Unsymmetrical Difunctionalization of Two Different C–H Bonds in One Pot Under Transition-Metal Catalysis

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Abstract Recent advancements in unsymmetrical difunctionalization based on the substitution of two different C–H bonds in one-pot are described. Due to the difficulty of controlling reactivity and selectivity, multi-functionalization via substitution of several C–H bonds to install different functional groups has been limited until recently, in comparison with well-studied functionalization via sequential addition to unsaturated π-bonds. This difunctionalization protocol provides an efficient and rapid approach to a library of structurally complicated target molecules through the formation of multiple C–X bonds with high atom- and step-economy.

1 Introduction

Selective construction of properly functionalized target molecules from simple and readily available starting materials in a small number of steps is an important goal in synthetic organic chemistry. In addition, the development of sustainable reaction processes with environmentally friendly and operationally safe technology is another key issue. If two or more C–X bonds can be formed in a one-pot operation with a single catalyst, a variety of molecules can be created more efficiently. A frequently utilized strategy is the multi-component cascade reaction via inter- and intra-molecular addition to unsaturated π-bonds. Various compounds have been synthesized elegantly with the site- and regioselective installation of appropriate functional groups.1 In past decades, transition-metal-catalyzed C–X bond formation via C–H bond cleavage has received considerable attention as a straightforward method to modify the structure and function of organic molecules.2 Because structurally complicated functional molecules are obtained through the activation of generally unreactive ubiquitous C–H bonds, they are highly useful in view of atom- and step-economy.

Even though much success has been achieved in this field, one C–H bond is usually activated and converted into another functional group in most of the reported transformations. Simultaneous multiple introduction of different functionalities with the activation of several C–H bonds existing in one or two molecules remains challenging. The major difficulty arises from site-selective control of multiple C–H functionalization, and examples are limited mainly to the introduction of the same functional group.3 This is because catalysts and directing groups that control the regioselectivity of the reaction are usually highly specific for one reaction, and therefore additional steps with different catalyst systems are required for the next C–H activation to install a different functional group.4 In addition, the correct choice of two functionalizing methods, in which the intermediate in the initial functionalization does not hamper the overall reaction sequence, is very important. Therefore, the strategy for unsymmetrical multiple functionalization of C–H bonds in a one-pot operation was limited until the last
decade. This short review focuses on recent advancements in the one-pot reaction involving two sequential C–H functionalizations with the formation of two different C–X bonds. The graphics in this short review show the initially installed functional group in red, and the secondary introduced group in blue, except for Scheme 1. Note that the following three types of transformations, which have already been highlighted in previous excellent reviews, have been omitted: (1) Annulation with multiple bonds existing in one molecule containing alkynes and alkenes (Scheme 1, eqs a and b), (2) Catellani-type coupling reactions using norbornene derivatives as promoters (eq c), and (3) cross-dehydrogenative coupling of two different (hetero)aromatic compounds (eq d).

2 ortho-Selective Functionalization of Two Different C–H Bonds Relative to the Directing Group

2.1 Unsymmetrical Difunctionalization with the Introduction of Similar Functional Groups

A one-pot method for formation of two different C–X bonds via two C–H bond cleavages involving rhodium-catalyzed direct alkenylation of a C–H bond of 1-phenylpyrazole was reported in 2009 by Miura, Satoh and co-workers. They demonstrated the one-pot synthesis of unsymmetrically substituted 1,3-dialkenylbenzene derivatives using a pyrazolyl moiety as the directing group. As a typical example, 1-phenylpyrazole was treated with n-butyl acrylate in the presence of [Cp*RhCl₂]₂ as the catalyst and Cu(OAc)₂·H₂O as the oxidant, followed by addition of an excess amount of styrene which, after 2–7 hours, furnished the corresponding meta-dialkenylated pyrazolylarene 1a in 74% yield (Scheme 2). Changing the order of addition of the two alkenes did not affect the reactivity. Olefination with tert-butyl acrylate required post-treatment with a catalytic amount of PdCl₂(PhCN)₂ to induce isomerization of the olefinic double bond and furnish the thermodynamically more stable E-isomer of 1b. As expected, dialkenylation with two equivalents of the same alkenes also occurred as a side reaction in most cases. However, the current rapid approach to functionalized meta-phenylene vinylene structures enabled the discovery of luminescence of the derivatives having a tert-butyl group, such as 1b, in the solid state.
In 2012, Gevorgyan et al. reported a palladium-catalyzed one-pot sequential acetoxylation and pivaloxylation of C–H bonds (Scheme 4).4c Using a 2-pyrimidyldiisopropylsilyl group as a directing group, 10 orthogonally protected resorcinol derivatives 3 were obtained in good yield. The acetyl group in the products could be selectively cleaved under basic conditions while keeping the pivaloyl group intact. The 2-pyrimidyldiisopropylsilyl group could also be removed easily or substituted with various other functional groups.5i

In 2017, Zhang, Fan and co-workers reported the synthesis of naphthoquinolinizone derivatives 6 via rhodium-catalyzed carbenoid insertion into two different C(sp^2)–H bonds of 2-aryl-3-cyanopyridine 4 followed by annulation (Scheme 5).11 The protocol provided a facile approach to azapyrene skeletons, which possess potentially unique biological and optical properties. Several control experiments revealed that the reaction proceeded via an initial carbene insertion followed by C-cyclization, and a second carbene insertion followed by N-cyclization (Scheme 5). Although the same functional group was introduced at two ortho-positions initially, the subsequent double cyclization led to the formation of the unsymmetrical structure.

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2.2 Unsymmetrical Difunctionalization with the Introduction of Different Functional Groups

As described so far, catalytic unsymmetrical difunctionalization of two C–H bonds existing in one molecule through three-component coupling reactions (i.e., difunctionalization via two sequential intermolecular bond formations) is limited, and most methods have been used to incorporate similar functional groups (see Schemes 13, 15, 22 and 30 for exceptions). Heteroatom-containing directing groups were indispensable for controlling the site selectivity of C–H bond activation. However, control of the chemoselectivity to achieve multiple functionalization was difficult, because directing groups are usually highly selective for a certain specific bond formation.

To overcome this limitation, Sahoo et al., in 2016, used benzoic acid derivatives having O-tethered double bonds as substrates and demonstrated unsymmetrical difunctionalization with the introduction of two different functional groups. They envisioned a one-pot sequential reaction involving a rapid intramolecular ortho-C–H hydroarylation followed by intermolecular functionalization of a second ortho-C–H bond. The use of a methylphenylsulfoximidoyl (MPS) moiety as a directing group and the combination of [RuCl2(p-cymene)]2 with AgSbF6 as the catalyst was essential to realize the expected transformation. Differently functionalized dihydrobenzofuran derivatives 7a and 7b were obtained by hydroarylation/amidation cascades with sulfonamides, and the reaction with phenyl vinyl sulfone obtained by hydroarylation/amidation cascades with sulfonamides, and the reaction with phenyl vinyl sulfone.

To achieve multiple functionalization of arylmethylphenyl sulfoximines through ortho-C–H alkylation/amidation of aroylmethyl phenyl sulfoximines, the reaction with phenyl vinyl sulfone introduced an alkyl group at the 5-position leading to 7c (Scheme 6).

Properly functionalized phenol derivatives are not only common structures observed in many pharmaceuticals and functional materials but are also useful building blocks in organic synthesis. However, conventional approaches toward their synthesis often require multi-step transformations using reactive organolithium reagents and harsh conditions, which limits the number of allowable functional group. In 2018, Zhou et al. reported the rhodium-catalyzed sequential ortho-C–H alkylation/amidation of N-phenoxycacetamides 9 leading to unsymmetrically substituted phenol derivatives 10 (Scheme 7).

The acetylamino group worked as an oxidizing directing group, which not only facilitated site-selective alkylation with diazomalonate but also generated an acetylamino group in the migration reaction step without using any oxidants under mild conditions. Diverse functional groups, such as methoxycarbonyl, chloro, and cyano groups, were compatible, and even bromo groups tolerated the reaction conditions. When using phenol derivatives having substitu-
ents at meta-positions, alkylation occurred selectively at the sterically less hindered position, and 1,2,3,4-tetra-substituted benzenes were formed exclusively as a single product after the overall reaction.

Several mechanistic studies revealed that the C(sp²)–H bond cleavage was involved in the rate-determining step, and a shift of an acetylamino group occurred intramolecularly. Because the use of N-(2-hydroxyphenyl)acetamide as a precursor did not provide the desired product, intramolecular C–H alkylation with diazo compounds occurred before the intramolecular 1,2-shift of the acetylamino group (Scheme 8).

Based on these results, the mechanism shown in Scheme 9 was proposed. First, ligand exchange of [Cp*RhCl₂]₂ with CsOAc provided Cp*Rh(OAc)₂ (Scheme 8). Coordination of the diazo compound to the rhodium center, followed by 1,2-migratory insertion of the aryl group provided the six-membered ring intermediate B. Next, Rh(V) nitrenoid intermediate D was formed via oxidative addition of Rh(III) into the N–O bond. Subsequent protonation leading to acyclic C, and then intramolecular electrophilic nitrenoid addition furnished deaeromatized intermediate E. Finally, product 10 was formed by sequential protonation of F and rearomatization along with the regeneration of A. In contrast to the aforementioned work of Sahoo (see Scheme 6), intermolecular C–H functionalization occurred prior to intramolecular C–H functionalization due to the slow generation of nitrenoid intermediate D.

This protocol can be also applied to the transformation of biologically active molecules such as estrone derivatives (Scheme 10). The first alkylation again occurred site selectively at the sterically less hindered position. This result confirmed that the current unsymmetrical ortho C–H functionalization provided a reliable shortcut to highly substituted phenol derivatives, which are inaccessible by conventional synthetic methods.

Recently, a similar strategy was described by Song et al. involving a palladium-catalyzed one-pot alkenylation (Heck reaction)/sulfenylation of aryl thiocarbamates (Scheme 11). For this difunctionalization, intermolecular alkenylation proceeded rapidly during the slow C–S bond formation by reductive elimination of a CAr–Pd–S species. Diverse trisubstituted and rearomatized tetrasubstituted benzenes were obtained using a catalytic amount of Pd(OAc)₂ and benzoquinone as the oxidant in an acidic medium. Styrene as well as acrylate esters could be used as coupling partners. When aryl thiocarbamates possessing two unsymmetrical meta C–H bonds were used, the initial intermolecular alkenylation occurred selectively at the sterically less hindered position.
The resulting products could be transformed into tetra-substituted phenol derivatives via ring opening of the oxathiol-2-one ring triggered by amination or saponification (Scheme 12). Although the use of an excess amount of the olefin was required to control the reactivity, excellent functional group compatibility and site selectivity proved the usefulness of this one-pot difunctionalization protocol.

2.3 ortho-Selective Unsymmetrical Difunctionalization Promoted by Two Different Directing Groups Appearing During the Progress of the Reaction

One-pot difunctionalization in a three-component coupling reaction was achieved by Qian, Dong and co-workers in 2014.17 The rhodacycle intermediate generated from the reaction of N-sulfonyl ketimines 12 and internal alkynes was trapped by different aldehydes leading to polycyclic products 13 (Scheme 13). Functional groups, including iodide, nitro, and alkoxycarbonyl, were all well-tolerated, and the substrate scope was broad. The addition of di-tert-butyl dicarbonate [(Boc)2O] was indispensable, with the two-component coupling product 14a being obtained as the major product without (Boc)2O (Scheme 13). Thus, the reaction mechanism shown in Scheme 14 is most plausible, which involves: (1) imino-group-directed ortho-C–H alkenylation leading to seven-membered ring rhodacycle intermediate G, (2) intramolecular cyclization via insertion of the alkynylrhodium species into the C=N bond, (3) amino-group-assisted C–H activation leading to azarhodacycle H followed by insertion of a formyl group, and (4) final dehydrogenative cyclization assisted by (Boc)2O, which promoted the leaving ability of the OH group, leading to 13. Although directing groups are usually highly specific for a certain C–H bond, they changed with the progress of the reaction in this difunctionalization.

Adapting a similar strategy, Sahoo et al. reported unsymmetrical annulation via the activation of two C(sp2)–H bonds.18 By controlling the pH of the reaction medium, two C–C and two C–N bonds were formed efficiently in a single operation. The reaction proceeded with broad substrate scope and good functional group tolerance, providing structurally complicated spiroisoquinolones 15 from readily accessible starting materials (Scheme 15). Based on the mechanistic studies, the following three key steps were
postulated in the current transformation (Scheme 16): (1) Initial annulation of the proximal C–H bond of the MPS group with alkynes under acidic conditions, (2) formation of an isoquinolone or pyridone intermediate along with regeneration of the ruthenium active species; the MPS group acted as an internal oxidant to promote this regeneration step,15 and (3) the second C–H bond annulation with quinone, which was assisted by the coordination of a ruthenium complex to the N–H bond of isoquinolone or pyridone, under basic conditions. Cu(OAc)₂ oxidized the Ru(0) species to the MPS group with alkynes under acidic conditions, (2) formation of quinones leading to spiro isoquinolones (Scheme 15), and (3) the second C–H bond annulation with quinone, which was assisted by the coordination of a ruthenium complex to the N–H bond of isoquinolone or pyridone, under basic conditions. Cu(OAc)₂ oxidized the Ru(0) species back to the reactive Ru(II) species in the second annulation step.

A unique skeletal reconstruction of benzyl aryl sulfoxides into dibenzothiophene-1-carbaldehydes 16 through unsymmetrical difunctionalization of two C–H bonds was reported by Anthonchick in 2011.19 Although the yields were moderate, variously substituted dibenzothiophene derivatives having unsymmetrical structures were obtained from simple precursors through the formal abstraction of four hydrogen atoms (Scheme 17). The transformation appears complicated, but the following pathway supported by several mechanistic studies was proposed (Scheme 18): (1) Formation of cyclic sulfoxide J promoted by sulfoxide group-assisted regioselective direct arylation of the C–H bond, (2) Pummerer rearrangement leading to mercaptoaldehyde K, and (3) sulfur-group-directed C–S bond formation. Addition of p-fluoriodobenzene and AgOAc was crucial for decreasing the catalyst loading of PdCl₂. In the absence of p-fluoriodobenzene, stoichiometric amounts of a palladium complex were required. This iodoarene was thought to play a key role in generating mononuclear Pd(IV) species, which then underwent reductive elimination along with C–H activation to produce palladacycle L. Interestingly, neither Pummerer rearrangement of the starting benzyl aryl sulfoxides nor arylation of several palladacycle intermediates with iodoarene was observed. Similar to the transformations shown in Schemes 13 and 15, two different directing groups appeared during the progress of the reaction, and promoted the current strictly defined reaction sequence.

![Scheme 15: Ruthenium-catalyzed unsymmetrical annulation with alkynes and quinones leading to spiro isoquinolones](image-url)

![Scheme 16: Stepwise annulation via two different C–H bond activations](image-url)

![Scheme 17: Palladium-catalyzed regioselective intramolecular arylation and sulfonylation of C–H bonds leading to dibenzothiophene-1-carbaldehydes](image-url)
3 ortho/meta-Selective C–H Bond Difunctionalization Relative to the Directing Group

In 2017, Li et al. reported a conceptually different one-pot difunctionalization based on ortho/meta C–H bond cleavage.20,21 The use of [RuCl2(p-cymene)]2 without ligands and bases allowed ortho-chlorination and meta-sulfonation of 2-phenoxypyridines 17 with arylsulfonyl chlorides. The typical promoter for meta-sulfonation of 2-phenylpyridines,22 K2CO3, did not improve the efficiency of the current ortho/meta-difunctionalization. The choice of solvent appears to be important, and the desired difunctionalized products 18 were obtained only in xylene or toluene. Although substituents at the meta-position of the 2-pyridyl group and strongly electron-withdrawing substituents shut down the reaction, site-selective incorporation of chloro and sulfonyl groups was observed in a variety of 2-aryloxypyridines and pyrimidines (Scheme 19). A 2-pyridyl group in the product could be removed to release the free phenolic hydroxy group by treatment with MeOTf followed by MeONa.

Insight into the reaction mechanism was obtained from the following reactions. First, the desired difunctionalized product 18a was obtained from 2-phenoxypyridine 19 having a p-tosyl group at the meta-position, indicating that chlorination occurred after sulfonation (Scheme 20, a). Second, the cyclic six-membered ruthenacycle intermediate 20 reacted with p-tosyl chloride to give the expected product 18a, quantitatively (Scheme 20, b). Third, the radical scavenger TEMPO completely quenched the reaction (Scheme 20, c).

Supported by the experimental results, a plausible reaction pathway involving complex 20a is shown in Scheme 21. First, the para position of the Ru–C bond of ruthenacycle intermediate 20a, generated via ortho C–H activation of 2-phenoxypyridine 17a, was attacked by p-tosyl chloride to form intermediate L.22 A strong para-directing effect of the Ru–C σ-bond determined the site-selectivity in this step.22

Oxidative addition of p-tosyl chloride gave Ru(IV) intermediate M, which then underwent reductive elimination to provide 18a and ruthenium complex N. Although the details of the regeneration of 20a by the reaction of N with another molecule of 17a was not described, the authors detected (chloromethyl)methylbenzene and p-tolyl-4-methylbenzenesulfonylthioate as side products under standard reaction conditions by GC-MS analysis. Thus, they concluded that p-tosyl chloride acted not only as a sulfonation and...
chlorination source, but also as an oxidant to regenerate 20a. Although the reaction efficiency was not high enough for practical use, this work demonstrated the novel strategy of unsymmetrical difunctionalization with the introduction of two different functional groups.

At about the same time, Ackermann et al. developed a three-component coupling reaction of 2-aryloxazolines, sec-alkyl halides (2-bromoalkanoates), and aryl halides.\(^2\) ortho-Arylation and meta-alkylation occurred efficiently with complete site selectivity in this reaction. First, they reported that the combination of a ruthenium(II) biscarboxylate complex \([\text{Ru}(\text{OCOR})_2(\text{p-cymene})]_2\) with \(\text{PPh}_3\) displayed excellent catalytic performance toward alkylation of meta C–H bonds with sec-alkyl halides.\(^2\) The yield was reduced to less than 5% using the typical \([\text{RuCl}_2(p\text{-cymene})]_2\) as the catalyst. In contrast to Li’s work using 2-phenoxypyridines as substrates (see Scheme 19), formation of ortho-halogenated products was not observed. Next, the simple addition of aryl bromides after completion of the initial meta-alkylation was found to provide variously substituted 2-aryloxazolines 21 in good yields. \([\text{Ru}(\text{OCOMes})_2(\text{p-cymene})]_2\) was used for aryloxazolines (Scheme 22), while a similar ruthenium complex containing a bulkier adamantyl group substituted ligand was chosen for other arylheterocycles, such as 1-aryl-1H-pyrazoles and 6-phenyl-7H-purines (Scheme 23).

Several control experiments confirmed that the reaction occurred via reversible C–H bond cleavage exclusively at the ortho-position (Scheme 24, a), and the stereochemistry of the sec-alkyl bromide was not preserved during meta-alkylation (Scheme 24, b). These observations could be rationalized by considering the mechanism of the typical ruthenium-catalyzed meta-alkylation, which involved attack of the radical species generated from sec-alkyl halides at the para-position of the Ru–C σ-bond of the ruthenacycle intermediate.\(^2\)

The good reactivity and high functional group tolerance observed in the initial alkylation allowed sequential ortho/meta-difunctionalization in a single operation simply by raising the temperature for the second arylation (Scheme 25). Most of the directing groups used in this study could be easily converted into various carbonyl groups, and the current difunctionalization technique provided a robust and straightforward approach to highly functionalized benzene derivatives.
Sequential Difunctionalization of Fused Aromatic Compounds and Heterocycles

Unsymmetrical difunctionalization of fused aromatic compounds, which have multiple potentially reactive C–H bonds with close bonding energies, is difficult. A unique example is the catalytic chloroamination of indoles with N-chloro-N,4-dimethylbenzenesulfonamide (TsMeNCl) reported by Liu et al. in 2011. Sequential difunctionalization of fused aromatic compounds and heterocycles in a single operation was also achieved using a stoichiometric amount of copper salts. Nicholas reported the bromoamination of indoles with oxime esters and CuBr·SMe2 (Scheme 27, a). Attempted catalytic variants of this reaction using NaBr, LiBr, and nBu4NBr as the external bromide source failed, instead giving 3-bromo-N-methylindole exclusively. Because this brominated indole was obtained as a side product, and not converted into the expected bromo-aminated product under the conditions shown in Scheme 27, a, the yield of the difunctionalized products in the current method were moderate to low. The authors proposed a mechanism involving electrophilic addition of a (AcO)CuIIIBr(N=CPh2) species at the 3-position of the indole ring followed by installation of a nucleophilic imino unit at the 2-position prior to reductive elimination of the copper species to form the C–Br bond. Recently, copper-mediated one-pot iodination and nitration was demonstrated by Jiang et al. (Scheme 27, b). 

One-pot C–H bond difunctionalization of indoles was also achieved using a stoichiometric amount of copper salts. Nicholas reported the bromoamination of indoles with oxime esters and CuBr·SMe2 (Scheme 27, a). Attempted catalytic variants of this reaction using NaBr, LiBr, and nBu4NBr as the external bromide source failed, instead giving 3-bromo-N-methylindole exclusively. Because this brominated indole was obtained as a side product, and not converted into the expected bromo-aminated product under the conditions shown in Scheme 27, a, the yield of the difunctionalized products in the current method were moderate to low. The authors proposed a mechanism involving electrophilic addition of a (AcO)CuIIIBr(N=CPh2) species at the 3-position of the indole ring followed by installation of a nucleophilic imino unit at the 2-position prior to reductive elimination of the copper species to form the C–Br bond. Recently, copper-mediated one-pot iodination and nitration was demonstrated by Jiang et al. (Scheme 27, b).
A rare example of difunctionalization involving C(sp³)-H bond activation was demonstrated by Baudoin. Treatment of a 2-chloro-3-alkylthiophene or -furan with aryl bromides resulted in sequential C(sp²)-H and C(sp³)-H bond arylation with a single palladium catalyst having tricyclopentylphosphine [P(Cyp)₃] as a ligand (Scheme 28, a). Since 1-chloro-2-alkyl-5-phenylthiophene was obtained as a by-product if the reaction was quenched before complete substrate conversion, intermolecular C(sp³)-H arylation occurred before intramolecular C(sp³)-H arylation. Good to high diastereoselectivity was achieved during C(sp³)-H arylation with the desymmetrization of two isopropyl groups. Intramolecular sequential arylation of C(sp²)-H and C(sp³)-H bonds was also conducted and revealed that the initial C(sp³)-H arylation occurred site selectively at a sterically less hindered position (Scheme 28, b).

In 2018, Murai and Takai developed conceptually different approaches that took advantage of the high site-selective control observed in the iridium-catalyzed intramolecular dehydrogenative silylation of aromatic C-H bonds. They found that sequential treatment of triethylsilane and bis(pinacolato)diboron with quinoline in the presence of an iridium complex resulted in the site-selective introduction of both silyl and boryl groups to the quinoline ring to provide 28a (Scheme 29, a). Control experiments revealed that this difunctionalization occurred via initial dehydrogenative silylation at the 8-position (Scheme 29, b) followed by direct C-H borylation at the 3- and 6-positions of the quinoline ring. Excess amounts of triethylsilane, the precatalyst [Ir(OMe)(cod)]₂, and 5,6-dimethyl-1,10-phenanthroline (29) were required for the difunctionalization of quinolines having no substituent at the 2-position due to the competitive formation of very stable iridium-quinoline complexes in the first silylation step. Introduction of alkyl groups at the 2-position greatly improved the reaction efficiency, and variously functionalized quinoline and acridine derivatives 28 were obtained in a one-pot operation (Scheme 30).

In this sequential difunctionalization, silylation proceeded under chelation control by the nitrogen of the quinoline ring, whereas borylation with additional ligand 29 was accomplished under steric control. Addition of 29 in the first silylation step to prevent chelation gave an inseparable mixture of silylated quinoline regioisomers. Although
both silylation and borylation were promoted by a single iridium catalyst, the reaction order was very important in controlling the selectivity. For example, borylation of 2-methylquinoline and 2,8-dimethylquinoline provided a mixture of mono- and diborylated quinoline derivatives (Scheme 31). Although its exact role was unclear, the silyl group at the 8-position was important for controlling the site selectivity in the second borylation step.

Electron-rich five-membered ring heteroarenes could also be applied in this sequential silylation and borylation (Scheme 32). Addition of dtbpy (4,4′-di-tert-butyl-2,2′-bipyridyl) was required for both the first silylation and second borylation steps of these substrates. A silyl group was introduced at the 1-position of these heterocycles in all cases. Adducts derived from competitive reductive dechlorination were not observed, and the reaction of the indole did not require protection of the N–H group.

All the substrates introduced so far contained heteroatoms, which was key to controlling the site-selectivity of the difunctionalization and increased the efficiency of the overall multistep reaction sequence. Reports on the unsymmetrical difunctionalization of pure aromatic hydrocarbons, which requires C–H activation without chelation assistance, are rare. In 2015, Murai and Takai demonstrated sequential silylation and borylation of pyrene using a similar strategy to that described above. Treatment of triethylsilane in the presence of [Ir(OMe)(cod)]$_2$ and 3,4,7,8-tetramethyl-1,10-phenanthroline followed by addition of bis(pinacolato)di-boron resulted in the selective introduction of both silyl and boryl groups at the 2- and 7-positions of pyrene, respectively, leading to compound 30 (Scheme 33). In this difunctionalization, both silylation and borylation proceeded under steric control. The resulting adduct 30 could be converted into the donor–acceptor substituted pyrene 31 by an additional two-step transformation.

Another example reported by the same research group was the sequential diarylation of azulene. Treatment with 2-bromothiophene followed by bromobenzene led to unsymmetrically substituted diarylazulene 32, albeit in low yield (Scheme 34). The fused structure of the cycloheptatrienyl cation and cyclopentadienyl anion can be drawn as a uniquely polarized resonance of azulene, which might be important to fix the reactive palladium species near the C–H bonds of the azulene. The yield was too low for practical use due to the difficulty of controlling the reactivity of the initial arylation with 2-bromothiophene. However, this one-pot protocol could potentially provide arylated azulene conjugates in a single operation, which is difficult to achieve by the conventional coupling reaction with generally unstable haloazulene derivatives.
5 Summary and Outlook

This short review is intended to attract the reader's attention and encourage future progress in the one-pot unsymmetrical difunctionalization of two C–H bonds. Noteworthy progress has been achieved in the last decade, and unique functionalized molecules have been constructed via one-pot operations. Although most of the products can be synthesized by stepwise transformations, the current one-pot protocols allow efficient shortcuts to many molecular architectures without purification of intermediates and removal of organic and inorganic wastes. While rhodium- and palladium-based catalysis was used initially, less expensive metals, such as ruthenium, are becoming more common these days. Ruthenium catalysis has also enabled site-selective ortho- and meta-difunctionalization relative to the directing groups. Recent sequential silylation and borylation of fused aromatic compounds has also introduced a new concept of the initial functionalization creating new reactive sites for the next regioselective functionalization.

Despite these significant advances, opportunities remain for further exploration in this field. (1) Some reported protocols required the subsequent addition of reagents and additives or different reaction conditions for each step. Although automated flow reaction systems can help to execute these intricate operations, development of a real 'one-pot' protocol allowing addition of all chemicals at the beginning without further additives or changes in the reaction conditions is desirable. Heterogeneous solid catalysts having several well-defined, uniform reactive sites may be suitable for this purpose. (2) Most of the reactions required heteroatom-containing directing groups to control the site selectivity of the C–H cleavage. Leveraging the C–H functionalization protocol without the aid of chelation control will expand the scope and applicability of the current difunctionalization.21 (3) Difunctionalization involving C(sp³)–H bond activation remains rare. Merging with radical transformations22,34 should provide several clues, although regioselective control of the C–H cleavage may be a key issue. (4) Application to the synthesis and screening of novel biologically active molecules and functional materials is currently limited. Although the correct design of precursors and optimization of the reaction order and conditions is required, the current protocol can provide rapid access to a library of target molecules with structural and functional diversity. The use of earth-abundant metal-based catalysts, such as manganese, iron, cobalt, nickel and copper complexes, will also improve the practicality of the difunctionalization protocol.26,35 This novel concept will find widespread application, especially in the field of pharmaceutical chemistry.36 Further synthetic potential is anticipated not only in academia but also in industry.

Finally, although this short review is as comprehensive as possible, it may not cover all relevant examples, as some of them may have been incorporated into the literature without the key words of 'difunctionalization', etc. Representative examples are highlighted, and any oversights are unintentional.

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References


For selected representative examples, see: (a) Yanagisawa, S.; Engle, K. M.; Shi, B.-F.; Yu, J.-Q. 

lation via a two-component coupling reaction was ignored because it results in the introduction of the same functional
group into the two different C–H bonds (i.e., not unsymmetrical differ-

For reviews on meta-C–H functionalization of aromatic com-


