period of 1 h, and stirring at 25 °C (or above) until the allylic acetate had disappeared as diagnosed by TLC. The solution was then cooled to 0 °C and an excess of aqueous ammonia solution was added slowly. After aqueous workup, the final separation was achieved via flash chromatography on silica gel using 1% triethylamine in all eluting solvents.

In summary, what we have presented is a very mild and efficient method for the formation of functionalized allylstannanes in a highly chemoselective and regioselective fashion. This functional group interconversion represents a net conversion of the electronic nature of the allyl acetate from electrophilic to nucleophilic (Figure 1). The ready availability of allyl acetates coupled with the high degree of selectivity exhibited by the aluminum–tin reagent makes this conversion a potentially valuable tool for organic synthesis. We are presently pursuing synthetic strategies revolving around this methodology.

Acknowledgment. We thank the National Institutes of Health (BI 1 F32 CA07473-01) for a fellowship to James W. Herndon and to the National Science Foundation for their generous support of our programs.

Registry No. 1, 92074-24-3; *cis*-**4**, 92097-37-5; *trans*-**4**, 92097-38-6; (*R**,*R**)-**5**, 92097-43-3; (*R**,*S**)-**5**, 92097-39-7; **6**, 92097-40-0; **7**, 60729-55-7; A, 92097-35-3; B, 92097-36-4; CH_3CH_2CHO, 123-38-6; $(Bu_3Sn)_2$, 813-19-4; Et_2AlCl, 96-10-6; (*E*)-$PhCH{=}CHCH_2OAc$, 21040-45-9; (*E*)-$PhCH{=}CHCH_2SnBu_3$, 74785-32-3; (*E*)-$(CH_3)_2C{=}CH(CH_2)C(CH_3){=}CHCH_2OAc$, 105-87-3; $(CH_3)_2C{=}CH(CH_2)_2C(CH_3)(OAc){=}CH_2$, 115-95-7; (*E*)-$(CH_3)_2C{=}CH(CH_2)_2C(CH_3){=}CHCH_2SnBu_3$, 67883-63-0; (*Z*)-$(CH_3)_2C{=}CH(CH_2)_2C(CH_3){=}CHCH_2SnBu_3$, 92097-30-8; 4-$BrC_6H_4(CH_2)_2C(CH_3)(OAc){=}CH_2$, 92097-41-1; (*E*)-4$BrC_6H_4(CH_2)_2C(CH_3){=}CHCH_2SnBu_3$, 92097-31-9; (*Z*)-4-$BrC_6H_4(CH_2)_2C(CH_3){=}CHCH_2SnBu_3$, 92097-32-0; $CH_3CO(CH_2)_{10}CH(OAc)CH{=}CH_2$, 92097-42-2; 17α-22-acetoxy-chola-4,23-dien-3-one, 92216-14-3; (17α,22*E*)-24-(tributylstannyl)-chola-4,22-dien-3-one, 92097-33-1; (17α,22*Z*)-24-(tributylstannyl)-chola-4,22-dien-3-one, 92097-34-2.

Supplementary Material Available: Characterization data for organostannanes from Table I, entries 4–7, and for compounds **5** and **6** (3 pages). Ordering information is given on any current masthead page.

On the Regiochemistry of Metal-Catalyzed Allylic Alkylation: A Model

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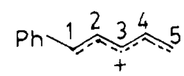
Allylic alkylation reactions with stabilized anions that proceed on metal templates introduce a new dimension for selectivity that is not necessarily bound by the structure of the substrate.[1-5] Regiocontrol, in particular, appears interesting but somewhat confusing. For example, Pd templates generally lead to reaction at the less hindered terminus of the allyl fragment,[1,6] Mo templates lead to reaction at the more hindered end with malonate as a nucleophile but not with more hindered nucleophiles,[2] and W templates have shown a bias for reaction at the more hindered position regardless of nucleophile.[3] While reaction at the less substituted terminus logically derives from the influence of steric factors, the source and, consequently, predictability of the reaction at the more hindered position is uncertain. We wish to suggest a model that addresses this major concern.

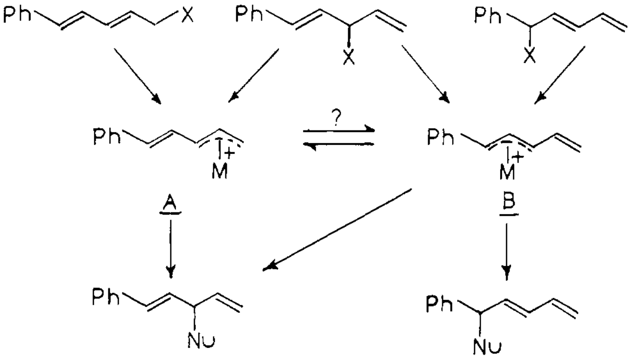
Table I. MO Calculations of Phenylpentadienyl Cation



	C(1)	C(2)	C(3)	C(4)	C(5)
			Total Charge		
MNDO	0.286	−0.226	0.246	−0.203	0.150
INDO	0.246	−0.059	0.239	−0.013	0.139
			p_z Occupancy[a]		
MNDO	0.618	1.141	0.658	1.114	0.722
INDO	0.654	1.087	0.688	1.044	0.791
			p_z Charge[a]		
MNDO	0.382	−0.141	0.342	−0.114	0.278
INDO	0.346	−0.087	0.312	−0.044	0.209
			LUMO Coefficients		
MNDO	−0.600	−0.014	0.556	−0.026	−0.355
INDO	0.571	0.016	−0.539	−0.003	0.392

[a] p_z occupancy and p_z charge refer to the π system orthogonal to the molecular plane.

Scheme I. Predicted Regioselectivity of Alkylation of the Phenylpentadienyl System



Allylmetal complexes can be viewed as allyl cations bonded to zero-valent metal. In order to generate the simplest possible model, we probed the question of the intrinsic bias for nucleophilic attack on the cation itself in the absence of any steric or metal effects. Lets consider the phenylpentadienyl cation. Table I lists relevant data from MNDO and INDO calculations. On the basis of charge considerations, the order of attack should be C(1) ~ C(3) > C(5). Frontier orbital considerations as revealed by the LUMO coefficients predict exactly the same order.

In order to test these predictions, we must realize that these complexes are η^3 species. Thus, in the absence of any Michael-type addition and assuming equilibration of the two regioisomeric η^3 complexes is slow relative to alkylation, the regiochemistry of alkylation will also depend on which complex is generated as shown in Scheme I. On the basis of charge and frontier orbital considerations, complex A should alkylate at C(3) and complex B almost equally at C(1) and C(3).

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(1) For palladium-catalyzed reactions, see: Trost, B. M.; Verhoeven, T. R. *Compr. Organomet. Chem.* **1982**, *8*, 779. Tsuji, J. "Organic Synthesis with Palladium Compounds"; Springer-Verlag: Berlin, 1980. Trost, B. M. *Tetrahedron* **1977**, *33*, 2615.

(2) For molybdenum templates, see: Trost, B. M.; Lautens, M. *Organometallics* **1983**, *2*, 1687; *J. Am. Chem. Soc.* **1983**, *105*, 3343; *J. Am. Chem. Soc.* **1982**, *104*, 5543.

(3) For tungsten templates, see: Trost, B. M.; Hung, M.-H. *J. Am. Chem. Soc.* **1983**, *105*, 7757.

(4) For nickel templates, see: Cuvigny, T.; Julia, M. *J. Organomet. Chem.* **1983**, *250*, C21. Consiglio, G.; Morandini, F.; Piccolo, O. *J. Chem. Soc., Chem. Commun.* **1983**, 112.

(5) For iron and cobalt templates, see: Roustan, J. L.; Merour, J. Y.; Houlihan, F. *Tetrahedron Lett.* **1979**, 3721.

(6) (a) Trost, B. M.; Verhoeven, T. R. *J. Am. Chem. Soc.* **1976**, *98*, 630. (b) Akermark, B.; Hansson, S.; Krakenberger, B.; Vitagliano, A.; Zetterberg, K. *Organometallics* **1984**, *3*, 679. (c) Keinan, E.; Sahai, M. *J. Chem. Soc., Chem. Commun.* **1984**, *648*. (d) Curtis, M. D.; Eisenstein, O. *Organometallics* **1984**, *3*, 887. Also see: Davies, S. G.; Green, M. L. H.; Mingos, D. M. P. *Tetrahedron* **1978**, *34*, 3047.

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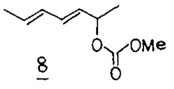
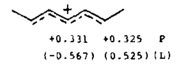
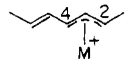
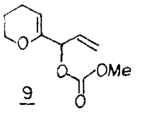
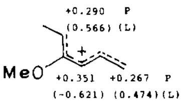
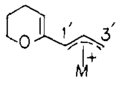
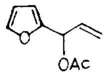
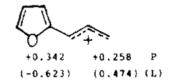
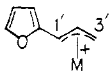
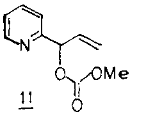
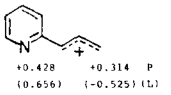
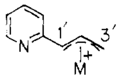
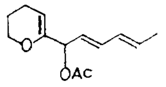
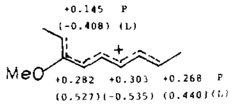
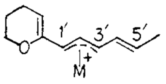
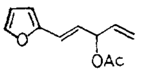
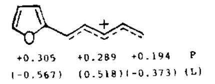
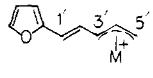
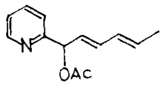
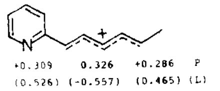
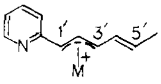
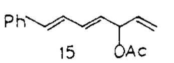
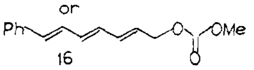
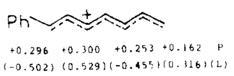
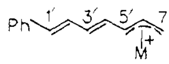
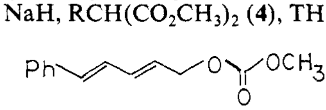
Table II. Selected Polyene Substrates, Model Related Cations, and Predicted Alkylation in Tungsten-Catalyzed Reactions

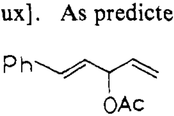
		prediction	
substrate	model cation[a]	complex	alkylation regiochemistry
 8			C(4) > C(2)
 9			C(1') > C(3')
 10			C(1') > C(3')
 11			C(1') > C(3')
 12			C(3') > C(1')
 13			C(3') > C(5')
 14			C(3') > C(1')
 15 or  16			C(5') > C(7')

[a] Numbers identified by P refer to p_z charge. Numbers in parentheses identified by (L) refer to LUMO coefficients.

To test these predictions, we subjected **1**, **2**, and **3** to W-catalyzed alkylations [~15 mol % $W(CO)_3(CH_3CN)_3$, 15 mol % bpy, NaH, $RCH(CO_2CH_3)_2$ (**4**), THF, reflux]. As predicted, **1** and **4** (R = H) gave a good selectivity for **6a**[7] (83%) with minor amounts of **5a**[7] (6%) and **7a**[7] (11%). An almost identical ratio was observed with a sterically more demanding nucleophile, an alkylated malonate [**4**, R^1 = $CH_2CH{=}CH_2$; **5b**[7] (9%), **6b**[7] (80%), **7b**[7] (11%)]. These results are in accord with complex A as the major species leading predominantly to **6**.[8] A small steric effect is noticeable in the slight increase in the amount of **5** by switching from **4**, R = H, to **4**, R = $CH_2CH{=}CH_2$.



1



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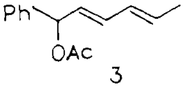

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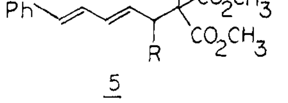

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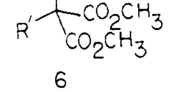

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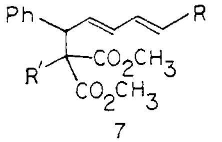


7

a, R = R^1 = H; b, R = H, R^1 = $CH_2CH{=}CH_2$; c, R = CH_3, R^1 = H; d, R = CH_3, R^1 = $CH_2CH{=}CH_2$

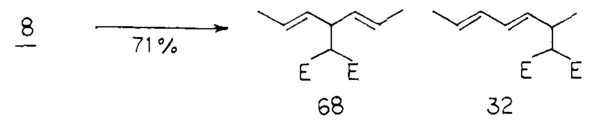
Subjecting **3** to similar conditions with **4**, R = H, led to a 1:1 mixture of **6c** (48%) and **7c** (48%) as well as a trace of **5c** (4%), in 65% yield, in excellent accord with predictions based upon complex B (Scheme I).[9] A steric effect can also operate to somewhat favor attack at C(3) over C(1). Thus, use of **4**, R = $CH_2CH{=}CH_2$, leads to a predominance of **6d** (58%) over **7d** (29%) as well as a somewhat enhanced amount of terminal attack

---

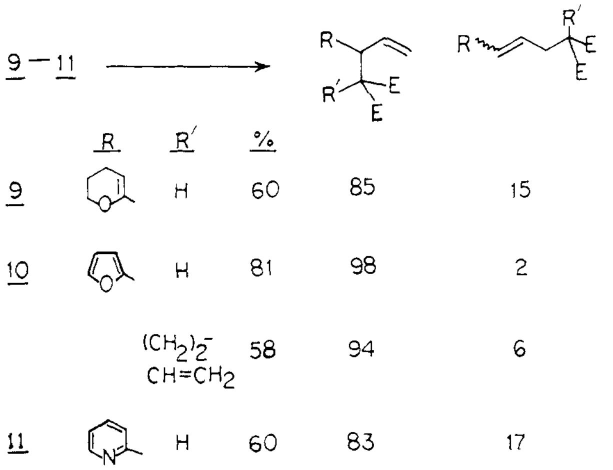
(7) All new compounds have been fully characterized by spectral means and elemental composition determined by combustion analysis or high-resolution mass spectrometry.

(8) The small amount of **7** arises either from some equilibration of A and B or by "conjugate" addition to A. No distinction is possible at this time.

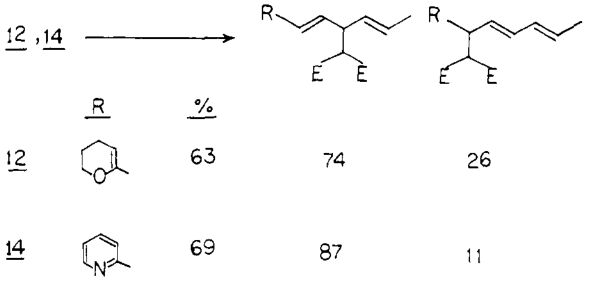
(9) The small amount of **5** can arise from some equilibration of B and A or by "conjugate" addition to B. No distinction is possible at this time.



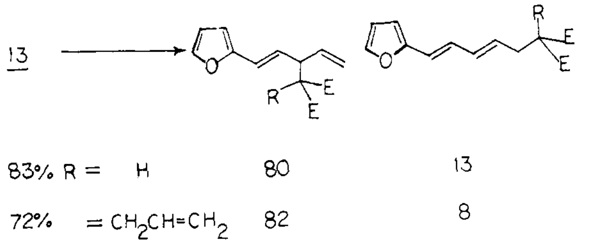
(1)



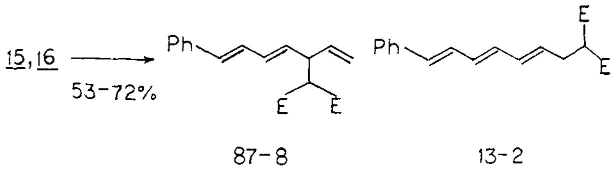
(2)



(3)



(4)



(5)

to give **5d** (13%) in 71% yield. The strikingly different results starting from **1** and **3** support the initial supposition that equilibration of complexes A and B is not important on the time scale for alkylation.

Use of **2** as substrate is complicated by the question of which complex, A or B (Scheme I), is generated. Experimentally, the product ratio was virtually identical with that derived from use of **1**—i.e., with **4**, R = H, **5a** (6%), **6a** (83%), **7a** (11%); with **4**, R = $CH_2CH{=}CH_2$, **5b** (4%), **6b** (84%), **7b** (12%). This fingerprint strongly suggests that the W template has a strong steric bias to generate complex A rather than complex B. Thus, regioselectivity in the initial ionization step based on steric factors combines with regioselectivity in the alkylation step based on electronic factors to give a good level of selectivity for formation of **6**.

These results strongly support the notion that W-catalyzed reactions, mainly, though not entirely, reflect the intrinsic electronic bias of the η^3-allyl system.[10] To test the generality of this correlation, we examined a variety of polyunsaturated systems. Table II summarizes some of these and the p_z charge and LUMO coefficients for the pertinent carbons of a related model cation. Equations 1–5[7] summarize the alkylation results. In each and every case, the predicted and observed regiochemistry agrees remarkably well.

While such electronic factors dominate in W-catalyzed reactions, steric factors tend to dominate in Pd-catalyzed reactions.[11] For example, alkylation of **1** with **4**, R = H, in the presence of $(Ph_3P)_4Pd$ gave mainly **5a**; alkylation of **3** under similar conditions gave mainly **6a**. In both instances, the nucleophile had a good selectivity for the less hindered carbon—a complementary regioselectivity to the tungsten reactions. Molybdenum catalysts appear to fall between these extremes—with unhindered nucleophiles electronic factors dominate but with sterically demanding nucleophiles steric factors dominate. With all catalysts, some exceptions exist or will be found—a clear indication that steric and electronic factors always operate but to varying degrees.[12] The selectivity observable makes these metal-catalyzed reactions of great value in the synthesis of highly unsaturated polyenes.

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Registry No. 1, 92056-47-8; **2**, 40022-82-0; **3**, 92056-48-9; **4** (R = H), 108-59-8; **4** (R = $CH_2CH{=}CH_2$), 40637-56-7; **5a**, 92056-50-3; **5b**, 92056-52-5; **5c**, 92056-57-0; **5d**, 92056-60-5; **6a**, 92056-49-0; **6b**, 92056-53-6; **6c**, 92056-55-8; **6d**, 92056-58-1; **7a**, 92056-51-4; **7b**, 92056-54-7; **7c**, 92056-56-9; **7d**, 92056-59-2; **8**, 92056-11-6; **9**, 92056-12-7; **10**, 87802-72-0; **11**, 87802-77-5; **12**, 92056-13-8; **13**, 92056-14-9; **14**, 92056-15-0; **15**, 92056-16-1; **16**, 92056-17-2; Pd, 7440-05-3; $(Ph_3P)_4Pd$, 14221-01-3; $CH_3CH{=}CHCH(CH{=}CHCH_3)CH(CO_2Me)_2$, 92056-30-9; $CH_3CH{=}CHCH{=}CHCH(CH_3)CH(CO_2Me)_2$, 92056-31-0; $PhCH{=}CHCH{=}CHCH(CH{=}CH_2)CH(CO_2Me)_2$, 92056-45-6; $PhCH{=}CHCH{=}CHCH{=}CHCH_2CH(CO_2Me)_2$, 92056-46-7; $W(CO)_3(CH_3CN)_3$, 16800-47-8; bpy, 366-18-7; phenylpentadienyl cation, 24765-29-5; heptadienyl cation, 92056-18-3; 3-methoxyheptadienyl cation, 92056-19-4; (2-furyl)propenyl cation, 92056-20-7; (2-pyridyl)propenyl cation, 92056-21-8; 3-methoxynonatrienyl cation, 92056-22-9; (2-furyl)pentadienyl cation, 92056-23-0; (2-pyridyl)hexadienyl cation, 92056-24-1; phenylheptatrienyl cation, 92056-25-2; dimethyl 1-(2,3-dihydro-1*H*-pyran-6-yl)allylmalonate, 92056-32-1; dimethyl 3-(2,3-dihydro-1*H*-pyran-6-yl)allylmalonate, 92056-33-2; dimethyl 1-(2-furyl)allylmalonate, 87802-87-7; dimethyl 3-(2-furyl)allylmalonate, 92056-34-3; dimethyl (1-(2-furyl)allyl)(3-butenyl)malonate, 92056-35-4; dimethyl (3-(2-furyl)allyl)(3-butenyl)malonate, 92056-36-5; dimethyl 1-(2-pyridyl)allyl malonate, 87802-92-4; dimethyl 3-(2-pyridyl)allyl malonate, 87802-93-5; dimethyl 1-(2,3-dihydro-1*H*-pyran-6-yl)-1,4-hexadien-3-ylmalonate, 92056-37-6; dimethyl 1-(2,3-dihydro-1*H*-pyran-6-yl)-2,4-hexadienylmalonate, 92056-38-7; dimethyl 1-(2-pyridyl)-1,4-hexadien-3-ylmalonate, 92056-39-8; dimethyl 1-(2-pyridyl)-2,4-hexadienylmalonate, 92056-40-1; dimethyl 1-(2-furyl)-1,4-pentadien-3-ylmalonate, 92056-41-2; dimethyl 5-(2-furyl)-2,4-pentadienylmalonate, 92056-42-3; dimethyl (1-furyl-1,4-pentadien-3-yl)(allyl)malonate, 92056-43-4; dimethyl (1-furyl-2,4-pentadienyl)(allyl)malonate, 92056-44-5.

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(10) In these metal-catalyzed reactions, several factors affecting regiochemistry will be operating simultaneously and will be of similar energy. Thus, we are seeking small differences among them. Thus, in these W reactions, steric effects can become more important. For example, with sulfone-stabilized anions, greater amounts of attack at the less-hindered position can be seen. Steric factors associated with metal must also be considered.

(11) Exceptions are the cases of neryl[6a] and prenyl acetate[6b] which alkylate at the more hindered terminus with malonate. We would now interpret these results as reflective of the intrinsic electronic bias of the allyl system.

(12) This model assumes that metal coordination of the allyl cation will not change the qualitative order but certainly will affect the quantitative values. The validity of such an assumption can be judged by the nature of the correlation, which is excellent. The different metals allow a manipulation of the transition state in its choice of which factors, steric or electronic, will dominate. We emphasize that we are only presenting a model that is valuable for predictive purposes. In the allylic alkylation with nonstabilized nucleophiles, where initial transfer occurs to the metal, the relative importance of these different effects may change. A systematic variation of these nucleophiles remains yet to be done.