LETTER

https://doi.org/10.1038/s41586-018-0366-x

# Direct arylation of strong aliphatic C–H bonds

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**Despite the widespread success of transition-metal-catalysed cross-coupling methodologies, considerable limitations still exist in reactions at $sp^3$-hybridized carbon atoms, with most approaches relying on prefunctionalized alkylmetal or bromide coupling partners[1,2]. Although the use of native functional groups (for example, carboxylic acids, alkenes and alcohols) has improved the overall efficiency of such transformations by expanding the range of potential feedstocks[3–5], the direct functionalization of carbon–hydrogen (C–H) bonds—the most abundant moiety in organic molecules—represents a more ideal approach to molecular construction. In recent years, an impressive range of reactions that form C($sp^3$)–heteroatom bonds from strong C–H bonds has been reported[6,7]. Additionally, valuable technologies have been developed for the formation of carbon–carbon bonds from the corresponding C($sp^3$)–H bonds via substrate-directed transition-metal C–H insertion[8], undirected C–H insertion by captodative rhodium carbenoid complexes[9], or hydrogen atom transfer from weak, hydridic C–H bonds by electrophilic open-shell species[10–14]. Despite these advances, a mild and general platform for the coupling of strong, neutral C($sp^3$)–H bonds with aryl electrophiles has not been realized. Here we describe a protocol for the direct C($sp^3$) arylation of a diverse set of aliphatic, C–H bond-containing organic frameworks through the combination of light-driven, polyoxometalate-facilitated hydrogen atom transfer and nickel catalysis. This dual-catalytic manifold enables the generation of carbon-centred radicals from strong, neutral C–H bonds, which thereafter act as nucleophiles in nickel-mediated cross-coupling with aryl bromides to afford C($sp^3$)–C($sp^2$) cross-coupled products. This technology enables unprecedented, single-step access to a broad array of complex, medicinally relevant molecules directly from natural products and chemical feedstocks through functionalization at sites that are unreactive under traditional methods.**

Metallaphotoredox catalysis has recently emerged as an effective strategy for C($sp^3$)–H functionalization[15]. Specifically, the merger of photoredox-mediated hydrogen atom transfer (HAT) and transition-metal catalysis has delivered several methods for the selective functionalization of activated C–H bonds based on low bond dissociation energies and/or polarity effects (α-heteroatom, benzylic and formyl)[10–14]. Inspired by these studies and a strong oxidant-mediated protocol for C($sp^3$)–H arylation[16], we proposed that combining a HAT catalyst capable of generating high-energy carbon-centred radicals from strong, inert C–H bonds with the elementary steps of nickel catalysis (aryl oxidative addition, reductive elimination) would enable the coupling of aliphatic carbon frameworks with a range of aryl bromide coupling partners.

We proposed that polyoxometalates (POMs), many of which possess high-energy excited states able to perform the desired C–H abstraction, would be ideal cocatalysts for the proposed transformation[17]. Of particular interest was the decatungstate anion ($[W_{10}O_{32}]^{4-}$), a POM that has been broadly used as an efficient HAT photocatalyst in various oxygenations, dehydrogenations, conjugate additions and, more recently, fluorinations of strong, unactivated, aliphatic C–H bonds[18–23] with bond dissociation energies of up to 100 kcal mol$^{-1}$ (for cyclohexane, ref. [24]). To our knowledge, the decatungstate anion has not previously been merged with transition-metal cross-couplings, and we hoped that such a combination of catalytic processes would enable access to a considerable breadth of carbon-centred radicals and aryl-functionalized products from abundant feedstocks (Fig. 1). Furthermore, the observed selectivity of decatungstate for the abstraction of electron-rich, sterically accessible C–H bonds[25] combined with the steric preference of nickel-catalysed cross-couplings suggested that our proposed dual-catalytic system could provide site-specific arylation of complex organic frameworks.

A detailed description of our proposed mechanism is illustrated in Fig. 2. Photoexcitation of tetrabutylammonium decatungstate (TBADT, **1**) followed by intersystem crossing would produce the triplet excited state (**2**) (with a lifetime, $\tau$, of 55 ns)[26]. Subsequent hydrogen atom

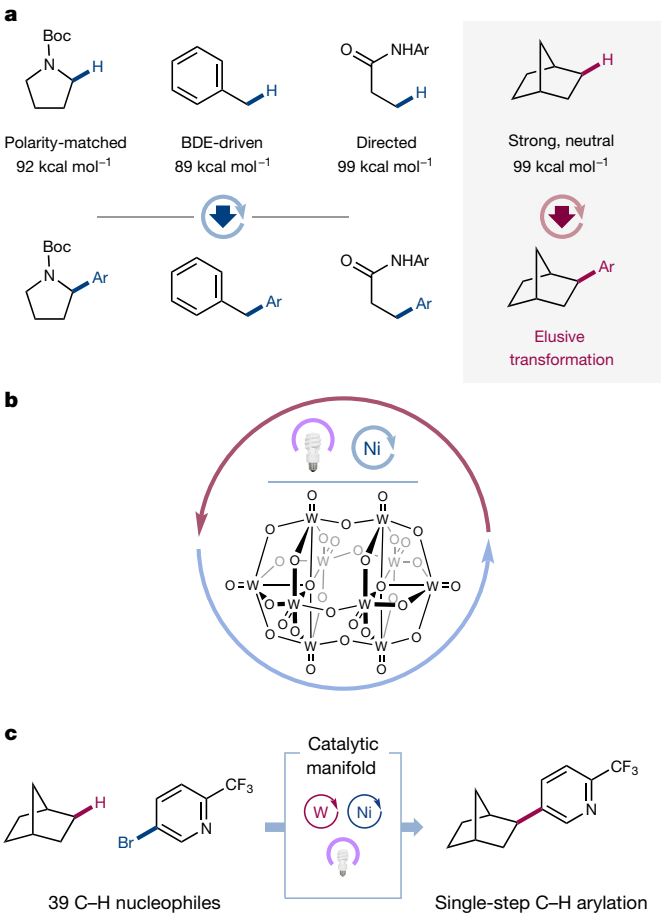


**Fig. 1 | Undirected aliphatic C–H arylation. a**, Traditional transition-metal-catalysed C($sp^3$)–H arylation methods rely on adjacent or distal functionality to facilitate C–H bond activation. **b**, This dual-catalytic approach involves the combination of light-driven, polyoxometalate-facilitated hydrogen atom transfer and nickel catalysis. **c**, Use of this catalytic manifold enables the direct arylation of strong, unactivated C–H bonds. Ar, aryl; BDE, bond dissociation energy; Boc, *tert*-butoxycarbonyl.

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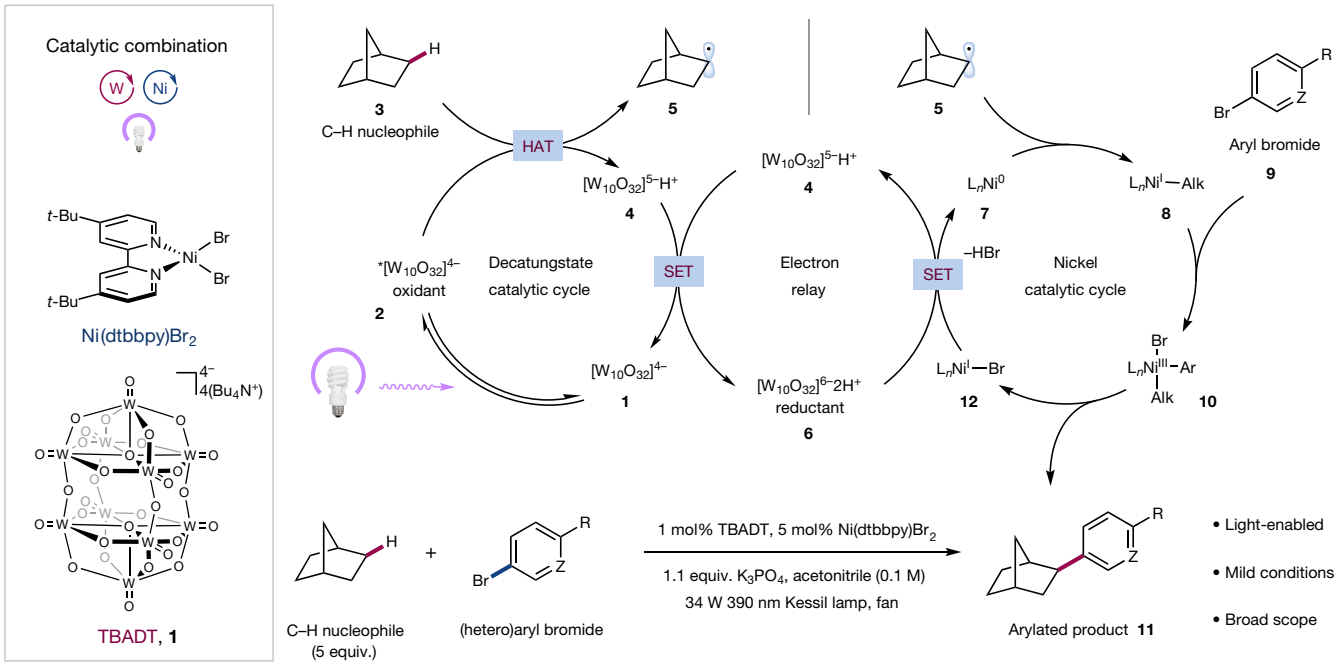


**Fig. 2 | Reaction scheme and proposed mechanism for C($sp^3$)–H arylation via a dual polyoxometalate HAT and nickel catalytic manifold.** The catalytic cycle begins with photoexcitation of the decatungstate anion **1** to provide triplet excited state **2**. HAT from nucleophile **3** affords reduced photocatalyst **4** and open-shell species **5**. Disproportionation of the reduced decatungstate species regenerates the active photocatalyst and affords the reducing hexa-anion **6**. $Ni^0$ species **7** subsequently captures alkyl radical **5**, furnishing $Ni^I$-alkyl species **8**. Oxidative addition into aryl electrophile **9** provides $Ni^{III}$ species **10**, which undergoes reductive elimination to afford the product (**11**) and $Ni^I$–Br species **12**. Single electron transfer (SET) between **6** and **12** regenerates **7** and **4**, closing both catalytic cycles. Alk, alkyl; dtbbpy, 4,4′-di-*tert*-butyl-2,2′-bipyridine; equiv., equivalents; L, ligand; TBADT, tetrabutylammonium decatungstate; *t*-Bu, *tert*-butyl.

abstraction from an alkyl nucleophile such as norbornane (**3**) by excited-state decatungstate (**2**) would readily afford singly reduced decatungstate (**4**) and carbon-centred radical **5**. Disproportionation of singly reduced decatungstate (**4**) would regenerate the active HAT photocatalyst **1** and concurrently form doubly reduced decatungstate (**6**)[26]. Two successive single-electron reductions of precatalyst Ni(dtbbpy)$Br_2$ (dtbbpy = 4,4′-di-*tert*-butyl-2,2′-bipyridine) ($E_p$ ($Ni^{II}/Ni^0$) = −1.47 V versus $Ag/Ag^+$ in acetonitrile, see Supplementary Information) by doubly reduced decatungstate (**6**) ($E_{1/2}^{red}$ ($[W_{10}O_{32}]^{5-}/[W_{10}O_{32}]^{6-}$) = −1.52 V versus $Ag/Ag^+$ in acetonitrile, see Supplementary Information) could initially afford $Ni^0$ species **7**, which after capture of alkyl radical **5** would furnish $Ni^I$-alkyl species **8**. Subsequent oxidative addition into aryl halide **9** by $Ni^I$-alkyl species **8** would afford $Ni^{III}$(aryl)(alkyl) species **10**. Reductive elimination would provide the desired cross-coupled product **11** as well as $Ni^I$ species **12**. A final single-electron transfer step between this $Ni^I$ species and the doubly reduced polyoxometalate **6** would regenerate the active $Ni^0$ catalyst **7**, as well as singly reduced TBADT (**4**), closing both catalytic cycles. An alternative mechanism involving the oxidative addition of $Ni^0$ catalyst **7** to aryl halide **9** could also be operative[27].

We began our investigation into the proposed transformation by exposing 5-bromo-2-trifluoromethylpyridine and cyclohexane to near-ultraviolet light (Kessil 34 W 390 nm light-emitting diodes (LEDs)) in the presence of the commercially available HAT photocatalyst TBADT, Ni(dtbbpy)$Br_2$, and potassium phosphate in acetonitrile. To our delight, we observed a 70% analytical yield of the desired cyclohexyl C–H arylation product. Critical to the success of the reaction was the exclusion of both oxygen and water (see Supplementary Information); however, the use of standard benchtop techniques was sufficient in this regard. Moreover, although five equivalents of the C–H nucleophile affords optimal yields, lower substrate loadings can be used albeit with diminished efficiency (see Supplementary Information).

With optimized conditions in hand, we next sought to examine the scope of the transformation with respect to the C–H-bearing partner. As shown in Fig. 3, a diverse array of organic frameworks proved to be competent coupling partners for the C–H arylation protocol. Cycloalkanes with various ring sizes ranging from five to eight carbons were arylated in good yields (**13**–**16**, 57%–70% yield). Linear aliphatic systems were likewise successful in the protocol (**17**–**20**, 41%–56% yield), with a greater-than-statistical preference observed for arylation of the less sterically demanding 2-position for all substrates, including *n*-hexane (**SI-1**, 48% yield, 60% selectivity). Electron-withdrawing substituents further improved this regiocontrol, highlighting the selectivity of decatungstate for more hydridic C–H bonds imparted by the electrophilic nature of its excited state[26]. Accordingly, we found ketones to be particularly effective in modulating regioselectivity, affording products that are functionalized distal to the electron-withdrawing carbonyl moiety (**21**, **22**, **31**–**35**, 31%–65% yield).

This C–H arylation protocol was also found to effectively functionalize a range of electronically diverse primary and secondary benzylic C–H bonds, which were arylated in moderate to good yields (**23**–**25**, 62%–71% yield, see Supplementary Information for three additional examples). Bridged bicyclic alkanes afforded arylated products with complete *exo*-selectivity (**26**–**29** and **35**, 40%–67% yield), probably owing to selective radical capture by nickel catalyst **7** on the less-hindered face. Functionalization of norbornane occurred selectively on the ethylene bridge (**26**, 61% yield). A bromide substituent on the bridging methylene of norbornane was tolerated and, moreover, strongly influenced site-selectivity, giving only the *anti* product (**27**, 67% yield). Notably, heteroatom-containing bicycles afforded the desired products in moderate to good yields (**28** and **29**, 40% and 60% yield, respectively). Arylated lactam **29** was subsequently subjected to ring-opening reductive conditions to afford carbocyclic nucleoside analogue **30** (94% yield), highlighting the utility of the C–H arylation protocol. Intriguingly, adamantane derivatives underwent arylation predominantly at the methylene position (**31** and **32**, 48% and 53% yield, respectively), an unexpected chemoselectivity given that decatungstate-catalysed adamantane functionalization affords 5:1 selectivity for methine positions when corrected for equivalent

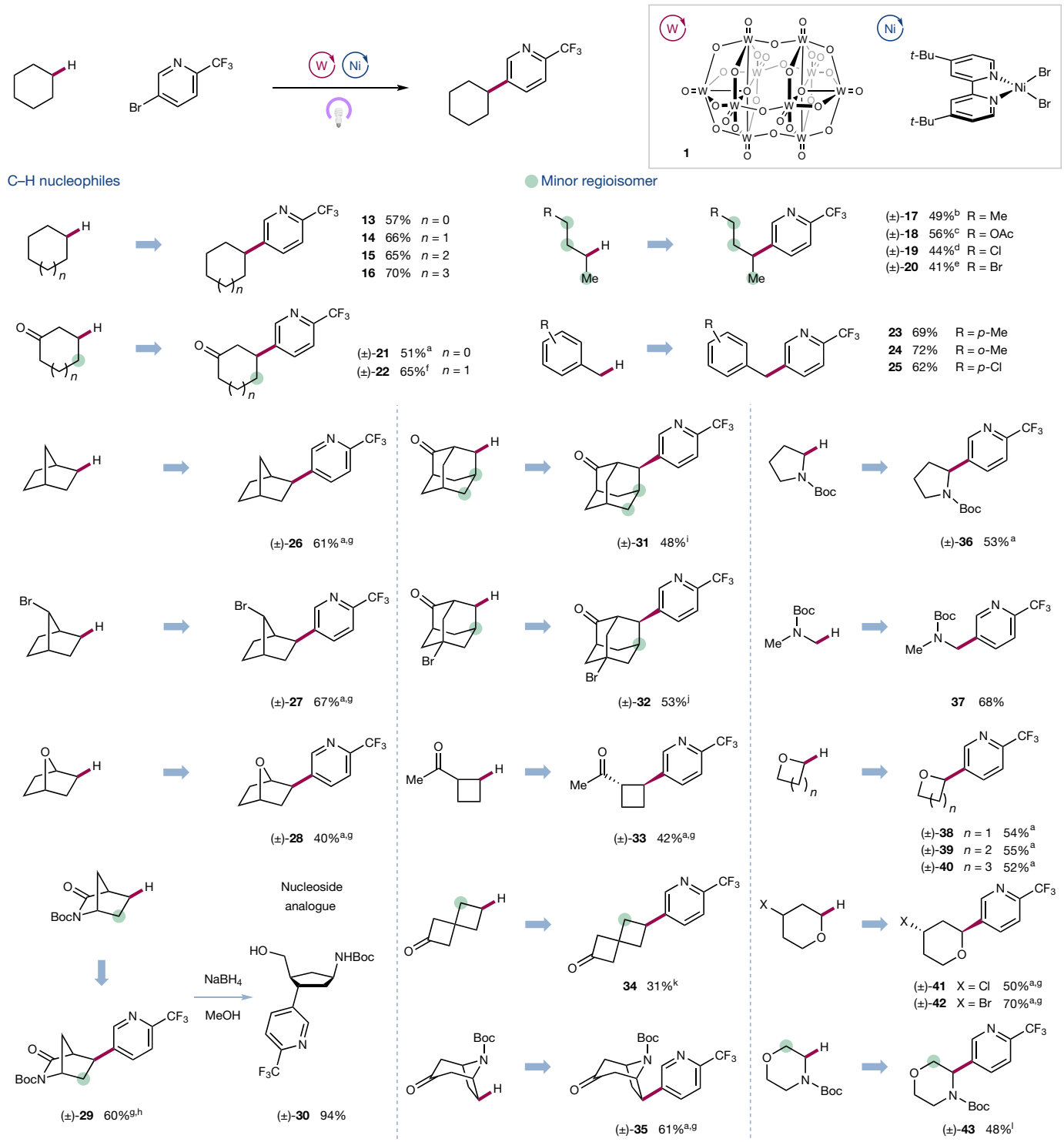


**Fig. 3 | Scope of the alkyl nucleophile coupling partner.** A broad range of C–H nucleophiles are selectively functionalized by this arylation protocol. Cyclic, acyclic and bicyclic aliphatic systems are amenable substrates. Heteroatom and carbonyl substituents electronically influence regioselectivity, and alkyl halides remain intact. All yields are isolated yields. Conditions as in Fig. 2. Green circles denote sites where notable amounts of other regioisomers are observed. See Supplementary Information for experimental details. Ac, acetyl; Boc, *tert*-butoxycarbonyl; d.r., diastereomeric ratio; Me, methyl; r.r., regioisomeric ratio. [a]>20:1 r.r.; [b]70% selectivity; [c]53% selectivity; [d]79% selectivity; [e]93% selectivity; [f]1.4:1 r.r.; [g]>20:1 d.r.; [h]2.5:1 r.r.; [i]79% selectivity, 3:1 d.r. (major); [j]1.8:1 r.r., 5.4:1 d.r. (major); [k]8.8:1 r.r.; [l]3.4:1 r.r.

hydrogen atoms[28]. This result further highlights the role of the nickel catalyst in determining the regioselectivity of C–C bond formation, presumably via reversible radical capture and selectivity-determining reductive elimination[27]. Four-membered rings were also competent substrates for this arylation protocol, with both an exocyclic ketone and a spirocyclic ketone affording the desired product in moderate yields (**33** and **34**, 42% and 31% yield, respectively). Tropinone, a common scaffold among natural products and pharmaceuticals[29], was also effectively subjected to this dual-catalysis protocol (**35**, 61% yield).

It is important to note that this transformation is not restricted to electronically neutral, unactivated C–H systems. Indeed, various α-heteroatom C–H nucleophiles were readily modified with excellent regioselectivity. As follows from the preference of decatungstate for the most hydridic and sterically accessible C–H bond, *tert*-butoxycarbonyl

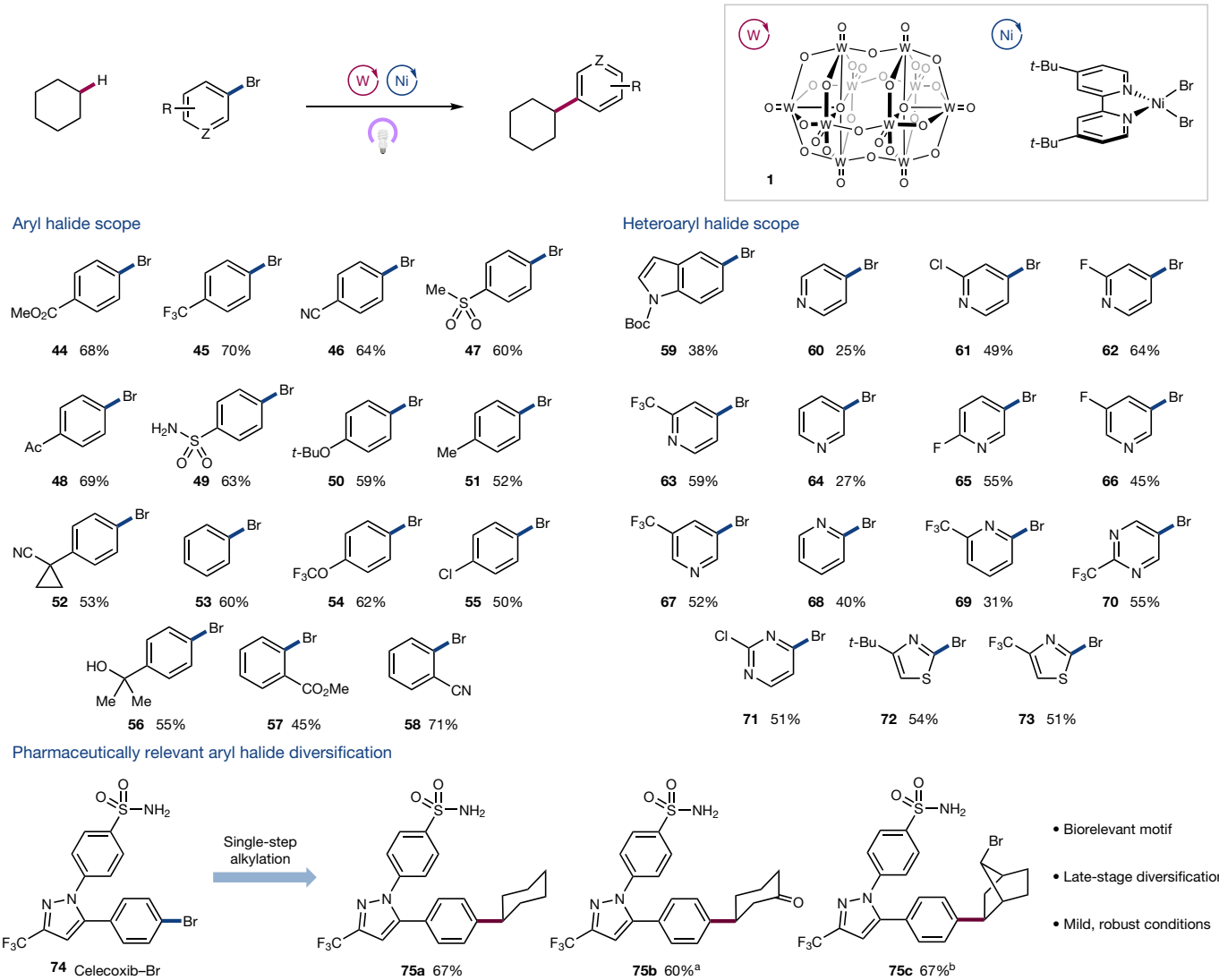


**Fig. 4 | Scope of the aryl halide coupling partner.** Various electronically diverse aryl bromides were functionalized in moderate to good yields, and unprotected polar functionalities such as alcohols and sulfonamides were well tolerated. Moreover, heteroaryl bromides including indoles, pyridines, pyrimidines and thiazoles were competent coupling partners in the transformation. Finally, the dual catalytic manifold was applied to the synthesis of several analogues of celecoxib. All yields are isolated yields. Conditions as in Fig. 2. See Supplementary Information for experimental details. [a]1.4:1 r.r.; [b]>20:1 d.r.

(Boc)-protected pyrrolidine was functionalized selectively at the α-amino position (**36**, 53% yield). Primary α-amino C–H nucleophile *N*-Boc dimethylamine was also found to be an effective substrate for the transformation (**37**, 68% yield). In addition to nitrogen-containing nucleophiles, various cyclic ethers were regioselectively functionalized in moderate to good yield at the α-oxy position (**38**–**43**, 48%–70% yield). Notable among these substrates, alkyl halides were well tolerated (**41** and **42**, 50 and 70% yield, respectively), opening avenues for subsequent synthetic manipulations. *N*-Boc-morpholine underwent C–H arylation predominantly at the α-amino C–H bond (**43**, 48% yield, 3.4:1 regioisomeric ratio (r.r.)). Useful amounts of the α-oxy product are generated in this case, in contrast to the quinuclidine-mediated triple catalytic arylation reported previously by our laboratory[10] (see Supplementary Information) as well as benzophenone-mediated cyanation[30], wherein exclusive α-amino functionalization is observed.

We next turned our attention to the scope of the aryl halide coupling partner. As shown in Fig. 4, a broad range of electron-deficient aryl bromides provided the desired products in good yield (**44**–**49**, 60%–70% yield). Furthermore, neutral and electron-rich substrates displayed useful coupling efficiencies (**50**–**54**, 52%–62% yield). Chlorine- and fluorine-bearing aryl bromides were alkylated selectively as well (**55** and **SI-5**, 50% and 55% yield, respectively), and free-alcohol-containing substrate **56** was also found to be a competent coupling partner (55% yield). *ortho*-Substituted aryl bromides were likewise alkylated in moderate to good yields (**57** and **58**, 45% and 71% yield, respectively). With respect to heteroaryl bromides, *N*-Boc-indole **59** underwent the desired transformation in useful efficiency (38% yield). A range of bromopyridines were alkylated in useful to good yields as well (**60**–**69**, 25%–64% yield). Bromopyrimidines were effective substrates (**70** and **71**, 55% and 51% yield, respectively), and both electron-rich and electron-deficient 2-bromothiazoles afforded the desired product in moderate yields (**72** and **73**, 54% and 51% yield, respectively). Lastly, the pharmaceutically relevant aryl halide **74**, a precursor to celecoxib was subjected to the reaction conditions with various alkyl C–H nucleophiles. Cyclohexane, cyclohexanone and 7-bromonorbornane were all coupled in good efficiencies (**75a**–**c**, 60%–67% yield), which demonstrates the utility of the protocol in cross-coupling complex aryl fragments with structurally diverse C–H nucleophiles.

Having demonstrated the applicability of the C–H arylation protocol to a broad array of C–H nucleophiles and aryl halide electrophiles, we next investigated its efficacy on naturally occurring aliphatic systems.

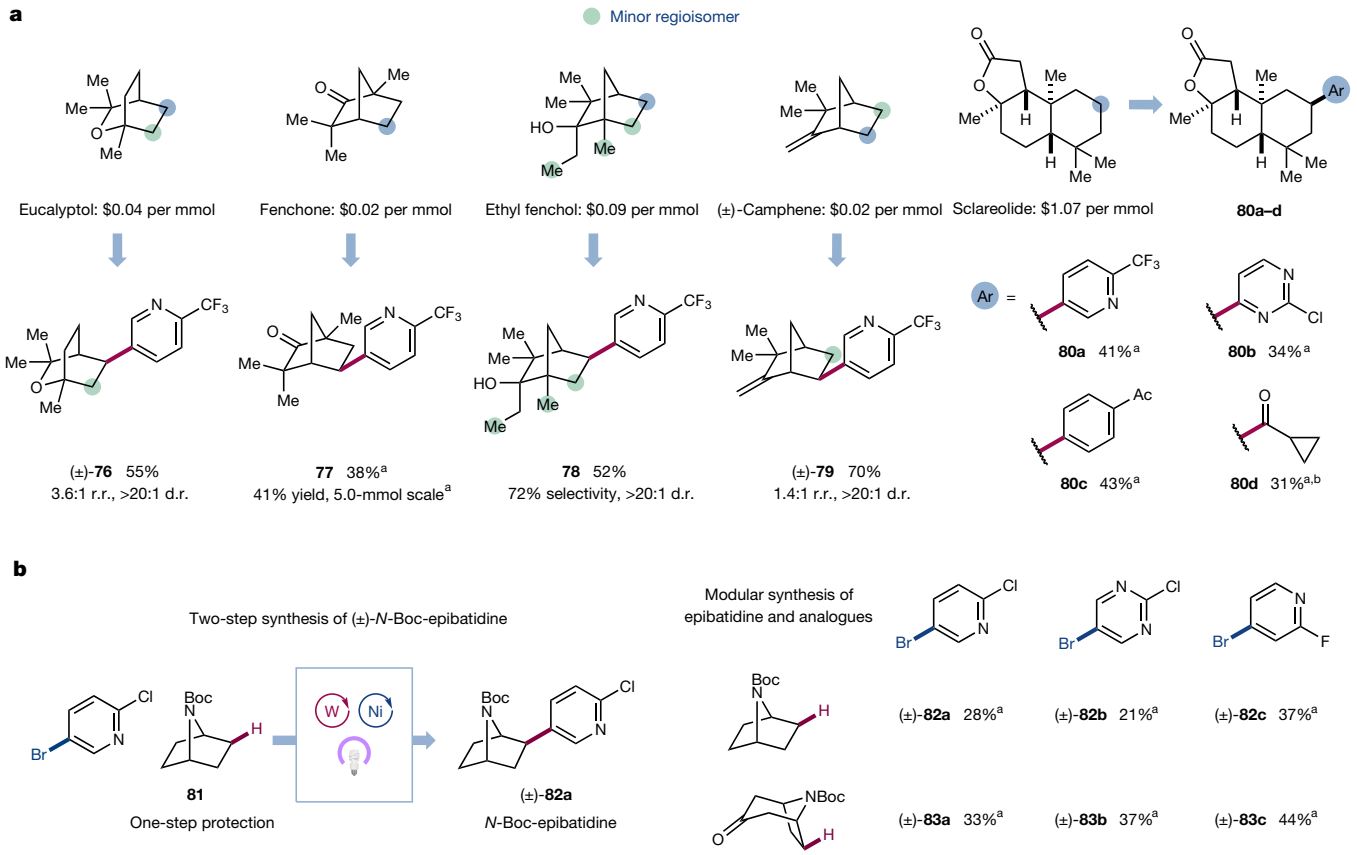


**Fig. 5 | Functionalization, synthesis and derivatization of natural products. a**, A series of abundantly available terpenoids serve as competent coupling partners in this dual catalytic protocol, affording complex arylated scaffolds in good yields. Major and minor isomers are denoted. **b**, (±)-*N*-Boc-epibatidine was synthesized in two steps from commercially available materials, and subsequently a small library of analogous compounds was constructed. [a]>20:1 r.r., >20:1 d.r.; [b]cyclopropane carbonyl chloride used as electrophilic coupling partner.

As illustrated in Fig. 5a, various inexpensive, abundant natural products were successfully functionalized under our standard conditions, enabling the rapid arylation of complex stereodefined frameworks at carbon sites that lack adaptive functional handles. The observed regioselectivities were in accordance with the expected preferences of this dual-catalytic manifold, as described above. A moderate yield of heteroarene-coupled eucalyptol was observed (**76**, 55% yield), with a strong preference for arylation at the most hydridic and sterically accessible C–H bond. Useful efficiencies were observed for the terpene fenchone, which was also found to be a suitable substrate on 5.0-mmol scale (**77**, 38% and 41% yield, respectively; see Supplementary Information for experimental details). A free-alcohol derivative of fenchone was also readily used in this protocol (**78**, 52% yield), and camphene, a terminal-olefin-containing natural product, was also an effective substrate for arylation (**79**, 70% yield). Lastly, we sought to illustrate the generality of this method by derivatizing the lactone sclareolide with a range of aryl and heteroaryl bromides (**80a–c**, 35%–43% yield). Notably, an alkyl acid chloride provided the sclareolide-derived ketone in useful efficiency (**80d**, 33% yield), which illustrates the capability of our transformation to install a range of functionality onto complex aliphatic substrates without the need for directing groups.

Finally, we demonstrated the application of this C–H arylation protocol towards the rapid generation of complex pharmaceutically relevant molecules. Our target was the natural product epibatidine, a potent non-opioid analgesic. Owing to its high toxicity, epibatidine has seen limited potential as a commercial pharmaceutical[31]; however, a range of epibatidine analogues have been investigated in a clinical setting[32]. We first targeted the synthesis of (±)-*N*-Boc-epibatidine from commercially available 7-azabicyclo[2.2.1]heptane. When *N*-Boc-protected amine substrate **81** and 2-chloro-5-bromopyridine were subjected to the reaction conditions, we observed an unoptimized 28% yield of protected epibatidine (**82a**) in two steps from the commercially available unprotected amine (Fig. 5b, see Supplementary Information for experimental details). To our knowledge, this is the shortest formal synthesis of (±)-epibatidine in the multitude of reported procedures to date[33]. Subsequently, we sought to demonstrate that diversification was possible by variation of both the alkyl fragment and the aryl bromide fragment. A representative sampling of heteroaryl bromides was coupled with bridged bicyclic amines to afford a small set of analogues in synthetically useful yields (**82b** to **83c**, 21%–44% yield). We have developed a robust method for the construction of C($sp^3$)–C($sp^2$) bonds from alkane nucleophiles and aryl bromide electrophiles. We believe that these results demonstrate the potential to use unactivated C–H bonds as nucleophiles in transition-metal-catalysed cross-coupling transformations.

## Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Received: 20 April 2018; Accepted: 6 June 2018;
Published online 1 August 2018.

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**Acknowledgements** The research reported here was supported by the National Institutes of Health National Institute of General Medical Sciences (R01 GM103558-03) and gifts from MSD, Bristol-Myers Squibb, Eli Lilly, Genentech, Pfizer and Johnson & Johnson. The authors thank C. Kraml, N. Byrne and L. Wilson (Lotus Separations) for compound purification and I. Pelczer for assistance in structure determination.

**Author contributions** I.B.P., T.F.B., P.J.S. and D.M.S. performed and analysed the experiments. I.B.P., T.F.B., P.J.S., D.M.S., D.A.D. and D.W.C.M. designed the experiments. I.B.P., T.F.B., P.J.S. and D.W.C.M. prepared the manuscript.

**Competing interests** The authors declare no competing interests.

**Additional information**

**Supplementary information** is available for this paper at https://doi.org/10.1038/s41586-018-0366-x.



**Correspondence and requests for materials** should be addressed to D.W.C.M.