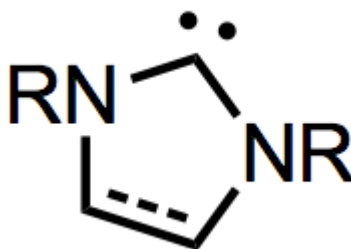


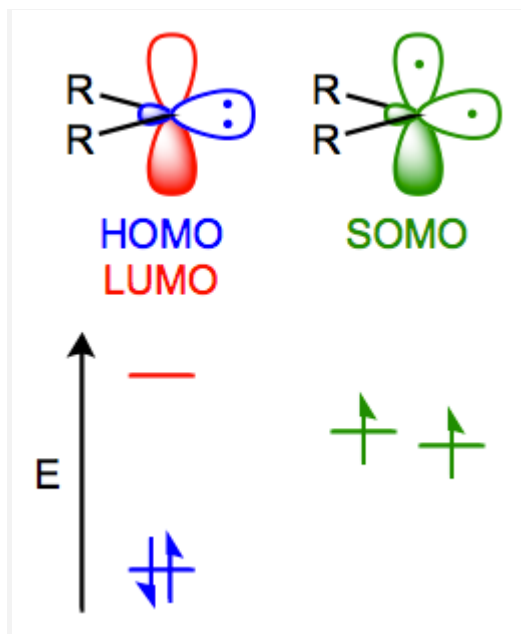
EPIC LIGAND SURVEY: N-HETEROCYCLIC CARBENES



Our romp through the common dative ligands continues with the ***N*-heterocyclic carbenes** (NHCs). Although we'll tackle carbenes in general in another post, NHCs deserve their own nod due to their unique structure, properties, and steric tunability. Unlike most metal carbenes, NHCs are typically unreactive when coordinated to a metal (with some exceptions). Like phosphines, they are commonly used to modulate the steric and electronic properties of metal complexes. In fact, the similarities between NHCs and phosphines are notable. Overall, few ligands are as effective as NHCs at ramping up the electron density on a metal center while remaining innocent.

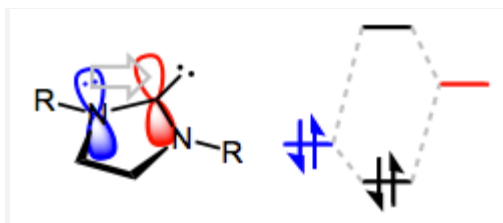
General Properties

Free NHCs contain carbon in the rarely encountered +2 oxidation state. In general, we can classify carbenes according to the nature of the two non-bonding electrons—if they are spin paired (one up and one down), the carbene is called a singlet; if their spins are parallel, we call the carbene a triplet. Whether a carbene is in the singlet or triplet state depends primarily on the difference in energy between its frontier orbitals—when the FMOs are close in energy, single occupation of each FMO (the triplet state) is likely. As the energy difference increases, the singlet state becomes more likely because the higher-energy FMO is less likely to be occupied.



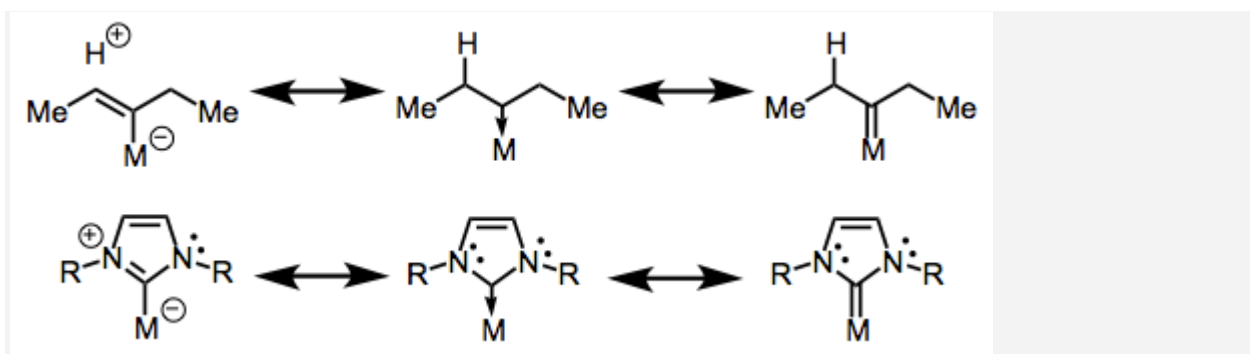
FMO pictures for singlet and triplet carbenes.

How do we tinker with the FMO energies, you ask? The nature of the R groups is key. When R is electron-donating, the energy of the LUMO is raised through a fairly straightforward $n \rightarrow 2p_z$ orbital interaction. An analogous interaction is responsible for the stability of carbocations adjacent to lone-pair-bearing heteroatoms (such as the [oxocarbenium ion](#)). Thanks to this orbital interaction, electron-donating groups stabilize the singlet state...and NHCs are no exception! The figure below depicts only one of two possible $n \rightarrow 2p_z$ interactions in free *N*-heterocyclic carbenes. The LUMOs of free NHCs are quite high in energy, relative to other kinds of carbenes.



Free NHCs are most definitely singlets.

This conclusion is important, because it helps explain why NHCs are strong σ -donors but relatively weak π -acceptors. On the other hand, your average metal-coordinated, alkyl carbene (alkylidene) is such a strong π -acceptor that it's always drawn with a metal-carbon double bond. The figure below depicts three different resonance structures one can draw for alkylidenes and NHCs. Take a look and ask yourself: which resonance structures are most important for each class of carbene?



Which resonance structures are important for the alkylidene and NHC?

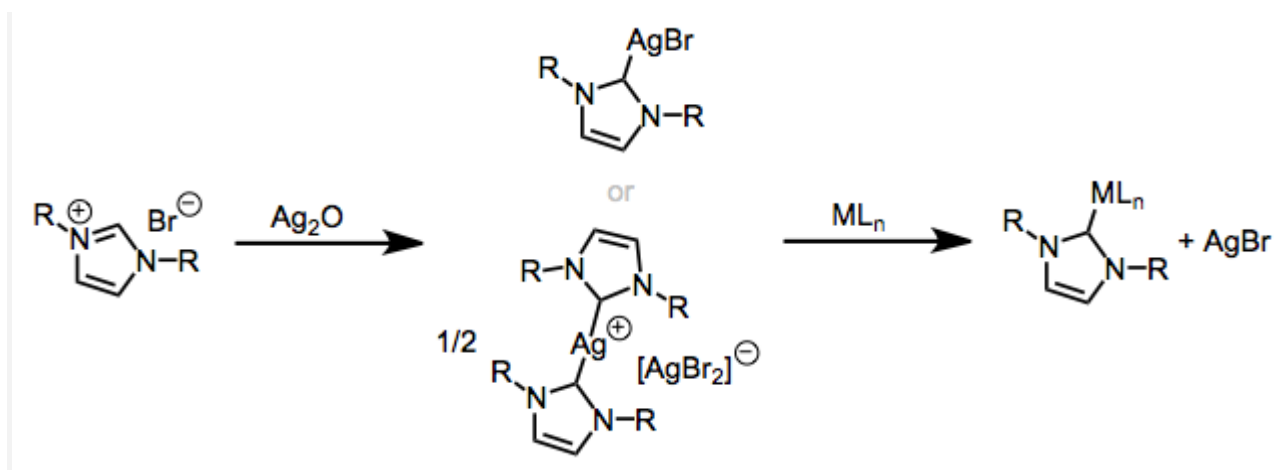
The charged and dative resonance structures for alkylidenes are unthinkable, but those resonance structures are important for the NHC. The double-bond resonance structure is occasionally seen for NHCs nowadays, but not very useful in my opinion. Put another way, backbonding is essentially a given for alkylidenes, but NHCs are relatively weak backbonders. Even more so than phosphines, NHCs pile electron density on the metal center through σ -donation. The charged resonance structure illustrates this idea well. You may have also noticed that I snuck a double bond into the NHC—the electronics of the NHC ligand can be tuned by adjusting the level of saturation of the azole ring. Benzimidazoles, in which the two “back” carbons are part of a benzene ring, are also possible. I’ll leave it up to you to figure out why, but the azole rings from least to most electron donating are:

benzimidazole < imidazole < imidazoline

The steric tunability of NHCs is phenomenal, thanks to their ease of synthesis. Aryl and methyl R groups are most commonly used. NHC complexes may be synthesized via deprotonation of the corresponding azolium salt followed by introduction of the metal (see below), so changing the R group is often just a matter of starting with a different imidazolium salt.

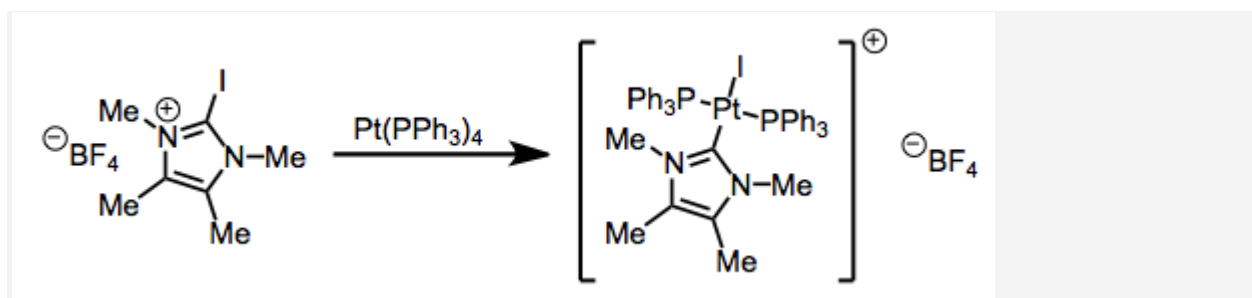
Synthesis

NHCs may be made through deprotonation of the corresponding azolium salts, which have pK_a 's in the range 21-24. Sterically bulky R groups permit isolation of the free NHC. A nice method that avoids the need for strong bases employs transmetallation from silver-NHC complexes. OM complexes of Au, Cu, Ni, Pd, Pt, Rh, Ir and Ru have been prepared using this method, which is driven forward by the insolubility of the silver halide.



Transmetalation from silver: a great method for the synthesis of NHC complexes.

Another attractive method involves direct oxidative addition into a C-H or C-I bond in the azolium ring; however, the substrate scope of this method is somewhat limited (notice that -H or -I makes its way onto the metal center as well).

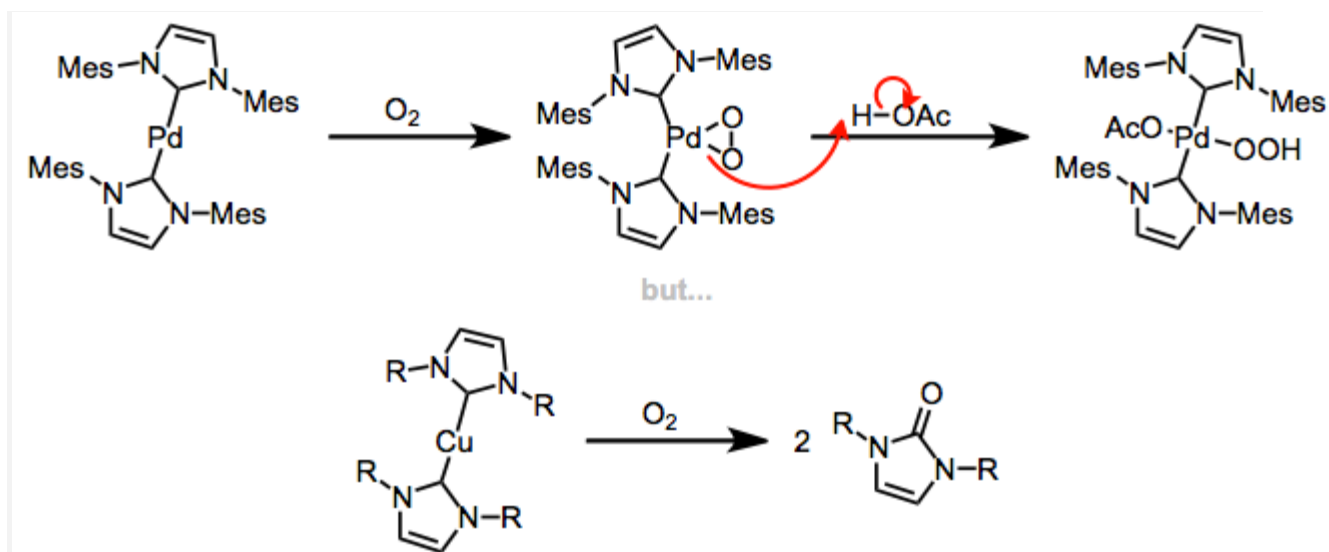


Oxidative addition with iodine-substituted imidazolium salts.

The synthesis of azolium precursors and NHC complexes is very well developed— for more information, check out this [nice overview](#) of NHC chemistry from the Baran group.

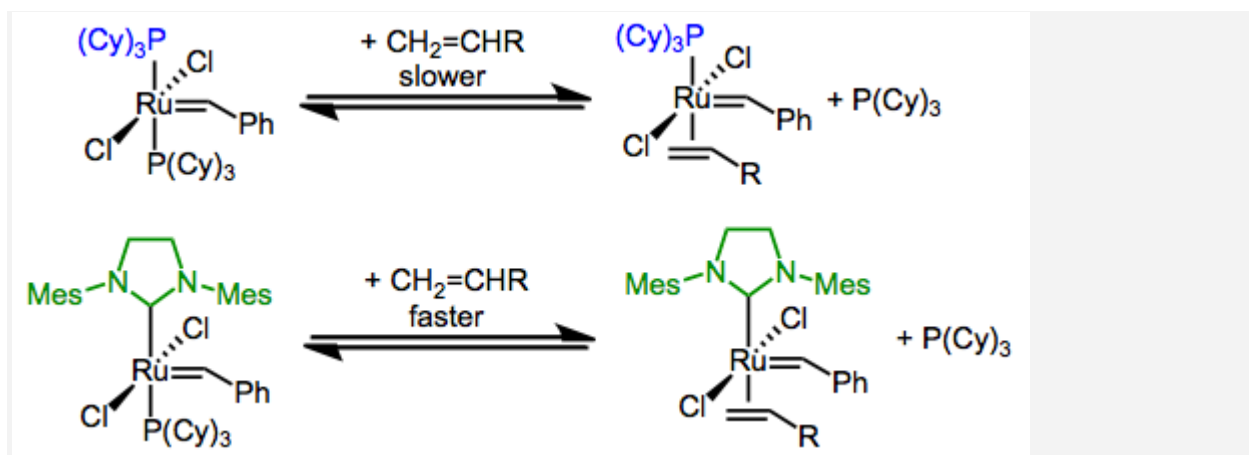
Reactions

Like phosphines, NHCs are most commonly spectator ligands that are used to tweak the electronic character and/or steric environment of the metal center. Given the similarity of NHCs to phosphines, we may legitimately wonder why they're useful. When might an NHC ligand be a better choice than a phosphine? Early in their history, NHCs were applied to transition-metal-catalyzed **oxidation** reactions, which may [wreak havoc](#) on oxidation-sensitive phosphines. Phosphorus famously loves to sit in the P(V) oxidation state when bound to oxygen, as any chemist with experience with the Wittig reaction is aware. NHCs aren't prone to the same fate, but are strong σ -donors nonetheless. Transition-metal-catalyzed oxidation reactions involving NHC ligands remain an active area of development—in some cases, oxidation of the NHC *is* a problem.



NHCs are clearly awesome ligands when oxidation with Pd is the goal. However, oxidation of the ligand is a problem for NHC-Cu complexes.

NHCs have been famously applied to the development of the Nobel-prize-winning **olefin metathesis** reaction. An early problem with olefin metathesis concerned the competition between olefin and phosphine for binding Grubbs's ruthenium catalyst. Olefin binding is necessary for the reaction to take place, but before that can happen, a phosphine ligand must depart from the catalyst. A switch of the *trans* ligand from phosphine to a more strongly σ -donating NHC speeds up ligand dissociation. This result has been attributed to the **trans effect**, the acceleration of ligand dissociation *trans* to certain ligands (notably NHCs, hydrides, olefins, and CO).



Phosphine dissociation is sped up when a phosphine is replaced with an NHC. Grubbs II, the lower complex, possesses higher metathesis activity than the top complex, Grubbs I.

The number of transformations mediated by NHC-containing complexes is growing by the day, and chemists have gotten pretty clever—check out [this recent report](http://organometallicchem.wordpress.com/2012/01/26/epic-ligand-survey-n-heterocyclic-carbenes/) of a bis-*mixed*-carbene complex that does hydrogenation chemistry! NHCs occupy a unique niche not addressed by any other types of ligands at present, and their importance continues to grow.

Coming up next is our first example of a ligand commonly found in purely organic compounds: the alkene. Backbonding will return yet again as we explore the unique (and definitely non-traditional) resonance structures associated with alkene complexes, and we'll discuss in detail the mechanistic possibilities for olefinic ligands, which are numerous. Thanks for reading!

Source : <http://organometallicchem.wordpress.com/2012/01/26/epic-ligand-survey-n-heterocyclic-carbenes/>