favor the pro-methallyl transition state.

The preceding examples establish that (+)-BBMP affords unique advantages as a chiral auxiliary in a two-step, enantioselective process consisting of amide C-alkylation and iodocyclization. This chemistry provides an effective means for the enantioselective preparation of *trans*-γ-butyrolactones.

Acknowledgment. We are grateful to the National Science Foundation (CHE-8704836), the National Institutes of Health (ES04699), and Firmenich SA (financial support for D.R.).

Supplementary Material Available: Experimental details for the preparation of and spectral data for (2*R*,6*R*)-2,6-bis((benzyloxy)methyl)-1-(4′-pentenoyl)piperidine, (2*R*,6*R*,2′*S*)-2,6-bis((benzyloxy)methyl)-1-(2′-methyl-4′-pentenoyl)piperidine (**10**), and (3*S*,5*R*)-dihydro-5-(iodomethyl)-3-methyl-2(3*H*)-furanone [(*S*,*R*)-**15**] (3 pages). Ordering information is given on any current masthead page.

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[12] The iodolactonization of racemic 2-methyl-1,6-heptadien-4-oic acid is ≈97:3 methallyl versus allyl selective. See: Kurth, M. J.; Brown, E. G.; Lewis, E. J.; McKew, J. C. *Tetrahedron Lett.* **1988**, *29*, 1517.

Palladium-Catalyzed Cross-Coupling of Aryl Halides and Olefinic Epoxides via Palladium Migration

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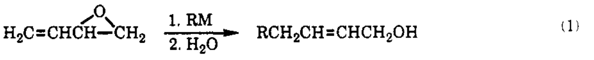
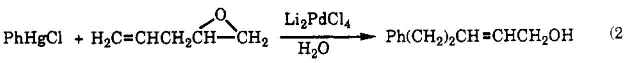
Summary: The palladium-catalyzed cross-coupling of aryl halides and olefinic epoxides bearing one to ten carbons between the two functional groups affords good yields of arylated allylic alcohols by a palladium migration process.

The cross-coupling of 3,4-epoxy-1-alkenes and stoichiometric amounts of organolithium, -boron, -copper, -mercury, -nickel, and -palladium compounds provides an important route to allylic alcohols (eq 1).[1] We have recently reported one example of the analogous arylation of 4,5-epoxy-1-pentene employing stoichiometric amounts of an arylmercurial and either stoichiometric or catalytic amounts of palladium salts (eq 2).[2] We now report a valuable, very general, new process for the synthesis of aryl allylic alcohols which employs catalytic amounts of palladium, a variety of olefinic epoxides, and organic halides rather than organometallic reagents.

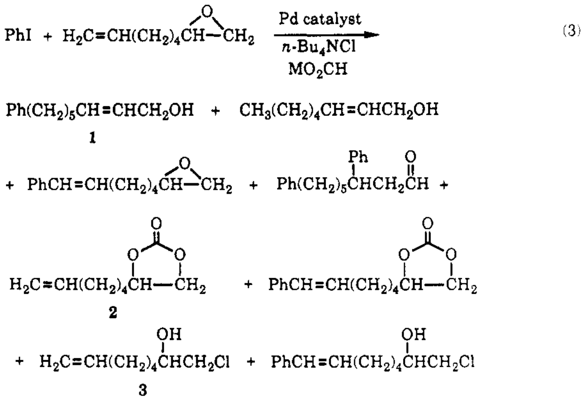


$$H_2C{=}CHCH\overset{O}{—}CH_2 \xrightarrow[2.\ H_2O]{1.\ RM} RCH_2CH{=}CHCH_2OH \quad (1)$$

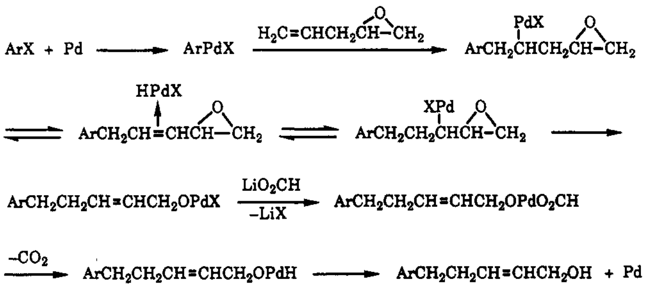


$$PhHgCl + H_2C{=}CHCH_2CH\overset{O}{—}CH_2 \xrightarrow[H_2O]{Li_2PdCl_4} Ph(CH_2)_2CH{=}CHCH_2OH \quad (2)$$

The cross-coupling of iodobenzene and 7,8-epoxy-1-octene was selected as a model system. In the presence of catalytic amounts of palladium and a reducing agent, the desired allylic alcohol **1** was obtained, alongside a variety of side products which were dependent upon the precise reaction conditions employed (eq 3). By a careful, systematic examination of the influence of a variety of palladium catalysts [3–10% $Pd(OAc)_2$ or $Pd(dba)_2$], reducing agents [1–3 equiv of MO_2CH (M = Li, Na, K, Et_3NH); Et_3N; Et_3SiH; n-Bu_3SnH], solvents [2–4 mL/mmol of PhI; DMF, 9:1 DMF/MeOH, DMSO, CH_3CN, THF, CH_2Cl_2], in the presence or absence of n-Bu_4NCl (1 equiv), H_2O (10 equiv), alkali metal halides [LiCl (1–2 equiv), NaI (1 equiv)], and bases [$NaHCO_3$, Na_2CO_3, Et_3N, i-Pr_2NEt, $(c\text{-}C_6H_{11})_2NEt$], we have been able to arrive at optimal conditions for the formation of the desired allylic alcohol **1**. By employing 1 equiv of PhI, 3 equiv of the olefinic epoxide, 10% $Pd(OAc)_2$, 1 equiv of n-Bu_4NCl, 3 equiv of LiO_2CH, 3 equivs of i-Pr_2NEt, and 1 equiv of LiCl at 50 °C in DMF (4 mL/mmol of ArI), we have been able to eliminate the majority of side products and obtain the desired alcohol **1** in 62% isolated yield. Only minor amounts of the products **2** and **3** arising from ring opening of the excess starting olefinic epoxide are observed, and they can usually be easily separated from the desired alcohol.



Scheme I



A variety of olefinic epoxides have been arylated in a similar fashion in good to excellent yields (Table I). Unlike the analogous arylation of long-chain olefinic alcohols,[3] the yields and regioselectivity here are observed to drop off as the distance between the C–C double bond and the epoxide increases. With 4,5-epoxy-1-alkenes, only aryl allylic alcohols arising from aryl addition to the terminal alkene carbon are observed. With longer chain olefinic epoxides, small amounts of aryl allylic alcohols arising from aryl addition to the internal carbon are also observed. The stereoselectivity of C–C double bond formation is similar to that observed with organoboron, or-

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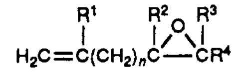
[1] (a) Larock, R. C. *Comprehensive Organic Transformations*; VCH Publishers, Inc.: New York, 1989; pp 123–124. (b) Marshall, J. A. *Chem. Rev.* **1989**, *89*, 1503.

[2] Larock, R. C.; Ilkka, S. J. *Tetrahedron Lett.* **1986**, *27*, 2211.

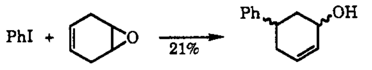
[3] Larock, R. C.; Leung, W.-Y.; Stolz-Dunn, S. K. *Tetrahedron Lett.* **1989**, *30*, 6629.

Table I. Palladium-Catalyzed Arylation of Olefinic Epoxides

entry	p-XC_6H_4I X =						reaction time, days	% isolated yield[a]	E/Z
		n	R^1	R^2	R^3	R^4			
1	H	1	H	H	Me	H	1	78	79:21
2	H	1	H	H	Me	Me	1	79	–[b]
3	H	2	H	H	H	H	1	65	76:24
4	H	2	H	Me	H	H	1	69	32:68
5	H	2	Me	Me	H	H	3	47	33:67
6	H	4	H	H	H	H	1.5	62	76:24
7	H	10	H	H	H	H	2	44	76:24
8	Me	4	H	H	H	H	1	55	77:23
9	MeO	4	H	H	H	H	1	65[c]	77:23
10	MeCO	4	H	H	H	H	1	62	75:25
11	EtO_2C	4	H	H	H	H	1	68[c]	80:20

[a] All products gave appropriate ^1H and ^{13}C NMR, IR, and mass spectral data. [b] Could not be determined by ^1H NMR spectroscopic analysis. [c] Contains 9% of diformate **2**.

ganocopper, and previous arylpalladium additions to 3,4-epoxy-1-alkenes.[1,2] The reaction accommodates important organic functional groups (entries 9–11), and the presence or absence of electron-donating or -withdrawing groups on the aryl halide has little effect on the yield or the stereoselectivity of the process (entries 8–11). However, more substituted double bonds, as in 4,5-epoxycyclohexene, afford lower yields of stereoisomeric arylation products (eq 4).



cis/trans = 67:33 (4)

This arylation process most likely proceeds as illustrated in Scheme I. The oxidative addition of aryl halides to Pd(O) and subsequent olefin insertion are well-established processes.[4] Only recently, however, has palladium migration chemistry been put to good use in organic synthesis.[3,5] Eventual palladium–oxygen ring opening[2] would appear to occur in either a syn or anti fashion, as evidenced by the formation of syn and anti alcohols in the phenylation of 4,5-epoxycyclohexene (eq 4). While palladium hydride migration from one face of a cycloalkene to the other has literature precedence[6] and would also account for the mixture of stoichiomeric alcohols, this process appears unlikely.[7] While organopalladium intermediates have previously been reduced by formate salts,[8] our process appears to be the first in which a palladium alkoxide has been reduced to an alcohol by a formate salt. Simultaneous formation of zerovalent palladium regenerates the catalyst.

In conclusion, we report the first generally useful method for the arylation of a wide variety of olefinic epoxides in which the C–C double bond and the epoxide are separated by one or more carbons. Unlike previous methods for the arylation of 3,4-epoxy-1-alkenes, our approach accommodates important functional groups, uses aryl halides, and requires only catalytic amounts of palladium, rather than employing stoichiometric amounts of organometallics which frequently cannot accommodate key organic functional groups.

Acknowledgment. We gratefully acknowledge the National Institutes of Health and the donors of the Petroleum Research Fund, administered by the American Chemical Society, for financial support, and Johnson Matthey, Inc., and Kawaken Fine Chemicals Co., Ltd., for the palladium catalysts.

Supplementary Material Available: General procedures and results for entries 1–11 (7 pages). Ordering information is given on any current masthead page.

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