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Synthetic routes to N-Heterocyclic Carbene precursors

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Introduction

N-Heterocyclic Carbenes (NHCs) are defined as singlet carbenes, in which the divalent carbenic center is connected directly to at least one nitrogen atom within the heterocycle.^{1,2} Wanzlick originally suggested their existence in the early 1960's,³ and proposed a practical way to generate them *in situ*. This early finding paved the way to their use as ligands in organometallic chemistry, as originally described in the seminal reports by Wanzlick⁴ and Öfele⁵ in 1968, and in the extensive work of Lappert in the 70s-80s.⁶ Nevertheless, the original chemists' perception of nucleophilic carbenes as elusive odd laboratory curiosities changed only in 1988, with the benchmark report, by Bertrand and colleagues,⁷ of the first stable (phosphino)(silyl)carbene, and in 1991, with the isolation and full characterization, by Arduengo and co-workers, of the stable, free NHC 1,3-di(adamantyl)imidazol-2-ylidene (IAd), obtained by deprotonation of its imidazolium precursor.⁸

Contrary to other carbenes which are generally found to be electrophilic, N-heterocyclic carbenes are electron-rich nucleophilic species, in which the carbene center benefits from the stabilization associated with both the σ -electron-withdrawing, and π -electron-donating character of the nitrogen centers. Due to their strong σ -electron donating properties, NHC ligands form stronger bonds with metal centers than most classical ligands, such as phosphines, thus giving transition metal complexes which are generally resistant to decomposition and can thus be used as pre-catalysts without excess of ligand.⁹ A further advantage for catalytic purposes rests on a better steric protection of the active site within the inner metal's coordination sphere, due to the fact that the exocyclic nitrogen substituents of the NHC are shielding the metal center in a fence-or fan-like fashion, more efficiently than tertiary phosphine can do with their cone angle pointing away from the metal center.

These beneficial features have contributed to the recognition of NHCs, firstly, as ubiquitous ligands in organometallic chemistry,¹⁰ as evidenced by numerous applications ranging from homogeneous catalysis to material and medicinal sciences,¹¹ and secondly, in their own right, as excellent nucleophilic organocatalysts.¹²

These successes have motivated intense research efforts toward the design and development of a growing diversity of fascinating new NHC architectures, where it appears that *the real challenge in the design of a given N-heterocyclic carbene rests on the construction of its precursor, almost systematically implying a critical cyclization reaction*. As the deprotonation of the heterocyclic ring precursors is by far the most commonly used method to access a free or ligated NHC, this review will only focus on the synthesis of such cationic heterocycles. Other methods for obtaining NHCs include: i) reduction of thiourea with molten potassium in boiling THF,¹³ ii) vacuum pyrolysis of an NHC-volatile compound adduct (like MeOH, CHCl₃, CHF₃, C₆F₅H),¹⁴ iii) *in-situ* release of NHC from NHC-CO₂ or NHC-metal (Sn^{II}, Mg^{II}, Zn^{II}) adducts,¹⁵ and iv) reduction of a chloroformamidinium salt with Hg(TMS)₂¹⁶ or with Pd(0) and Ni(0) complexes.¹⁷ Nevertheless, the starting NHC-substrate adducts used in methods ii) and iii) are often derived from the corresponding azolium salts and will thus be treated in this review. The synthesis of the thioureas, substrates of methods i) and iv), will not be included, due to the relative narrow applicability scope and limited examples of such methods.

Accordingly, the present review will cover the syntheses of cyclic formamidinium salts **A**, precursors of diaminocarbenes (whatever the nature of the backbone is), of oxazolium salt **B** and thiazolium salt **C**, of pyrrolidinium salts **D** (precursors of Cyclic (Alkyl)(Amino)Carbenes (CAAC)), and of phosphazinium salts **E** (precursors of cyclic (Amino)(Phosphino)Carbenes) (Chart 1).¹⁸

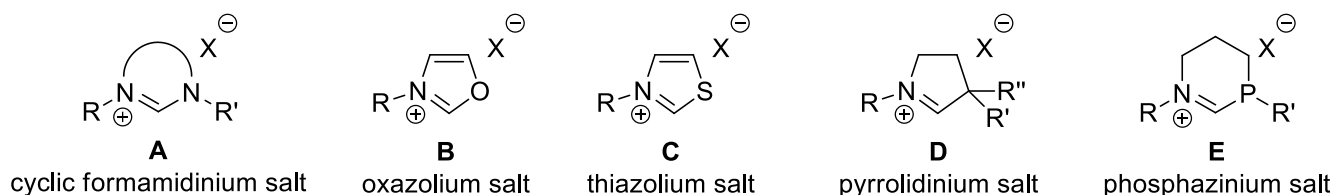


Chart 1. N-Heterocyclic structures taken into account in this review.

An obvious and straightforward strategy to access these compounds consists in the quaternization of a nitrogen atom on a pre-existing neutral N-substituted imidazole, oxazole or thiazole. However, as the syntheses of these heterocyclic compounds are well-documented in literature,^{19,20,21} the present review

will focus on the direct formation of the cationic (or mesoionic) cycle through a cyclization step.

Considering that an NHC precursor is constructed by assembly of three distinct subunits, namely, i) a pre-carbenic unit, ii) an amino unit, and iii) a backbone functionality (Chart 2), the myriad of synthetic protocols which have been reported so far can be classified in a simple and logical way upon consideration of the nature of the latest sub-unit being installed in the final cyclization step:

1. Ring closure by introduction of the pre-carbenic unit;
2. Ring closure by linkage of the backbone to the pre-assembled pre-carbenic and amino units;
3. Ring closure by introduction of the amino moiety.

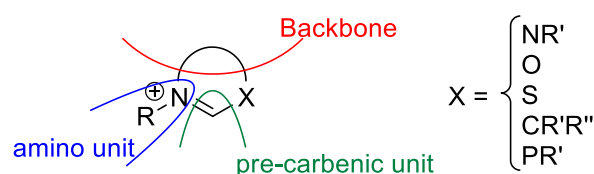


Chart 2. Schematic differentiation and classification of general synthetic pathways to NHC precursors, based on the nature of the unit introduced in the final ring closing step.

2. Cyclization by introduction of the pre-carbenic atom-moiety

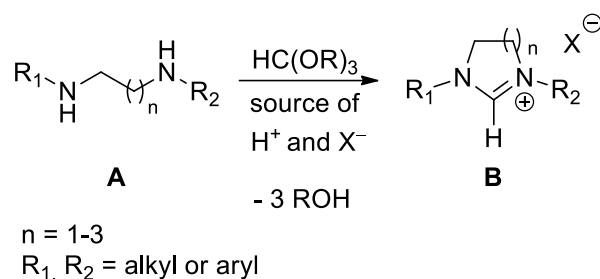
Introduction of the C₁ pre-carbenic unit in the final ring closing stage is still the most widely used strategy to NHC precursors, since it is generally high-yielding, easy to perform, and tolerates various substituents.

Depending on the desired core of the N-heterocyclic carbene precursor, several reagents which allow introduction of the carbenic carbon-moiety have been identified. In this section, we will give an overview of the different possibilities along with representative examples.

2.1 Trialkyl orthoformate (HC(OR)₃) as the pre-carbenic unit

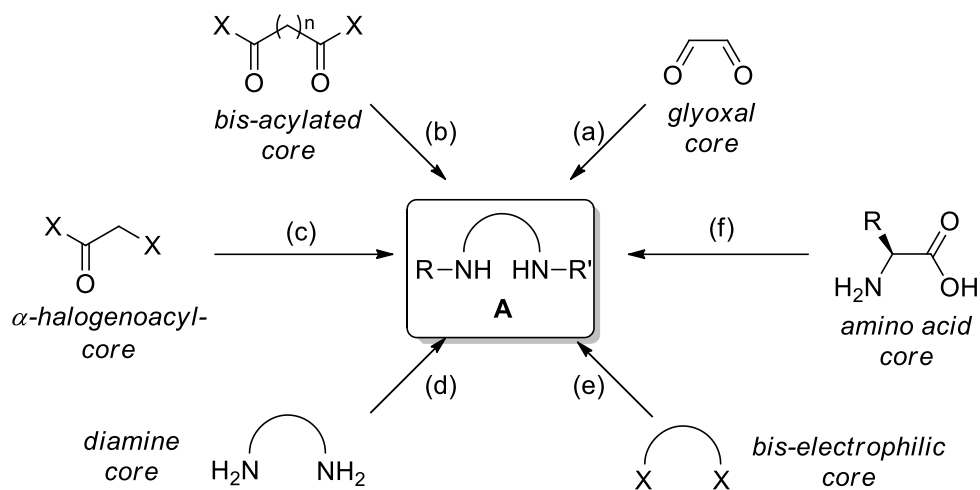
In 1991 Saba and Kaloustian reported that treatment of N,N'-disubstituted α - ω -alkanediamines **A** with trialkyl orthoformate in the presence of a source of protons and anions led to the corresponding cyclic formamidinium salt **B**, generally obtained in high yield (>90%) as shown in

Scheme 1.²² This method was also found to work efficiently for the synthesis of triazolium salts, a special case described at the end of this section.



Scheme 1. General route to the cyclic formamidinium salt **B** by condensation of a diamine with trialkyl orthoformate.

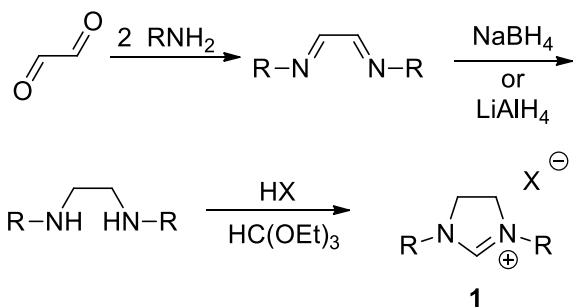
Such a reaction constitutes the final step of a huge number of NHC-precursors syntheses since it is usually high-yielding and easy to perform. Indeed, the salts generally precipitate, and can thus be recovered by simple filtration. Formally, any tethered secondary diamine may thus be converted into the corresponding cyclic formamidinium salt, the major issue being to find a suitable synthesis for the starting diamine **A** (Scheme 2). Depending on the characteristics of the target NHC-precursor (nature of the linking backbone and of the nitrogen substituents, presence of a chirality, or of annelated cycles ...), several synthetic pathways to substituted diamines have been developed, which could be sorted into six major strategies: (a) formation of a bis-imine and reduction; (b) bis-acylation of two amines and reduction; (c) mono-alkylation and mono-acylation of two amines followed by reduction; (d) substitution on an existing diamine core; (e) substitution of a bis-electrophilic core by amines; (f) use of an α -aminoacid as building block.



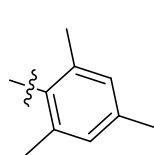
Scheme 2. Major synthetic strategies to access the N,N'-disubstituted-tethered diamines.

2.1.1 Condensation-reduction route

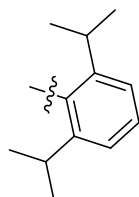
The synthesis of symmetrical imidazolinium salts in a three-step sequence following the pathway (a) in Scheme 2 was originally described by Arduengo and co-workers in 1999.²³ In a general synthetic protocol, a diimine is first formed by condensation of an aryl- or alkylamine with glyoxal, and subsequently reduced to the corresponding diamine, isolated as the free base or as the dihydrochloride salt at this stage. Cyclization occurs using triethyl orthoformate as the C₁-building block (and one equivalent of acid if starting from the free diamine) with formation of the corresponding imidazolinium salt **1** (Scheme 3).



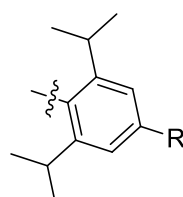
Examples of R groups used with this method



1a (54%)
(Arduengo)

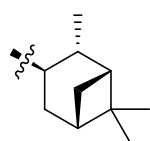
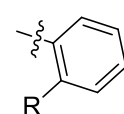


1b (45%)
(Arduengo)

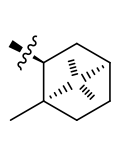


R = NEt₂ **1c** (77%)
R = OMe **1d** (35%)
R = F **1e** (52%)
R = Cl **1f** (31%)
R = SO₃⁻ **1g** (76%)
(Plenio)

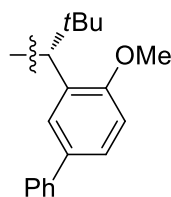
R = *t*Bu **1h** (88%)
R = *i*Pr **1i** (94%)
(Ying)
R = Ph **1j** (96%)
(Bellemin-Laponnaz)



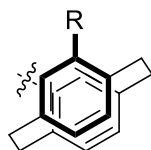
1k (64%)
(Hartwig)



1l (92%)
(Hartwig)



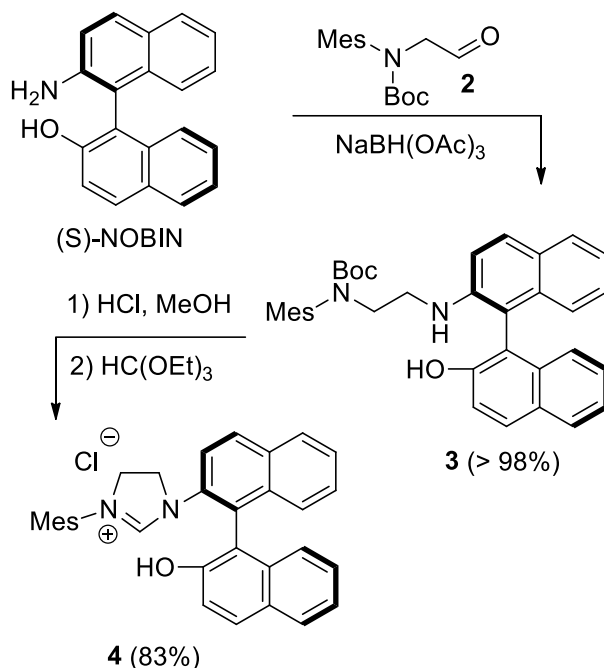
1m (88%)
(Kündig)



R = H **1n** (61%)
R = Ph **1o** (62%)
R = Cy **1p** (50%)
R = *o*-anisyl **1q** (51%)
(Andrus)

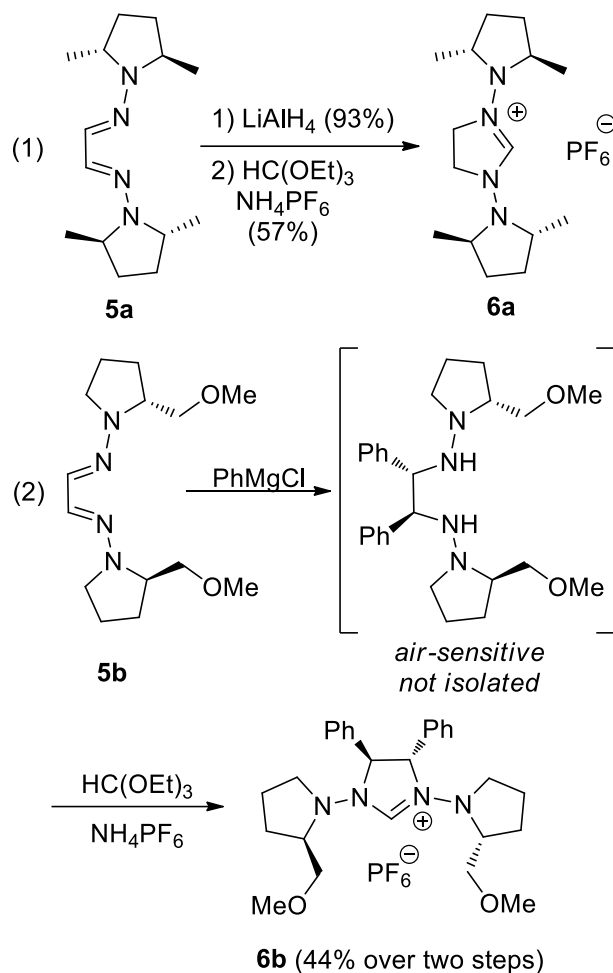
Scheme 3. Synthesis of the symmetrical imidazolium chlorides **1a-q** in a three-step sequence: glyoxal condensation with an arylamine, reduction of the resulting diimine, followed by cyclization with triethyl orthoformate.

This synthetic route now remains the most popular standard protocol to access common imidazolinium salts, since it is applicable to a wide variety of primary amines as illustrated by the selected examples provided in Scheme 3. For example, variation of the aryl group (e.g., 1-naphthyl, 3,5-dimethylphenyl, 4-biphenyl, 2-methylphenyl, 2,6-dimethylphenyl) was studied by several authors including Noels and co-workers,²⁴ Plenio and co-workers,²⁵ who generated a series of symmetrical diarylimidazolinium salts (**1c-g**) bearing various *para* substituents, Ying and co-workers²⁶ and Bellemin-Laponnaz and co-workers.²⁷ with mono, *ortho*-substituted aryl groups as nitrogen-substituents (**1h-j**). A number of C_2 -symmetric chiral imidazolinium salts bearing an asymmetric α -carbon atom on nitrogen were also prepared starting from the corresponding enantiopure alkylamine (**1k-m**),^{28,29} and even bearing extremely bulky, chiral *para*-cyclophanic moieties as substituents (**1n-q**).³⁰ Finally, other imidazolinium salts were prepared by this method, which is not limited to the above representative examples.³¹ Unfortunately, given that the first condensation step, an equilibrated reaction, is reversible, mixing glyoxal with two different amines always leads to a statistical distribution of the three expected diimine products, thereby restricting the scope of the method to the case of symmetrical imidazolinium salts. Nevertheless, Hoveyda and co-workers were able to apply the method to the synthesis of the unsymmetrical (and chiral) imidazolinium salt **4** from (*S*)-NOBIN in a two-step sequence with the Boc-protected amino aldehyde **2** as the key coupling partner (Scheme 4).³² Deprotection of the Boc group occurred during the formation of the dihydrochloride salt of the diamine. However, compound **2** had to be synthesized first from mesitylamine in a three-step route, which makes the overall synthetic procedure quite long.



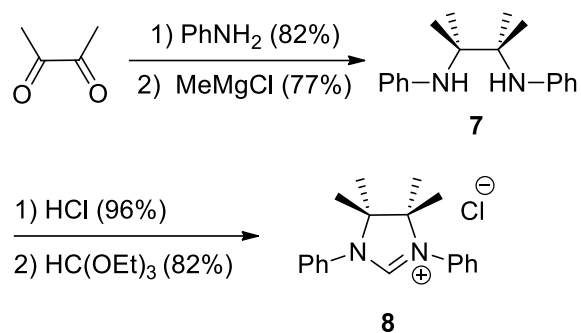
Scheme 4. Synthesis of the unsymmetrical, chiral imidazolium chloride **4** according to Hoveyda (Mes = 2,4,6-trimethylphenyl).

Lassaletta and co-workers also applied this method to the cyclization of bis-hydrazine to yield 1,3-bis(*N,N*-dialkylamino)imidazolium salt **6a**, providing a new family of chiral *N*-heterocyclic carbene precursors (Scheme 5, eq. 1).³³ Noticeably, the introduction of a chiral backbone into the target structure may also be accomplished using proline derivatives. For example, the stereoselective addition of PhMgCl to glyoxal RAMP bis-hydrazone **5b**,³⁴ followed by the direct treatment of the air sensitive intermediate bis-hydrazine with HC(OEt)₃ and NH₄PF₆ afforded **6b** in 44% yield.



Scheme 5. Synthesis of the 1,3-bis(*N,N*-dialkylamino)imidazolium salts **6a** and **6b** derived from chiral *N,N*-dialkylhydrazines.

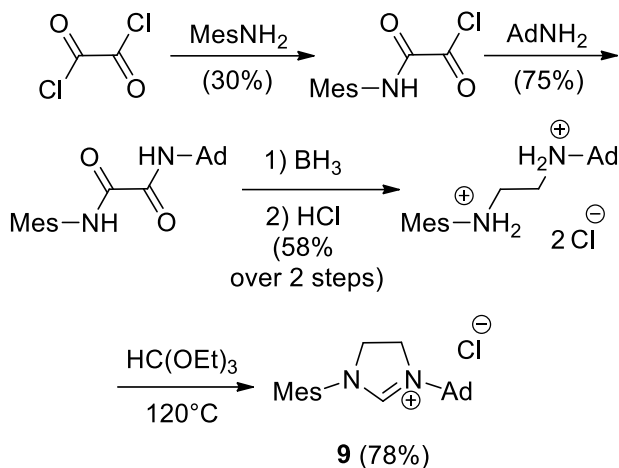
Following the same strategy, Grubbs and co-workers reported the introduction of a tetra-substituted backbone on the imidazolium salt.³⁵ Condensation of 2,3-butanedione with aniline, followed by treatment of the resulting diimine with a methyl Grignard reagent, afforded the corresponding diamine **7** which was subsequently converted into the imidazolium salt **8** in the presence of an excess of triethyl orthoformate (Scheme 6). The same group also reported the introduction of an allyl group by reaction of the Grignard reagent with the diazabutadiene compound followed by reduction of the second imine function.³⁶



Scheme 6. Synthesis of the imidazolium salt **8** incorporating a tetra-substituted backbone.

2.1.2 Bis-acylation / reduction route

The use of oxalyl chloride or derivatives such as mono-ethyl oxalyl chloride to synthesize N,N'-disubstituted-1,2-diamines retains the advantages of Arduengo's methodology in that it requires only inexpensive reagents and is practical for large-scale syntheses, while providing increased modularity and flexibility, allowing in particular the synthesis of unsymmetrical imidazoliums. Mol and co-workers first reported the synthesis of the mixed adamantyl/mesityl N-heterocyclic precursor 1-(1-adamantyl)-3-mesityl-imidazolium chloride **9** via reaction of an amine with oxalyl chloride followed by the reaction of a second amine with the intermediate acyl chloride (Scheme 7).³⁷ The oxalamide thus formed was subsequently reduced and cyclized using triethyl orthoformate. Since control of mono- vs. bis-amidation with oxalyl chloride could be sometimes problematic, ethyl oxalyl chloride was alternatively used to give access to unsymmetrical imidazolium salts.³⁸



Scheme 7. Synthesis of 1-adamantyl-3-mesitylimidazolium chloride **9**, according to Mol and co-workers (Mes = 2,4,6-trimethylphenyl; Ad = 1-adamantyl).

Due to its simplicity and its tolerance to functional groups, this approach is now the most widely used strategy for making unsymmetrical imidazolium salts and some representative examples are described in Chart 3. These include imidazoliums bearing aryl groups with different steric and/or electronic properties (**10b-g**),³⁹ various functional groups (**10a**),^{38a,40} or bearing a chiral alkyl chain derived from aminoalcohols (**10h**)⁴¹ and even complex bis-imidazolium structures (**10i**)⁴² could be reached with this method.

Grubbs and co-workers reported an analogous synthesis of the six-membered, bulky 1,3-dimesityl-5,5-dimethyltetrahydropyrimidinium salt **11** in good yields starting from mesitylamine and dimethylmalonyl dichloride (Scheme 8).⁴³

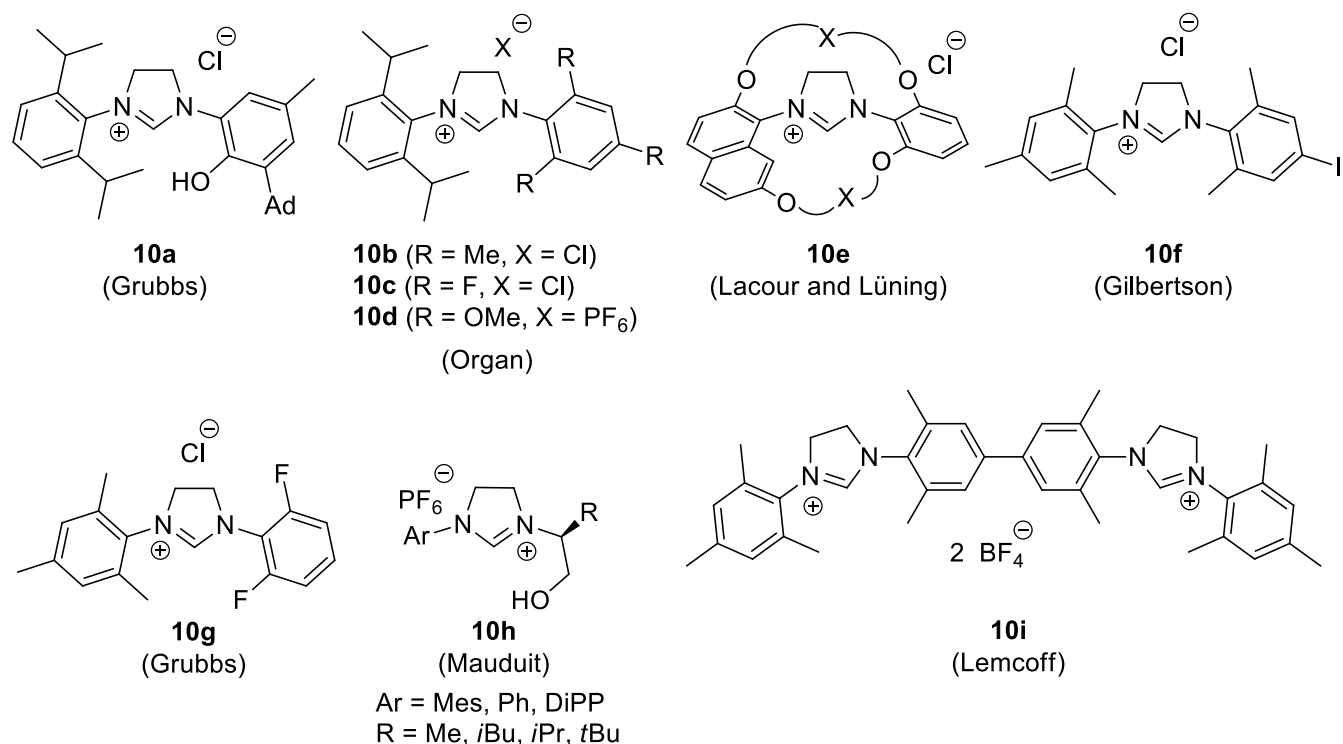
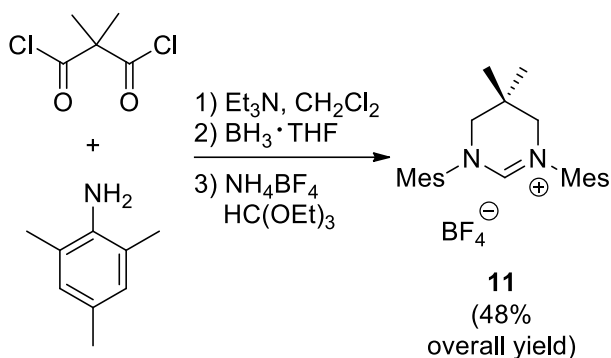


Chart 3. Unsymmetrical imidazolium salts obtained by the “oxalic” route.

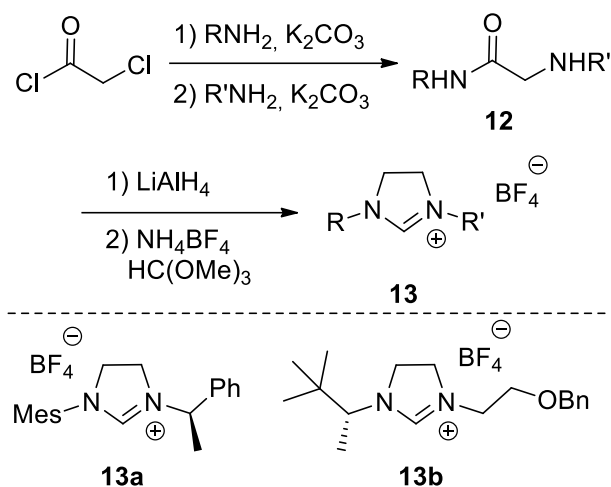


Scheme 8. Synthesis of tetrahydropyrimidinium salt **11**.

2.1.3 Acylation-alkylation / reduction route

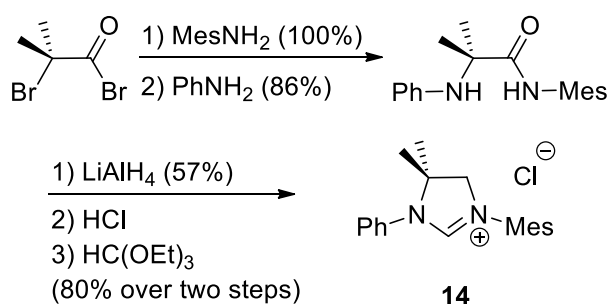
Kotschy and co-workers reported the modular synthesis of N-heterocyclic carbene precursors starting from chloroacetyl chloride (Scheme 9).⁴⁴ In a first step, nucleophilic addition of an amine to chloroacetyl chloride followed by nucleophilic substitution of the resulting α -chloroacetamide by a second amine furnished the corresponding α -aminoacetamides **12**. After reduction with lithium aluminium hydride, treatment with trimethyl orthoformate in presence of ammonium tetrafluoroborate

afforded various imidazolium salts **13** (Scheme 9). The yield of each step is good and the method is applicable to a large variety of amines and anilines (R, R' = aryl, alkyl, chiral alkyl groups).



Scheme 9. Synthesis of the imidazolium salts **13** starting from chloroacetyl chloride according to Kotschy.

The major advantage of this method compared to the earlier one resides in the possibility to differentiate the two carbon atoms in positions 4 and 5 of the imidazolium core. Grubbs *et al.* applied this strategy to the synthesis of the unsymmetrically substituted N-heterocyclic carbene precursor **14** bearing a *gem*-dimethyl group adjacent to the N-phenyl substituent (Scheme 10).³⁵ The desired imidazolium salt was obtained in good yield from 2-bromo-2-methylpropionyl bromide.



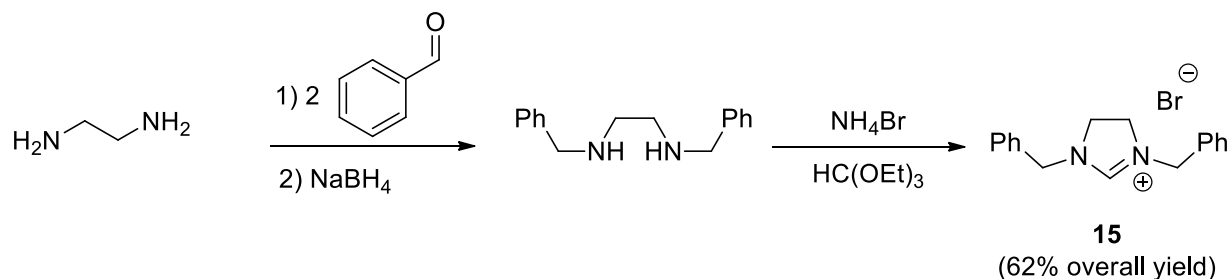
Scheme 10. Synthesis of **14** bearing a *gem*-dimethyl group adjacent to the N-phenyl substituent.

2.1.4 Starting from a pre-formed diamine core

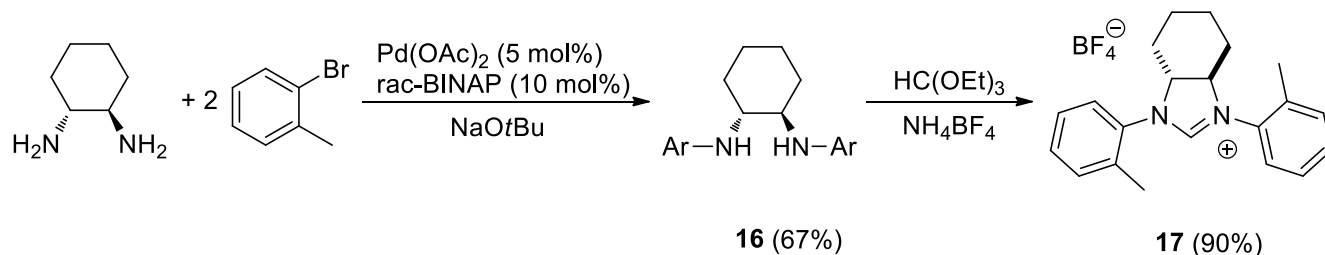
Primary diamines may be used as readily available building blocks to access various N-containing heterocyclic salts (pathway (d), Scheme 2), since a lot of these amines are commercially available or

easily obtained by a straightforward procedure.⁴⁵ Depending on the nature of the substituents (alkyl or aryl group), two main distinct methods were used for the *mono*-functionalization of each amine as depicted in Scheme 11. The first one consists in an indirect reductive amination as illustrated by the synthesis of 1,3-dibenzylimidazolium bromide **15**.⁴⁶ Compared to direct alkylation, it has the obvious advantage that it stops at the stage of *mono*-N-substitution. However, carbon atoms directly connected to the nitrogen atoms are necessarily primary (i.e. -CH₃) or secondary (i.e. -CH₂R) and this precludes any introduction of chirality in close proximity of the heterocyclic imidazolium core. The second method for functionalization, the Buchwald-Hartwig amination⁴⁷ gives easy access to valuable N,N'-diarylimidazolium salts, as illustrated by the synthesis of compound **17** which was the first report based on this strategy.⁴⁸ Indeed, reaction of (1*R*,2*R*)-1,2-diaminocyclohexane with two equivalents of 2-bromotoluene in the presence of NaOtBu and a catalytic amount of Pd(OAc)₂ and *rac*-BINAP led to the corresponding secondary diamine **16** in 67% yield. Treatment with triethyl orthoformate and ammonium tetrafluoroborate thus gave the imidazolium tetrafluoroborate salt **17** in 90% yield.

Pathway 1: indirect reductive amination



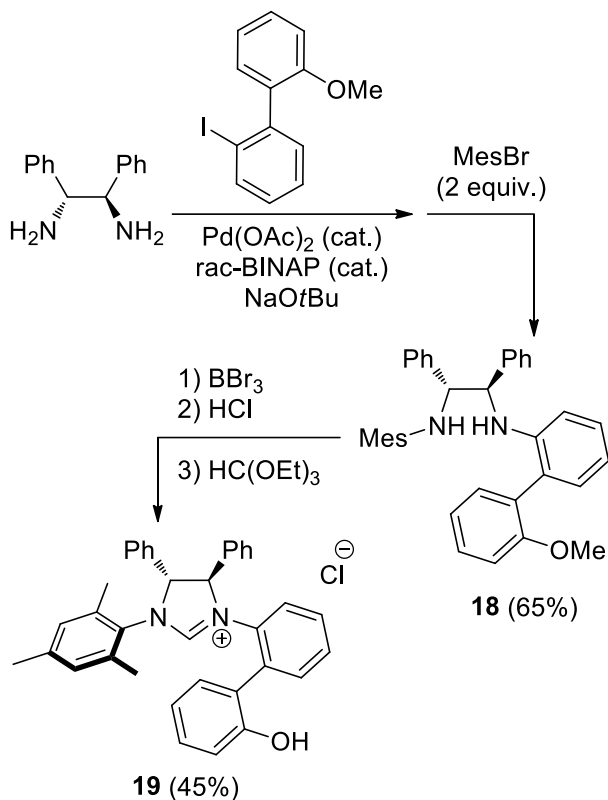
Pathway 2: Buchwald-Hartwig amination



Scheme 11. The two major pathways for the *mono*-substitution of the primary diamines and subsequent cyclization.

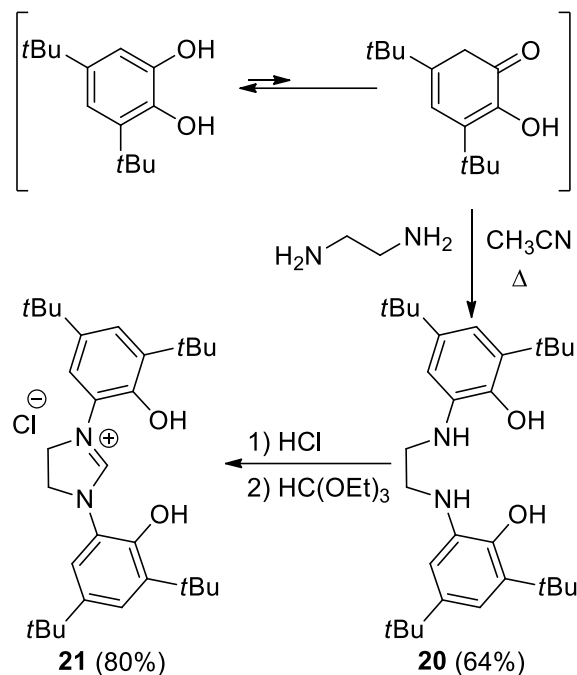
Hoveyda and co-workers showed that the latest method may be used to synthesize unsymmetrical

chiral carbene precursors. Thus, treatment of (*1R,2R*)-diphenylethylenediamine with one equivalent of aryl iodide in the presence of palladium catalyst followed by addition of an excess of mesityl bromide led to the formation of the corresponding diamine **18** in 65% overall yield. Deprotection of the methyl ether and treatment with HCl and triethyl orthoformate gave the desired chiral enantiopure imidazolium **19** in 45% yield (Scheme 12).⁴⁹



Scheme 12. Synthesis of the unsymmetrical imidazolium salt **19** via successive Buchwald-Hartwig arylations on (*1R,2R*)-diphenylethylenediamine.

Based on a similar strategy following pathway 1, Bellemin-Laponnaz, Dagorne and co-workers reported the synthesis of the potentially tridentate pincer-type NHC pre-ligand **21**,⁵⁰ where the key step is the coupling between 3,5-di-*tert*-butylcatechol and ethylenediamine to form *N,N*-bis(3,5-di-*tert*-butyl-2-hydroxyphenyl)-ethylenediamine **20** (Scheme 13).⁵¹ The originality of this approach is to take advantage of the keto-enol equilibrium in the starting catechol.



Scheme 13. Synthesis of the symmetrical bis-aryloxide imidazolium chloride **21** starting from 3,5-di-*tert*-butylcatechol and ethylenediamine.

This strategy is particularly efficient for the construction of chiral NHC precursors possessing a chiral backbone, and has been applied to a huge number of chiral imidazolium salts. As the chiral information contained in the backbone has to be transmitted to the active space at the metal centre of catalyst by means of the two nitrogen substituents, the latter are often a sterically hindered dissymmetric aryl group such as **22** or a bulky benzyl-type substituent such as **23** (Chart 4). By steric repulsion, the two N-substituents arrange in such a way that they reflect the C_2 -symmetry of the backbone.⁵² One of the nitrogen-arms could also contain a second coordinating functionality in order to provide a bidentate ligand and to rigidify the chiral structure of the catalytically active centre (compounds **24-25**, Chart 4 and compound **19**, Scheme 12).⁵³ All but a few of these imidazolium salts derive from enantiopure 1,2-diphenylethylenediamine, but during the past few years, some other chiral skeletons have appeared, as illustrated by the camphor-derived chiral NHC precursor **26**.⁵⁴ It constitutes also one of the methods of choice for elaborating bigger cationic heterocyclic precursors and/or bearing a particular backbone. The application scope is illustrated by the selected examples depicted in Chart 4. First, cyclic

formamidiniums with a fully saturated backbone (such as **27**) were synthesized by Cavell.⁵⁵ Richeson and colleagues reported in 2003 a novel family of carbenes based on the perimidine core.⁵⁶ The NHC-precursors **28a-c** were derived from the same N-isopropyl-1,8-diaminonaphthalene intermediate, with the second N-substituent being attached either by reaction of the amine-group with an electrophilic compound (acetone for **28a**, pivaloyl chloride for **28b**) followed by reduction with lithium aluminium hydride, or with 3,5-dimethylphenyl iodide using Ullmann's coupling conditions for **28c**. Stahl and co-workers reported the synthesis of constrained 1,3-dialkyldiazepinium salts **29-30** from 2,2'-diaminobiphenyl (**29**) or from (R)-2,2'-diaminobinaphthyl (**30**).⁵⁷ The NHC ligands derived from such seven-membered amidinium exhibit a torsional twist that may be of interest for the development of efficient asymmetric catalysts. Interestingly, the authors noticed that the cyclization was unsuccessful for N,N'-diaryl amines. Such a lack of reactivity was assumed to be a consequence of the weak nucleophilicity of the diaryl-substituted nitrogen atoms in this case. Finally, Bielawski and Siemeling independently developed the chemistry of diaminocarbene[3]ferrocenophanes derived from the formamidinium **31**.⁵⁸

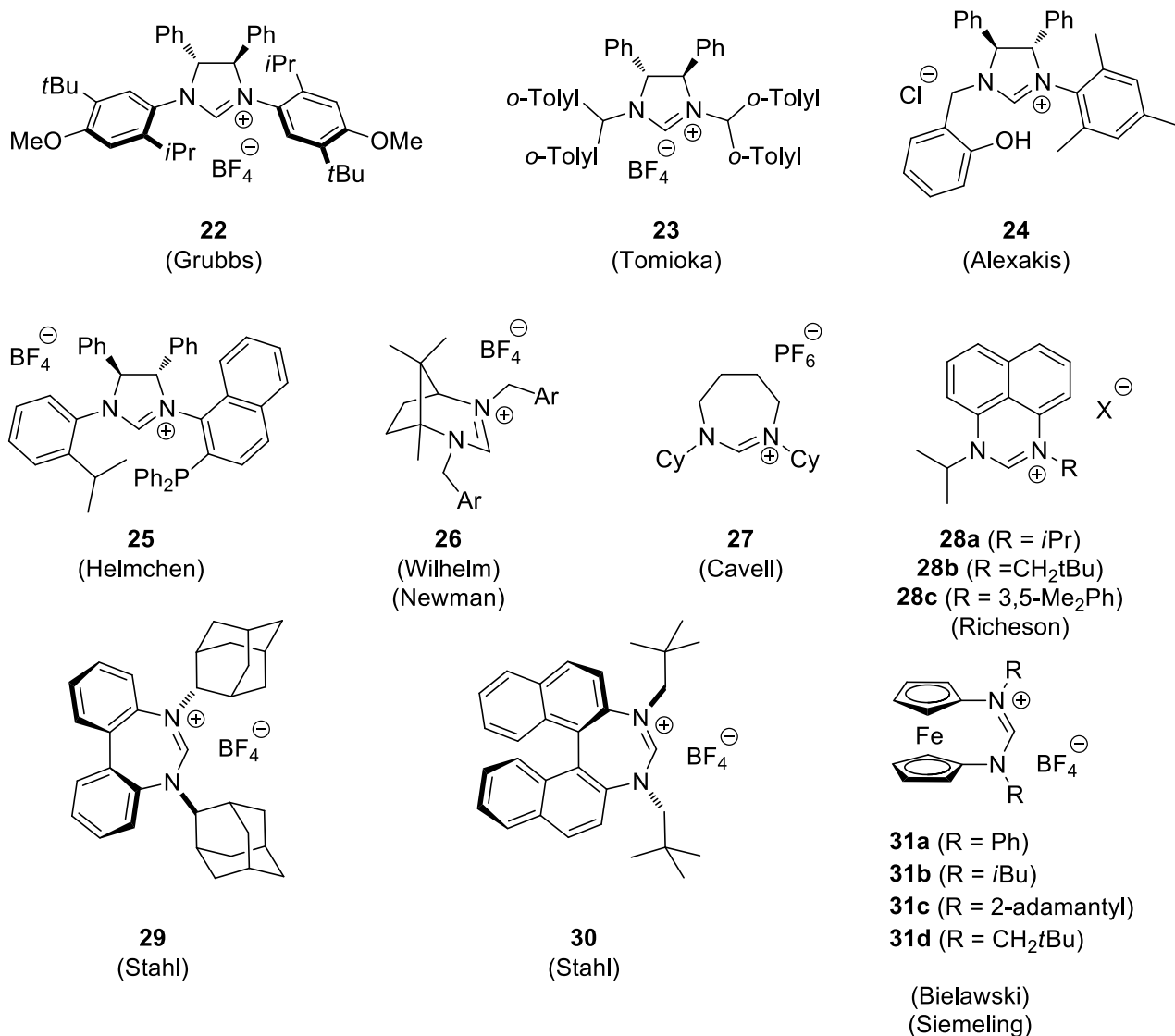
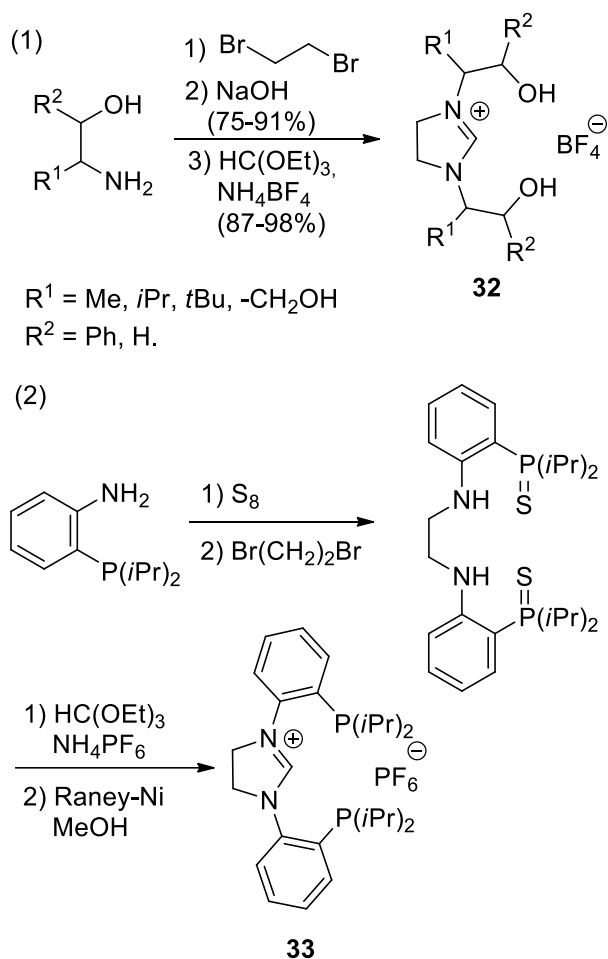


Chart 4. Scope of the synthesis of NHC precursors from pre-formed diamines.

2.1.5 Reaction on a bis-electrophilic core

Primary amines react rapidly with alkyl halides to yield secondary ammonium salts, R₂NH₂⁺X⁻. Although it is known that these reactions don't stop cleanly after a single alkylation has occurred, direct alkylation of amines with 1,2-dibromoethane appears as an efficient way to access the imidazolium salts. Wilhelm and co-workers used this method to synthesize chiral imidazolium salts bearing two hydroxy substituents (Scheme 14, eq. 1).⁵⁹ The reaction of amino alcohols and 1,2-dibromoethane at 100°C for 10 hours (neat conditions) followed by a work-up under basic conditions led to the corresponding bis(amino alcohol) in good yields. The imidazolium salts **32** were then prepared by

treatment with triethyl orthoformate in the presence of ammonium tetrafluoroborate. In the same manner, the saturated NHC-based PCP pre-ligand **33** was obtained by alkylation of *o*-diisopropylphosphinoaniline - protected as a phosphine sulfide - (Scheme 14, eq. 2) under neat conditions. The classical trialkylorthoformate route followed by reduction of the sulfides led to the bis(phosphine) imidazolium salt **33**.⁶⁰

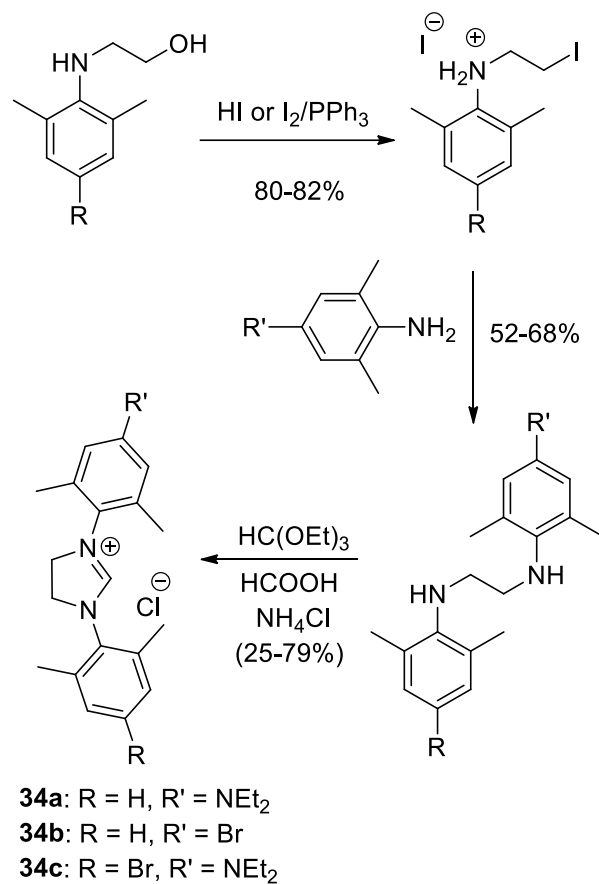


Scheme 14. Synthesis of tridentate pre-ligands **32** and **33** starting from 1,2-dibromoethane.

Gautier and co-workers recently showed that the ‘classical’ SIMes imidazolium salt could be obtained in 53% overall yield by using this alkylating route. Reaction of mesitylamine with 1,2-dibromoethane was efficiently conducted in methanol as solvent.⁶¹

Plenio and co-workers used an indirect approach to synthesize unsymmetrical imidazolium salts. Starting from the *N*-β-hydroxyethyl substituted 2,6-dimethylanilines, treatment with HI or Ph₃P/I₂

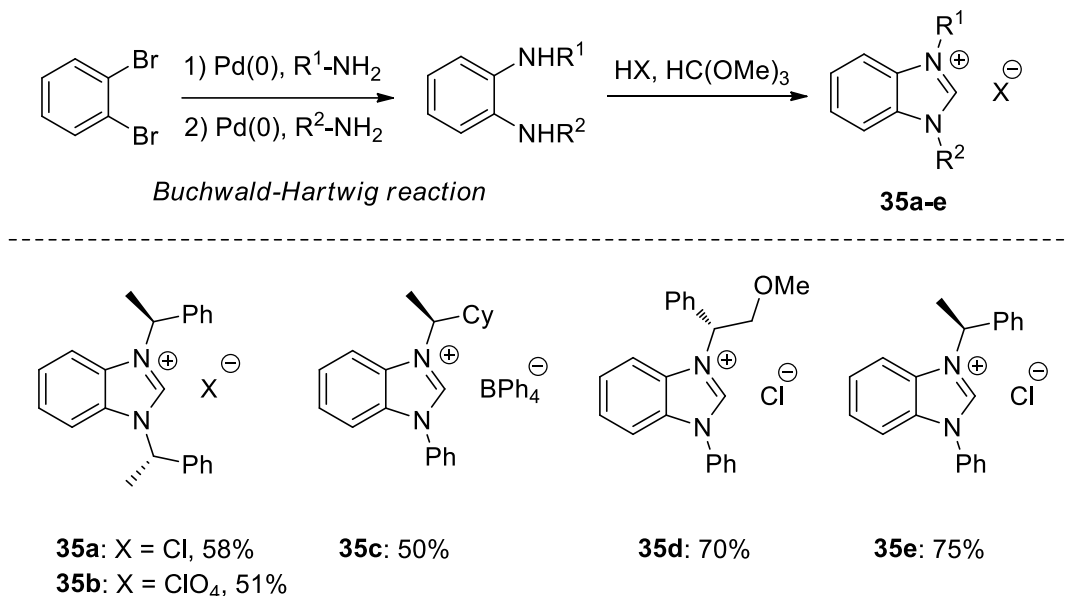
generates the respective N- β -iodoethyl anilinium salt. Subsequent nucleophilic substitution of the iodide by 2,6-dimethylanilines (4 -R = Br or NEt₂) affords the diamines, which then undergo cyclization to the corresponding imidazolinium salts **34a-c** using triethyl orthoformate (Scheme 15).^{25b} The latest two steps were carried out in a one-pot reaction by Gilbertson and co-workers.⁶² This approach is compatible with a number of potentially reactive groups (i.e. aminoalcohols, aminophenols) and provides an extremely easy access to unsymmetrical imidazolinium salts.



Scheme 15. Synthesis of unsymmetrical imidazolinium salts **34** via successive nucleophilic substitutions of halides according to Plenio *et al.*

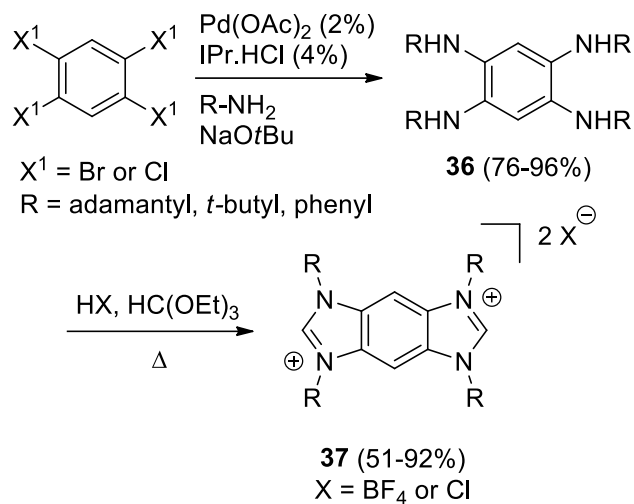
Benzimidazolium salts are also important precursors of NHCs. The first reported literature methods for the synthesis of such salts were focusing on N-alkylation reactions which are inappropriate for the introduction of chirality directly at the carbon alpha to the nitrogen atom. Diver and collaborators reported a versatile synthesis of these compounds based on a successive Buchwald-Hartwig amination

on 1,2-dibromobenzene and ring closure with triethyl orthoformate.⁶³ They particularly focused on the introduction of α -chiral primary amines onto the nitrogen substituents to form the chiral benzimidazolium salts **35a-e** as precursors of asymmetric NHC-based catalysts (Scheme 16).



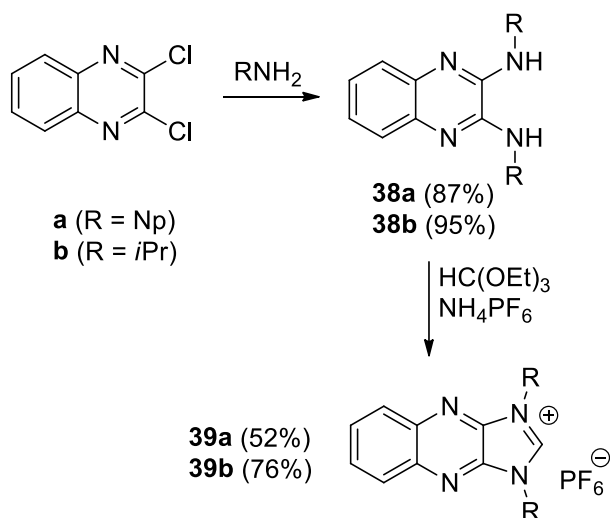
Scheme 16. Synthesis of chiral benzimidazolium salts **35** using the tandem Buchwald-Hartwig substitution-triethyl orthoformate cyclization.

Bielawski and co-workers extended this synthetic methodology to the benzobis(imidazolium) salts **37** as proligands for bimetallic carbene complexes, via the formation of 1,2,4,5-tetrakis(alkyl- and arylamino)benzenes (Scheme 17).⁶⁴ The Buchwald-Hartwig amination reaction proved to be efficient with various amines including 1-adamantylamine, *tert*-butylamine, aniline, relatively bulky mesitylamine and electron-rich *o*-anisidine. Ring closure was carried out by subjecting tetra-amines **36** to acidified triethyl orthoformate solutions at high temperatures. It should be noted that the mesitylated derivative did not afford the corresponding benzobis(imidazolium) salt.



Scheme 17. Synthesis of the benzo-bis(imidazolium) salt **37** using successive Buchwald-Hartwig amination/triethyl orthoformate cyclization.

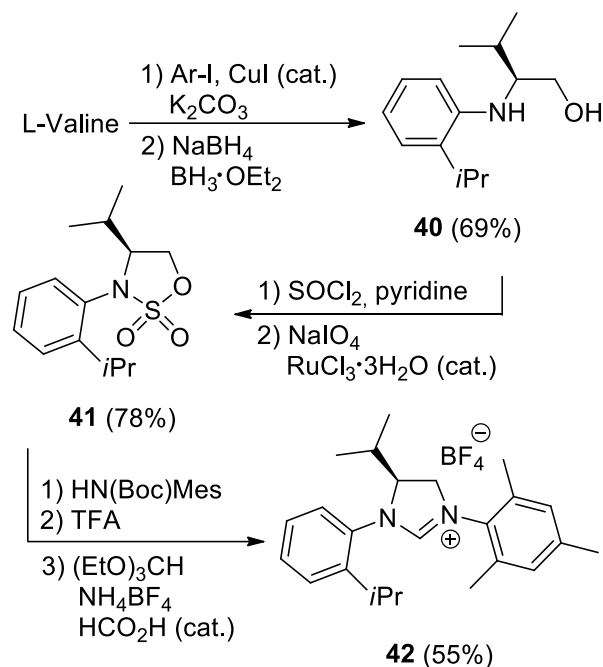
Finally, Heinicke and co-workers reported the synthesis of a quinoxaline-annelated diaminocarbene which derived from the azolium **39** (Scheme 18).⁶⁵ Here, the intermediate diamine **38** was simply obtained by double nucleophilic aromatic substitution of 2,3-dichloroquinoxaline by alkylamines (neopentylamine or isopropylamine).



Scheme 18. Synthesis of quinoxaline-annelated imidazolium salt **39**.

2.1.6 α -aminoacid as building block

Blechert and co-workers recently described a practical method for the synthesis of chiral unsymmetrically substituted NHC systems (Scheme 19). The sulfamidate **41** was obtained in four steps and 54% overall yield starting from L-valine. Nucleophilic attack using Boc-mesidine followed by triethyl orthoformate cyclization gave the desired salt **42** in 55% (three steps).⁶⁶ Smith also reported the synthesis of imidazolium salts from L-phenylalanine and L-valine but this protocol suffers from a lack of generality.^{52b}

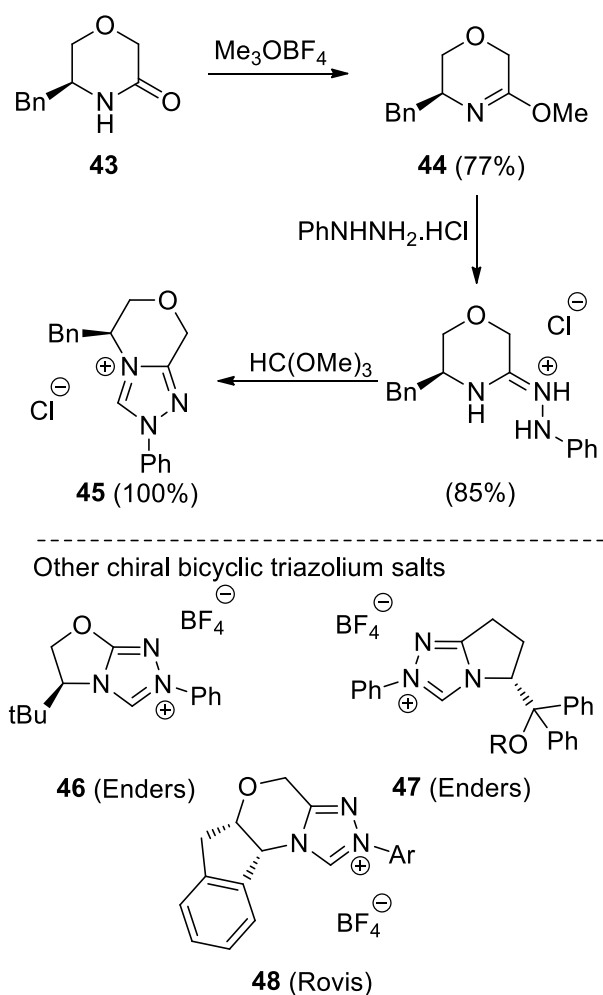


Scheme 19. Synthesis of unsymmetrically substituted NHC precursors **42**.

The introduction of the “pre-carbenic” fragment using trialkyl orthoformate under acidic conditions is now a well developed procedure, applicable to imidazolium, benzimidazolium, tetrahydropyrimidinium, diazepinium salts as well as to more complex structures. For a specific substrate, investigators have at their disposal a palette of methods, each having its own advantages and limitations. For example, it should be noted that no reduction is involved in pathways (d) and (e) (Scheme 2), rendering them suitable for substituents sensitive toward reduction. Thus, these methods are therefore complementary to the pathways (a-c).

2.1.7 Triazolium salts and benzoxazolium salts

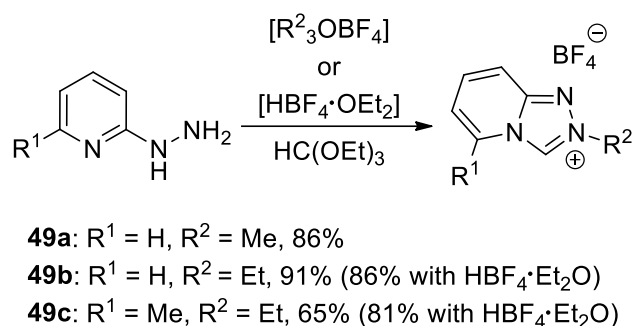
Cyclization using trialkyl orthoformates also proved to be efficient for the synthesis of triazolium and benzoxazolium salts and this section will deal with their synthesis.⁶⁷ In 1998, Leeper and colleagues reported the first synthesis of an enantiopure bicyclic triazolium in a three-step sequence starting from lactam **43**, derived from L-phenylalaninol (Scheme 20).⁶⁸ After activation of the amide function by methylation with Meerwein's reagent to form the methyl iminoester **44**, nucleophilic addition of phenylhydrazine hydrochloride followed by cyclization using trimethyl orthoformate yielded the triazolium salt **45**. For example, chiral enantiopure oxazolidinone- or pyroglutamic acid-based systems (respectively **46**⁶⁹ and **47**⁷⁰) or aminoindanol-based triazolium salts **48**⁷¹ were synthesized by this way.



Scheme 20. Synthesis of chiral bicyclic triazolium chloride **45** by Leeper, and other examples of

bicyclic triazolium structures.

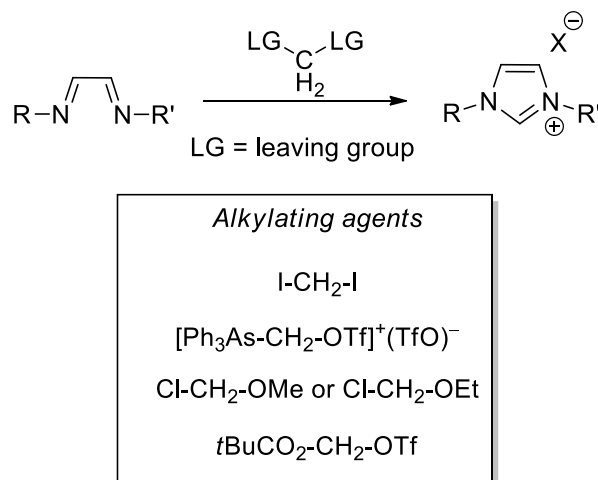
Pyrido-annulated triazolium salts **49a-c** were prepared by You and co-workers, using a one-pot procedure. Reaction of the commercially available hydrazine with trialkyloxonium in the presence of trialkyl orthoformate gave directly the desired compound in high yield (Scheme 21). Alternatively, the alkylation may be performed using HBF_4 in diethyl ether rather than a trialkyloxonium salt.⁷²



Scheme 21. Synthesis of pyrido-annulated triazolium salts **49**.

2.2 1,1-Bis(electrophile) compounds as C_1 provider

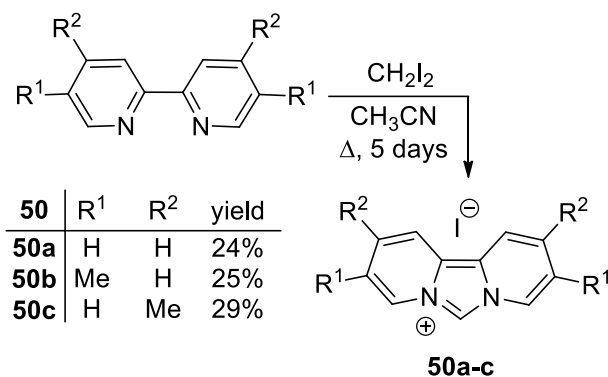
NHC precursors may also be obtained by double nucleophilic substitutions on 1,2-diimines by means of 1,1-bis(electrophile), *i.e.* methylene compounds bearing two leaving groups. Scheme 22 displays several examples of dialkylating reagents that were used for that purpose. The present section will discuss these various possibilities.



Scheme 22. Formation of imidazolium salts by means of 1,1-bis(electrophile) compounds.

2.2.1 Gem-dihalides as C1 building block

The synthesis of dipyridoimidazolium salts **50a-c** was firstly described by Sasse and co-workers, who reported the double nucleophilic substitution of several 2,2'-bipyridyl derivatives with methylene iodide as early as 1963 (Scheme 23).⁷³

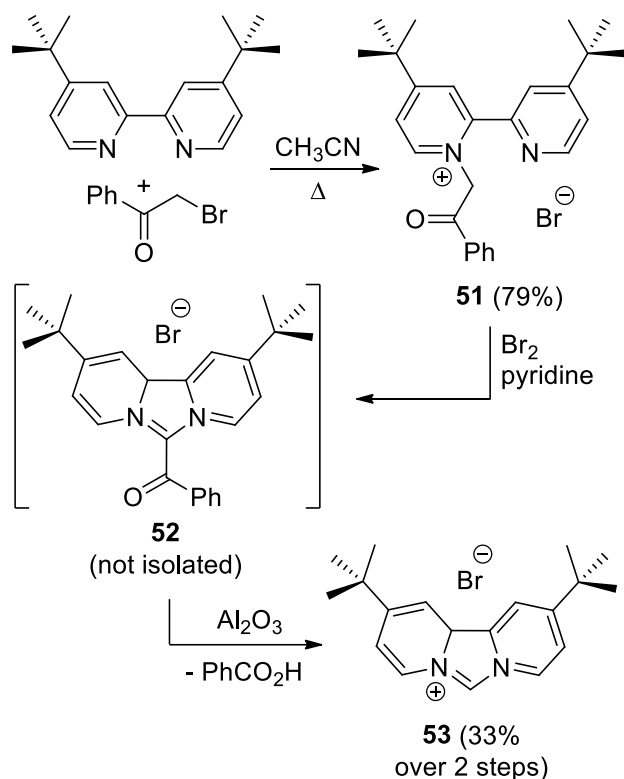


Scheme 23. Synthesis of dipyridoimidazolium iodides **50a-c** using methylene iodide.

However, this reaction is inappropriate for bipyridyl compounds bearing electron-withdrawing groups like 4,4'-diphenyl-2,2'-bipyridyl, 5,5'-diethoxycarbonyl-2,2'-bipyridyl or 2,2'-biquinoyl, which show a decrease of the nucleophilic character of the heteroatoms.

The same authors also reported another method for the synthesis of 6-carboxy-substituted-dipyridoimidazolium bromides of type **52** using α -haloketones in combination with bromine,^{73b,74} and more recently, Kunz and co-workers used this approach to yield dipyridoimidazolium bromide **53** bearing *tert*-butyl groups at the 2- and 10-positions of the bipyrido moiety (26% overall yield) (Scheme 24).⁷⁵ Thus, 1-acylmethyl-2-(2-pyridyl)pyridinium bromide **51** was obtained by reaction of 2,2'-bipyridyls with 2-bromoacetophenone. Addition of bromine was accompanied by a bromoform reaction, followed by cyclization through a nucleophilic substitution of the α -position of the ketone by the second nitrogen to yield, after aromatization, the 6-carboxydipyridoimidazolium bromide **52**. Passing **52** over a column charged with activated neutral aluminium oxide led to a deacylation (Sasse and co-workers had already noted the possibility to induce this deacylation by acid or base catalysis) and finally to

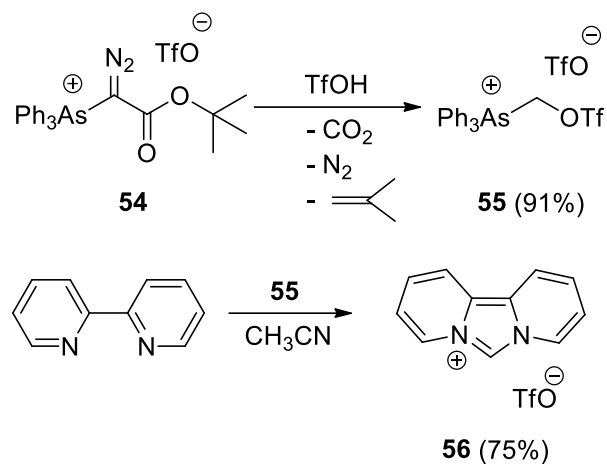
dipyridoimidazolium bromide **53**.



Scheme 24. Synthesis of 2,10-di-*tert*-butyl-dipyridoimidazolium salt **53**.

2.2.2 Using Weiss' reagent

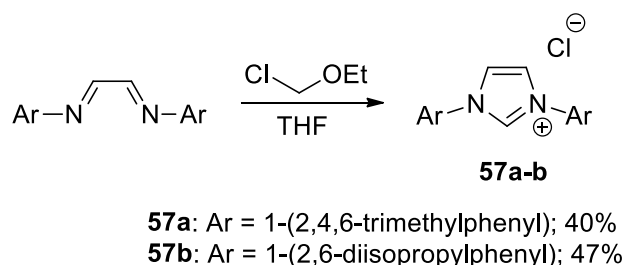
Weiss and co-workers described an alternative synthesis of dipyridoimidazolium salts using an arsonium salt as alkylating agent.⁷⁶ Starting from the elaborated diazo compound **54**,⁷⁷ reaction with trifluoromethanesulfonic acid afforded the arsonium salt **55**, a powerful bis-electrophile which may be used to cyclize 2,2'-bipyridine into dipyridoimidazolium triflate **56** in 75% yield (Scheme 25). Although higher yields were obtained through this method, the potentially harmful use of an arsenic derivative obviously reduces the attractiveness of Weiss' pathway.



Scheme 25. Synthesis of dipyridoimidazolium salt **56** by means of the arsonium-based alkylating agent **55**.

2.2.3 Using chloromethyl ethers

The synthesis of imidazolium salts using chloromethylalkyl ethers (alkyl = methyl or ethyl) was originally described by Arduengo and co-workers in 1999.²³ Starting from symmetrical 1,2-diimines, this route was applied to the synthesis of mesityl and 2,6-diisopropylphenyl derivatives **57a-b** (Scheme 26). Although higher yields of the imidazolium **57a** were obtained via the one-pot synthesis previously described by the same group (see part 3.1), the chloromethylethyl ether synthetic pathway provides a direct and convenient access to hindered imidazolium salts and is easy to perform on a small scale (typically < 1 g). Notably, as the imidazolium chlorides **57** precipitate during the course of the reaction, a simple filtration is required to isolate them, without the need of additional purification.



Scheme 26. Cyclization of 1,2-diimines into imidazolium salts **57a-b** using chloromethylethyl ether.

This procedure was particularly used for the synthesis of bulky and/or highly substituted imidazolium salts, such as the tetrasubstituted imidazolium **58**,⁷⁸ the dendritic-type **59** (and its higher dendritic analogues),⁷⁹ the super bulky 2,6-terphenyl substituted **60**,⁸⁰ or bis(imino)acenaphthene-based **61** (Chart 5).^{81,82}

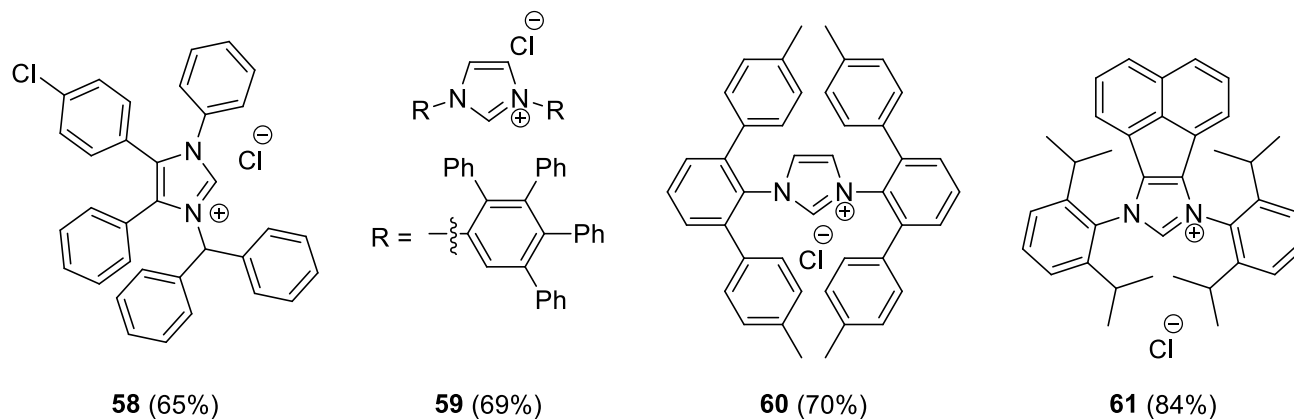


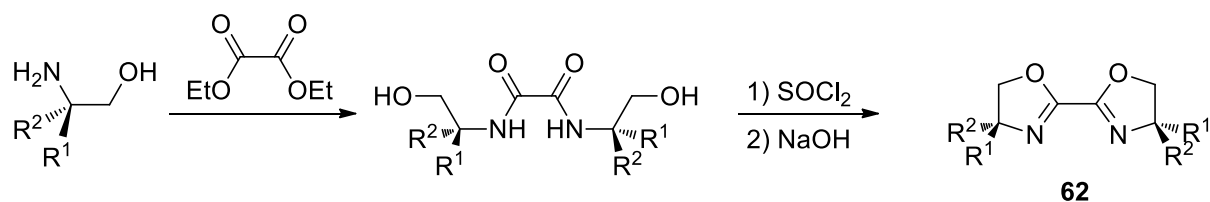
Chart 5. Examples of imidazolium chlorides obtained via the chloromethyl ethyl ether route.

2.2.4 Using chloromethyl pivalate (“Glorius’ reagent”)

Arduengo’s procedure using chloromethylethyl ether is nevertheless inappropriate for the synthesis of bisoxazoline-derived imidazolium salts (IBiox·HX) since the halide anions generated *in situ* are seen to open the oxazoline ring, thereby preventing the formation of the expected imidazolium salt. Therefore, Glorius and colleagues developed an efficient alternative for the formation of rigid NHC architectures derived from bis-oxazolines. The use of silver triflate in combination with chloromethyl pivalate led to the conversion of bisoxazoline to 4,5-dialkoxy-substituted tricyclic imidazolium salts **64** (Scheme 27), by means of the *in-situ* generated and highly reactive (trifluoromethanesulfonato)methyl pivalate reagent **63**.⁸³ In order to avoid the formation of any bis-oxazoline silver complex, the silver chloride formed by reaction of AgOTf with chloromethyl pivalate needs to be filtered before being reacted with the bisoxazoline. Starting from achiral or enantiopure α -aminoalcohols, the bisoxazoline **62** compounds were classically synthesized in a three-step sequence via amide formation from amino alcohols with diethyl oxalate, followed by chlorination of the remaining alcohol-function with SOCl₂ and base-mediated cyclization.⁸⁴ This route allowed to introduce a variety of substituents R¹ and R² on the C4

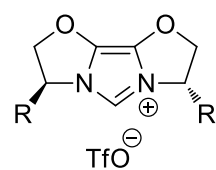
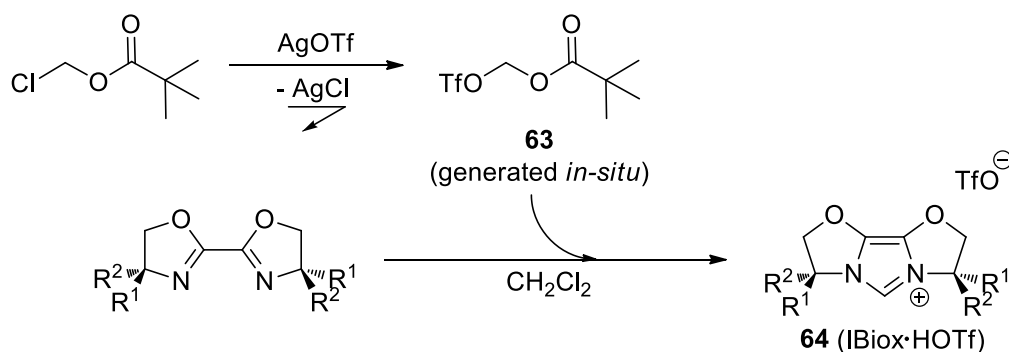
position of the oxazoline rings. Whereas the first publication dealt with the synthesis of the chiral IBiox-derived imidazolium triflate **64a-c**,⁸⁵ the authors subsequently applied this synthetic route to various sterically hindered bis-oxazoline derived imidazolium salts **64d-h** exhibiting restricted flexibility, brought by different carbocycle ring sizes ranging from two cyclopentyl rings to two cyclododecyl rings.^{86,87} More recently, the (-)-menthyl derived IBiox salt **64i** was obtained via the same route.⁸⁸ Imidazolium salts **64d-h** exhibit conformationally flexible cycloalkyl rings,⁸³ but in the particular case of (-)-menthyl derived IBiox salt **64i**, the presence of the additional alkyl substituents on the cyclohexyl ring tends to shift the equilibrium toward the most sterically demanding conformation.

Synthesis of bisoxazolines

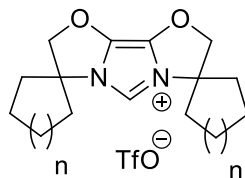


(70-90% over three steps)

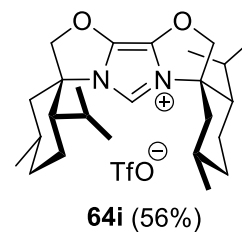
Formation of the imidazolium triflates



64a: R = *i*Pr, 80%
64b: R = *t*Bu, 75%
64c: R = Bn, 36%



64d: n = 1, 54%
64e: n = 2, 64%
64f: n = 3, 52%
64g: n = 4, 50%
64h: n = 8, 53%



Scheme 27. Synthesis of IBiox·HOTf **64** using trifluoromethylsulfonyloxymethyl pivalate **63** formed by addition of silver triflate to chloromethyl pivalate.

The same group also extended the application scope of this procedure to 2-imino-oxazolines and 2-iminopyridines to form respectively the unsymmetrical bicyclic imidazolium triflates **65a-b**⁸⁵ and 2H-imidazo[1,5-a]pyridin-4-ium bromides **66a-e** (isolated after an anion-exchange),⁸⁹ as well as to thiazole-annulated imidazoliums **67a-b** (Chart 6).⁹⁰ It should be noted that attempts to apply this methodology to bis-thiazoles failed to provide the corresponding imidazolium ring and stopped at the first alkylation stage.

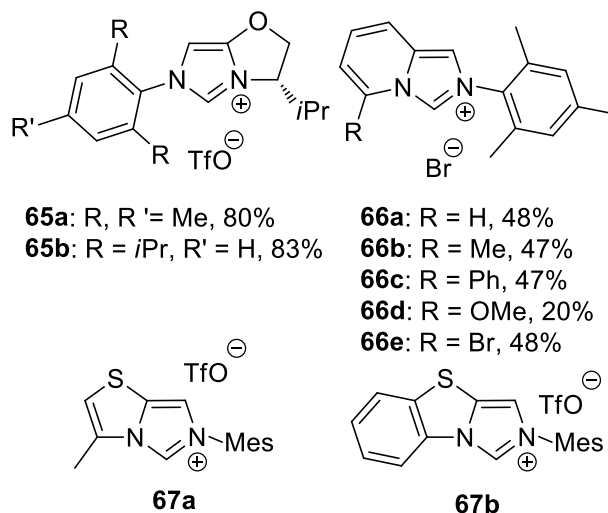


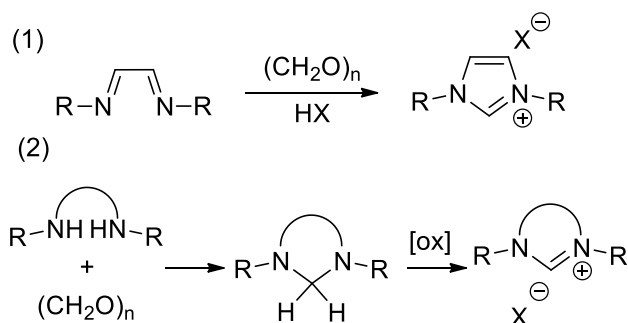
Chart 6. Unsymmetrical imidazolium salts obtained via the chloromethyl pivalate/silver triflate route.

The utilization of “Glorius’ reagent” was found to be quite versatile since, besides the examples discussed above, it was successfully applied to the synthesis of more classical imidazolium salts from the corresponding bis-imines.^{25c,65,82a,91} In some cases, silver triflate could even be omitted. However, the substrate scope of this route (and of all the alkylation methods actually) is limited to “non-enolizable” bis-imines, since a competitive and preferential alkylation reaction may occur at the α -carbon due to an imine-enamine equilibrium.

2.3 Using paraformaldehyde as the pre-carbenic unit

Paraformaldehyde can be employed as C₁-building block for the synthesis of both unsaturated and saturated NHC-precursors. As shown in Scheme 28, treatment of 1,2-diimines with paraformaldehyde in

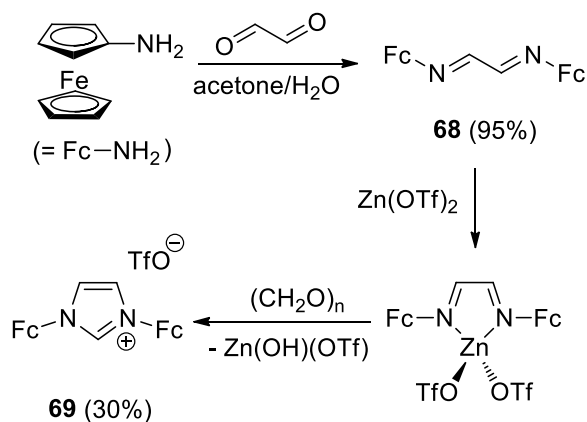
the presence of one equivalent of acid affords the corresponding imidazolium salts (eq. 1), whereas the parallel treatment of diamines leads to cyclic amins which can be further converted into the corresponding cyclic formamidinium salts by oxidation (eq. 2).



Scheme 28. Synthesis of (un)saturated NHC-precursors using paraformaldehyde as C₁ building block.

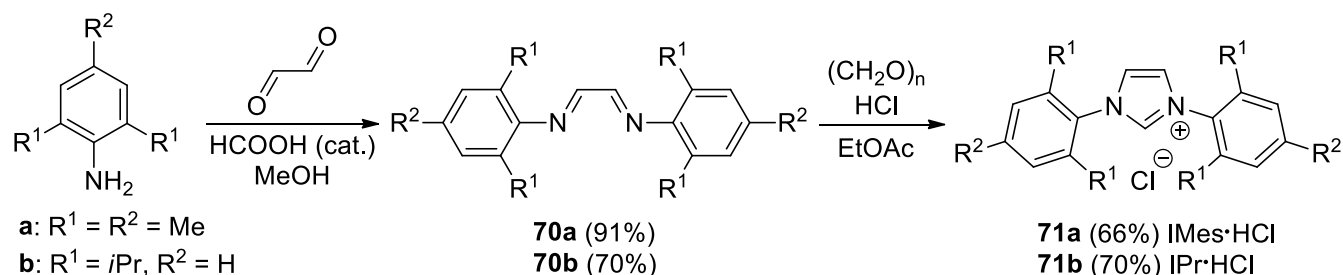
2.3.1 Imidazolium salts

The condensation of a N,N'-diaryldiazabutadiene (DAD) with paraformaldehyde was first reported by Bildstein and co-workers and applied to the synthesis of redox-active ferrocenyl-substituted NHC-precursors in 1999.⁹² Starting from N,N'-diferrocenyl-1,4-diaza-1,3-butadiene **68** which can be easily prepared in 95% yield by condensation of aminoferrocene with aqueous glyoxal, the N,N'-disubstituted imidazolium salt **69** was then synthesized by activation of N,N'-diferrocenyl-1,4-diaza-1,3-butadiene with the strong Lewis acid Zn(OTf)₂ followed by ring closure with paraformaldehyde and elimination of zinc hydroxide triflate albeit in low yield (Scheme 29).



Scheme 29. Synthesis of N,N'-diferrocenylimidazolium triflate **69**.

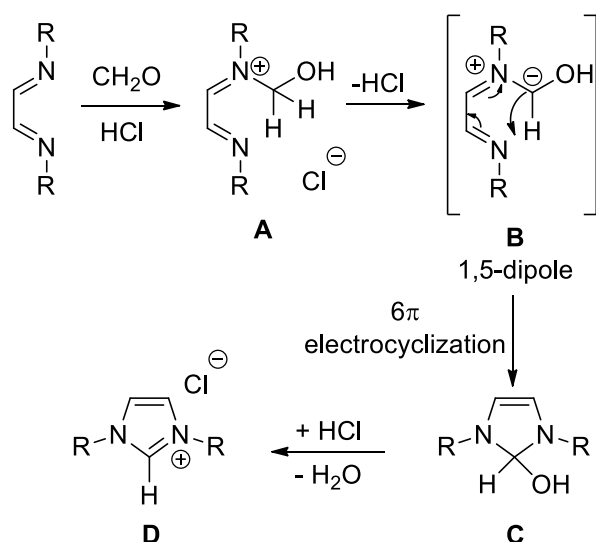
Soon after, Nolan and co-workers developed an efficient and scalable synthesis for the formation of the most studied and used imidazolium chlorides IMes·HCl (**71a**) and IPr·HCl (**71b**) (Scheme 30).⁹³ Typically, mixing the substituted aniline with aqueous glyoxal in methanol with a catalytic amount of acid leads to the rapid precipitation of the diazabutadienes **70a-b**. In a second step, the bis-imines **70a-b** are reacting with paraformaldehyde and hydrogen chloride (4M in dioxane) under anhydrous conditions. The imidazolium chlorides **71a-b** are precipitating along the course of the reaction and are collected as white to beige powders. This procedure works well for the title compounds **71**, but, as all the synthetic methods for imidazolium salts, it remains capricious and the conditions should be adapted to each substitution pattern of the imidazolium. Nevertheless, this route is efficient for a large number of anilines with various substituents,^{24,25} except those with strongly electron-withdrawing groups (i.e. -CF₃ or -NO₂), and even for alkylamines.⁹⁴ However, unsymmetrical imidazolium salts are not accessible since the condensation of amines with glyoxal is an equilibrium reaction and would lead to a mixture of diazabutadienes. As a special case, 2-iminopyridines are suitable substrates for this cyclization and lead to the formation of 2H-imidazo[1,5-a]pyridin-4-ium salts.⁹⁵



Scheme 30. Synthesis of symmetrical N,N'-diaryl-imidazolium salts **71a-b**.

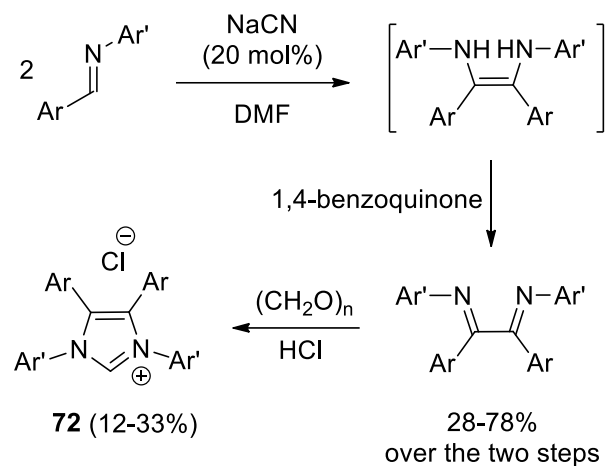
Hintermann reported an improved procedure for the synthesis of **71a-b**, consisting in using chlorotrimethylsilane instead of anhydrous hydrogen chloride as a cheaper and more readily available chloride source.⁹⁶ Under such optimized conditions, the yields were improved up to 69% and 81% for **71a** and **71b** respectively. The same author also proposed a plausible mechanism based on an 1,5-dipolar cyclization (Scheme 31): Alkylation of the diazabutadiene by formaldehyde and HCl (or

Me₃SiCl) leads to the iminium salt **A**. Loss of HCl from **A** gives an imino-azomethynylidene 1,5-dipole **B**, which subsequently undergoes a 6 π electrocyclicization⁹⁷ to form the hydroxyimidazoline **C**. Elimination of water by reprotonation then generates the imidazolium salt **D**.



Scheme 31. Plausible mechanism for the condensation of diazabutadiene with formaldehyde in the presence of acid.

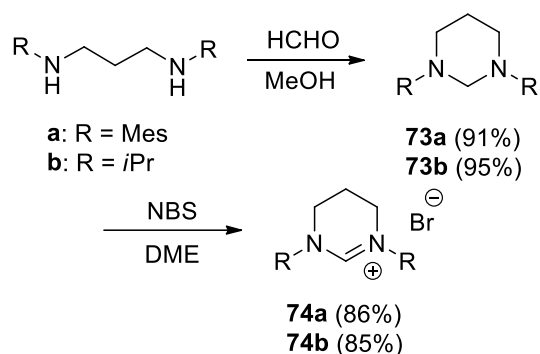
Miller and co-workers reported a new and interesting method for the synthesis of highly substituted NHC-precursors such as 1,3,4,5-tetraarylimidazolium salts **72**. This involves a cyanide ion-catalyzed intermolecular coupling of aromatic aldimines followed by oxidation with 1,4-dibenzoquinone to give symmetrical diketimines, whereas the cyclization is achieved by using paraformaldehyde under acidic conditions (Scheme 32).⁹⁸ Notably, this catalysis proved to be efficient to access 1,2-diimines with sterically demanding substituents.⁹⁹



Scheme 32. Synthesis of C-aryl and N-aryl substituted imidazolium salts **72**.

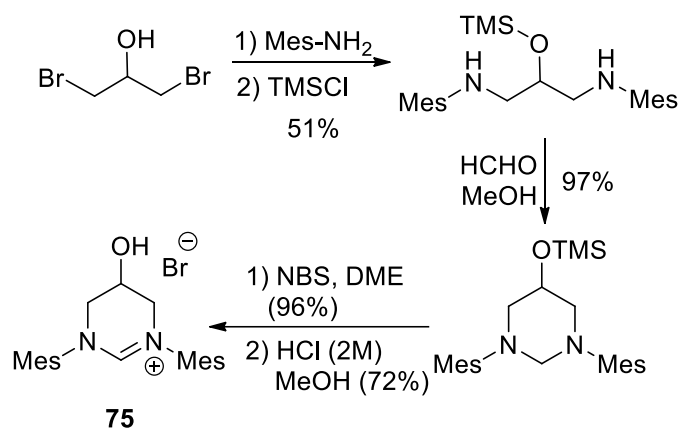
2.3.2 Via oxidation of a cyclic aminal

Perillo and co-workers firstly reported the synthesis of saturated 6-membered NHC-precursors using the paraformaldehyde route. 1-aryl-3-substituted-3,4,5,6-tetrahydropyrimidinium salts were prepared by cyclization of the corresponding diamines into hexahydropyrimidines,¹⁰⁰ followed by dehydrogenation using *N*-halosuccinimide.¹⁰¹ Buchmeiser and colleagues applied this method to the preparation of symmetrical 1,3-dimesityl- and 1,3-diisopropyl-3,4,5,6-tetrahydropyrimidinium bromides **74a-b**. The cyclization of *N,N'*-disubstituted-propane-1,3-diamine by means of aqueous formaldehyde afforded the corresponding 1,3-disubstituted-hexahydropyrimidine **73a-b** which was then reacted with *N*-bromosuccinimide to yield **74a-b** (Scheme 33).¹⁰²



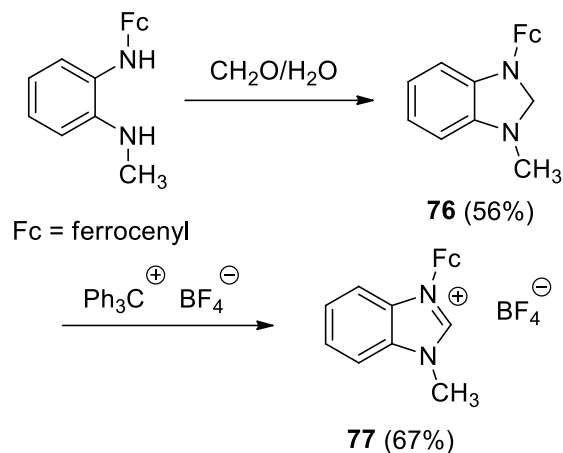
Scheme 33. Synthesis of 1,3-dimesityl- and 1,3-diisopropyl-3,4,5,6-tetrahydropyrimidinium bromides **74a-b**.

Using the same approach, 5-hydroxy-1,3-dimesityl-3,4,5,6-tetrahydropyrimidinium bromide was synthesized from 1,3-bis(mesitylamino)-2-hydroxypropane, which was subject to *O*-protection with chlorotrimethylsilane prior to cyclization with paraformaldehyde and addition of N-bromosuccinimide to afford an *O*-protected tetrahydropyrimidinium salt (Scheme 34). Deprotection yielded the 5-hydroxy-1,3-dimesityl-3,4,5,6-tetrahydropyrimidinium bromide **75** which may be further functionalized to be used as a supported catalyst precursor.¹⁰³ It should be noted that the cyclization step here requires only neutral conditions, contrary to the triethyl orthoformate route, and therefore is applicable to acid-sensitive substrates. Probably for the same reasons, Cavell and co-workers used this route for the synthesis of a seven-membered NHC-precursor containing a strained 5,6-dioxolane moiety.^{55a}



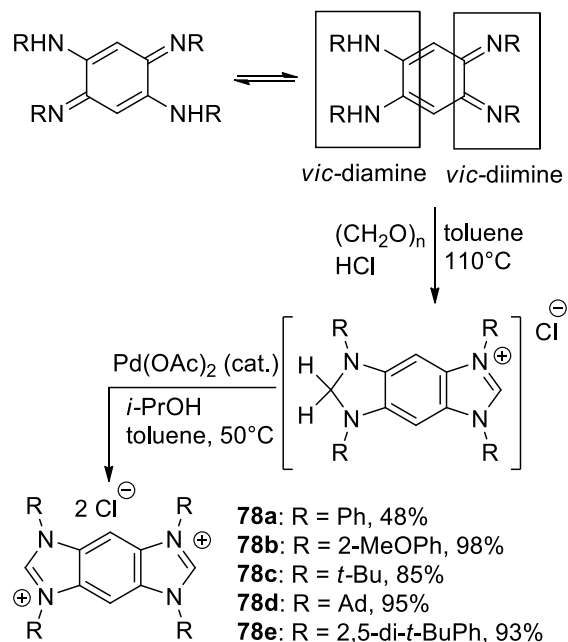
Scheme 34. Synthesis of 5-hydroxy-1,3-dimesityl-3,4,5,6-tetrahydropyrimidinium derivative **75**.

The paraformaldehyde route is applicable to benzimidazolium derivatives as well. The condensation of N-ferrocenyl-N'-methyl-1,2-diaminobenzene with aqueous formaldehyde was found to afford the 1-ferrocenyl-3-methyl-benzimidazoline **76** which was then oxidized with trityl tetrafluoroborate into the benzimidazolium tetrafluoroborate **77** (Scheme 35).¹⁰⁴



Scheme 35. Synthesis of the ferrocenyl-substituted benzimidazolium salt **77**.

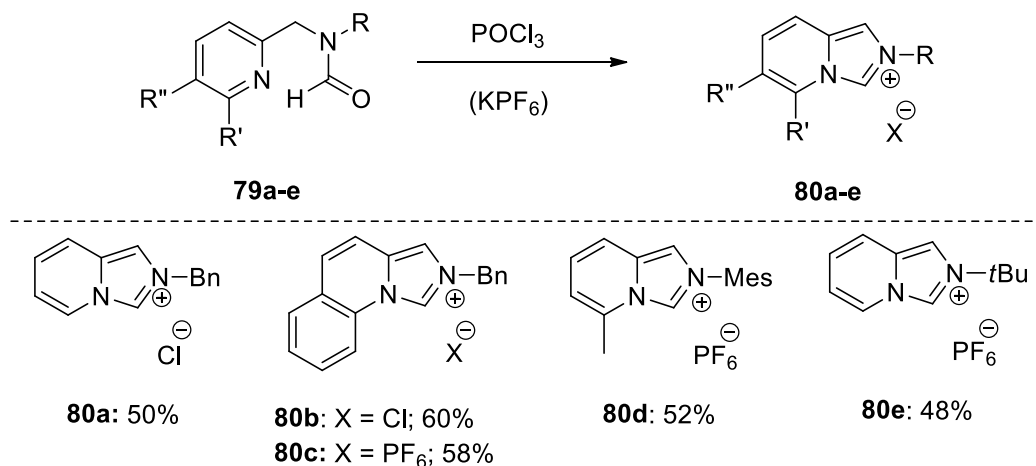
Finally, an analogous cyclization reaction was carried out on 2,5-diamino-1,4-benzoquinonediimines which may exhibit an *ortho*- and *para*-quinoid equilibrium to yield annulated benzimidazolium/*N,N'*-aminal hybrids.¹⁰⁵ The Pd-mediated oxidation¹⁰⁶ of this intermediate afforded the respective benzobis(imidazolium) salts **78a-e** (Scheme 36).



Scheme 36. One-pot cyclization/oxidation reaction sequence to yield various benzobis(imidazolium) salts **78a-e**.

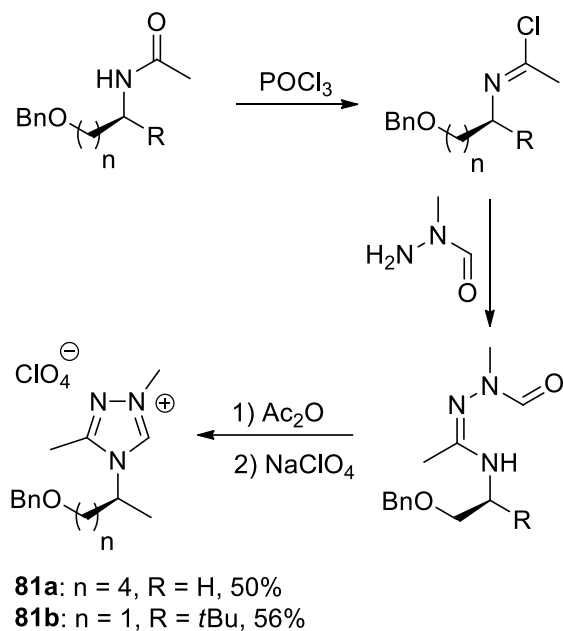
2.4 Cyclization *via* a pre-installed formamide

A less common method to access imidazolium salts is based on the formation of a formamide followed by cyclization. For example, Lassaletta and colleagues used an intramolecular condensation reaction of formamide derivatives **79a-e** using phosphoryl chloride to yield imidazo[1,5-a]pyridinium salts **80a-e** (Scheme 37) in moderate yields (48-60%).¹⁰⁷



Scheme 37. Intramolecular cyclization of formamide derivatives **79a-e** into imidazo[1,5-a]pyridinium salts **80a-e**.

Triazolium salts may also be formed by formamide cyclization.¹⁰⁸ Starting from *O*-benzyl protected aminoalcohols, the synthesis of triazolium salts **81a-b** was achieved in a one-pot procedure using phosphoryl chloride to yield isolable imidoyl chlorides, which were subsequently reacted with *N*-formyl-*N*-alkylhydrazine (obtained from alkyl hydrazine and methyl formate).¹⁰⁹ Cyclization with acetic anhydride followed by anion exchange afforded the desired triazolium perchlorates (Scheme 38). Benzyl deprotection gave hydroxy-functionalized triazolium salts which were then attached to a Merrifield resin.



Scheme 38. One-pot synthesis of trialkyl-substituted triazolium salts **81a-b**.

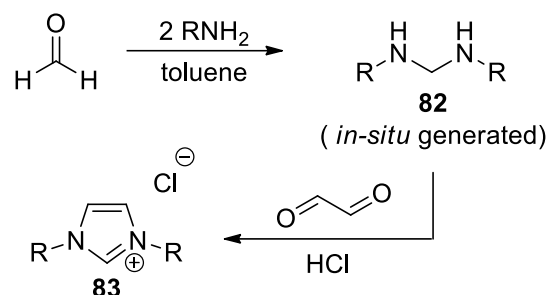
3. Ring closing by the final introduction of the backbone

Whereas the previous section dealt with cyclization reactions involving the final introduction of the C_1 pre-carbenic unit, we will consider here the second general synthetic route consisting in a capping of the pre-carbenic unit with the desired heterocyclic backbone. We will show that this strategy does not only produces "classical" heterocyclic precursors, but also provides access to more unusual compounds, and is thus complementary to the one presented above. This section will be organized around the nature of the pre-carbenic function, i.e. i) reaction onto an amination moiety, ii) functionalization of a formamidine and cyclization onto iii) an imine, iv) a phosphoformamidinate and v) a thioformamide.

3.1 Condensation onto an amination moiety

The synthesis of N,N' -disubstituted symmetric imidazolium salts by one-pot condensation between glyoxal, two equivalents of aliphatic or aromatic amine, and an equivalent of paraformaldehyde in the presence of hydrochloric acid was actually the original procedure patented by Arduengo in 1991.¹¹⁰ In a typical experiment, this protocol starts with the dropwise addition of two equivalents of the amine to a

suspension of paraformaldehyde in toluene, leading to the *in-situ* formation of the N,N'-disubstituted aminal **82** (Scheme 39). The imidazolium chloride **83** is then obtained through the condensation of this intermediate with one equivalent of hydrochloric acid and one equivalent of aqueous glyoxal.



Scheme 39. One-pot, four-component procedure for the preparation of imidazolium chlorides **83** according to Arduengo.

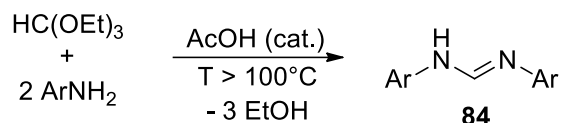
Although this synthetic strategy is straightforward and is efficient for a number of alkyl and aryl amines (for example: *i*-propylamine,¹¹⁰ *n*-propylamine,¹¹⁰ *p*-toluidine,¹¹⁰ cyclohexylamine,¹¹¹ chiral 1-(aryl)alkylamines,¹¹² mesitylamine,¹¹³ 3,5-di-*tert*-butylaniline¹¹⁴), it suffers from a lack of generality since the majority of anilines and/or sterically congested amines fail to react or lead to low yields of product (in particular, IPr·HCl could not be synthesized) and from the characteristic generation of dark-brown to black impurities which render the imidazolium purification tedious, requiring numerous washings and/or column chromatographic workup. For these reasons, after having been the only one available for a while, the method has given way to cleaner and more efficient ones.

3.2 Cyclization starting from a N,N'-disubstituted formamidine

This strategy emerged quite recently (6-7 years ago) and is now used more and more frequently because of the numerous possibilities afforded for making the "classical" NHC-precursors but also more sophisticated structures only available by this route. In a first part, the synthesis of N,N'-disubstituted formamidines - the common starting platform - is detailed. Then, the different cyclizations are listed by the type of cyclization involved.

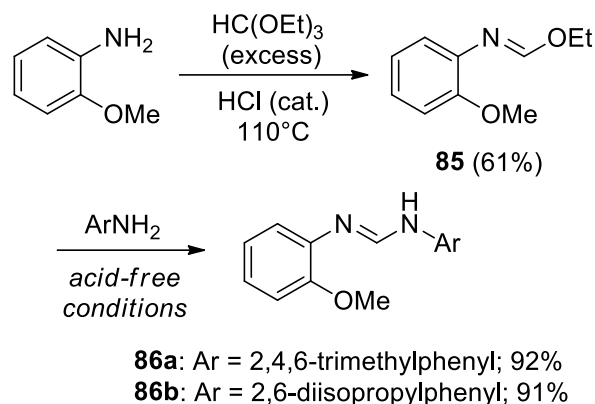
3.2.1 Preparation of N,N'-disubstituted formamidines

N,N'-diarylformamidines have been known for more than a century¹¹⁵ and a simple, practical synthesis was first disclosed by Roberts in 1949, who evidenced in particular the key catalytic role of acids.¹¹⁶ Formamidines **84** are indeed obtained in one-step through the condensation of one equivalent of triethyl orthoformate with two equivalents of a primary aniline in the presence of a catalytic amount of acetic acid (usually 5 mol%) at a temperature over 110-120°C (Scheme 40). The ethanol is distilled out of the reaction mixture to shift the equilibrium to the formation of the symmetric N,N'-diarylformamidine **84**. The procedure is high yielding, easy to perform, can be carried out on large scale, and is efficient for a large palette of anilines.¹¹⁷ As the N,N'-diarylformamidines **84** are also air- and moisture stable, all those advantages make them ideal starting materials for the construction of symmetric and cyclic formamidiniums, the precursors of the most common cyclic diaminocarbenes.



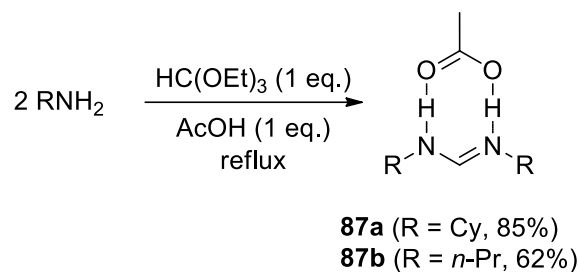
Scheme 40. General scheme for the preparation of symmetric N,N'-diarylformamidines **84**.

Unsymmetric N,N'-diarylformamidines could also be obtained by a slight modification of the procedure. As an illustrating example, the synthesis of N-(anisid-2-yl)-N'-arylformamidine **86a-b** is represented in Scheme 41.¹¹⁸ In a first step, the ethyl formimidate **85** was obtained by the acid-catalyzed condensation of *o*-anisidine with an excess of triethyl orthoformate, according to the procedure described by DeWolfe.¹¹⁹ Condensation of this iminoester with a second equivalent of aniline under acid-free conditions yielded formamidines **86a-b** in good yields. The absence of any trace of acid is necessary in order to render this second reaction irreversible and thus to exclude a thermodynamic distribution of the aryl groups on the two nitrogen atoms.¹²⁰



Scheme 41. Stepwise synthesis of unsymmetric diarylformamidines **86a-b**.

In contrast to anilines, alkyl amines failed to react with triethyl orthoformate under the conditions stated in Scheme 40. Taylor *et al.* indeed demonstrated that a full equivalent of acetic acid (relative to triethyl orthoformate) is required for the formation of the N,N'-dialkylformamidinium acetates **87a-b** (Scheme 42).¹²¹ These compounds were purified by crystallization (**87a**) or even by direct distillation (**87b**). The free N,N'-dialkylformamidines could then be generated by deprotonation with sodium carbonate. Nevertheless, some precautions have to be taken, since the N,N'-dialkylformamidines are usually more sensitive toward hydrolysis than their aryl-substituted congeners.

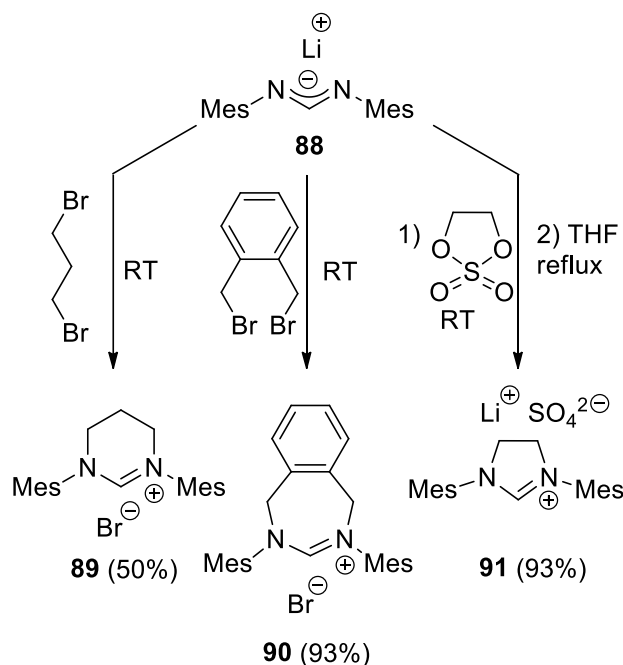


Scheme 42. Synthesis of N,N'-dialkylformamidinium acetates **87a-b**.

3.2.2 Cyclization via a bis-alkylation route

In 2006, Bertrand and co-workers reported the preparation of 5-, 6- and 7-membered carbene precursors **89-91** via reaction of the lithium formamidinate **88** (simply obtained by deprotonation of the corresponding formamidine with *n*BuLi in THF) with different alkyl bis-electrophiles (Scheme 43).¹²²

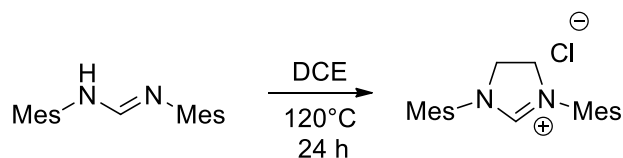
1,3-dibromopropane and α,α' -dibromo-*o*-xylene are suitable alkylating reagents for the preparation of **89** and **90** respectively. However, the imidazolium **91** is not available by addition of 1,2-dibromoethane to **88**, since a preferred HBr-elimination reaction occurs due to the high basicity of the formamidinate anion. Fortunately, the 1,3,2-dioxathiolane-2,2-dioxide readily acts as the bis-electrophile, but, as alkylsulfonates are less reactive than alkyl bromides, the quaternization of the second nitrogen needs to be performed at higher temperature in this case.



Scheme 43. Bis-alkylation of lithium formamidinate **88** according to Bertrand and co-workers.

Though the latter protocol is straightforward, it necessitates inert/moisture free conditions and is thus limited to substrates that tolerate a strong organolithium reagent. So, the alternate use of a neutral formamidine would be highly desirable for a more convenient synthesis. Grubbs and Kuhn thus developed in 2008 a very simple and straightforward preparation of imidazolium chlorides involving the direct reaction of formamidines with an excess of dichloroethane (DCE) (Scheme 44).¹²³ The reactions were carried out in 10-20 equivalents of neat dichloroethane in the presence of a slight excess of an external base (diisopropylethylamine, DIPEA) (method A) or without any base (method B). In the latter case, one half of the starting formamidine serves as sacrificial base and can thus be recovered at

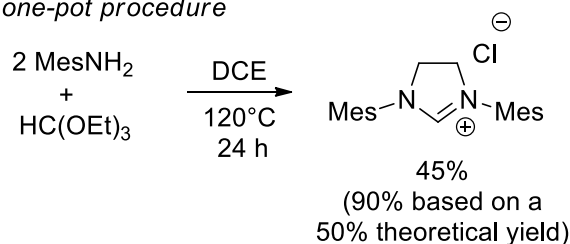
the end of the reaction. Yields are generally good to excellent but are seen to decrease with the steric hindrance brought by the *ortho* substituents of the aryl groups. Unsymmetric formamidines were also found to be suitable substrates, except dialkylformamidines probably due to their high basicity. Finally, the symmetric N,N'-diarylformamidine, as intermediate and base, could even be formed *in-situ* in a one-step, three-component synthesis starting from aniline, triethyl orthoformate and DCE.



method A: with *i*Pr₂NEt, yield = 92%

method B: no base, yield = 49%
(98% based on a 50% theoretical yield)

one-pot procedure

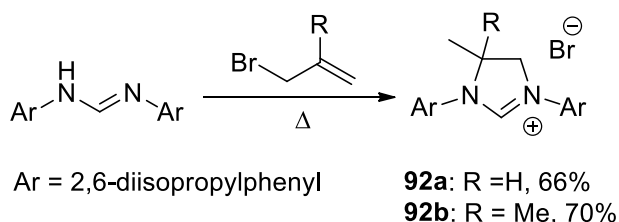


Scheme 44. Synthesis of SIMes·HCl by alkylation with dichloroethane (DCE) according to Grubbs.

Around the same period, Cavell, Dervisi, Fallis and co-workers reported a similar procedure based on the use of a bis-electrophile in presence of half an equivalent of potassium carbonate in refluxing acetonitrile. This allowed the preparation of an extended range of cyclic carbene precursors exhibiting various ring sizes including imidazolium, tetrahydropyrimidinium and tetrahydrodiazepinium cores.¹²⁴ Both preparations can be carried out in air, without any special precaution and are operative on large-scale (20 - 30 g were reported). Inherent to the alkylation reaction, some undesirable side-products are formed by alternative ring-closure with a N-mesityl-N'-(pyridin-2-yl)-formamidine as substrate (due to the competition between pyridyl- and formamidinyl-nitrogens),¹¹⁸ or with 1,4-dichlorobut-2-ene as bis-electrophile (SN2 vs SN2' reaction).¹²⁵ Fortunately, the formation of such side products can be avoided by simple optimization of the temperature conditions, and by using bromoalkyl instead of iodoalkyl.

3.2.3 Cyclization by alkylation-hydroiminium sequence

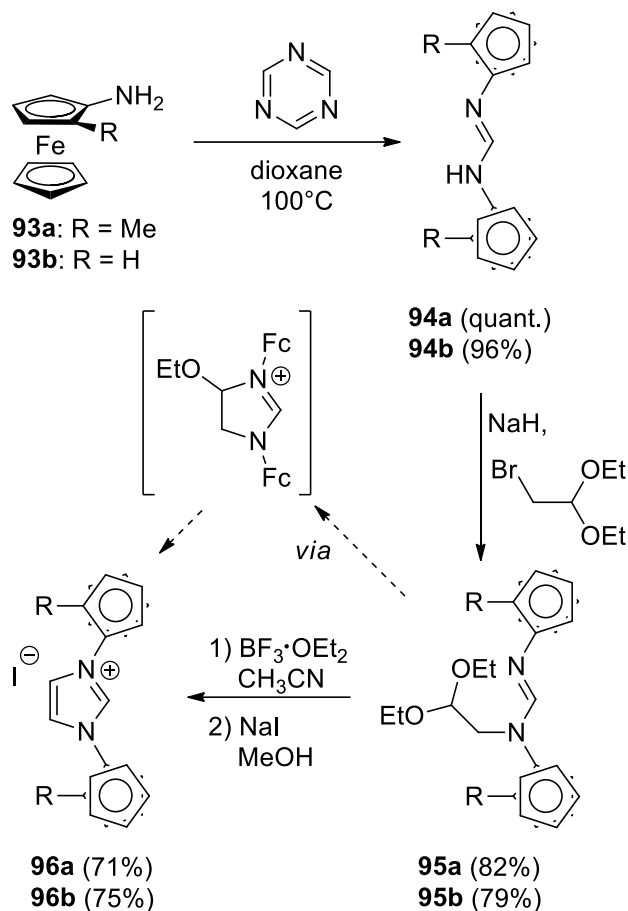
In 2007, Bertrand and colleagues reported the synthesis of cyclic iminium chlorides by a "hydroiminium" strategy (see section 3.3 for details). Despite the increased basicity of formamidines relative to imines, these authors successfully applied this methodology to the synthesis of imidazolium salts (Scheme 45).¹²⁶ Starting with the reaction of the formamidine with allyl chloride, they first developed a two-step sequence where the intermediate alkenylformamidine is isolated and subsequently reacts with hydrogen chloride to form the corresponding imidazolium salt. However, since HX, needed for the second step, is generated *in-situ* by the alkylation reaction, the synthesis of imidazolium salts **92a-b** can be performed in a one-pot procedure (Scheme 45), which constitutes a valuable practical advantage.



Scheme 45. Synthesis of **92a-b** using a one-pot, alkylation-hydroiminium procedure.

3.2.4 Cyclization by alkylation-condensation reactions

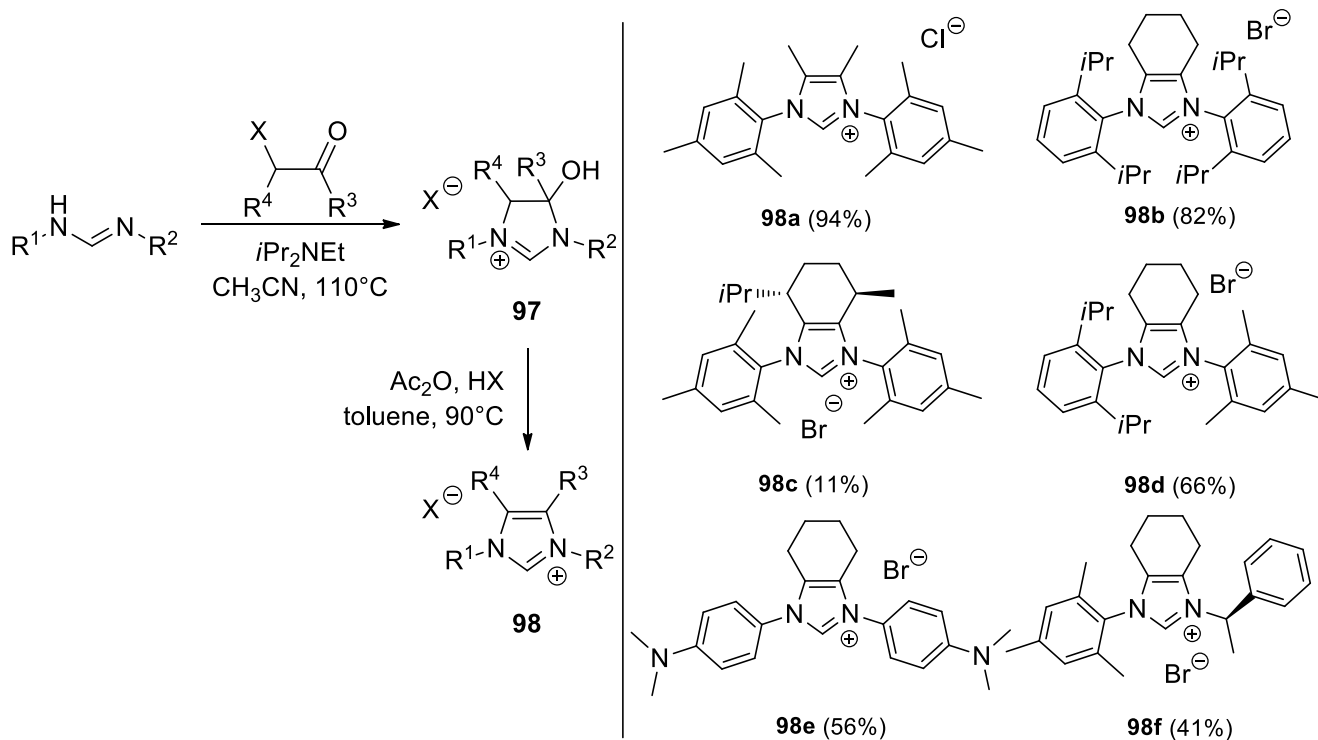
In 2005, Togni and coworkers reported a new synthetic strategy for the preparation of chiral and achiral N,N'-diferrocenylimidazolium salts **96a-b**,¹²⁷ starting from the electron rich, strongly nucleophilic and air-sensitive aminoferrocenes **93a-b** (Scheme 46).¹²⁸ In this special case, the formation of formamidines **94a-b** was accomplished by the introduction of the methinyl group from *s*-triazine,¹²⁹ whereas the C₂-fragment was introduced by treating **94a-b** with sodium hydride and bromoacetaldehyde-diethylacetal to give the acetal intermediates **95a-b**. Addition of an excess of BF₃·OEt₂ led to cyclization into 4-ethoxyimidazolium cations, and under prolonged heating allowed the aromatization of the imidazolium core by ethanol elimination. The imidazolium iodides **96a-b** were finally isolated after a counter-anion exchange with an excess of NaI in methanol.



Scheme 46. Formation of imidazolium iodides **96a-b** by use of bromoacetaldehyde diethylacetal.

Glorius and co-workers recently reported a versatile and modular one-pot method for the preparation of 4,5-dialkylimidazolium salts **98**.¹³⁰ The procedure involves the use of α -halo ketones, which are commercially available or easily prepared, for example, by bromination of ketones. In the key step, formamidines and the α -halo ketones are coupled at 110°C in presence of diisopropylethylamine (*i*Pr₂NEt) in acetonitrile to yield the 4-hydroxyimidazolinium salts **97**, which are the same intermediates as in the heterocyclic interconversion strategy developed by Fürstner et al. (see section 4.1). The aromatic imidazolium salts were obtained by an acylation-induced dehydration using acetic anhydride at 90°C. 19 examples were given with various 4,5-substitution patterns ranging from simple alkyl substituents (**98a**), to 4,5-annelated achiral (**98b**) or even chiral (**98c**) cycle, with sterically (**98d**) and/or electronically (**98e**) different aryl groups on the nitrogens and even with a chiral alkyl arm (**98f**).

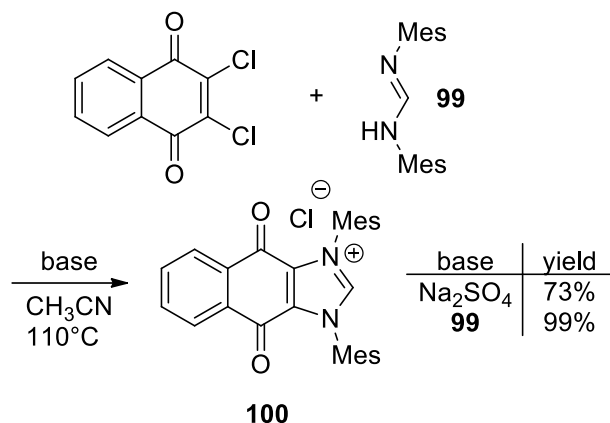
Noticeably, the procedure was recently used by Bertrand and co-workers for the synthesis of C2-substituted imidazolium salts, namely the N,N'-bis(1,3-bis(2,6-diisopropylphenyl)-2,4-diphenylimidazolium salts.¹³¹ By deprotonation of these precursors, the generation and the isolation of the first *free* “abnormal” NHC were possible.¹³²



Scheme 47. Modular one-pot preparation of various 4,5-dialkylimidazolium salts according to Glorius' method.

3.2.5 Cyclization via an amination reaction

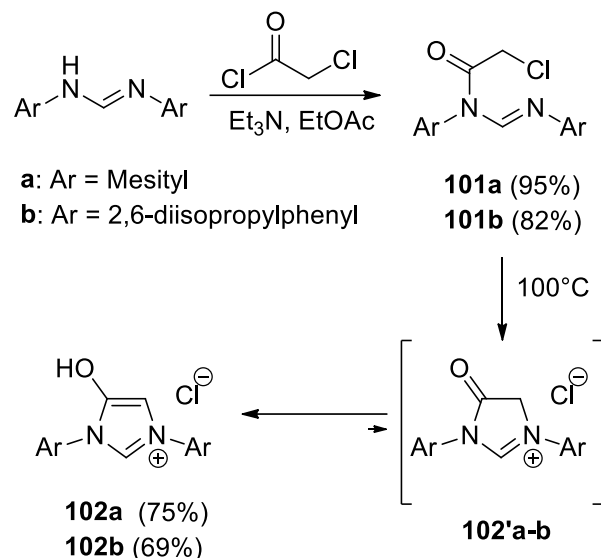
In 2006, Bielawski and coworkers reported the first synthesis of quinone-annulated imidazol-2-ylidene, whose imidazolium precursor **100** was obtained by a condensation reaction between N,N'-dimesitylformamidine **99** and 2,3-dichloro-1,4-naphthoquinone in acetonitrile under mildly basic conditions (Na_2SO_4).¹³³ Although the yield was already satisfactory (73%), they recently found that the use of an additional equivalent of formamidine as sacrificial base in place of sodium sulfate yields quantitatively a 1:1 mixture of **100** and formamidinium chloride **99**·HCl, from which the product can be easily isolated after a selective regeneration of **99** with NaHCO_3 .¹³⁴



Scheme 48. Synthesis of the quinone-annulated imidazolium chloride **100**.

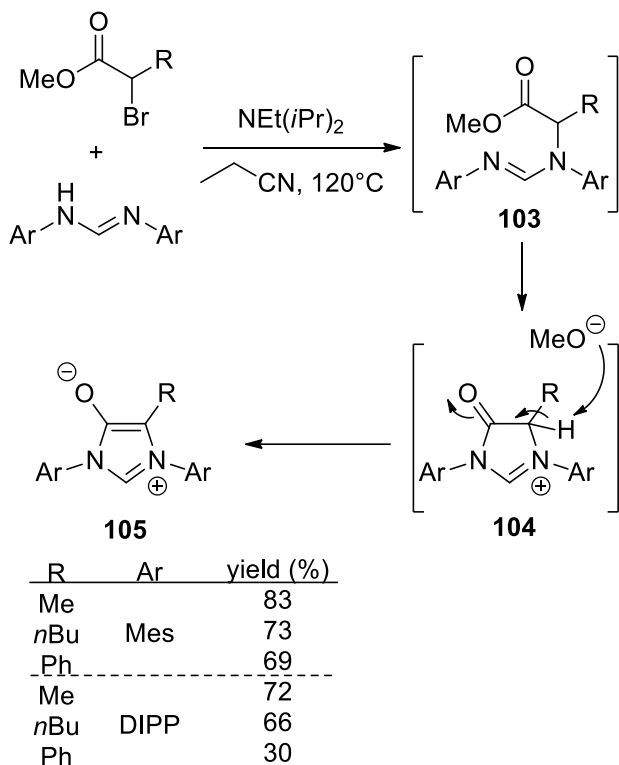
3.2.6 Cyclization via an alkylation-acylation sequence

In 2009, César, Lavigne and co-workers reported the synthesis of a new anionic 5-membered N-heterocyclic carbene, namely a lithium imidazol-2-ylidene-4-olate bearing an enolate unit as the C₂ heterocyclic backbone.¹³⁵ Based on the keto-/enol- equilibrium of hydroxyaromatics, the 4-hydroxyimidazolium chloride **102**, precursor of this carbene, was prepared in two steps by acylation of the N,N'-diarylformamidines with chloroacetyl chloride, giving compound **101**, which was readily cyclized by quaternization of the second nitrogen. The intermediate 4-oxoimidazolium **102'** was not detected due to its fast conversion into the more stable 4-hydroxyimidazolium **102** (Scheme 49). Clearly, here, the aromaticity of the imidazolium ring appears as the driving force favoring an equilibrium shift toward the enol form.



Scheme 49. Synthesis of 4-hydroxyimidazolium chlorides **102** according to César and Lavigne.

Soon after, Glorius and coworkers, in analogy to their synthetic procedure for imidazolium salts based on α -halo ketones (see section 3.2.4), developed a straightforward preparation of 5-substituted-imidazolium-4-olate **103** (Scheme 50).¹³⁶ This one-pot procedure starts with the alkylation of the formamidine with an α -bromo methylester in presence of Hünig's base (*i*Pr₂NEt) to form the intermediate **103**, which readily cyclizes by quaternization of the second nitrogen to yield the 4-oxoimidazolinium salt **104** and finally the mesomeric betaine¹³⁷ **105** with concomitant formation of methanol. This reaction was found to be specific for the methyl α -bromo esters, since reactions with ethyl esters stop after the substitution step. Several substitution patterns of the zwitterion were synthesized but as in the previous example, the method was found to be limited to N,N'-diarylformamidines. Noticeably, the 5-unsubstituted mesoionic heterocycle analogous to **105** was also generated and isolated by deprotonation of compound **102** with triethylamine.



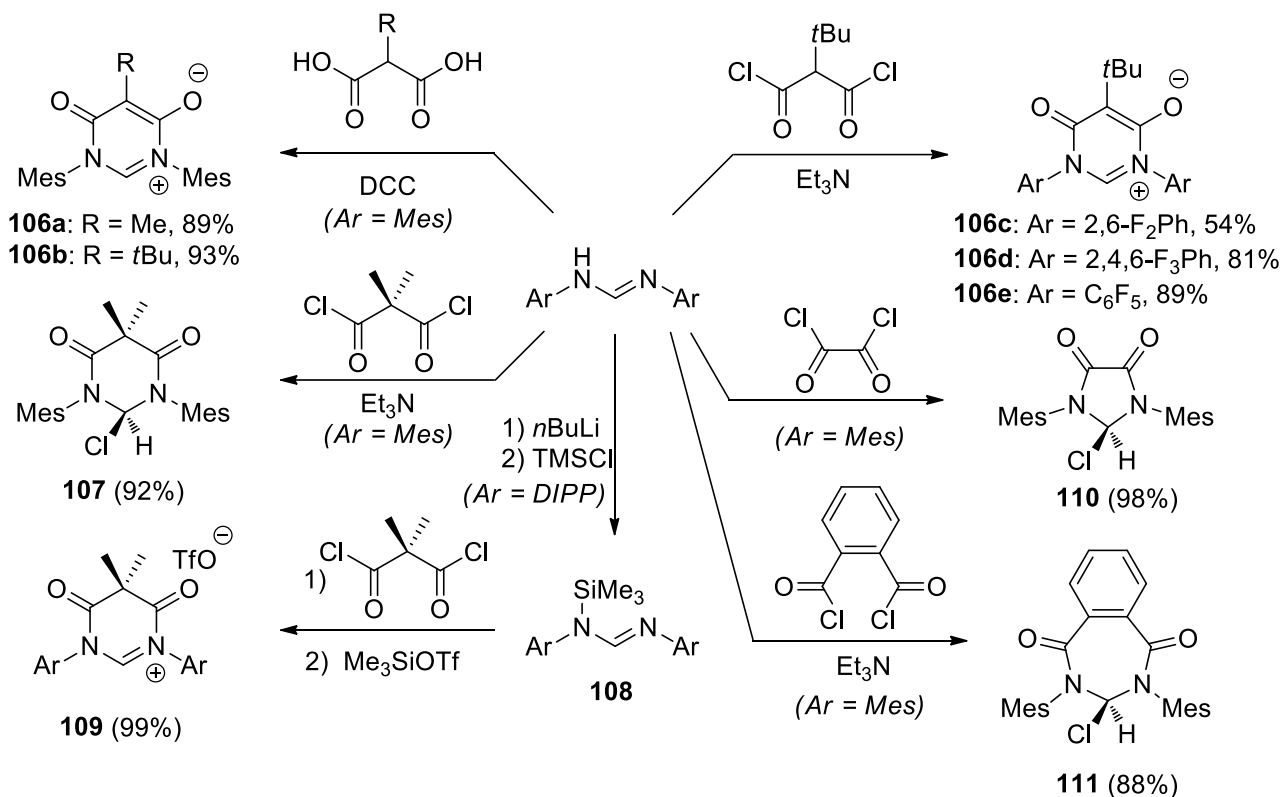
Scheme 50. Synthesis of the zwitterionic imidazolium-4-olate **105** by Glorius and co-workers

3.2.7 Cyclization by bis-acylation of the formamidine

Whereas pyrimidinium betaines of type **106** have been repeatedly reported in literature,¹³⁸ they were only recently found to be suitable precursors for the preparation of a series of anionic six-membered NHCs bearing a malonate backbone (Scheme 51).¹³⁹ Mesoionic heterocycles **106a-b** were obtained by a high-yielding peptide-type coupling between N,N'-dimesitylformamidine and a mono-substituted malonic acid with dicyclohexylcarbodiimide (DCC) as the activator. Alternatively, such compounds could be generated by reacting a formamidine directly with a mono-substituted malonyl dichloride derivative in presence of a base as exemplified by the synthesis of compounds **106c-e**.¹⁴⁰ These compounds are neutral, stable against air and moisture and can be easily purified by column chromatography. Concerning their electronic structure, they are best described as constituted by two separate π -electrons subunits: a six- π -electron malonate unit and a 4- π -electron formamidinium unit; but in order to have a more classical view of the distribution of double bonds and charges within the

betaine, the mesomeric structure represented in Scheme 51 is also used.

In a transposition of the latter procedure, compound **107** was prepared by coupling N,N'-dimesitylformamidinium with dimethylmalonyl dichloride in dichloromethane in the presence of an excess of triethylamine as a base.¹⁴¹ Surprisingly, it did not display any salt-like character, being in particular soluble in aromatic solvents. The compound is in fact a masked formamidinium formulated as **107**, in which the incipient chloride anion has attacked the C(2) carbon center of the diamidomethyne nucleus, rendered sufficiently electrophilic by the attachment of the two electron-withdrawing carbonyl functionalities onto the nitrogen atoms.¹⁴² Nevertheless, **107** can be deprotonated to yield the corresponding diamidocarbene. The intermediate formamidinium **108** was even prepared and isolated (the synthesis of **108** was actually anterior to that of **107**).¹⁴³ For this purpose, weakly nucleophilic chloride atoms were trapped as chlorotrimethylsilane by means of trimethylsilylformamidinium **108** and trimethylsilyl triflate. Compound **109** was found to rapidly decompose in presence of water and other coordinating solvents, including THF. This high reactivity is a testament of the highly electrophilic nature of the cation. In that sense, the "chloride-stabilized" compound **107** was thought to be a more convenient NHC-precursor. More recently, the 5-membered analogue of **107**, namely the 2-chloro-4,5-dioxoimidazolidine **110**, was synthesized in 98% yield by direct treatment of the formamidinium with oxalyl chloride.¹⁴⁴ In that case, no base is required since oxalyl chloride is much more reactive than dimethyl malonyl dichloride. Whereas the 4,5-dioxoimidazolin-2-ylidene derived from **110** is not stable in the free form, it could be generated at low temperature and immediately trapped by sulfur, isocyanide or a metallic precursor. Finally, this family was extended to 7-membered heterocycles with the synthesis of the 2-chloro-1,3-diazepin-4,7-dione **111** through condensation of N,N'-dimesitylformamidinium with phthaloyl chloride.¹⁴⁵



Scheme 51. Bis-acylations of formamidines leading to five-, six- and seven-membered heterocyclic compounds.

3.2.8 Introduction of an inorganic backbone

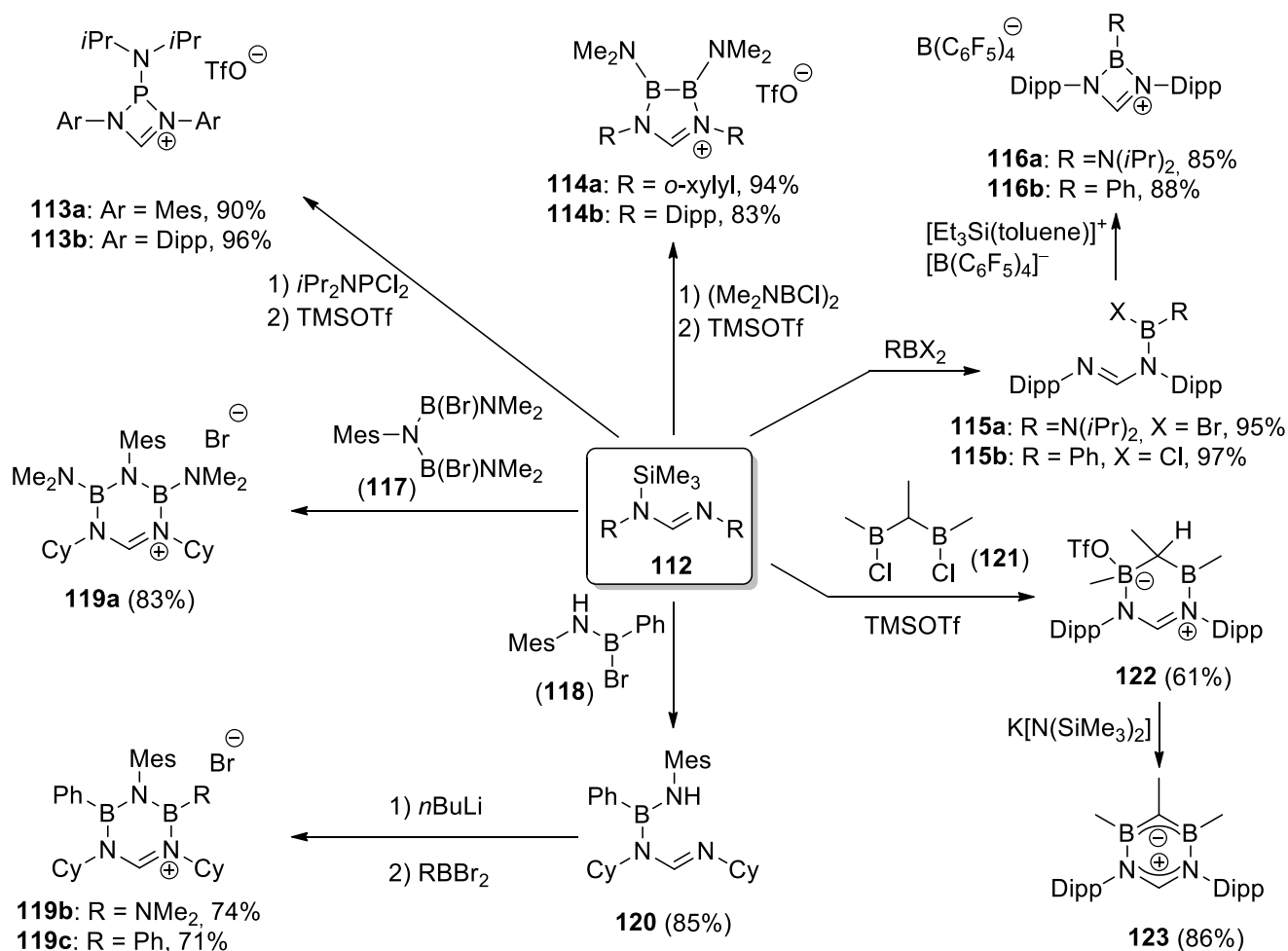
The term “NHC with an inorganic backbone” refers here to a cyclic diaminocarbene whose skeleton contains main-group elements such as phosphorus and boron. Actually, all the precursors for such NHCs were obtained by grafting the inorganic moiety to a N-silyl-N,N'-disubstituted formamidine **112** (Scheme 52).

In 2004, Grubbs and Despagne-Ayoub successfully prepared the four-membered, phosphorus-containing cation **113** by coupling **112** with an aminodichlorophosphine in presence of trimethylsilyl trifluoromethanesulfonate (TMSOTf).¹⁴⁶ The latter reagent allowed the cyclization by abstraction of the chloride atom from the phosphorus center, which additionally facilitates the work-up since the only by-product is then the easily removable chlorotrimethylsilane. Soon after, Roesler and co-workers reported the first example of an NHC incorporating a boron-containing backbone, consisting of a 5-membered

B₂N₂C ring and generated from the imidazolium triflate **114**.¹⁴⁷ The diboron moiety was introduced using Grubbs' strategy with TMSOTf as the chloride scavenger. However, this strategy had to be adapted in the case of the four- π -electron, four-membered BN₂C cation reported by Bertrand and colleagues¹⁴⁸ Treatment of **112** with dibromodi(isopropylamino)borane indeed afforded the acyclic derivative **115a** in excellent yield. But the halogen-exchange with TMSOTf only gave the opened form **115** with trifluoromethanesulfonate instead of bromide. Fortunately, the use of tetra(pentafluorophenyl)borate [B(C₆F₅)₄]⁻, an even weaker coordinating anion, led to the desired cyclization product **116a**. It was then shown that compounds **116** were not antiaromatic despite the presence of 4 π -intracyclic electrons. The antiaromatic energy is released by a weak π -interaction between the endocyclic nitrogens and the boron center and an extensive delocalization over the NCN unit. The empty p orbital of boron is stabilized either by the lone pair of the exocyclic nitrogen in **116a** or even by the phenyl ring in **116b**, albeit to a smaller extent.

Six-membered, boron-containing cations were also reported, first by the group of Bertrand with the cationic carbon-containing heterocyclic equivalent of borazine **119**.¹⁴⁹ The symmetric, diisopropylamino-substituted derivative **119a** was obtained in one-step by condensation of **112** with compound **117**. Noticeably, the use of TMSOTf was not found necessary in this case to shift the reaction toward cyclization. The modulation of boron substituents necessitates another synthetic approach since 1,3-dibromo-1,3-diborane are only readily available with amino substituents. Thus, reaction of formamidine **112** with *B*-bromo aminoborane **118** yields the acyclic formamidine **120**, which cyclizes after deprotonation with *n*-butyllithium and reaction with a substituted dibromoborane into dissymmetric **119b** and symmetric **119c** in 74% and 71% yields respectively. Here again, the six π -electrons of the heterocycle are divided into two separate allyl moieties: a cationic four π -electron NCN and a neutral two π -electron BNB fragment. Finally, Roesler and co-workers reported the anionic equivalent **123** of **119** by formally replacing the (NR) fragment at the heterocyclic position 5 by an isolobal (CR)⁻ fragment.¹⁵⁰ The synthesis starts with the coupling of **112** with 1,1-

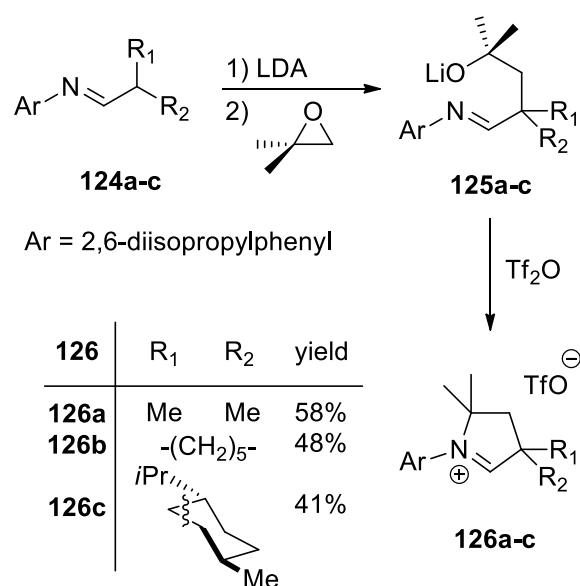
bis(methylchloroboryl)ethane **121** in presence of TMSOTf to form the zwitterionic heterocycle **122**, in which the triflate group is coordinated to one of the boron atoms in the solid state. The ^1H , ^{13}C and ^{11}B NMR spectra indicate a dissociation of the triflate in solution and the formation of an ion-pair with a C_s -symmetry. Deprotonation of **122** with potassium hexamethyldisilazide (KHMDs) cleanly yields the 1,5-diaza-2,4-diborine **123** exhibiting a planar $\text{N}_2\text{B}_2\text{C}_2$ heterocycle. As in the case of compound **119**, the six π -electrons appear to be distributed over two allyl-like fragments, a 4 π -electron N_2C^+ and a 2 π -electron B_2C^- system, to form a zwitterionic structure, rather than being delocalized over the entire ring framework. It should be also noted that despite being formally an anionic N-heterocyclic carbene, the compound generated by deprotonation of **123** with *n*BuLi or PhCH₂K behaves better as a phenylide than as a "real" N-heterocyclic carbene.¹⁵¹



Scheme 52. Synthesis of NHC-precursors featuring an inorganic backbone.

3.3 Cyclization by quaternization of an imine

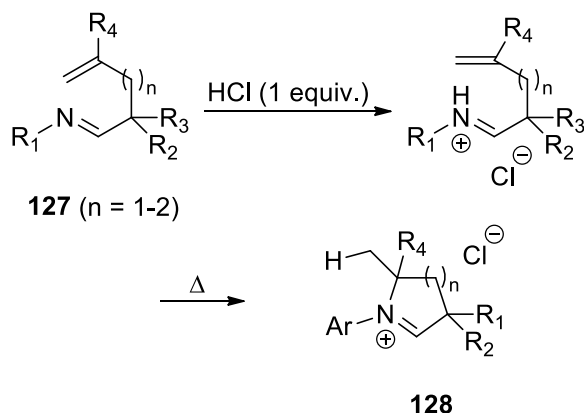
In 2005, Bertrand and coworkers published the synthesis of a new series of stable cyclic (alkyl)(amino)carbenes (CAAC) bearing one nitrogen atom and a quaternary carbon atom connected to the carbene center.¹⁵² Their pyrrolidinium precursors **126** were originally obtained through a three-step reaction (Scheme 53), where the imine **124** (simply obtained by condensation between the corresponding aniline and aldehyde) was deprotonated by lithium diisopropylamide (LDA) and alkylated with 1,2-epoxy-2-methylpropane to form the lithium alkoxide **125** which was directly converted into the iminium **126** via a highly reactive tertiary alkyl triflate intermediate.



Scheme 53. Original synthesis of the cyclic iminium compound **126**.

Although the above method can be carried out in one-pot without isolation of intermediates, it requires the use of highly reactive reagents and produces only moderate yields (41-58%) of the final product. This led the same group to develop an alternate strategy starting from alkenylaldimines and involving an intramolecular “hydroiminiumation” as the key cyclization step (Scheme 54).^{126,153} They were encouraged in this way by previous studies reporting that hydroamination of weakly basic amines can be catalyzed by Brønstedt acids.¹⁵⁴ Considering that imines are less basic than amines, the “hydroiminiumation” reaction was found to be a powerful cyclization strategy in this case. The addition

of a stoichiometric amount of HCl to the alkenylaldimine **127** results in a protonation of the sp^2 -nitrogen atom, whereas subsequent heating induces a clean and regioselective ring closure via formal addition of the N-H bond to the pendant C=C double bond (Scheme 54). This methodology was both applied to the formation of five-membered rings and six-membered rings in good yields and could be scaled up quite easily.¹⁵⁵

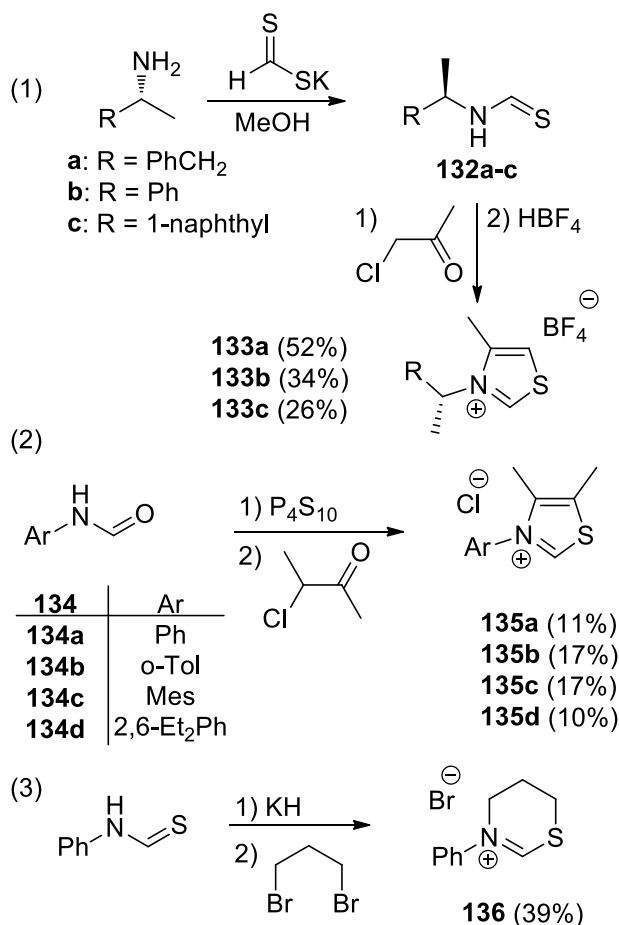


Scheme 54. Formation of the cyclic aldiminium **128** by an intramolecular "hydroiminium" methodology.

3.4 Cyclization starting from a N,P-disubstituted phosphoramidate

Since N,P-disubstituted phosphazinium salts **131** appeared potentially suitable precursors for the generation of the corresponding free (Amino)(Phosphino)Carbenes (P-NHCs), they were synthesized by Bertrand and co-workers in 2008.¹⁵⁶ It was then shown that P-NHC can be generated only from compound **131bb** due to a competitive deprotonation between positions 2 and 4 of the cationic heterocycle. Compounds **131** were synthesized from phosphoramidines **130** by a bis-alkylation procedure (Scheme 55), by analogy with the authors' previous report on formamidines.¹²² Few examples of phosphamidines and phosphamidinates had been reported,¹⁵⁷ but none of their synthetic procedures is applicable to the preparation of phosphoramidines, since they would involve the use of unstable formimide chlorides $[RN=C(H)Cl]$, or of acidic hydrogen cyanide which would protonate the second phosphide reagent. Fortunately, the reaction of primary lithium phosphide $Mes^*P(H)Li$ ($Mes^* =$

sequence starts with the *in-situ* generation of N-thioformyl anilines from the formanilidines **134** (simply obtained by reacting the aniline with the mixed formyl-acetyl anhydride) and phosphorus pentasulfide (Scheme 56, eq. 2). Condensation with 3-chlorobutanone gives the desired 4,5-dimethylthiazolium chlorides **135** in low yields (10-17%). Finally, Bertrand and co-workers reported the synthesis of the 1,3-thiazinium bromide **136** by reacting N-phenyl thioformamide with 1,3-dibromopropane, albeit in moderate yield (39%) (Scheme 56, eq. 3).¹²²



Scheme 56. Preparation of N,S-containing cationic heterocycles from thioformamides.

An alternative strategy is based on the formation of a cyclic thiazoline-2-thione from a thiocarbamate and its subsequent oxidation to the cationic thiazolium. This synthetic route was successfully employed to access bicyclic thiazolium perchlorates **137a-b**,¹⁶³ or chiral, atropisomeric thiazolium perchlorate **138** (Chart 7).¹⁶⁴

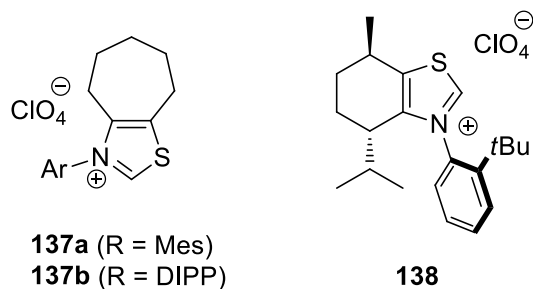
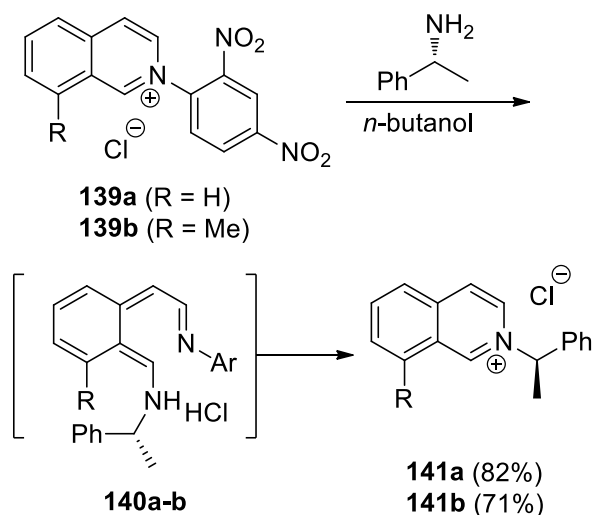


Chart 7. Thiazolium salts obtained by oxidation of their corresponding thiazoline-2-thiones.

4. Final introduction of the amino moiety

4.1 Via an heterocyclic interconversion

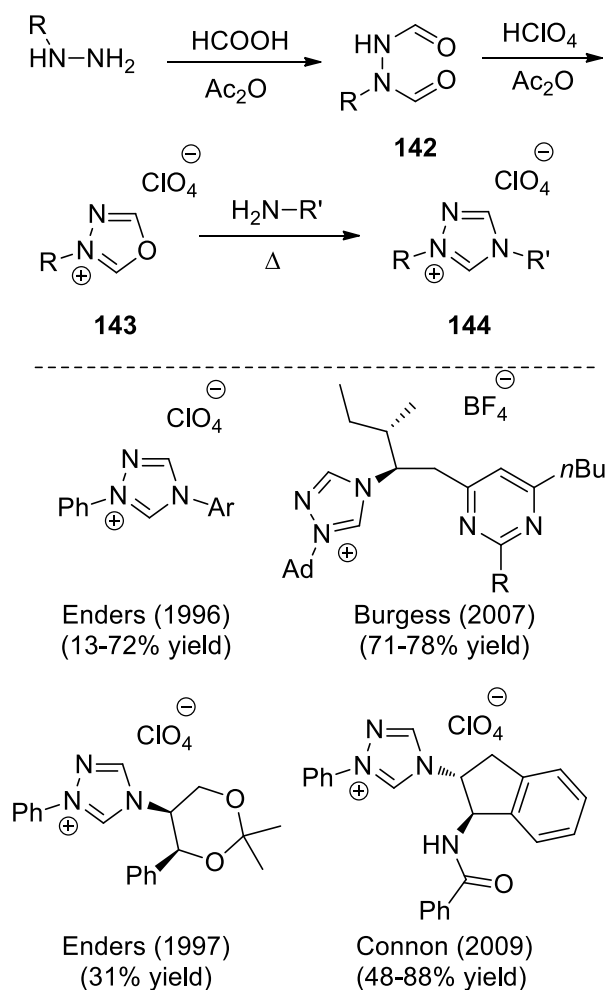
Lassaletta and co-workers reported the preparation of isoquinolinium salts **141a-b** by a Zincke reaction between salts **139a-b**, easily prepared by aromatic nucleophilic substitution of 1-chloro-2,4-dinitrobenzene with isoquinoline, and (R)-phenylethylamine (Scheme 57).^{165,166} This heterocyclic interconversion is thought to proceed through a ring-opening / ring closing sequence via intermediates such as **140a-b**.¹⁶⁷



Scheme 57. Zincke reaction leading to chiral isoquinolinium chlorides **141a-b**.

A versatile and convenient preparation of 1,4-disubstituted-1,2,4-triazolium salts is based on a procedure first described by Boyd et al.¹⁶⁸ Starting from an alkyl or an aryl hydrazine, the bisformyl hydrazines **142** can be obtained using the mixed anhydride of formic acid and acetic acid. Dehydration

of the latter in the presence of acetic anhydride and perchloric acid affords the corresponding 1,3,4-oxadiazolium perchlorates **143**. Reaction of the latter with a primary alkyl- or arylamine $R'-NH_2$ results in a ring-opening/ring-closing sequence leading to the desired 1,2,4-triazolium perchlorates **144** (Scheme 58).¹⁶⁹ This strategy has been applied by several groups for the construction of simple to complex triazolium architectures, as exemplified in Scheme 58.¹⁷⁰ It is noteworthy that chiral amines are suitable substrates and that tetrafluoroboric acid can advantageously replace the hazardous perchloric acid. However, the reaction of oxadiazolium **143** with *N,N*-dialkyl hydrazines to yield the corresponding compound **144** does not work even under forcing conditions.¹⁷¹ An obvious limitation of this strategy is the impossibility to annelate the triazolium core with another cycle to build a rigid chiral bicyclic structure which would normally give better stereoselective induction (see part 2.1.7).

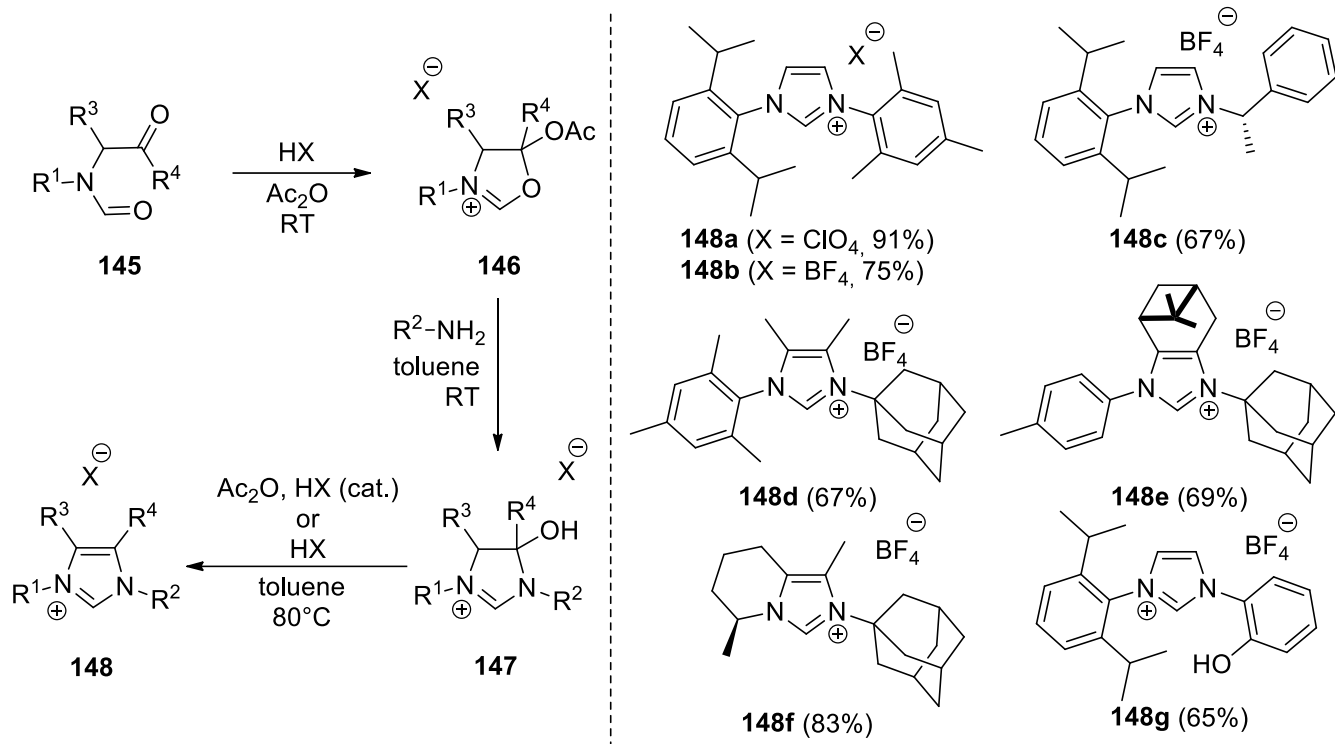


Scheme 58. General Scheme for the synthesis of 1,2,4-triazolium perchlorates **144** via the

intermediacy of 1,3,4-oxadiazolium **143** and some representative examples of triazolium salts obtained by this strategy (yields refer to the last step **143** → **144**) (Ad = 1-adamantyl).

Following a similar strategy, Fürstner and co-workers developed in 2006 a new, convenient and flexible method for the preparation of unsymmetrical imidazolium salts.¹⁷² The procedure starts from compound **145**, where the carbenic carbon atom and the backbone are already installed on the first amine respectively as a formyl and a β -ketoalkyl groups (Scheme 59). Surprisingly, reaction of **145** with one equivalent of HClO₄ or HBF₄ in acetic anhydride does not lead to the aromatic oxazolium analogous to **143** but stops at the intermediate acetal stage **146**. Condensation of this oxazolinium moiety with a second amine of choice proceeds smoothly to yield the 4-hydroxyimidazolinium salt **147**, which aromatizes by dehydration to finally afford the desired imidazolium salt **148**. As shown by selected examples, this methodology is quite general and versatile, since it accommodates alkyl and aryl amines, acyclic and cyclic backbones, chirality onto the amine and the backbone (no racemization occurs), tertiary alkyl substituents and functional groups on the nitrogen atoms, and bicyclic structures.

Soon after, Bode and co-workers used this methodology to synthesize a series of chiral aminoindanol-derived imidazolium salts of type **149**,¹⁷³ analogues of their well-known chiral triazolium, and Azumaya and Saito for unsymmetrical N,N'-diarylimidazolium **150** (Chart 8).¹⁷⁴



Scheme 59. General scheme for preparation of unsymmetrical imidazoliums according to Fürstner et al. and representative examples of the application scope.

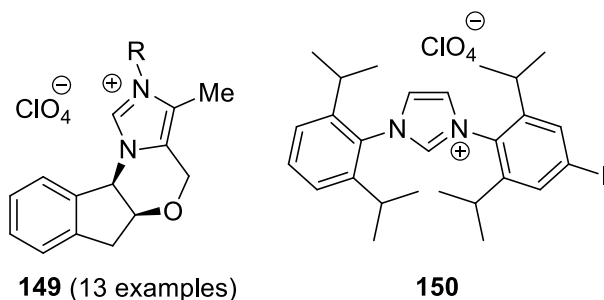
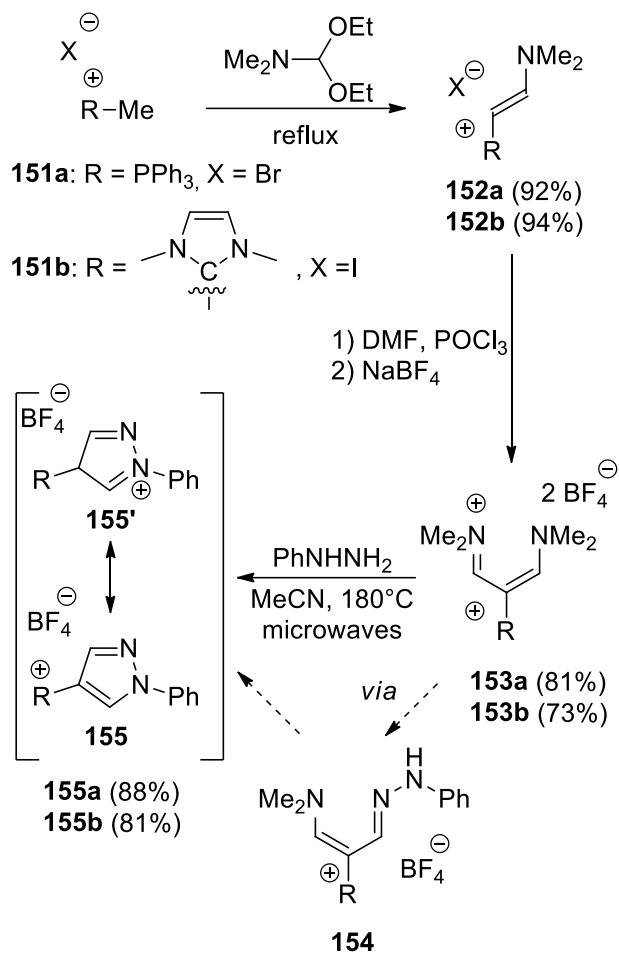


Chart 8. Imidazolium salts synthesized according to Fürstner's method.

4.2 Through condensation with an hydrazine derivative

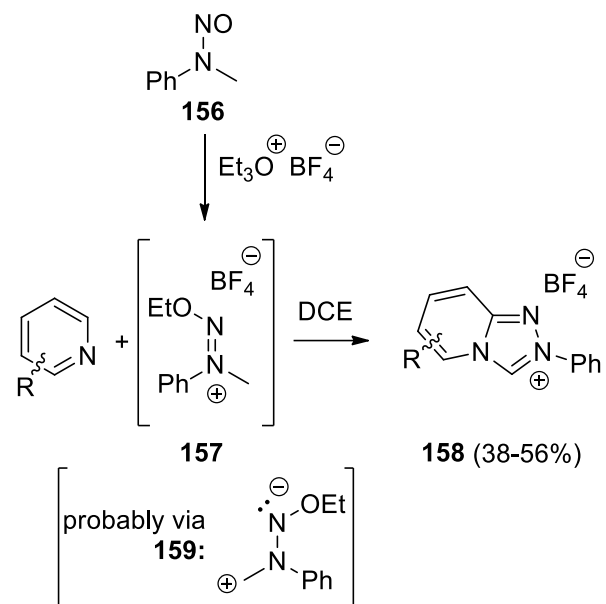
In 2008, the groups of Kawashima and Fürstner independently introduced a new N-heterocyclic carbene, namely a (amino)(ylidic)carbene (AYC), in which the carbene centre is directly connected to an amino atom and to a sp²-hybridized anionic carbon atom.¹⁷⁵ Although the synthesis of their cationic precursors was first prepared by a simple quaternization of the N atom of an indol-derived ylide,

Fürstner *et al.* developed a more elaborated and flexible synthesis of these compounds (Scheme 60). Key intermediates of the procedure were the 2-phosponiovinamidinium **153a** and 2-(imidazolium)vinamidinium **153b**, which derived from methyltriphenylphosphonium bromide **151a** and 1,2,3-trimethylimidazolium iodide **151b** respectively through a two-step sequence.¹⁷⁶ Noticeably, the reactivity of the 2-methylimidazolium **151b** is comparable of that of methylphosphonium **151a**. It could be explained by the analogy between phosphonium ylides and ene-1,1-diamines, deprotonation products of **151a** and **151b**.¹⁷⁷ Condensation of **153** with phenylhydrazine gave first the acyclic intermediate **154**, which under higher heating in a microwave oven cyclized with elimination of dimethylamine to give the desired cationic heterocycles **155**. Whereas two resonance forms **155** and **155'** are conceivable, the X-ray diffraction structures of **155a-b** suggest that the mesomeric extreme **155** gains importance, wherein the positive charge largely resides on the lateral R group (a phosphonium for **155a**, an imidazolium for **155b**).



Scheme 60. Synthesis of cationic 1,2-diazolium salts **155a-b** according to Fürstner and coll.

Finally, Lassaletta and collaborators synthesized the series of heterocycle-annulated triazolium salts **158**.¹⁷⁸ For this purpose, they used a slight modification of an original procedure by Eicher and co-workers,¹⁷⁹ based on alkoxydiazonium cation **157**, easily accessible by the alkylation of nitrosamine **156** with triethyloxonium tetrafluoroborate. Albeit not fully confirmed, the formation of **158** is thought to proceed via the dipole **159** obtained by deprotonation of **157**.¹⁸⁰



Scheme 61. Synthesis of triazolium salts **158** according to Lassaletta and co-workers.

5. Conclusion

N-heterocyclic carbenes have become an essential tool in the field of organometallic chemistry with many diversified applications. Their attractiveness as ligands in catalysis is a result of several beneficial features: (i) the stability of their complexes, resulting in high robustness of the system against air, moisture or heat; (ii) the importance of steric effects, which may be modulated by playing either with the nature of R substituents on the nitrogen atom, and/or with the size of the ring; (iii) their modulable electronic character having for example an impact on diverse elementary steps of a catalytic cycle (oxidative addition, reductive elimination ...); and finally (iv), as shown in the present account, the rich diversity and efficiency of synthetic methods giving access to their precursors.

The aim of this review was to lay out a general user's guide for the synthesis of azolium salts that have been used as carbene precursors. The need to obtain an increasing variety of N-heterocyclic carbene architectures has motivated the search for better methods to access their precursors. To date, and apart from the classical quaternization of the nitrogen atom of a neutral imidazole (or parent), the chemist has the option to form the expected cationic cycle through a final cyclization step, which can be achieved through three different strategies (according to the unit introduced during the last cyclization step), each having its own advantages and limitations. Ultimately, it is possible to modulate the size and the number of heteroatoms of the heterocycle and to introduce independently various substituents.

Finally, as revealed by the present overview, progress in the organic synthesis of NHC precursors in recent years has been so rapid that it is no doubt that with ongoing creative investigations in this area, many exciting new archetypes of N-heterocyclic carbenes are still to be discovered in the near future.

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¹ For reviews on carbenes in general, see: (a) Bourissou, D.; Guerret, O.; Gabbai, F. P.; Bertrand, G. *Chem. Rev.* **2000**, *100*, 39; (b) de Frémont, P.; Marion, N.; Nolan, S. P. *Coord. Chem. Rev.* **2009**, *253*, 862; (c) Canac, Y.; Soleilhavoup, M.; Conejero, S.; Bertrand, G. *J. Organomet. Chem.* **2004**, *689*, 3857.

² For cyclic carbenes other than diaminocarbenes, see the following reviews: (a) Melaimi, M.; Soleilhavoup, M.; Bertrand, G. *Angew. Chem. Int. Ed.* **2010**, DOI: 10.1002/anie.201000165; (b) Schuster, O.; Yang, L.; Raubenheimer, H. G.; Albrecht, M. *Chem. Rev.* **2009**, *109*, 3445; (c) Öfele, K.; Tosch, E.; Taubmann, C.; Herrmann, W. A. *Chem. Rev.* **2009**, *109*, 3408.

³ Wanzlick, H.-W. *Angew. Chem. Int. Ed. Engl.* **1962**, *1*, 75.

⁴ (a) Wanzlick, H.-W.; Schönherr, H. J. *Angew. Chem. Int. Ed. Engl.* **1968**, *7*, 141; see also: (b) Arduengo III, A. J.; Goerlich, J. R.; Krafczyk, R.; Marshall, W. J. *Angew. Chem. Int. Ed.* **1998**, *37*, 1963.

⁵ Öfele, K. *J. Organomet. Chem.* **1968**, *12*, P42.

⁶ For reviews, see: (a) Lappert, M. F. *J. Organomet. Chem.* **1988**, *358*, 185; (b) Cardin, D. J.; Cetinkaya, B.; Lappert, M. F. *Chem. Rev.* **1972**, *72*, 545.

⁷ Igau, A.; Grützmacher, H.; Baceiredo, A.; Bertrand, G. *J. Am. Chem. Soc.* **1988**, *110*, 6463.

⁸ Arduengo III, A. J.; Harlow, R. L.; Kline, M. *J. Am. Chem. Soc.* **1991**, *113*, 361.

⁹ Reviews on stereoelectronic parameters of NHCs: (a) Dröge, T.; Glorius, F. *Angew. Chem. Int. Ed.* **2010**, *49*, 6940; (b) Clavier, H.; Nolan, S. P. *Chem. Commun.* **2010**, *46*, 841; (c) Kühl, O. *Coord. Chem. Rev.* **2009**, *253*, 2481; (d) Díez-González, S.; Nolan, S. P. *Coord. Chem. Rev.* **2007**, *251*, 874; (e) Cavallo, L.; Correa, A.; Costabile, C. Jacobsen, H. *J. Organomet. Chem.* **2005**, *690*, 5407; (f) Strassner, T. *Top. Organomet. Chem.* **2004**, *13*, 1.

¹⁰ For books, see: (a) Glorius, F., Ed. *N-Heterocyclic Carbenes in Transition Metal Catalysis*; Topics in Organometallic Chemistry, Vol. 21; Springer-Verlag: Berlin/Heidelberg, 2007; (b) Nolan, S. P., Ed. *N-Heterocyclic Carbenes in Synthesis*; Wiley-VCH: New York, 2006.

¹¹ For selected reviews, see: (a) Mercks, L.; Albrecht, M. *Chem. Soc. Rev.* **2010**, *39*, 1903; (b) Teyssot, M.-L.; Jarrousse, A.-S.; Manin, M.; Chevry, A.; Roche, S.; Norre, F.; Beaudoin, C.; Morel, L.; Boyer, D.; Mahiou, R.; Gautier, A. *Dalton Trans.* **2009**, 6894; (c) Tapu, D.; Dixon, D. A.; Roe, C. *Chem. Rev.* **2009**, *109*, 3385; (d) Samojłowicz, C.; Bieniek, M.; Grela, K. *Chem. Rev.* **2009**, *109*, 3708; (e) Poyatos, M.; Mata, J. A.; Peris, E. *Chem. Rev.* **2009**, *109*, 3677; (f) McGuinness, D. *Dalton Trans.* **2009**, 6915; (g) Lin, J. C. Y.; Huang, R. T. W.; Lee, C. S.; Bhattacharyya, A.; Hwang, W. S.; Lin, I. J. B. *Chem. Rev.* **2009**, *109*, 3561; (h) Jacobsen, H.; Correa, A.; Poater, A.; Costabile, C.; Cavallo, L. *Coord. Chem. Rev.* **2009**, *253*, 687; (i) Hindi, K. M.; Panzner, M. J.; Tessier, C. A.; Cannon, C. L.; Youngs, W. J. *Chem. Rev.* **2009**, *109*, 3859; (j) Arnold, P. L.; Casely, I. J. *Chem. Rev.* **2009**, *109*, 3599; (k) Marion, N.; Nolan, S. P. *Acc. Chem. Res.* **2008**, *41*, 1440; (l) Hahn, F. E.; Jahnke, M. C. *Angew. Chem. Int. Ed.* **2008**, *47*, 3122; (m) Díez-González, S.; Nolan, S. P. *Acc. Chem. Res.* **2008**, *41*, 349; (n) Cavell, K. *Dalton Trans.* **2008**, 6676; (o) Gade, L. H.; Bellemin-Lapponnaz, S. *Coord. Chem. Rev.* **2007**, *251*, 718; (p) Kantchev, E.; O'Brien, C.; Organ, M. *Angew. Chem. Int. Ed.* **2007**, *46*, 2768; (q) César, V.; Bellemin-Lapponnaz, S.; Gade, L. H. *Chem. Soc. Rev.* **2004**, *33*, 619; (r) Herrmann, W. A. *Angew. Chem. Int. Ed.* **2002**, *41*, 1290.

¹² For reviews, see: (a) Nair, V.; Vellalath, S.; Babu, B. P. *Chem. Soc. Rev.* **2008**, *37*, 2691; (b) Enders, D.; Niemeier, O.; Henseler, A. *Chem. Rev.* **2007**, *107*, 5606; (c) Marion, N.; Díez-González, S.; Nolan, S. P. *Angew. Chem. Int. Ed.* **2007**, *46*, 2988; (d) Enders, D.; Balensiefer, T. *Acc. Chem. Res.* **2004**, *37*, 534.

¹³ Denk, M. K.; Hezarkhani, A.; Zheng, F. L. *Eur. J. Inorg. Chem.* **2007**, 3527.

¹⁴ (a) Nyce, G. W.; Csihony, S.; Waymouth, R. M.; Hedrick, J. L. *Chem. Eur. J.* **2004**, *10*, 4073; (b) Trnka, T. M.; Morgan, J. P.; Sanford, M. S.; Wilhelm, T. E.; Scholl, M.; Choi, T.-L.; Ding, S.; Day, M. W.; Grubbs, R. H. *J. Am. Chem. Soc.* **2003**, *125*, 2546; (c) Scholl, M.; Ding, S.; Lee, C. W.; Grubbs, R. H. *Org. Lett.* **1999**, *1*, 953; (d) Cetinkaya, B.; Cetinkaya, E.; Chamizo, J. A.; Hitchcock, P. B.; Jasim, H. A.; Kücükbay, H. K.; Lappert, M. F. *J. Chem. Soc. Perkin Trans. 1* **1998**, 2047; (e) Enders, D.; Breuer, K.; Raabe, G.; Runsink, J.; Teles, J. H.; Melder, J. P.; Ebel, K.; Brode, S. *Angew. Chem. Int. Ed. Engl.* **1995**, *34*, 1021; (f) Wanzlick, H.-W.; Esser, F.; Kleiner, H.-J. *Chem. Ber.* **1963**, *96*, 1208.

¹⁵ (a) Bantu, B.; Pawar, G. M.; Decker, U.; Wurst, K.; Schmidt, A. M.; Buchmeiser, M. R. *Chem. Eur. J.* **2009**, *15*, 3103; (b) Bantu, B.; Pawar, G. M.; Wurst, K.; Decker, U.; Schmidt, A. M.; Buchmeiser, M. R. *Eur. J. Inorg. Chem.* **2009**, 1970; (c) Duong, H. A.; Tekavec, T. N.; Arif, A. M.; Louie, J. *Chem. Commun.* **2004**, 112; (d) Voutchkova, A. M.; Appelhans, L. N.; Chianese, A. R.; Crabtree, R. H. *J. Am. Chem. Soc.* **2005**, *127*, 17624.

¹⁶ Otto, M.; Conejero, S.; Canac, Y.; Romanenko, V. D.; Rudzevitch, V.; Bertrand, G. *J. Am. Chem. Soc.* **2004**, *126*, 1016.

¹⁷ (a) Kremzow, D.; Seidel, G.; Lehmann, C. W.; Fürstner, A. *Chem. Eur. J.* **2005**, *11*, 1833; (b) McGuinness, D. S.; Cavell, K. J.; Yates, B. F.; Skelton, B. W.; White, A. H. *J. Am. Chem. Soc.* **2001**, *123*, 8317.

¹⁸ We have chosen to represent the heterocycles with localized double bonds rather than with delocalized structures. This is a pure formalism keeping in mind the objective to obtain clearer drawings and precise views of the electronic structure of these compounds.

¹⁹ For a comprehensive review on the synthesis of oxazoles, see: Boyd, G. V. in *Science of Synthesis*, Vol. 11 (Ed.: Schaumann, E.), Thieme, Stuttgart, 2001, p 383.

²⁰ For a comprehensive review on the synthesis of thiazoles, see: Kikelh, D.; Urleb, U. in *Science of Synthesis*, Vol. 11 (Ed.: Schaumann, E.), Thieme, Stuttgart, 2001, p. 627.

²¹ For reviews on the synthesis of imidazoles, see: (a) Kamijo, S.; Yamamoto, Y. *Chem. Asian J.* **2007**, *2*, 568; (b) Grimmett M. R. in *Comprehensive Heterocyclic Chemistry*, Vol. 5 (Eds.: Katritzky, A. R.; Rees, C. W.), Pergamon, Oxford, 1984, p. 345; (c) Grimmett M. R. in *Advances in Heterocyclic Chemistry*, Vol. 27 (Eds.: Katritzky, A. R.; Boulton, A. J.), Academic, New York, 1980, p. 241; (d) Grimmett M. R. in *Science of Synthesis*, Vol. 12 (Ed.: Neier R.), Thieme, Stuttgart, 2002, p. 325.

²² Saba, S.; Brescia, A.-M.; Kaloustian, M. K. *Tetrahedron Lett.* **1991**, *32*, 5031.

²³ Arduengo, III, A. J.; Krafczyk, R.; Schmutzler, R.; Craig, H. A.; Goerlich, J. R.; Marshall, W. J.; Unverzagt, M. *Tetrahedron* **1999**, *55*, 14523.

²⁴ Delaude, L.; Szypa, M.; Demonceau, A.; Noels A. F. *Adv. Synth. Catal.* **2002**, *344*, 749.

²⁵ (a) Leuthäüßer, S.; Schwarz, D.; Plenio, H. *Chem. Eur. J.* **2007**, *13*, 7195; (b) Leuthäüßer, S.; Schmidts, V.; Thiele, C. M.; Plenio, H. *Chem. Eur. J.* **2008**, *14*, 5465; (c) Fleckenstein, C.; Roy, S.; Leuthäusser, S.; Plenio, H. *Chem. Commun.* **2007**, 2870.

²⁶ Kantchev, E. A. B.; Ying, J. Y. *Organometallics* **2009**, *28*, 289.

²⁷ Fliedel, C.; Maise-François, A.; Bellemin-Lapponnaz, S. *Inorg. Chim. Acta* **2007**, *360*, 143.

²⁸ Lee, S.; Hartwig, J. F. *J. Org. Chem.* **2001**, *66*, 3402.

²⁹ (a) Jia, Y.-X.; Hillgren, J. M.; Watson, E. L.; Marsden, S. P.; Kündig, E. P. *Chem. Commun.* **2008**, 4040; (b) Kündig, E. P.; Seidel, T. M.; Jia, Y.-X.; Bernardinelli, G. *Angew. Chem. Int. Ed.* **2007**, *46*, 8484.

³⁰ Ma, Y.; Song, C.; Ma, C.; Sun, Z.; Chai, Q.; Andrus, M. B. *Angew. Chem. Int. Ed.* **2003**, *42*, 5871.

³¹ See for examples: (a) Sashuk, V.; Schoeps, D.; Plenio, H. *Chem. Commun.* **2009**, 770; (b) Schoeps, D.; Buhr, K.; Dijkstra, M.; Ebert, K.; Plenio, H. *Chem. Eur. J.* **2009**, *15*, 2960; (c) Balof, S. L.; P'Pool, S. J.; Berger, N. J.; Valente, E. J.; Shiller, A. M.; Schanz, H.-J. *Dalton Trans.* **2008**, 5791.

³² Van Veldhuizen, J. J.; Garber, S. B.; Kingsbury, J. S.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2002**, *124*, 4954.

³³ Alcarazo, M.; Roseblade, S. J.; Alonso, E.; Fernandez, R.; Alvarez, E.; Lahoz, F. J.; Lassaletta, J. *J. Am. Chem. Soc.* **2004**, *126*, 13242.

³⁴ Enders, D.; Meiers, M. *Synthesis* **2002**, 2542.

³⁵ Chung, C. K.; Grubbs, R. H. *Org. Lett.* **2008**, *10*, 2693.

³⁶ Allen, D. P.; Van Wingerden, M. M.; Grubbs, R. H. *Org. Lett.* **2009**, *11*, 1261.

³⁷ Dinger, M. B.; Nieczyk, P.; Mol, J. C. *Organometallics* **2003**, *22*, 5291.

³⁸ (a) Waltman, A. W.; Grubbs, R. H. *Organometallics* **2004**, *23*, 3105; (b) Vougioukalakis, G. C.; Grubbs, R. H. *Organometallics* **2007**, *26*, 2469.

³⁹ (a) Hadei, N.; Kantchev, E. A. B.; O'Brien, C. J.; Organ, M. G. *J. Org. Chem.* **2005**, *70*, 8503; (b) Vougioukalakis, G. C.; Grubbs, R. H. *Chem. Eur. J.* **2008**, *14*, 7545; (c) Ritter, T.; Day, M. W.; Grubbs, R. H. *J. Am. Chem. Soc.* **2006**, *128*, 11768; (d) Winkelmann, O.; Linder, D.; Lacour, J.; Näther, C.; Lüning, U. *Eur. J. Org. Chem.* **2007**, 3687; (e) Xu, G.; Gilbertson, S. R. *Org. Lett.* **2005**, *7*, 4605; (f) Makino, T.; Masu, H.; Katagiri, K.; Yamasaki, R.; Azumaya, I.; Saito, S. *Eur. J. Inorg. Chem.* **2008**, 4861.

⁴⁰ Kuriyama, M.; Shimazawa, R.; Shirai, R. *Tetrahedron* **2007**, *63*, 9393.

⁴¹ Clavier, H.; Coutable, L.; Guillemin, J. C.; Mauduit, M. *Tetrahedron: Asymmetry* **2005**, *16*, 921.

-
- ⁴² Tzur, E.; Ben-Asuly, A.; Diesendruck, C. E.; Goldberg, I.; Lemcoff, N. G. *Angew. Chem. Int. Ed.* **2008**, *47*, 6422.
- ⁴³ Yun, J.; Marinez, E. R.; Grubbs, R. H. *Organometallics* **2004**, *23*, 4172.
- ⁴⁴ Paczal, A.; Bényei, A. C.; Kotschy, A. *J. Org. Chem.* **2006**, *71*, 5969.
- ⁴⁵ For a general review on vicinal diamines, see: Lucet, D.; Le Gall, T.; Mioskowski, C. *Angew. Chem. Int. Ed.* **1998**, *37*, 2580.
- ⁴⁶ Huynh, H. V.; Han, Y.; Jothibasu, R.; Yang, J. A. *Organometallics* **2009**, *28*, 5395.
- ⁴⁷ (a) Wolfe, J. P.; Wagaw, S.; Buchwald, S. L. *J. Am. Chem. Soc.* **1996**, *118*, 7215; (b) Driver, M. S.; Hartwig, J. F. *J. Am. Chem. Soc.* **1996**, *118*, 7217.
- ⁴⁸ Seiders, T. J.; Ward, D. W.; Grubbs, R. H. *Org. Lett.* **2001**, *3*, 3225.
- ⁴⁹ Van Veldhuizen, J. J.; Campbell, J. E.; Giudici, R. E.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2005**, *127*, 6877.
- ⁵⁰ (a) Bellemin-Lapponnaz, S.; Welter, R.; BreLOT, L.; Dagorne, S. *J. Organomet. Chem.* **2009**, *694*, 604; (b) Romain, C.; BreLOT, L.; Bellemin-Lapponnaz, S.; Dagorne, S. *Organometallics* **2010**, *29*, 1191.
- ⁵¹ Min, K. S.; Weyermuller, T.; Bothe, E.; Wieghardt, K. *Inorg. Chem.* **2004**, *43*, 2922.
- ⁵² (a) Luan, X.; Wu, L.; Drinkel, E.; Mariz, R.; Gatti, M.; Dorta, R. *Org. Lett.* **2010**, *12*, 1912; (b) Duguet, N.; Donaldson, A.; Leckie, S. M.; Kallström, E. A.; Campbell, C. D.; Shapland, P.; Brown, T. B.; Slawin, A. M. Z.; Smith, A. D. *Tetrahedron: Asymmetry* **2010**, *21*, 601; (c) Kehrli, S.; Martin, D.; Rix, D.; Mauduit, M.; Alexakis, A. *Chem. Eur. J.* **2010**, *16*, 9890; (d) Selim, K. B.; Matsumoto, Y.; Yamada, K.-I.; Tomioka, K. *Angew. Chem. Int. Ed.* **2009**, *48*, 8733; (e) Luan, X.; Mariz, R.; Robert, C.; Gatti, M.; Blumentritt, S.; Linden, A.; Dorta, R. *Org. Lett.* **2008**, *10*, 5569; (f) Matsumoto, Y.; Yamada,

K.-i.; Tomioka, K. *J. Org. Chem.* **2008**, *73*, 4578; (g) Xu, L.; Shi, Y. *J. Org. Chem.* **2008**, *73*, 749; (h) Matsumoto, Y. Tomioka, K. *Tetrahedron Lett.* **2006**, *47*, 5843; (i) Funk, T. W.; Berlin, J. M.; Grubbs, R. H. *J. Am. Chem. Soc.* **2006**, *128*, 1840; (j) Berlin, J. M.; Goldberg, S. D.; Grubbs, R. H. *Angew. Chem. Int. Ed.* **2006**, *45*, 7591; (k) Bappert, E.; Helmchen, G. *Synlett* **2004**, 1789; (l) Jensen, D. R.; Sigman, M. S. *Org. Lett.* **2003**, *5*, 63.

⁵³ (a) Jackowski, O.; Alexakis, A. *Angew. Chem. Int. Ed.* **2010**, *49*, 3346; (b) Uchida, T.; Katsuki, T. *Tetrahedron Lett.* **2009**, *50*, 4741; (c) Brown, M. K.; May, T. L.; Baxter, C. A.; Hoveyda, A. H. *Angew. Chem. Int. Ed.* **2007**, *46*, 1097.

⁵⁴ (a) Reddy, P. V. G.; Tabassum, S.; Blanrue, A.; Wilhelm, R. *Chem. Commun.* **2009**, 5910; (b) Cavell, K. J.; Elliott, M. C.; Nielsen, D. J.; Paine, J. S. *Dalton Trans.* **2006**, 4922; (c) Herrmann, W. A.; Baskakov, D.; Herdtweck, E.; Hoffmann, S. D.; Bunlaksananusorn, T.; Rampf, F.; Rodefeld, L. *Organometallics* **2006**, *25*, 2449; (d) Newman, P. D.; Cavell, K. J.; Kariuki, B. M. *Organometallics* **2010**, *29*, 2724.

⁵⁵ Iglesias, M.; Beetstra, D. J.; Stasch, A.; Horton, P. N.; Hursthouse, M. B.; Coles, S. J.; Cavell, K. J.; Dervisi, A.; Fallis, I. A. *Organometallics* **2007**, *26*, 4800.

⁵⁶ (a) Bazinet, P.; Yap, G. P. A.; Richeson, D. S. *J. Am. Chem. Soc.* **2003**, *125*, 13314; (b) Bazinet, P.; Ong, T.-G.; O'Brien, J. S.; Lavoie, N.; Bell, E.; Yap, G. P. A.; Korobkov, I.; Richeson, D. S. *Organometallics* **2007**, *26*, 2885.

⁵⁷ (a) Scarborough, C. C.; Popp, I. A.; Guzei, B. V.; Stahl, S. S. *J. Organomet. Chem.* **2005**, *690*, 6143; (b) Scarborough, C. C.; Grady, M. J. W.; Guzei, I. A.; Gandhi, B. A.; Bunel, E. E.; Stahl, S. S. *Angew. Chem. Int. Ed.* **2005**, *44*, 5269.

⁵⁸ (a) Khramov, D. M.; Rosen, E. L.; Lynch, V. M.; Bielawski, C. W. *Angew. Chem. Int. Ed.* **2008**, *47*, 2267; (b) Siemeling, U.; Färber, C.; Bruhn, C. *Chem. Commun.* **2009**, 98; (c) Siemeling, U.; Färber, C.;

Leibold, M.; Bruhn, C.; Mücke, P.; Winter, R. F.; Sarkar, B.; Hopffgarten, M. V.; Frenking, G. *Eur. J. Inorg. Chem.* **2009**, 4607; (d) Rosen, E. L.; Varnado, C. D.; Tennyson, A. G.; Khramov, D. M.; Kamplain, J. W.; Sung, D. H.; Cresswell, P. T.; Lynch, V. M.; Bielawski, C. W. *Organometallics* **2009**, *28*, 6695.

⁵⁹ Jurcík, V.; Gilani, M.; Wilhelm, R. *Eur. J. Org. Chem.* **2006**, 5103.

⁶⁰ Steinke, T.; Shaw, B. K.; Jong, H.; Patrick, B. O.; Fryzuk, M. D. *Organometallics* **2009**, *28*, 2830.

⁶¹ Roche, S. P.; Teysstot, M.-L.; Gautier, A. *Tetrahedron Lett.* **2010**, *51*, 1265.

⁶² Prasad, B. A. B.; Gilbertson, S. R. *Org. Lett.* **2009**, *11*, 3710.

⁶³ (a) Rivas, F. M.; Riaz, U.; Giessert, A.; Smulik, J. A.; Diver, S. T. *Org. Lett.* **2001**, *3*, 2673; for the preparation of chiral N,N'-disubstituted 1,2-benzenediamines, see: (b) Rivas, F. M.; Riaz, U.; Diver, S. T. *Tetrahedron: Asymmetry* **2000**, *11*, 1703.

⁶⁴ (a) Tennyson, A. G.; Rosen, E. L.; Collins, M. S.; Lynch, V. M.; Bielawski, C. W. *Inorg. Chem.* **2009**, *48*, 6924; (b) Er, J. A. V.; Tennyson, A. G.; Kamplain, J. W.; Lynch, V. M.; Bielawski, C. W. *Eur. J. Inorg. Chem.* **2009**, 1729; (c) Khramov, D. M.; Boydston, A. J.; Bielawski, C. W. *Org. Lett.* **2006**, *8*, 1831; (d) Khramov, D. M.; Boydston, A. J.; Bielawski, C. W. *Angew. Chem. Int. Ed.* **2006**, *45*, 6186; (e) Boydston, A. J.; Williams, K. A.; Bielawski, C. W. *J. Am. Chem. Soc.* **2005**, *127*, 12496.

⁶⁵ Saravanakumar, S.; Kindermann, M. K.; Heinicke, J.; Köckerling, M. *Chem. Commun.* **2006**, 640.

⁶⁶ Tiede, S.; Berger, A.; Schlesiger, D.; Rost, D.; Lühl, A.; Blechert, S. *Angew. Chem. Int. Ed.* **2010**, *49*, 3972.

⁶⁷ Benzoxazolium salts have been synthesized only once by this method, see: Bellemin-Laponnaz, S. *Polyhedron* **2010**, *29*, 30.

-
- ⁶⁸ Knight, R. L.; Leeper, F. J. *J. Chem. Soc. Perkin Trans. 1* **1998**, 1891.
- ⁶⁹ Enders, D.; Kallfass, U. *Angew. Chem. Int. Ed.* **2002**, *41*, 1743.
- ⁷⁰ Enders, D.; Niemeier, O.; Balensiefer, T. *Angew. Chem. Int. Ed.* **2006**, *45*, 1463.
- ⁷¹ (a) Kerr, M. S.; Read de Alaniz, J.; Rovis, T. *J. Am. Chem. Soc.* **2002**, *124*, 10298; (b) Kerr, M. S.; Read de Alaniz, J.; Rovis, T. *J. Org. Chem.* **2005**, *70*, 5725; (c) For a review, see: Rovis, T. *Chem. Lett.* **2008**, *37*, 2; (d) Ma, Y.; Wei, S.; Wu, J.; Yang, F.; Liu, B.; Lan, J.; Yang, S.; You, J. *Adv. Synth. Catal.* **2008**, *350*, 2645.
- ⁷² Ma, Y.; Wei, S.; Lan, J.; Wang, J.; Xie, R.; You, J. *J. Org. Chem.* **2008**, *73*, 8256.
- ⁷³ (a) Calder, I. C.; Spotswood, T. M.; Sasse, W. H. F. *Tetrahedron Lett.* **1963**, *2*, 95; (b) Calder, I. C.; Sasse, W. H. F. *Aust. J. Chem.* **1965**, *18*, 1819.
- ⁷⁴ Calder, I. C.; Sasse, W. H. F. *Aust. J. Chem.* **1968**, *21*, 1023.
- ⁷⁵ Nonnenmacher, M.; Kunz, D.; Rominger, F.; Oeser, T. *Chem. Commun.* **2006**, 1378.
- ⁷⁶ Weiss, R.; Reichel, S.; Handke, M.; Hampel, F. *Angew. Chem. Int. Ed.* **1998**, *37*, 344.
- ⁷⁷ Weiss, R.; Seubert, J.; Hampel, F. *Angew. Chem. Int. Ed. Engl.* **1994**, *33*, 1952.
- ⁷⁸ Kison, C.; Opatz, T. *Synthesis* **2006**, *21*, 3727.
- ⁷⁹ Sato, H.; Fujihara, T.; Obora, Y.; Tokunaga, M.; Kiyosu, J.; Tsuji, Y. *Chem. Commun.* **2007**, 269.
- ⁸⁰ Alexander, S. G.; Cole, M. L.; Morris, J. C. *New J. Chem.* **2009**, *33*, 720.
- ⁸¹ (a) Vasudevan, K. V.; Butorac, R. R.; Abernethy, C. D.; Cowley, A. H. *Dalton Trans.* **2010**, *39*, 7401; (b) Tapu, D.; Owens, C.; VanDerveer, D.; Gwaltney, K. *Organometallics* **2008**, *28*, 270.

⁸² Other examples: (a) Hirsch-Weil, D.; Abboud, K. A.; Hong, S. *Chem. Commun.* **2010**, *46*, 7525; (b) Ma, Q.; Ma, Y.; Liu, X.; Duan, W.; Qu, B.; Song, C. *Tetrahedron: Asymmetry* **2010**, *21*, 292; (c) Seo, H.; Hirsch-Weil, D.; Abboud, K. A.; Hong, S. *J. Org. Chem.* **2008**, *73*, 1983.

⁸³ For a small account, see: Würtz, S.; Glorius, F. *Acc. Chem. Res.* **2008**, *41*, 1523.

⁸⁴ For reviews, see: (a) Grant, T. G.; Meyers, A. I. *Tetrahedron* **1994**, *50*, 2297; (b) Peer, M.; de Jong, J. C.; Langer, T.; Rieck, H.; Schell, H.; Sennhann, P.; Sprinz, J.; Steinhagen, H.; Wiese, B.; Helmchen, G. *Tetrahedron* **1996**, *52*, 7547.

⁸⁵ Glorius, F.; Altenhoff, G.; Goddard, R.; Lehmann, C. W. *Chem. Commun.* **2002**, 2704.

⁸⁶ Altenhoff, G.; Goddard, R.; Lehmann, C. W.; Glorius, F. *Angew. Chem. Int. Ed.* **2003**, *42*, 3690.

⁸⁷ Altenhoff, G.; Goddard, R.; Lehmann, C. W.; Glorius, F. *J. Am. Chem. Soc.* **2004**, *126*, 15195.

⁸⁸ Würtz, S.; Lohre, C.; Fröhlich, R.; Bergander, K.; Glorius, F. *J. Am. Chem. Soc.* **2009**, *131*, 8344.

⁸⁹ Burstein, C.; Lehmann, C. W.; Glorius, F. *Tetrahedron* **2005**, *61*, 6207.

⁹⁰ Lohre, C.; Fröhlich, R.; Glorius, F. *Synthesis* **2008**, 2221.

⁹¹ (a) Suisse, J. M.; Bellemin-Laponnaz, S.; Douce, L.; Maise-François, A.; Welter, R. *Tetrahedron Lett.* **2005**, *46*, 4303; (b) Suisse, J. M.; Douce, L.; Bellemin-Laponnaz, S.; Maise-François, A.; Welter, R.; Miyake, Y.; Shimizu, Y. *Eur. J. Inorg. Chem.* **2007**, 3899.

⁹² Bildstein, B.; Malaun, M.; Kopacka, H.; Wurst, K.; Mitterböck, M.; Ongania, K.-H.; Opromolla, G.; Zanello, P. *Organometallics* **1999**, *18*, 4325.

⁹³ (a) Nolan, S. P. U. S. Patent 7109348, **2006**; (b) Jafarpour, L.; Stevens, E. D.; Nolan, S. P. *J. Organomet. Chem.* **2000**, *606*, 49.

-
- ⁹⁴ Böhler, C.; Stein, D.; Donati, N.; Grützmacher, H. *New J. Chem.* **2002**, *26*, 1291.
- ⁹⁵ Chien, C.-H.; Fujita, S.; Yamoto, S.; Hara, T.; Yamagata, T.; Watanabe, M.; Mashima, K. *Dalton Trans.* **2008**, 916.
- ⁹⁶ Hintermann, L. *Beilstein J. Org. Chem.* **2007**, *3*, 22.
- ⁹⁷ (a) Huisgen, R. *Angew. Chem. Int. Ed. Engl.* **1980**, *19*, 947; (b) Taylor, E. C.; Turchi, I. J. *Chem. Rev.* **1979**, *79*, 181.
- ⁹⁸ Ogle, J. W.; Zhang, J.; Reibenspies, J. H.; Abboud, K.; Miller, S. A. *Org. Lett.* **2008**, *10*, 3677.
- ⁹⁹ (a) Powell, A. B.; Bielawski, C. W.; Cowley, A. H. *J. Am. Chem. Soc.* **2010**, *132*, 10184; (b) Powell, A. B.; Brown, J. R.; Vasudevan, K. V.; Cowley, A. H. *Dalton Trans.* **2009**, 2521; (c) Powell, A. B.; Bielawski, C. W.; Cowley, A. H. *J. Am. Chem. Soc.* **2009**, *131*, 18232.
- ¹⁰⁰ Donia, R. A.; Shotton, J. A.; Bentz, L. O.; Smith, G. E. P. *J. Org. Chem.* **1949**, *14*, 952.
- ¹⁰¹ Orelli, L. R.; Garcia, M. B.; Perillo, I. A. *Heterocycles* **2000**, *53*, 2437.
- ¹⁰² Mayr, M.; Wurst, K.; Ongania, K.-H.; Buchmeiser, M. R. *Chem. Eur. J.* **2004**, *10*, 1256.
- ¹⁰³ Mayr, M.; Buchmeiser, M. R. *Macromol. Rapid Commun.* **2004**, *25*, 231.
- ¹⁰⁴ Bildstein, B.; Malaun, M.; Kopacka, H.; Ongania, K.-H.; Wurst, K. *J. Organomet. Chem.* **1999**, *572*, 177.
- ¹⁰⁵ Boydston, A. J.; Khramov, D. M.; Bielawski, C. W. *Tetrahedron Lett.* **2006**, *47*, 5123.
- ¹⁰⁶ Schwarz, D. E.; Cameron, T. M.; Hay, P. J.; Scott, B. L.; Tumas, W.; Thorn, D. L. *Chem. Commun.* **2005**, 5919.

-
- ¹⁰⁷ Alcarazo, M.; Roseblade, S. J.; Cowley, A. R.; Fernández, R.; Brown, J. M.; Lassaletta, J. M. *J. Am. Chem. Soc.* **2005**, *127*, 3290.
- ¹⁰⁸ (a) Enders, D.; Gielen, H.; Breuer, K. *Molecules Online* **1998**, *2*, 105; (b) For a minireview, see: Enders, D.; Gielen, H. *J. Organomet. Chem.* **2001**, *617-618*, 70.
- ¹⁰⁹ Dorn, H.; Zubek, A.; Hilgetag, G. *Chem. Ber.* **1965**, *98*, 3377.
- ¹¹⁰ Arduengo III, A. J. U.S. Patent 5,077,414, 1991.
- ¹¹¹ Herrmann, W., A.; Köcher, C.; Goossen, L., J. EP Patent 9701296, 1997.
- ¹¹² Winn, C. L.; Guillen, F.; Pytkowicz, J.; Roland, S.; Mangeney, P.; Alexakis, A. *J. Organomet. Chem.* **2005**, *690*, 5672.
- ¹¹³ (a) Voges, M. H.; Rømming, C.; Tilstet, M. *Organometallics* **1999**, *18*, 529; (b) Cole, M. J.; Junk, P. C. *CrystEngComm* **2004**, *6*, 173.
- ¹¹⁴ Berlin, J. M.; Grubbs, R. H.; Schrodi, Y.; Steward, I. C. W.O. Patent 2007075427, 2007.
- ¹¹⁵ (a) Claisen, L. *Ann.* **1895**, *287*, 360; (b) Walther, R. *J. Prakt. Chem.* **1895**, *52*, 429; (c) Walther, R. *J. Prakt. Chem.* **1896**, *53*, 472.
- ¹¹⁶ Roberts, R. M. *J. Org. Chem.* **1949**, *14*, 277.
- ¹¹⁷ See for representative examples: (a) Cole, M. L.; Junk, P. C. *J. Organomet. Chem.* **2003**, *666*, 55; (b) Cotton, F. A.; Haefner, S. C.; Matonic, J. H.; Wang, X.; Murillo, C. A. *Polyhedron* **1997**, *16*, 541; (c) Tamaoki, A.; Yamamoto, K.; Maeda, K. JP patent 55049353, 1980.
- ¹¹⁸ Binobaid, A.; Iglesias, M.; Beetstra, D. J.; Kariuki, B.; Dervisi, A.; Fallis, I. A.; Cavell, K. J. *Dalton Trans.* **2009**, 7099.

-
- ¹¹⁹ DeWolfe, R. H. *J. Org. Chem.* **1962**, *27*, 490.
- ¹²⁰ Roberts, R. M. *J. Am. Chem. Soc.* **1950**, *72*, 3603.
- ¹²¹ Taylor, E. C.; Ehrhart, W. A. *J. Org. Chem.* **1963**, *28*, 1108.
- ¹²² Jazzar, R.; Liang, H.; Donnadiou, B.; Bertrand, G. *J. Organomet. Chem.* **2006**, *691*, 3201.
- ¹²³ Kuhn, K. M.; Grubbs, R. H. *Org. Lett.* **2008**, *10*, 2075.
- ¹²⁴ Iglesias, M.; Beetstra, D. J.; Knight, J. C.; Ooi, L.-L.; Stasch, A.; Coles, S.; Male, L.; Hursthouse, M. B.; Cavell, K. J.; Dervisi, A.; Fallis, I. A. *Organometallics* **2008**, *27*, 3279.
- ¹²⁵ Iglesias, M.; Beetstra, D. J.; Cavell, K. J.; Dervisi, A.; Fallis, I. A.; Kariuki, B.; Harrington, R. W.; Clegg, W.; Horton, P. N.; Coles, S. J.; Hursthouse, M. B. *Eur. J. Inorg. Chem.* **2010**, 1604.
- ¹²⁶ Jazzar, R.; Bourg, J.-B.; Dewhurst, R. D.; Donnadiou, B.; Bertrand, G. *J. Org. Chem.* **2007**, *72*, 3492.
- ¹²⁷ Bertogg, A.; Camponovo, F.; Togni, A. *Eur. J. Inorg. Chem.* **2005**, 347.
- ¹²⁸ Togni, A.; Hayashi, T. Eds. *Ferrocenes*, Wiley-VCH: Weinheim, 1995.
- ¹²⁹ Grundmann, C.; Kreutzberger, A. *J. Am. Chem. Soc.* **1955**, *77*, 6559.
- ¹³⁰ Hirano, K.; Urban, S.; Wang, C.; Glorius, F. *Org. Lett.* **2009**, *11*, 1019.
- ¹³¹ Aldeco-Perez, E.; Rosenthal, A. J.; Donnadiou, B.; Parameswaran, P.; Frenking, G.; Bertrand, G. *Science* **2009**, *326*, 556.
- ¹³² For reviews on abnormal NHCs, see: (a) reference 2b; (b) Albrecht, M. *Chem. Commun.* **2008**, 3601; (c) Arnold, P. L.; Pearson, S. *Coord. Chem. Rev.* **2007**, *251*, 596.
- ¹³³ Sanderson, M. D.; Kamplain, J. W.; Bielawski, C. W. *J. Am. Chem. Soc.* **2006**, *128*, 16514.

-
- ¹³⁴ Tennyson, A. G.; Lynch, V. M.; Bielawski, C. W. *J. Am. Chem. Soc.* **2010**, *132*, 9420.
- ¹³⁵ (a) Benhamou, L.; César, V.; Gornitzka, H.; Lugan, N.; Lavigne, G. *Chem. Commun.* **2009**, 4720; (b) Benhamou, L.; Vujkovic, N.; César, V.; Gornitzka, H.; Lugan, N.; Lavigne, G. *Organometallics* **2010**, *29*, 2616.
- ¹³⁶ Biju, A.; Hirano, K.; Fröhlich, R.; Glorius, F. *Chem. – Asian J.* **2009**, *4*, 1786.
- ¹³⁷ For a definition see: (a) Newton, C. G.; Ramsden, C. A. *Tetrahedron* **1982**, *38*, 2965; (b) Ollis, W. D.; Stanforth, S. P.; Ramsden, C. A. *Tetrahedron* **1985**, *41*, 2239.
- ¹³⁸ For examples, see: (a) Bettreich, M.; Bendikov, M.; Chaffins, S.; Perepichka, D. F.; Dautel, O.; Duong, H.; Helgeson, R.; Wudl, F. *Angew. Int. Chem. Ed.* **2002**, *41*, 3688; (b) Deutschmann, T.; Ritter, H. *Macromol. Chem. Phys.* **2000**, *201*, 1200; (c) Fulda, K.-U.; Maassen, E.; Ritter, H.; Sperber R.; Tieke, B. *Langmuir* **1996**, *12*, 854; (d) Gotthardt, H.; Schenk, K.-H. *Angew. Chem. Int. Ed. Engl.* **1985**, *24*, 608; (e) Potts, K. T.; Sorm, M. *J. Org. Chem.* **1972**, *37*, 1422.
- ¹³⁹ (a) César, V.; Lugan, N.; Lavigne, G. *J. Am. Chem. Soc.* **2008**, *130*, 11286; (b) César, V.; Lugan, N.; Lavigne, G. *Chem. Eur. J.* **2010**, *16*, 11432.
- ¹⁴⁰ Hobbs, M. G.; Knapp, C. J.; Welsh, P. T.; Borau-Garcia, J.; Ziegler, T.; Roesler, R. *Chem. Eur. J.* **2010**, DOI: 10.1002/chem.201001698.
- ¹⁴¹ (a) César, V.; Lugan, N.; Lavigne, G. *Eur. J. Inorg. Chem.* **2010**, 361; (b) Hudnall, T. W.; Moerdyk, J. P.; Bielawski, C. W. *Chem. Commun.* **2010**, 4288.
- ¹⁴² Such an attack was already reported leading to a similar structure, see: Barsa, E. A.; Richter, R. *J. Org. Chem.* **1986**, *51*, 4483.
- ¹⁴³ (a) Hudnall, T. W.; Bielawski, C. W. *J. Am. Chem. Soc.* **2009**, *131*, 16039; (b) Hudnall, T. W.; Moorhead, E. J.; Gusev, D. G.; Bielawski, C. W. *J. Org. Chem.* **2010**, *75*, 2763.

¹⁴⁴ (a) Hobbs, M. G.; Forster, T. D.; Borau-Garcia, J.; Knapp, C. J.; Tuononen, H. M.; Roesler, R. *New J. Chem.* **2010**, *34*, 1295; (b) Braun, M.; Frank, W.; Reiss, G. J.; Ganter, C. *Organometallics* **2010**, *29*, 4418.

¹⁴⁵ Hudnall, T. W.; Tennyson, A. G.; Bielawski, C. W. *Organometallics* **2010**, *29*, 4569.

¹⁴⁶ (a) Despagnet-Ayoub, E.; Grubbs, R. H. *J. Am. Chem. Soc.* **2004**, *126*, 10198; (b) Despagnet-Ayoub, E.; Grubbs, R. H. *Organometallics* **2005**, *24*, 338.

¹⁴⁷ Krahulic, K. E.; Enright, G. D.; Parvez, M.; Roesler, R. *J. Am. Chem. Soc.* **2005**, *127*, 4142.

¹⁴⁸ Ishida, Y.; Donnadiou, B.; Bertrand, G. *Proc. Natl. Acad. Sci.* **2006**, *103*, 13585.

¹⁴⁹ Präsang, C.; Donnadiou, B.; Bertrand, G. *J. Am. Chem. Soc.* **2005**, *127*, 10182.

¹⁵⁰ Forster, T. D.; Krahulic, K. E.; Tuononen, H. M.; McDonald, R.; Parvez, M.; Roesler, R. *Angew. Chem. Int. Ed.* **2006**, *45*, 6356.

¹⁵¹ Krahulic, K. E.; Tuononen, H. M.; Parvez, M.; Roesler, R. *J. Am. Chem. Soc.* **2009**, *131*, 5858.

¹⁵² (a) Lavallo, V.; Canac, Y.; Präsang, C.; Donnadiou, B.; Bertrand, G. *Angew. Chem. Int. Ed.* **2005**, *44*, 5705; (b) Bertrand, G.; Lavallo, V.; Canac, Y. WO Patent 2006138166, 2006.

¹⁵³ (a) Zeng, X.; Frey, G. D.; Kinjo, R.; Donnadiou, B.; Bertrand, G. *J. Am. Chem. Soc.* **2009**, *131*, 8690; (b) Jazzar, R.; Dewhurst, R. D.; Bourg, J.-B.; Donnadiou, B.; Canac, Y.; Bertrand, G. *Angew. Chem. Int. Ed.* **2007**, *46*, 2899.

¹⁵⁴ (a) Rosenfeld, D. C.; Shekhar, S.; Takemiya, A.; Utsunomiya, M.; Hartwig, J. F. *Org. Lett.* **2006**, *8*, 4179; (b) Motokura, K.; Nakaagiri, N.; Mori, K.; Mizugaki, T.; Ebitani, K.; Jitsukawa, K.; Kaneda, K. *Org. Lett.* **2006**, *8*, 4617; (c) Lapis, A. A. M.; DaSilveira Neto, B. A.; Scholten, J. D.; Nachtigall, F. A.; Eberlin, M. N.; Dupont, J. *Tetrahedron Lett.* **2006**, *47*, 6775; (d) Li, Z. G.; Zhang, J. L.; Brouwer,

C.; Yang, C. G.; Reich, N. W.; He, C. *Org. Lett.* **2006**, *8*, 4175; (e) Anderson, L. L.; Arnold, J.; Bergman, R. G. *J. Am. Chem. Soc.* **2005**, *127*, 14542; (f) Schlummer, B.; Hartwig, J. F. *Org. Lett.* **2002**, *4*, 1471.

¹⁵⁵ This procedure has been also patented, see: Mignani, G. WO patent 2008125568, 2008.

¹⁵⁶ Frey, G. D.; Song, M.; Bourg, J.-B.; Donnadiou, B.; Soleilhavoup, M.; Bertrand, G. *Chem. Commun.* **2008**, 4711.

¹⁵⁷ (a) Boéré, R. T.; Cole, M. L.; Junk, P. C.; Masuda, J. D.; Wolmershäuser, G. *Chem. Commun.* **2004**, 2564; (b) Wang, Z. X.; Wang, D. Q.; Dou, J. M. *J. Organomet. Chem.* **2003**, *665*, 205; (c) Becker, G.; Heck, J. R.; Hübler, U.; Schwarz, W.; Würthwein, E. U. *Z. Anorg. Allg. Chem.* **1999**, *625*, 2008; (d) Westerhausen, M.; Digeser, M. H.; Schwarz, W. *Inorg. Chem.* **1997**, *36*, 521; (e) Westerhausen, M.; Digeser, M. H. *Z. Anorg. Allg. Chem.* **1997**, *623*, 1237; (f) Paasch, K.; Nieger, M.; Niecke, E. *Angew. Chem. Int. Ed. Engl.* **1995**, *34*, 2369; (g) Issleib, K.; Schmidt, H.; Leissring, E. *Synth. React. Inorg. Met.-Org. Chem.* **1988**, *18*, 215; (h) Becker, G.; Uhl, W.; Wessely, H. J. *Z. Anorg. Allg. Chem.* **1981**, *479*, 41; (i) Issleib, K.; Schmidt, H.; Meyer, H. *J. Organomet. Chem.* **1978**, *160*, 47.

¹⁵⁸ Song, M.; Donnadiou, B.; Soleilhavoup, M.; Bertrand, G. *Chem. Asian J.* **2007**, *2*, 904.

¹⁵⁹ Götze, J. *Chem. Ber.* **1938**, *71*, 2289.

¹⁶⁰ (a) Sheehan, J. C.; Hara, T. *J. Org. Chem.* **1974**, *39*, 1196; (b) Sheehan, J. C.; Hunneman, D. H. *J. Am. Chem. Soc.* **1966**, *88*, 3666.

¹⁶¹ See also: (a) Tagaki, W.; Tamura, Y.; Yano, Y. *Bull. Chem. Soc. Jpn.* **1980**, *53*, 478; (b) Zhao, C.; Chen, S.; Wu, P.; Wen, Z. *Huaxue Xuebao* **1988**, *46*, 784.

¹⁶² Vougioukalakis, G. C.; Grubbs, R. H. *J. Am. Chem. Soc.* **2008**, *130*, 2234.

¹⁶³ (a) Biju, A. T.; Wurz, N. E.; Glorius, F. *J. Am. Chem. Soc.* **2010**, *132*, 5970; (b) Hirano, K.; Biju, A. T.; Piel, I.; Glorius, F. *J. Am. Chem. Soc.* **2009**, *131*, 14190; (c) Lebeuf, R.; Hirano, K.; Glorius, F. *Org. Lett.* **2008**, *10*, 4243.

¹⁶⁴ Pesch, J.; Harms, K.; Bach, T. *Eur. J. Org. Chem.* **2004**, 2025.

¹⁶⁵ Gómez-Bujedo, S.; Alcarazo, M.; Pichon, C.; Álvarez, E.; Fernández, R.; Lassaletta, J. M. *Chem. Commun.* **2007**, 1180.

¹⁶⁶ For a previous example, see: Barbier, D.; Marazano, C.; Das, B. C.; Potier, P. *J. Org. Chem.* **1996**, *61*, 9596.

¹⁶⁷ For a description of the mechanism and reviews on the Zincke reaction, see: a) Génisson, Y.; Marazano, C.; Mehmandoust, M.; Gnecco, D.; Das, B. C. *Synlett* **1992**, 431; b) Kost, A. N.; Gromov, S. P.; Sagitullin, R. S. *Tetrahedron* **1981**, *37*, 3423; c) Becher, J. *Synthesis* **1980**, 589.

¹⁶⁸ (a) Boyd, G. V.; Summers, A. J. H. *J. Chem. Soc. C* **1971**, 409; (b) Boyd, G. V. *Chem. Commun.* **1967**, 954.

¹⁶⁹ For a minireview, see: Enders, D.; Gielen, H. *J. Organomet. Chem.* **2001**, *617-618*, 70.

¹⁷⁰ (a) O'Toole, S. E.; Cannon, S. J. *Org. Biomol. Chem.* **2009**, *7*, 3584; (b) Chen, D.; Banphavichit, V.; Reibenspies, J.; Burgess, K. *Organometallics* **2007**, *26*, 855; (c) Teles, J. H.; Ebel, K.; Enders, D.; Breuer, K. (BASF AG), DE19704273, 1997; (d) Teles, J. H.; Melder, J.-P.; Ebel, K.; Schneider, R.; Gehrler, E.; Harder, W.; Brode, S.; Enders, D.; Breuer, K.; Raabe, G. *Helv. Chim. Acta* **1996**, *79*, 61.

¹⁷¹ (a) Ros, A.; Alcarazo, M.; Iglesias-Sigüenza, J.; Díez, A.; Álvarez, E.; Fernández, R.; Lassaletta, J. M. *Organometallics* **2008**, *27*, 4555; (b) Alcarazo, M.; Fernández, R.; Álvarez, E.; Lassaletta, J. M. *J. Organomet. Chem.* **2005**, *690*, 5979.

¹⁷² (a) Fürstner, A.; Alcarazo, M.; César, V.; Lehmann, C. W. *Chem. Commun.* **2006**, 2176; (b) Fürstner, A.; Alcarazo, M.; César, V.; Krause, H. *Org. Synth.* **2008**, 85, 34.

¹⁷³ (a) Struble, J. R.; Bode, J. W. *Tetrahedron* **2008**, 64, 6961; (b) Struble, J. R.; Kaeobamrung, J.; Bode, J. W. *Org. Lett.* **2008**, 10, 957.

¹⁷⁴ Makino, T.; Masu, H.; Katagiri, K.; Yamasaki, R.; Asumaya, I.; Saito, S. *Eur. J. Inorg. Chem.* **2008**, 4861.

¹⁷⁵ (a) Nakafuji, S.-Y.; Kobayashi, J.; Kawashima, T. *Angew. Chem. Int. Ed.* **2008**, 47, 1141; (b) Fürstner, A.; Alcarazo, M.; Radkowski, K.; Lehmann, C. W. *Angew. Chem. Int. Ed.* **2008**, 47, 8302; (c) Kobayashi, J.; Nakafuji, S.-Y.; Yatabe, A.; Kawashima, T. *Chem. Commun.* **2008**, 6233; (d) Alcarazo, M.; Stork, T.; Anoop, A.; Thiel, W.; Fürstner, A. *Angew. Chem. Int. Ed.* **2010**, 49, 2542.

¹⁷⁶ **153a** was already reported in the literature, see: Gompper, R.; Kujath, E.; Wagner, H.-U. *Angew. Chem. Int. Ed. Engl.* **1982**, 21, 543.

¹⁷⁷ Fürstner, A.; Alcarazo, M.; Goddard, R.; Lehmann, C. W. *Angew. Chem. Int. Ed.* **2008**, 47, 3210 and references therein.

¹⁷⁸ Iglesias-Sigüenza, J.; Ros, A.; Díez, E.; Alcarazo, M.; Álvarez, E.; Fernández, R.; Lassaletta, J. M. *Dalton Trans.* **2009**, 7113.

¹⁷⁹ Eicher, T.; Hünig, S.; Nikolaus, P. *Angew. Chem. Int. Ed. Engl.* **1967**, 6, 699.

¹⁸⁰ Eicher, T.; Hünig, S.; Hansen, H. *Angew. Chem. Int. Ed. Engl.* **1967**, 6, 699.

Biographies

Laure Benhamou



Laure Benhamou was born in 1983 in Châtenay Malabry, France. She studied chemistry at the Université Paul Sabatier in Toulouse. In 2009, she obtained her PhD degree under the supervision of Dr. G. Lavigne and Dr. V. César at the “Laboratoire de Chimie de Coordination du CNRS” working on functionalized N-heterocyclic carbene ligands. She is currently a postdoctoral associate in the group of Prof. D. Zargarian at the “Université de Montréal” working on the chemistry of Nickel(III) complexes. In 2011, she will join Prof. E. P. Kündig at the University of Geneva (Switzerland) as a postdoctoral fellow.

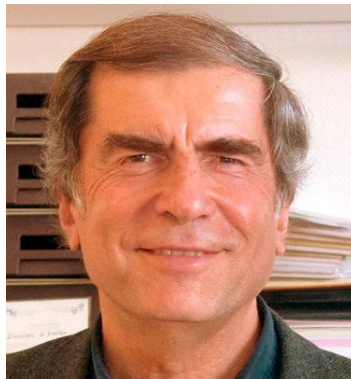
Edith Chardon



Edith Chardon was born in 1985 in Orléans, France. In 2008, she received her M.Sc. from the University of Rennes I as well as her engineering degree from the Ecole Nationale Supérieure de Chimie de Rennes (France). She is currently PhD student in the group of Dr. Stéphane Bellemin-

Lapponnaz in Strasbourg and the group of Dr. Gilles Guichard in Bordeaux (France) investigating the chemistry of N-heterocyclic carbenes and their biomedical applications.

Guy Lavigne



Guy Lavigne earned his degrees in chemistry at the *University Paul Sabatier*, in Toulouse. He was appointed as CNRS research scientist in 1973 and graduated from the *University Pierre & Marie Curie* (Paris VI) where he received the “*Doctorat d’Etat es Sciences*” in 1979 under the guidance of Professor Yves Jeannin. He joined the *Laboratoire de Chimie de Coordination* (LCC) in Toulouse in 1980. After post-doctoral studies at UCLA with Herbert D. Kaesz (1983-1984), he was promoted CNRS senior research scientist (Directeur de recherches) at the LCC in 1988, originally working in the field of base-promoted reactions of ruthenium carbonyls, a work highlighted in *Angewandte Chemie* (2000). He is presently head of the group “Molecular design of transition metal pre-catalysts” at LCC-CNRS. His present research projects are focusing on the conceptual and experimental design of ruthenium-based pre-catalysts including Ru(0) carbonyl complexes (for C-H/olefin coupling), and Ru(II) complexes for olefin metathesis and transfer hydrogenation. In addition, the group is now focusing on a conceptually new family of anionic N-heterocyclic carbenes paving the way to zwitterionic catalysts and their readily modulable functionalized derivatives. Amongst diverse professional activities, Guy Lavigne has been president of the coordination chemistry division of the “*Société Chimique de France*” (2006-2009) and is presently member of the European board of the Division of Inorganic Chemistry of EuCheMS.

Stéphane Bellemin-Laponnaz



Stéphane Bellemin-Laponnaz studied chemistry at Université Joseph Fourier (Grenoble) and Université Louis Pasteur (Strasbourg). In 1994, he joined the group of Professor John A. Osborn at Université Louis Pasteur to obtain his doctorate in 1998 studying the chemistry of oxo compounds. In 1999, he became a member of the group of Professor Gregory C. Fu at Massachusetts Institute of Technology (Cambridge, MA) as a postdoctoral fellow working on kinetic resolution and phosphametalocene chemistry. In late 2000, he joined the group of Professor Lutz H. Gade at Université Louis Pasteur (currently at University of Heidelberg) as a CNRS researcher and recently moved at the Institut de Physique et Chimie des Matériaux de Strasbourg as a CNRS Director of Research. His research is mainly focused on organometallic chemistry, coordination chemistry and homogeneous catalysis. He was awarded a Bronze Medal by the CNRS in 2005 and Coordination Chemistry Section Prize of the Société Chimique de France in 2009.

Vincent César



Vincent César was born in 1977 in Nancy, France. He studied chemistry at the Ecole Normale Supérieure in Lyon, where he obtained an “Agrégation” in Physical Sciences (major in chemistry) in 2000. He completed his thesis in 2004 under the supervision of Prof. L. H. Gade and Dr. S. Bellemin-Laponnaz at the “Université Louis Pasteur” in Strasbourg working on chiral oxazoliny/N-heterocyclic carbene ligands. He then joined Prof. A. Fürstner at the Max Planck Institut für Kohlenforschung in Mülheim (Germany) as an Alexander-von-Humboldt fellow. In 2006, he was appointed CNRS researcher at the “Laboratoire de Chimie de Coordination du CNRS” in Toulouse, where he is working with Dr. G. Lavigne. His research is mainly focused on the design and development of new N-Heterocyclic Carbenes for organometallic chemistry and homogeneous catalysis.