectra of 3 bidentate compounds . .	12
2.3	The aromatic region of the <sup>1</sup> HNMR spectra showing bidentate - terdentate conversion . . . . .	13
2.4	Proton-explicit skeletal drawing of 2,2':6',2''-terpyridine . . . . .	13
4.1	Overview of mechanistic pathways . . . . .	19
4.2	Reaction energies for three mechanistic pathways . . . . .	21

# Chapter 1

## Introduction

### 1.1 Inorganic Chemistry

Common distinctions split most chemical compounds into one of two categories: organic and inorganic. Organic molecules contain carbon and hydrogen, with or without additional nitrogen, oxygen, phosphorus, sulfur, and the halides. Inorganic chemistry is, therefore, considered to be the remainder of the molecules possible. While they may include some aspect of organic chemistry (especially in organometallic molecules), the main structural motif or reactive center is a non-organic feature. These inorganic compounds can range from compounds such as lithium or grignard reagents with significant organic influence, to metallic alloys or mineral compounds. With such a wide range of possibilities, inorganic chemistry has many facets. A widely active research area is the development and testing of transition metal complexes for catalytic, photo-physical, biochemical or manufacturing uses.



## 1.2 Photochemistry & Catalysis

A report of the first synthesized organometallic complex was published by Zeise in 1831.<sup>1</sup> To form what is now known as Zeise's salt,  $\text{K}[\text{PtCl}_3(\text{C}_2\text{H}_4)] \cdot \text{H}_2\text{O}$ , he mixed platinum chloride with ethanol, followed by a reaction with potassium chloride.<sup>2</sup> After some controversy to the composition of this, it was confirmed by Griess and Martius,<sup>3</sup> and later expanded upon by Birnbaum.<sup>4</sup>

The field of organometallics was expanded greatly by Frankland,<sup>2</sup> and many of his complexes were catalytically active. Further development of this new type of chemistry quickly led to useful catalysts for the conversion of petroleum products or the production or destruction of other chemicals to be developed using nearly all of the transition metals. These catalysts take all forms, from simple olefin and halide compounds to multi-metallic complexes with large organic ligands.

Some of the most interesting organometallic catalysts since the late 1990s have been the development of earth metal pincer complexes to replace noble metal or early transition metal catalysts, which are often more toxic or expensive to produce. Brookhart and Gibson published a series of papers<sup>5-8</sup> on the use of iron and cobalt with bis(imino)pyridine ligands to perform ethylene polymerization at rates exceeding those of similar noble metal complexes and metallocenes.<sup>9</sup> The role of the ligand in the mechanism is still up for debate, but many modified systems have been synthesized and tested since the first work was published.<sup>10</sup>

Many of these types of pincer complexes are photochemically active. In transition metal complexes, the interaction between the metal atom(s) and the ligands can cause significant electron mobility upon the absorption of incident photons. The metal atom's  $d$  orbitals typically lie at or near the Highest Occupied Molecular Orbital (HOMO) energy, while the ligands often have low energy anti-bonding orbitals ( $\pi^*$ ) at the Lowest Unoc-

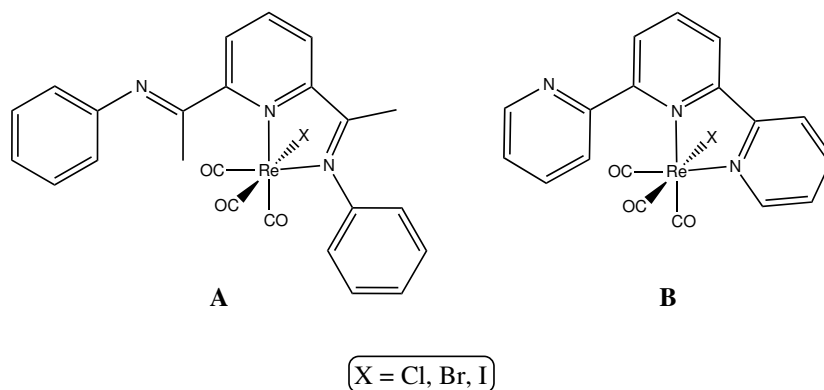
cupied Molecular Orbital (LUMO) levels. When a photon is absorbed and is promoted from the ground state to the excited state, that state is geographically removed from the metal centre, this motion of the electron is labelled a Metal-Ligand Charge Transfer (MLCT). Formally, the metal atom is oxidized by the photons, this oxidation allows for redox reactivity at the metal centre for as long as the electron remains removed to the ligand. Relaxation (through photon emission via fluorescence or phosphorescence, or via vibrational or other motion processes) can return the electron to the metal to reform the ground electronic state.

## 1.3 Rhenium

Rewrite to  
more verbose

Rhenium compounds display a broad scope of applications ranging from catalysis<sup>11–13</sup> to radiopharmaceutical applications,<sup>14,15</sup> as well as possessing interesting fundamental photophysical properties.<sup>16</sup> Since the mid-1970's, complexes containing the  $\alpha$ -diimine  $\text{Re}^{\text{I}}$  tricarbonyl core have attracted a great deal of attention due to their attractive photochemical properties with pseudo-octahedral *fac*- $[\text{L}_2\text{Re}(\text{CO})_3\text{X}]$  and *fac*- $[\text{L}_2(\text{L}')\text{Re}(\text{CO})_3]^+$  complexes being the dominant species.<sup>17–27</sup> A large family of compounds with these formulations have been accessed by the addition of chelating diimine  $\sigma$ -donor ligands to  $[\text{Re}(\text{CO})_5\text{X}]$  with the quantitative replacement of two *cis* carbonyls in the  $\text{Re}^{\text{I}}$  starting material.<sup>17,28–35</sup> Significantly, these reactions form only bidentate coordinated ligands with *facial* tricarbonyl isomers as products even when a potentially tridentate  $\sigma$ -donor, such as bis(imino)pyridine or 2,2':6',2''-terpyridine are employed in the reaction (Figure 1.1).<sup>36–38</sup> These robust species have been examined for potential applications in organic light-emitting diodes (OLEDs),<sup>39</sup> chemosensors and biotechnology probes,<sup>40–44</sup> fluorescence microscopy imaging of cells,<sup>40,45,46</sup> and the photochemical reduction of  $\text{CO}_2$  to  $\text{CO}$ .<sup>47–51</sup> Among the key photophysical features of these  $\alpha$ -diimine  $\text{Re}^{\text{I}}$  compounds is the

electron transfer capability of this system and the interplay between the Re center and the well-known non-innocent redox-activity of the ligands.<sup>52</sup>



**Figure 1.1** Two common *fac*-[L<sub>2</sub>Re(CO)<sub>3</sub>X] complexes with tridentate  $\sigma$ -donor ligands: L = bis(imino)pyridine (**A**) and 2,2':6',2''-terpyridine (**B**)

Further development of this chemistry has been restricted by the limited structural and electronic variability of the common pseudo-octahedral *fac*-[L<sub>2</sub>ReX(CO)<sub>3</sub>] (L<sub>2</sub> =  $\alpha$ -diimine) products. While these systems continue to receive considerable attention, studies detailing the coordination chemistry of the meridionally-coordinated tridentate triimine Re<sup>I</sup> dicarbonyl core are quite limited.<sup>53</sup> For example, while  $\kappa^3(\text{terpy})\text{Re}(\text{CO})_2\text{Cl}$  was initially reported in 1988,<sup>54</sup> closer analysis of the reported analytical data (including <sup>1</sup>H NMR) indicate that this compound is more likely  $\kappa^2\text{LRe}(\text{CO})_3\text{Cl}$ . A more recent report for this compound provides spectroscopic details of this species as well as the preliminary report for the generation of [ $\kappa^3(\text{terpy})\text{Re}(\text{CO})_2\text{L}$ ]<sup>+</sup> cations (L = PPh<sub>3</sub>, PEt<sub>3</sub>, NC<sub>5</sub>H<sub>5</sub>, and NCCH<sub>3</sub>).<sup>55</sup> Finally, the <sup>1</sup>H NMR data for  $\kappa^3(\text{terpy})\text{Re}(\text{CO})_2\text{Br}$  has been reported.<sup>38</sup>

In order to fully exploit the potential of this versatile family of compounds, the limits imposed by the bidentate coordination need to be addressed. Furthermore, it would appear that, on the basis of the tridentate ligands that have been investigated, the

concerted effort to produce the tridentate species has been unsuccessful. Attracted by this challenge we sought to synthesize, crystallographically authenticate, and investigate the photophysical properties of low-valent rhenium pincer complexes displaying an N,N',N''-chelated terpyridine array.

Take out  
spoilers

We recently reported the conversion of bidentate bis(imino)pyridine complexes 2,6-{2,6-Me<sub>2</sub>C<sub>6</sub>H<sub>3</sub>N=CPh}<sub>2</sub>(NC<sub>5</sub>H<sub>3</sub>)Re(CO)<sub>3</sub>X (X = Cl, Br) into tridentate pincer ligand compounds, 2,6-{2,6-Me<sub>2</sub>C<sub>6</sub>H<sub>3</sub>N=CPh}<sub>2</sub>(NC<sub>5</sub>H<sub>3</sub>)Re(CO)<sub>2</sub>X (X = Cl, Br).<sup>53</sup> This transformation was performed in the solid-state by controlled heating of these bidentate species above 200°C in a tube furnace under a flow of nitrogen gas giving excellent yields ( $\geq 95\%$ ). These compounds defined a new coordination environment for Re<sup>I</sup> carbonyl chemistry where the metal center is supported by a planar, tridentate pincer coordinated bis(imino)pyridine ligand.

Complexes of 2,2':6',2''-terpyridine (terpy) are of interest due to the conceptual relationship to established bis(imino)pyridine compounds.<sup>56,57</sup> Herein, we provide rational synthetic procedures to these novel species as well as their characterization and analysis of their visible electronic transitions. These results will broaden the accessibility of such compounds for investigation and application. This report for the unconventional but accessible synthesis of tridentate pincer complexes promises to enhance the versatile chemistry of Re<sup>I</sup> and yield new venues for exploration.

This thesis will be a discussion of the development of chemistry of Re<sup>I</sup> complexes, their characterization, and comparison of structural and photo-physical properties to computed values. Further exploration of the CO<sub>2</sub> reduction by photo-catalysis of these new complexes will be analyzed. This thesis will also take a more detailed look at specifics of the mechanisms proposed for current Re<sup>I</sup> diimine catalysts, and propose new geometries for prior mechanistic steps based on experimental, computational, and

literature review work.

# Chapter 2

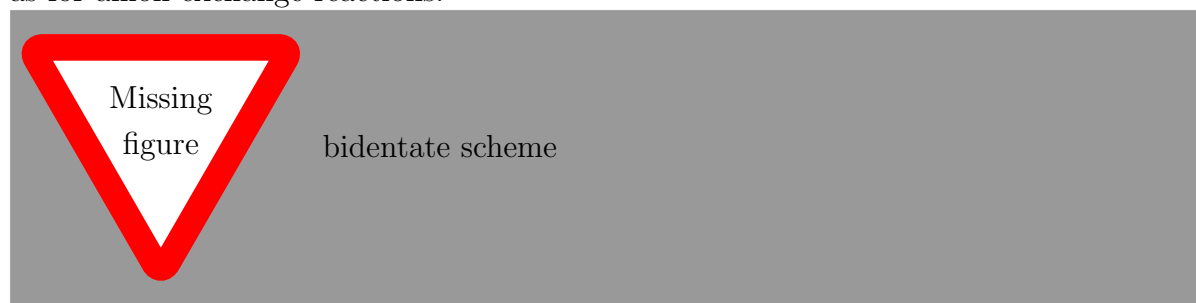
## New Coordination Geometries for $\text{Re}^{\text{I}}$

### 2.1 Introduction

As mentioned previously in the thesis introduction,  $\text{Re}^{\text{I}}$  compounds have been typically bidentate ( $\kappa^2$ ) compounds, even when using a potentially terdentate ( $\kappa^3$ ) ligand such as bis(imino)pyridine or terpyridine (refer to Figure 1.1). The chemistry of this rhenium  $\alpha$ -imino complex has been extensively investigated, with over 1700 references appearing in a structure search for that metal-ligand motif. The extraction of an additional carbonyl and the chelation of the pendant arm of the ligand was attempted to extend the pi system of the ligand and its interaction with the metal centre. This was first demonstrated by prior work in our group for the bis(imino)pyridine ligand.<sup>53</sup>

## 2.2 Synthesis of Bidentate and Terdentate $\text{Re}^{\text{I}}$ Complexes

Similar to the prior work, synthesis began with the production of the bidentate complex  $\kappa^2(\text{terpy})\text{Re}(\text{CO})_3\text{X}$  ( $\text{X} = \text{Cl}, \text{Br}$ ) by coordination of 2,2':6',2''-terpyridine (Sigma) with a  $\text{Re}(\text{CO})_5\text{X}$  (Strem) starting material in dry toluene at reflux for 4 hours, as shown in Scheme 2.1. A bright yellow powder precipitated from solution and was collected by filtration, washed with cold hexanes, and dried *in vacuo* to a good yield of **1** and **2** respectively.<sup>i</sup> These bidentate compounds were characterized fully and used without further purification to produce  $\kappa^3(\text{terpy})\text{Re}(\text{CO})_2\text{X}$  ( $\text{X} = \text{Cl}, \text{Br}$ ) via thermolysis, as well as for anion exchange reactions.

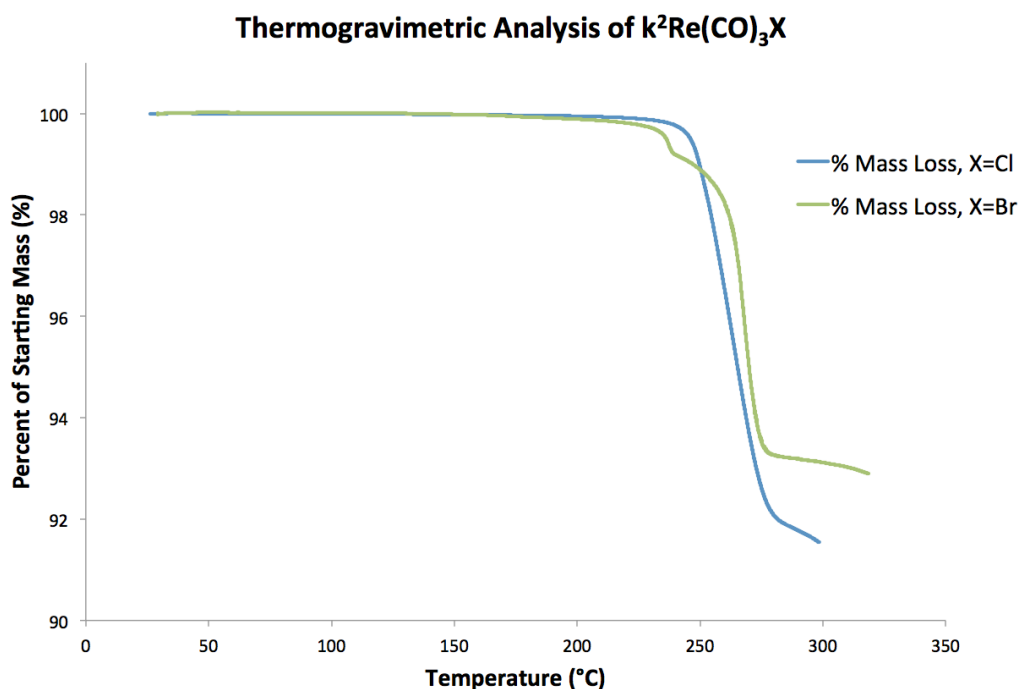


**Scheme 2.1** Synthesis of **1** and **2**

Thermolysis was completed via a method first described by Buckingham with an osmium complex.<sup>58</sup> In this method, a ceramic sample boat was placed in a tube furnace at elevated temperature, under a flowing atmosphere of  $\text{N}_2$ . After some time, the sample is removed and collected at nearly quantitative yield. Determination of the appropriate thermolysis temperature was performed by Thermogravimetric Analysis (TGA) of the

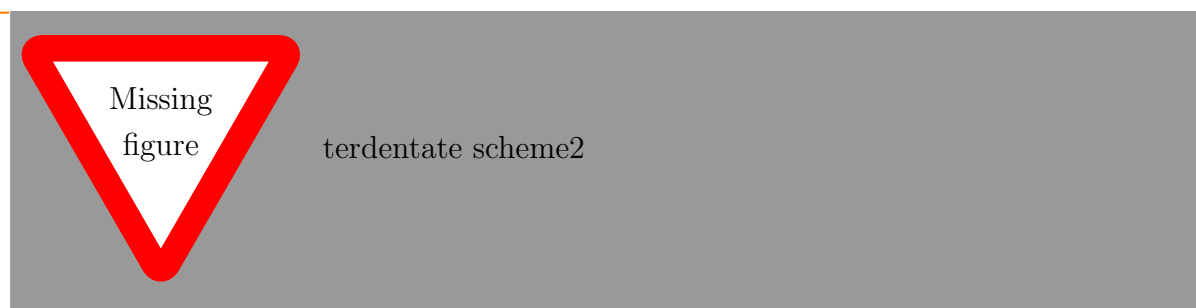
<sup>i</sup>Experimental details for all compounds can be seen in Appendix A Experimental Procedures

sample. A 6-8 % mass loss (dependant on sample) indicated the departure of one carbonyl group from the complex. Results of TGA on **1** and **2** is shown in Figure 2.1. For **1**, thermolysis was performed at 240°C, and for **2** thermolysis was performed at 260°C, yielding **3** and **4** respectively, at quantitative yields.



**Figure 2.1** Results of TGA analysis on **1** and **2**

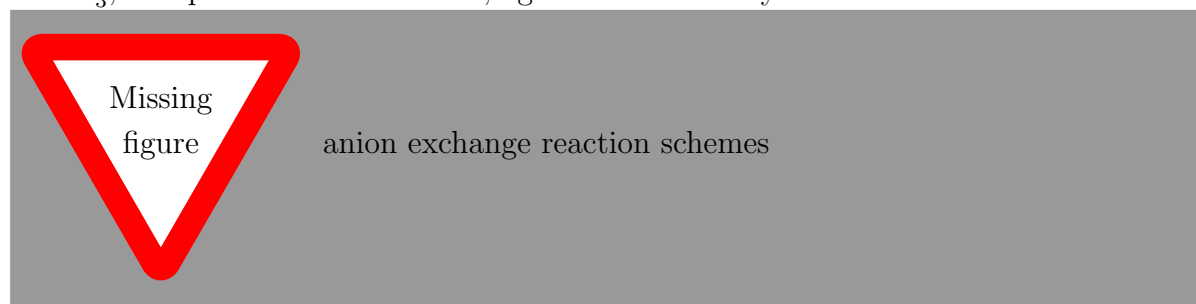
Further discuss TGA & terdentate rxn to build a space to put in scheme2



Further reactions were carried out on the above products to yield triflate and cyano

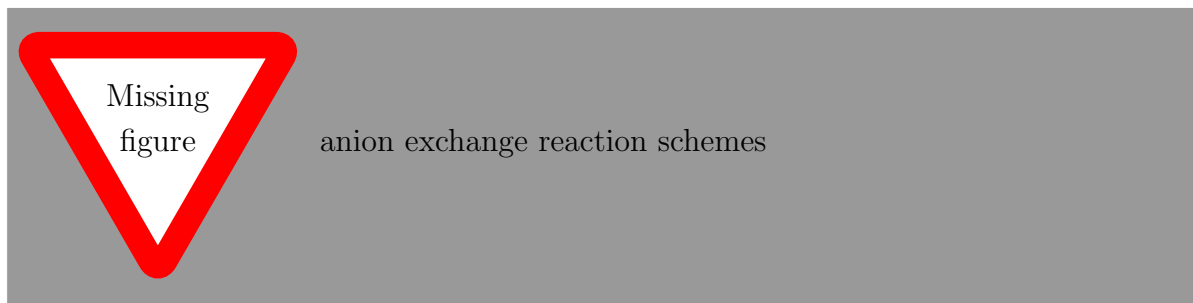


complexes of bidentate and terdentate geometries. These anion exchange reactions were performed by the addition of the silver salt to **1** or **3**, to precipitate AgCl, leaving  $\kappa^2(\text{terpy})\text{Re}(\text{CO})_3\text{CN}$  (**5**),  $\kappa^3(\text{terpy})\text{Re}(\text{CO})_2\text{CN}$  (**6**),  $\kappa^2(\text{terpy})\text{Re}(\text{CO})_3\text{OTf}$  (**7a**) and  $\kappa^3(\text{terpy})\text{Re}(\text{CO})_2\text{OTf}$  (**8a**), as shown in Scheme 2.2. Resulting in only moderate yields, **7b** and **8b** were synthesized by the direct addition of neat triflic acid ( $\text{CF}_3\text{SO}_3\text{H}$ ) to **1** and **2** respectively. HCl was released, the solutions were quenched by addition of aqueous  $\text{NaCO}_3$ , and product was collected, again at moderate yield.



**Scheme 2.2** Anion exchange pathways to synthesize **3** - **8b**

A pseudo-tridentate complex was targeted to compare  $\text{CO}_2$  photoreduction performance with the previously prepared catalysts. Typical  $[\text{L}_2\text{L}'\text{Re}(\text{CO})_n]^+$  ( $n = 2, 3$ ) targets exchange the halide for a neutral phosphine or imine type ligand, resulting in a cationic species with weakly coordinated anion (typically  $\text{BF}_4^-$ ,  $\text{OTf}^-$ ,  $\text{BArF}^-$  or other anion). Instead, we targeted the  $\text{L}_2\text{L}'\text{Re}(\text{CO})_2\text{Cl}$  ( $\text{L} = \text{bipy}$ ,  $\text{L}' = 4\text{-}t\text{-butylpyridine}$ ) compound (**9**) via two similar methods (Scheme 2.3).



**Scheme 2.3** Synthesis of  $\text{L}_2\text{L}'\text{Re}(\text{CO})_2\text{Cl}$  ( $\text{L} = \text{bipy}$ ,  $\text{L}' = 4\text{-}t\text{-butylpyridine}$ ) (**9**)

## 2.3 Characterization

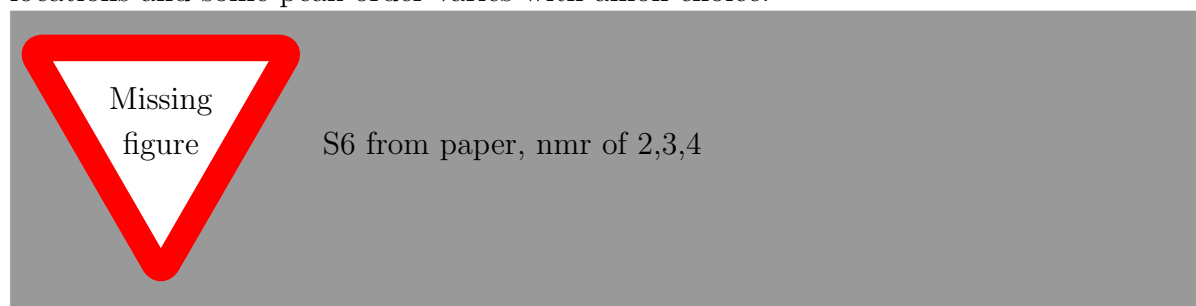
Characterization was performed on each of the products synthesized as discussed above. Nuclear Magnetic Resonance (NMR) analysis, x-ray crystallography, as well as UV-Vis and IR spectroscopy was performed. Computational Density Functional Theorem (DFT) methods were used to solve the geometries, and Time Dependant Density Functional Theorem (TD-DFT) was performed to predict UV-Vis spectra and identify electronic transitions.

### 2.3.1 NMR Analysis

Proton NMR was performed on each of the samples. Each sample was dissolved completely in deuteroacetonitrile ( $\text{CD}_3\text{CN}$ ) and analysis was performed on a Bruker AVANCE 400 MHz spectrometer. Data was processed from the FID signal via the TopSpin program, and spectra were analyzed using ACD NMR Processor v12.0.

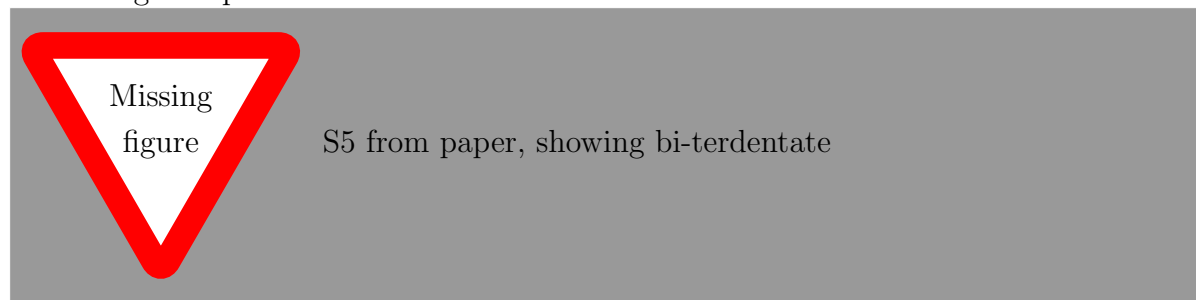
Detailed peak analysis comparing bidentate samples **1**, **3**, **5**, and **7** or terdentate **2**, **4**, **6**, and **8** show little difference between samples. This is due to the distance between

the anion and any protons on the ligand. While anions with different  $\sigma$  donor strength marginally impact the metal-ligand interactions, these have only small effect on the location of peaks, shifting between samples by typically less than 0.1 ppm. As is shown in Figure 2.2, the characteristic shape of each spectra remains constant, only exact peak locations and some peak order varies with anion choice.



**Figure 2.2** The aromatic region of the  $^1\text{H}$ NMR spectra for compounds (red), (green), and (blue)

The characteristic feature in the NMR spectra after the transformation from bidentate to terdentate (e.g. sample **1** to **2**) is the simplification of the signals in the aromatic region (between 7 and 9 ppm). This simplification is due to the increased symmetrization of the ligand, while the  $\kappa^2$  bidentate ligand has a freely rotating pendant group, the  $\kappa^3$  terdentate ligand is in a more rigidly fixed geometry. Prior work in literature and in our group shows the temperature dependence of the rate of rotation of this pendant arm for various ligand species.



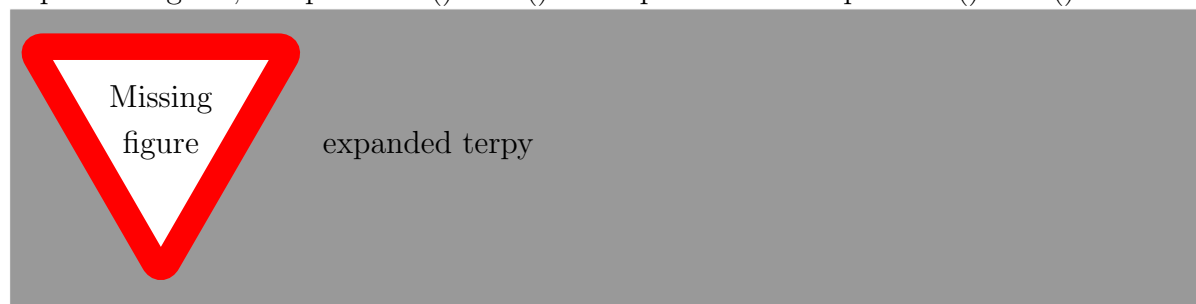
check compounds & spectra

Get paper citation

Titel's Thesis citation

**Figure 2.3** The aromatic region of the  $^1H$ NMR spectra for compounds (red) and (blue), showing the simplification of the spectra upon the conversion from bidentate to terdentate

The simplification of peaks due to the symmetrization of the ligand results in the peaks from ( ) and ( ) aligning with their mirror peaks at ( ) and ( ). ?? shows the proton expanded ligand, the peaks at ( ) and ( ) correspond with the protons ( ) and ( ).



**Figure 2.4** Proton-explicit skeletal drawing of 2,2':6',2''-terpyridine

Carbon NMR ( $^{13}C$ ) was attempted on the complexes as well. Unfortunately,  $Re^I$  complexes perform poorly in  $^{13}C$  NMR experiments, the signal to noise ratio is incredibly poor (if a signal is even visible). The effect of this is a lack of  $^{13}C$  NMR analysis of these compounds in literature, with a very few exceptions.

### 2.3.2 X-Ray Crystallography

Rewrite section from paper on xray results

### 2.3.3 Spectroscopy

Base writing off of paper.

### **Infrared Spectroscopy**

This can be short... discuss triplet to doublet

### **UV-Vis Spectroscopy**

This will be longer. Should be lots of discussion about results differences. I need to  
a) highlight the importance of anion exchange, and then b) highlight the importance of  
bidentate vs. terdentate

### **2.3.4 Conclusions**

Conclusion shows that manipulations can be done, this affects the photophysical  
properties of the compounds and may affect the photochemical

# Chapter 3

## Photocatalysis of CO<sub>2</sub>

### 3.1 Introduction

Only 6 years after Re<sup>I</sup> complexes using 2,2'-bipyridine were characterized, Hawecker, Ziessel, and Lehn showed the effectiveness of the compound for the catalytic photoreduction of CO<sub>2</sub>.<sup>47</sup> Since then, many have shown the efficacy of a wide range of  $\alpha$ -diimino complexes for the reaction, and expansion of the systems to dimetallic complexes with ruthenium and osmium as electron transfer agents has produced a wide range of results. The mechanism of reduction has been subject of some debate, while mechanisms have been proposed since Lehn et. al. soon after their original publication,<sup>48</sup> modifications have been submitted routinely over the past decades. Further discussion and a proposal of a new mechanism geometry based on computational and experimental data can be read in chapter 4.

check ref  
names

a few refer-  
ences

refer to these  
as well. Red  
Light paper?

references,  
Morris, JACS  
dimer, mech.  
basis

## 3.2 Photocatalytic Reactions with New Compounds

The photocatalytic cycle is, simply, a photon-induced MLCT, followed by the extraction of an electron from a sacrificial reductant. This radical, negatively charged species sheds the anion, opening up a reaction site. Reaction between a CO<sub>2</sub>, a proton (from the decomposition of the reductant or elsewhere), and the catalyst yields any number of CO, H<sub>2</sub>O, formate (HCO<sub>2</sub><sup>-</sup>), or carbonate (CO<sub>3</sub>H<sup>-</sup>), depending on the mechanistic pathway.

### 3.2.1 Conditions

Reaction conditions in use in literature have remained typically unchanged since the original papers. A mixture of N,N-dimethylformamide (DMF) with either Triethanolamine (TEOA) or Triethylamine (TEA) at a 5:1 ratio is used to make a 1.0 mM solution of catalyst, with 'excess' (a 1.1 to 25 molar ratio) electrolyte salt (typically Et<sub>4</sub>NX or t-Bu<sub>4</sub>NX, where X = halide in catalyst) added as a stabilizer. Solutions are degassed by bubbling of CO<sub>2</sub> and a consistent headspace is left to form over the solution. The reaction is

getginfo — monitored via GC analysis of the headspace, using a .

### 3.2.2 Experimental Results

Both bidentate and terdentate  $\kappa^n(\text{terpy})\text{Re}(\text{CO})_{5-n}\text{X}$  (n=2,3) complexes show no activity for CO<sub>2</sub> reduction. Modification of testing time, light source, product analysis methods, solvent, sacrificial reductant, pH, presence of electrolyte, presence of H<sub>2</sub>O, or variation of anion (X=Cl, Br, OTf, CN) shows no change of this inactivity. Testing of  $\kappa^2(\text{bipy})\text{Re}(\text{CO})_3\text{Cl}$  under the same reaction conditions shows production of approximately 6 mL CO from CO<sub>2</sub> (20% conversion) in 1 hour of photolysis with visible ( $\lambda \geq 400\text{nm}$ ) light.

SubSubSection

SubSubSection

SubSubSection

### **3.3 Section**

### **3.4 Section**


#### **3.4.1 Subsection**



# Chapter 4

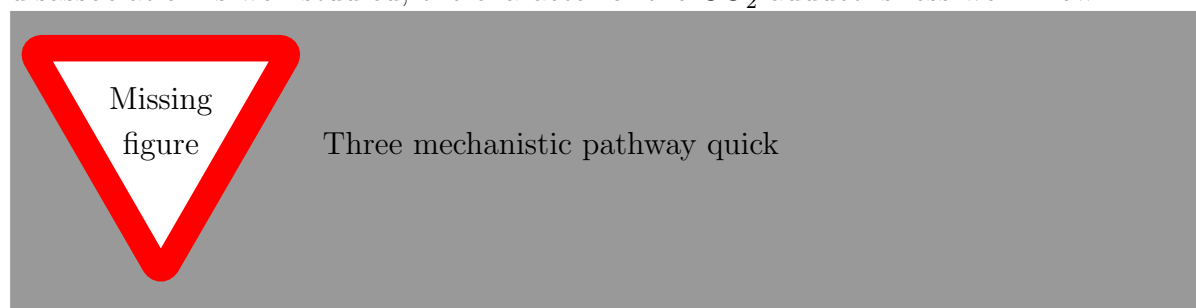
## Mechanism of CO<sub>2</sub> Reduction

### 4.1 Introduction

Within three years of the originally reported bipyridine rhenium I catalyst, experimental studies on the mechanism of the photocatalytic reduction of CO<sub>2</sub> were available in the literature.<sup>48</sup>  Studies continue on the mechanism up to the present day<sup>59,60</sup>, utilizing new investigative techniques as they become available, this includes the use of DFT methods to elucidate geometries of intermediates and transition states for of the multi-step cycle. Transition metal catalysis is a non-trivial problem computationally, especially when considering a metal from the lower period. These elements contain a large amount of electrons, many of which can be involved in non-covalent interactions with the ligands and catalyzed products. Solving for this complex system becomes non-trivial and computationally expensive. For this reason, no overview of the mechanism as investigated by DFT methods has ever been made available in the literature.

## 4.2 Literature Mechanisms

Prior work in the literature has proposed three general mechanistic pathways for the photoreduction of CO<sub>2</sub>. In general, as seen in Figure 4.1, these pathways result in the formation of CO and H<sub>2</sub>O, formate (HCO<sub>2</sub><sup>-</sup>), or carbonate (CO<sub>3</sub>H<sup>-</sup>) anions. The formation of carbonate proceeds via the formation of a catalyst dimer over a molecule of CO<sub>2</sub>, with the insertion of a second molecule of CO<sub>2</sub> to produce the carbonate and a molecule of CO. Formation of formate occurs via insertion of CO<sub>2</sub> to a rhenium hydride bond. The formation of CO without carbonate or formate by-products occurs via the coordination of CO<sub>2</sub> to an open site on the metal, followed by a double proton addition and the release of a molecule of H<sub>2</sub>O prior to the loss of one of the four carbonyl groups to open up the axial site for halide re-coordination. The activation of the catalyst with respect to radicalization, electron abstraction from the sacrificial reductant, and anion disassociation is well studied, the character of the CO<sub>2</sub> adduct is less well known.



**Figure 4.1** An overview of the mechanistic pathways of photochemical CO<sub>2</sub> reduction

Many of the intermediates have been synthesized in various studies, indicating their reasonable stability. While individual portions of the mechanism have been studied computationally in the past, no over-arching study has compared methods relative to each other. Furthermore, while the formation of CO with H<sub>2</sub>O is the most anticipated

Make mechanism (or get morris?)

Ref. Sullivan and Gilbert

refs

pathway (due to the lack of formation of carbonate or formate in most studies), no literature pathway exists to explain the addition of CO<sub>2</sub> to the open site of the radical catalytic species without a three body reaction step (catalyst, CO<sub>2</sub> and H<sup>+</sup> together) or without formate reorganization. Furthermore, no mechanism proposed thus far explains the <sup>12</sup>CO to <sup>13</sup>CO isotopic exchange demonstrated by Lehn's group in 1986.<sup>48</sup>

### 4.3 Consequences From $\kappa^2$ Terpyridine Complex Inactivity

The lack of reactivity of the  $\kappa^2(\text{terpy})\text{Re}(\text{CO})_3\text{X}$  motif of complexes contrasting to the activity of the originally published  $\kappa^2(\text{bipy})\text{Re}(\text{CO})_3\text{X}$  indicates some influence of the ligand on the mechanism. While the terdentate complex can be rationalized to be inactive due to its short-lived excited state (as seen in the lack of fluorescence), this explanation does not suffice for the fluorescing bidentate complex. Other substituted bipyridine ligands are known to be active for photocatalytic reduction, identifying the most likely conflicting feature of the terpyridine ligand to be the pendant arm, and its availability for chelation to the metal centre. While in the radical eximer form, the chelation site is sterically blocked by one of the three carbonyl groups. However, reorganization of the substituent carbonyls from a *facial* orientation to a *meridional* could allow for the free pyridine to form the metal-ligand bond, resulting in compound (X).

Due to the ease of migration of the carbonyl groups, it is proposed that the mechanism that follows pathway X does not occur entirely axial to the ligand, but begins with coordination of a CO<sub>2</sub> molecule in between the *facial*-CO ligands, forcing a carbonyl to the axial position. This CO<sub>2</sub> bound in the plane of the ligand then undergoes hydrogenation to produce a molecule of H<sub>2</sub>O. After the departure of the water molecule,

fluorescence tests on 1,2

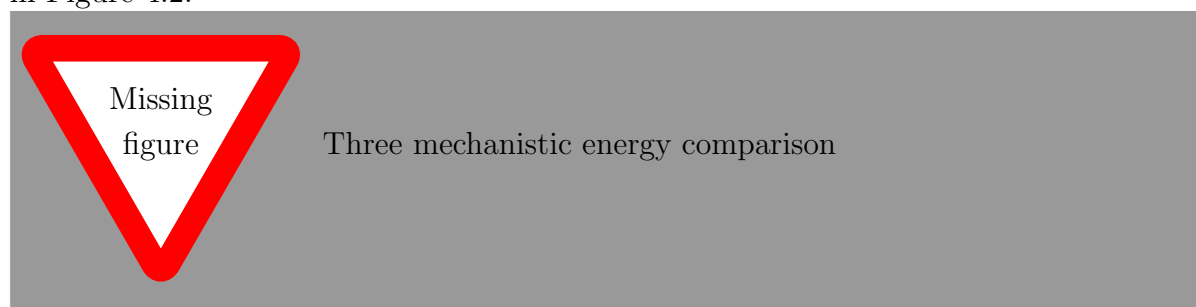
ref lehn88?

Set up a detailed naming scheme that will work for the entire chapter, likely having to start with

the catalyst is left as a tetracarbonyl cation. While any of the carbonyl groups could be labile, the carbonyl at the axial position is replaced by the halide to return to the starting catalyst.

## 4.4 Comparison Between Mechanistic Pathways

The overall energies for each of the mechanistic pathways shown in Figure 4.1 are shown in Figure 4.2.



**Figure 4.2** An overview of the energies of the three mechanistic pathways of photochemical CO<sub>2</sub> reduction

SOLVE EN-  
ERGY

### 4.4.1 Subsection

SubSubSection

SubSubSection

SubSubSection

# Chapter 5

## Conclusions

The target  $\text{Re}^{\text{I}}$  terdentate terpyridine compounds were successfully synthesized, characterized, and tested for photocatalytic  $\text{CO}_2$  reduction. The catalysts show no activity for the reduction, in contrast to the known excellent bipyridine compounds.

The reaction mechanisms were studied successfully with DFT methods, resulting in the proposed new geometry for the production of CO with no carbonate or formate anions. This new geometry does not conflict with known experimental studies, yet avoids three-body mechanistic steps.

# Appendix A

## Experimental Procedures

Experimental synthesis and characterization data for the compounds discussed in this thesis are shown below by compound number:

### **A.1   1**

Compound

### **A.2   2**

Compound

### **A.3   3**

Compound

## **A.4 4**

Compound

# Glossary of Terms

**DFT** Density Functional Theorem.

**DMF** N,N-dimethylformamide.

**HOMO** Highest Occupied Molecular Orbital.

**LUMO** Lowest Unoccupied Molecular Orbital.

**MLCT** Metal-Ligand Charge Transfer.

**NMR** Nuclear Magnetic Resonance.

**TD-DFT** Time Dependant Density Functional Theorem.

**TEA** Triethylamine.

**TEOA** Triethanolamine.

**TGA** Thermogravimetric Analysis.



# Bibliography

1. Zeise, W. C. *J. Physik und Chemie (Schweigger)* **1831**, 62, 393–441.
2. Hunt, L. B. *Platinum Metals Review* **1984**, 28, 76–83.
3. Griess, J. P.; Martius, C. A. *Compt rendus*. **1861**, 53, 922–925.
4. Birnbaum, K. *Ann. Chem. (Liebig)* **1868**, 145, 67–77.
5. Small, B. L.; Brookhart, M. *Journal of the American Chemical Society* **1998**, 120, 7143–7144.
6. Small, B. L.; Brookhart, M.; Bennett, A. M. A. *Journal of the American Chemical Society* **1998**, 120, 4049–4050.
7. J. P. Britovsek, G.; C. Gibson, V.; J. McTavish, S.; A. Solan, G.; J. P. White, A.; J. Williams, D.; J. P. Britovsek, G.; S. Kimberley, B.; J. Maddox, P. *Chem. Commun.* **1998**, 849–850.
8. Britovsek, G. J. P.; Bruce, M.; Gibson, V. C.; Kimberley, B. S.; Maddox, P. J.; Mastroianni, S.; McTavish, S. J.; Redshaw, C.; Solan, G. A.; Strömberg, S.; White, A. J. P.; Williams, D. J. *Journal of the American Chemical Society* **1999**, 121, 8728–8740.
9. Gibson, V. C.; Redshaw, C.; Solan, G. A. *Chemical Reviews* **2007**, 107, PMID: 17488059, 1745–1776.
10. Boudier, A.; Breuil, P.-A. R.; Magna, L.; Olivier-Bourbigou, H.; Braunstein, P. *Chem. Commun.* **2014**, 50, 1398–1407.
11. Dudle, B.; Rajesh, K.; Blacque, O.; Berke, H. *Journal of the American Chemical Society* **2011**, 133, 8168–8178.
12. Jain, K. R.; Herrmann, W. A.; Kühn, F. E. *Coordination Chemistry Reviews* **2008**, 252, Chiral Catalysis, 556–568.
13. Kuninobu, Y.; Takai, K. *Chemical Reviews* **2011**, 111, 1938–1953.
14. Bartholoma, M.; Valliant, J.; Maresca, K. P.; Babich, J.; Zubieta, J. *Chem. Commun.* **2009**, 493–512.
15. Schibli, R.; Schubiger, A. **2002**, 29, 1529–1542.

16. Coogan, M.; Fernández-Moreira, V.; Kariuki, B.; Pope, S.; Thorp-Greenwood, F. *Angewandte Chemie International Edition* **2009**, *48*, 4965–4968.
17. Giordano, P. J.; Wrighton, M. S. *Journal of the American Chemical Society* **1979**, *101*, 2888–2897.
18. Fredericks, S. M.; Luong, J. C.; Wrighton, M. S. *Journal of the American Chemical Society* **1979**, *101*, 7415–7417.
19. Sacksteder, L.; Zipp, A. P.; Brown, E. A.; Streich, J.; Demas, J. N.; DeGraff, B. A. *Inorganic Chemistry* **1990**, *29*, 4335–4340.
20. Caspar, J. V.; Meyer, T. J. *The Journal of Physical Chemistry* **1983**, *87*, 952–957.
21. Yam, V. W.-W. *Chem. Commun.* **2001**, 789–796.
22. Feliz, M.; Rodriguez-Nieto, F.; Ruiz, G.; Wolcan, E. *Journal of Photochemistry and Photobiology A: Chemistry* **1998**, *117*, 185–192.
23. Ruiz, G.; Wolcan, E.; Feliz, M. *Journal of Photochemistry and Photobiology A: Chemistry* **1996**, *101*, 119–125.
24. Lin, R.; Fu, Y.; Brock, C. P.; Guarr, T. F. *Inorganic Chemistry* **1992**, *31*, 4346–4353.
25. Hino, J. K.; Della Ciana, L.; Dressick, W. J.; Sullivan, B. P. *Inorganic Chemistry* **1992**, *31*, 1072–1080.
26. Walters, K. A.; Kim, Y.-J.; Hupp, J. T. *Inorganic Chemistry* **2002**, *41*, 2909–2919.
27. Striplin, D.; Crosby, G. *Coordination Chemistry Reviews* **2001**, *211*, 163–175.
28. Martin, T. A.; Ellul, C. E.; Mahon, M. F.; Warren, M. E.; Allan, D.; Whittlesey, M. K. *Organometallics* **2011**, *30*, 2200–2211.
29. Abel, E. W.; Wilkinson, G. *J. Chem. Soc.* **1959**, 1501–1505.
30. Kirkham, W. J.; Osborne, A. G.; Nyholm, R. S.; Stiddard, M. H. B. *J. Chem. Soc.* **1965**, 550–553.
31. Zingales, F.; Sartorelli, U.; Trovati, A. *Inorganic Chemistry* **1967**, *6*, 1246–1248.
32. Gamelin, D. R.; George, M. W.; Glyn, P.; Grevels, F.-W.; Johnson, F. P. A.; Klotzbuecher, W.; Morrison, S. L.; Russell, G.; Schaffner, K.; Turner, J. J. *Inorganic Chemistry* **1994**, *33*, 3246–3250.
33. Martí, A. A.; Mezei, G.; Maldonado, L.; Paralitici, G.; Raptis, R. G.; Colón, J. L. *European Journal of Inorganic Chemistry* **2005**, *2005*, 118–124.
34. Morse, D. L.; Wrighton, M. S. *Journal of the American Chemical Society* **1976**, *98*, 3931–3934.
35. Giordano, P. J.; Fredericks, S. M.; Wrighton, M. S.; Morse, D. L. *Journal of the American Chemical Society* **1978**, *100*, 2257–2259.

36. Granifo, J.; Bird, S. J.; Orrell, K. G.; Osborne, A. G.; Šik, V. *Inorganica Chimica Acta* **1999**, *295*, 56–63.
37. Orrell, K. G.; Osborne, A. G.; Šik, V.; da Silva, M. W.; Hursthouse, M. B.; Hibbs, D. E.; Malik, K. A.; Vassilev, N. G. *Journal of Organometallic Chemistry* **1997**, *538*, 171–183.
38. Abel, E. W.; Dimitrov, V. S.; Long, N. J.; Orrell, K. G.; Osborne, A. G.; Pain, H. M.; Sik, V.; Hursthouse, M. B.; Mazid, M. A. *J. Chem. Soc., Dalton Trans.* **1993**, 597–603.
39. Gong, X.; Ng, P. K.; Chan, W. K. *Advanced Materials* **1998**, *10*, 1337–1340.
40. Lo, K. K.-W.; Louie, M.-W.; Zhang, K. Y. *Coordination Chemistry Reviews* **2010**, *254*, 18th International Symposium on the Photochemistry and Photophysics of Coordination Compounds Sapporo, 2009, 2603–2622.
41. Lin, T.-P.; Chen, C.-Y.; Wen, Y.-S.; Sun, S.-S. *Inorganic Chemistry* **2007**, *46*, 9201–9212.
42. Slone, R. V.; Yoon, D. I.; Calhoun, R. M.; Hupp, J. T. *Journal of the American Chemical Society* **1995**, *117*, 11813–11814.
43. D. Beer, P.; Timoshenko, V.; Maestri, M.; Passaniti, P.; Balzani, V. *Chem. Commun.* **1999**, 1755–1756.
44. Beer, P. D.; Hayes, E. J. *Coordination Chemistry Reviews* **2003**, *240*, 35 Years of Synthetic Anion Receptor Chemistry 1968–2003, 167–189.
45. Amoroso, A. J.; Arthur, R. J.; Coogan, M. P.; Court, J. B.; Fernandez-Moreira, V.; Hayes, A. J.; Lloyd, D.; Millet, C.; Pope, S. J. A. *New J. Chem.* **2008**, *32*, 1097–1102.
46. Amoroso, A. J.; Coogan, M. P.; Dunne, J. E.; Fernandez-Moreira, V.; Hess, J. B.; Hayes, A. J.; Lloyd, D.; Millet, C.; Pope, S. J. A.; Williams, C. *Chem. Commun.* **2007**, 3066–3068.
47. Hawecker, J.; Lehn, J.-M.; Ziessel, R. *J. Chem. Soc., Chem. Commun.* **1983**, 536–538.
48. Hawecker, J.; Lehn, J.-M.; Ziessel, R. *Helvetica Chimica Acta* **1986**, *69*, 1990–2012.
49. Takeda, H.; Ishitani, O. *Coordination Chemistry Reviews* **2010**, *254*, Inorganic Reaction Mechanisms A Tribute to Ralph Pearson on the occasion of his 90th birthday, 346–354.
50. Christensen, P.; Hamnett, A.; Muir, A. V. G.; Timney, J. A. *J. Chem. Soc., Dalton Trans.* **1992**, 1455–1463.
51. Sullivan, B. P.; Bolinger, C. M.; Conrad, D.; Vining, W. J.; Meyer, T. J. *J. Chem. Soc., Chem. Commun.* **1985**, 1414–1416.
52. Caulton, K. G. *European Journal of Inorganic Chemistry* **2012**, *2012*, 435–443.

53. Jurca, T.; Chen, W.-C.; Michel, S.; Korobkov, I.; Ong, T.-G.; Richeson, D. S. *Chemistry – A European Journal* **2013**, *19*, 4278–4286.
54. Juris, A.; Campagna, S.; Bidd, I.; Lehn, J. M.; Ziessel, R. *Inorganic Chemistry* **1988**, *27*, 4007–4011.
55. Black, D. R.; Hightower, S. E. *Inorganic Chemistry Communications* **2012**, *24*, 16–19.
56. Russell, S. K.; Darmon, J. M.; Lobkovsky, E.; Chirik, P. J. *Inorganic Chemistry* **2010**, *49*, PMID: 20143847, 2782–2792.
57. Tondreau, A. M.; Atienza, C. C. H.; Weller, K. J.; Nye, S. A.; Lewis, K. M.; Delis, J. G. P.; Chirik, P. J. *Science* **2012**, *335*, 567–570.
58. Buckingham, D.; Dwyer, F.; Goodwin, H.; Sargeson, A. *Australian Journal of Chemistry* **Jan. 1964**, *17*, 315–324.
59. Koike, K.; Okoshi, N.; Hori, H.; Takeuchi, K.; Ishitani, O.; Tsubaki, H.; Clark, I. P.; George, M. W.; Johnson, F. P. A.; Turner, J. J. *Journal of the American Chemical Society* **2002**, *124*, 11448–11455.
60. Machan, C. W.; Sampson, M. D.; Chabolla, S. A.; Dang, T.; Kubiak, C. P. *Organometallics* **2014**, *Accepted Article*, DOI: 10.1021/om500044a.

# Todo list

Rewrite to more verbose . . . . .	3
Take out spoilers . . . . .	5
Figure: bidentate scheme . . . . .	8
Read Reference buckingham1964 . . . . .	8
check that value . . . . .	9
Further discuss TGA & terdentate rxn to build a space to put in scheme2 . . . .	9
Figure: terdentate scheme2 . . . . .	9
Figure: anion exchange reaction schemes . . . . .	10
ref . . . . .	10
Figure: anion exchange reaction schemes . . . . .	10
Figure: S6 from paper, nmr of 2,3,4 . . . . .	12
check compounds & spectra . . . . .	12
Get paper citation . . . . .	12
Titel's Thesis citation . . . . .	12
Figure: S5 from paper, showing bi-terdentate . . . . .	12
check compounds & spectra . . . . .	13
Put in nmr peak values . . . . .	13
Figure: expanded terpy . . . . .	13
why poor, show an ok result & discuss . . . . .	13
Rewrite section from paper on xray results . . . . .	13
Base writing off of paper. . . . .	13
This can be short... discuss triplet to doublet . . . . .	14
This will be longer. Should be lots of discussion about results differences. I need to a)hilight the importance of anion exchange, and then b) hilight the importance of bidentate vs. terdentate . . . . .	14
Conclusion shows that manipulations can be done, this affects the photophysical properties of the compounds and may affect the photochemical . . . . .	14
check ref names . . . . .	15
a few references . . . . .	15
refer to these as well. Red Light paper? . . . . .	15
references, Morris, JACS dimer, mech. basis . . . . .	15
getgcinfo . . . . .	16

more . . . . .	18
Figure: Three mechanistic pathway quick . . . . .	19
Make mechanism (or get morris?) . . . . .	19
Ref. Sullivan and Gilbert . . . . .	19
refs . . . . .	19
fluorescence tests on 1,2 . . . . .	20
ref lehn88? . . . . .	20
Set up a detailed naming scheme that will work for the entire chapter, likely having to start with M## or similar motif. . . . .	20
computationally back it up . . . . .	20
pathway numbrs as well . . . . .	20
Figure: Three mechanistic energy comparison . . . . .	21
SOLVE ENERGY . . . . .	21