

Synthesis of Functionalized Anthraquinones, Phthalates and Quinolines
by Site-Selective Suzuki-Miyaura Cross-Coupling Reactions



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DEDICATION

This work is dedicated to.....

The dream has just been vanished,.....My Mother

.....Never forget her

ACKNOWLEDGMENT

In the name of ALLAH, the Beneficent, the Merciful, Ubiquitous, Omniscient. Praise be to Allah; without his blessings this work would never been accomplished.

I want to express my philosophy which I have practiced along my study and found it precious more than my work inside the laboratory or even writing this thesis, at least from my point of view. Chemists especially those who are working in the field of organic synthesis often define their achievement in the terms of numbers; numbers of the chemical compounds that they have made; or numbers of novel reactions that they could developed. Yet, As far as I can see, the greatest achievements along my study journey are the successful and deep relationships that I have developed. This is my well-practiced philosophy and therefore I am writing this acknowledgment to admit my sincere gratitude to those people who helped me throughout past years and without their support I could not finish this work.

I would like to express my grateful and appreciation to my advisor Prof. Peter Langer (PL) for his constant advice, guidance, insight, and for sharing his extensive knowledge of chemistry. PL's scientific integrity has been both inspiring and motivating over the years. Also I thank the entire PL group for their friendship and support.

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Outside of the individual Langer group members with whom I've worked directly, I would like to collectively thank the group for creating a peaceful and pleasurable work atmosphere. It certainly has been interested to watch the development of what once was a collection of individuals evolve to what have so called the Langer Group. I am proud to be part of them.

I would like to take the opportunity to especially thank the DAAD Foundation for providing me a scholarship over three and a half past years, deep gratitude for the contact person of Iraqi section Frau. Steuernagel for her kindness.

I want to thank all of my friends, for supporting me whatever they could and for their cordiality.

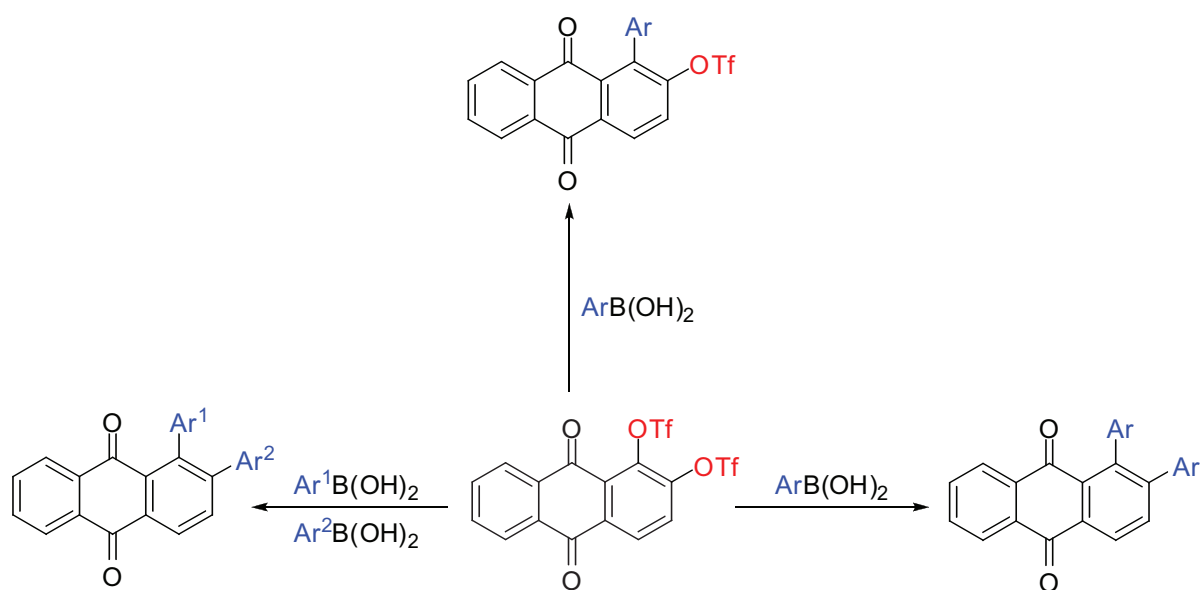
Finally, I would like to thank all members of my family who have provided me patience, heartiest feelings and eternity support over past years. My deep respect and appreciation goes to my father. He has been always an inspiration for me, and my grateful to you for his special emotions towards me along the past years. My elder brother Ehab: my best friend, my mentor and my pillar of encouragement. I know him as far as I know myself, and on most days I felt he knows me better than I know myself. I could not imagine living a single day of my life without his support and guidance. To my younger sis Redhab, younger bro Nifal and the youngest sis Rehab; all thanks to you for your enormous encouragement, your goodwill, love and support. In addition, I would like to thank my family, which means to me not only my relatives but also my friends. Without you, this thesis would never see the light.

Rostock, 26.10.2010

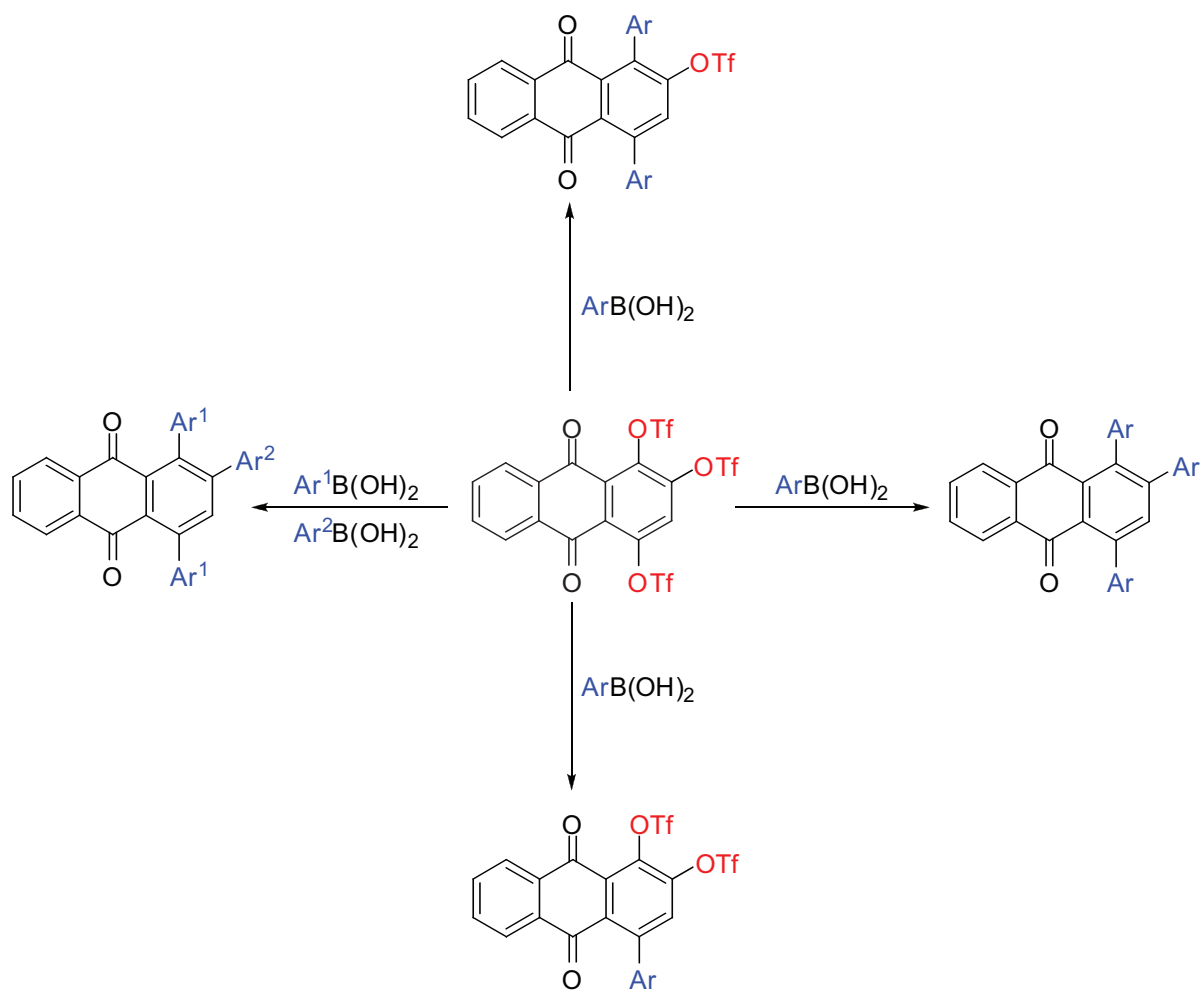
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SUMMARY

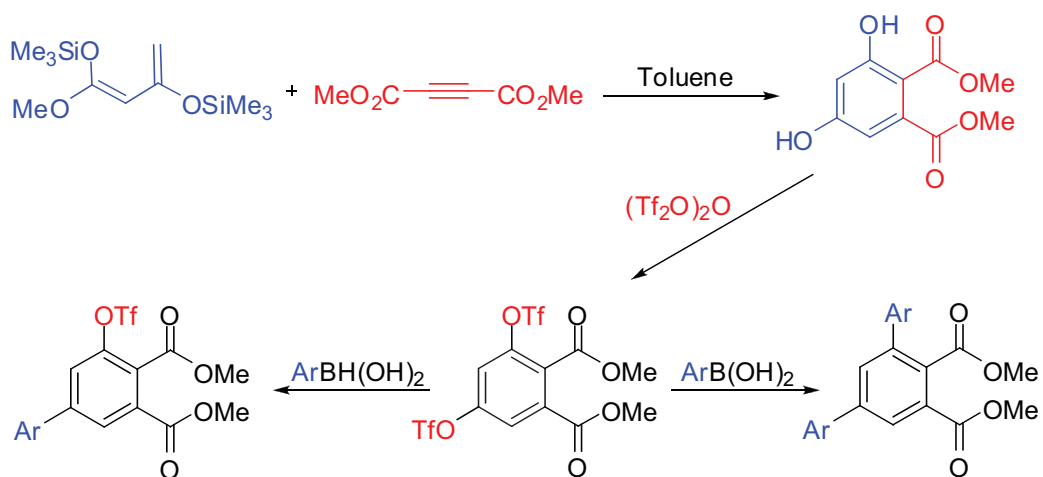
Suzuki coupling reactions of the bis(triflate) of alizarin afforded 1,2-diarylanthraquinones. The reaction of the bis(triflate) with 1 equivalent of arylboronic acids proceeded with very good site-selectivity. The first attack occurred at carbon atom C-1 at the electronically more deficient position. Unsymmetrical 1,2-diarylanthraquinones were obtained by one-pot Suzuki coupling reactions with different arylboronic acids. The reactions were carried out by using $\text{Pd}(\text{PPh}_3)_4$ as a catalyst and K_3PO_4 as a base.



The reaction of the tris(triflate) of purpurin and 4 equivalents of arylboronic acids afforded 1,2,4-triarylanthraquinones. The reactions with 2 equivalents of arylboronic acids resulted in very good yields and proceeded with very good site-selectivity. The first attack occurred at carbon atom C-4 and the second one occurred at carbon atom C-1.



I also studied the synthesis of dimethyl 3,5-dihydroxyphthalate starting from the reaction of 1-methoxy-1,3-bis(trimethylsilyloxy)-1,3-diene with dimethyl acetylenedicarboxylate. The reaction of the bis(triflate) of the product with arylboronic acids gave arylated phthalates with very good site-selectivity in favour of carbon atom C-5.



The reaction of 5,7-dibromo-8-hydroxyquinoline and triflic acid anhydride afforded the triflate in good yield. The reaction of the latter with 2 equivalents of arylboronic acids occurred at carbon atoms C-5 and C-7. The reaction with one equivalent of arylboronic acid occurred at carbon atom C-5.

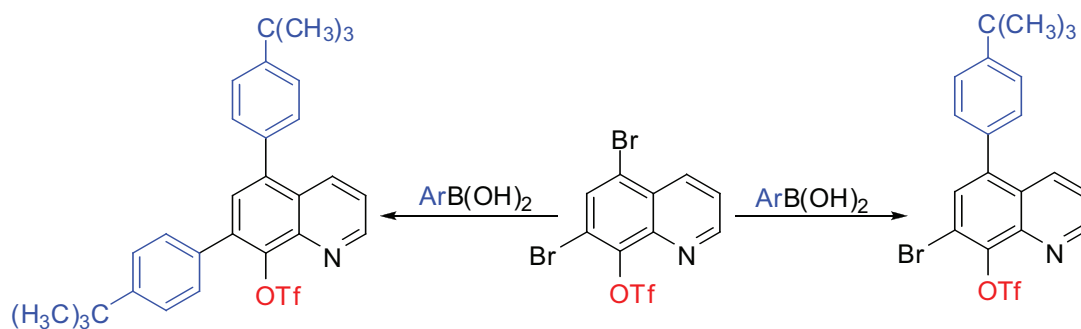


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LIST OF ABBREVIATIONS

Å	Angstrom
Ac	Acetate
aq.	Aqueous
Ar	Aryl
9-BBN	9-Borabicyclo[3.3.1]nonane
Boc	N- <i>tert</i> -butoxycarbonyl
calcd	Calculated
Cp	Cyclopentadiene
Cy	Cyclohexyl
dba	Dibenzylideneacetone
DEM	Diethoxymethane
DEPT	Distortion-less Enhancement by Polarization Transfer
DME	Dimethyl Ether
DMF	N,N-Dimethylformamide
DMSO	Dimethylsulfoxide
dppb	Bis-1,4-(diphenylphosphino)butane
dppf	1,1'- Bis(diphenylphosphanyl)ferrocene
dt	Doublet of triplet
EtOBpin	2-Ethoxy-4,4,5,5-tetramethyl-1,3,2-dioxaborolane
g	Gram(s)
HB(lpc) ₂	Disiamylborane
Hz	Hertz
η^4	<i>Tetrahapto</i>
η^5	<i>Pentahapto</i>
KHB(OPr ^{<i>i</i>}) ₃	Potassium Trisopropoxyborohydride
LDA	Lithium Diisopropylamide
MOM	Methoxyethane
mp	Melting Point
NMR	Nuclear Magnetic Resonance
NOE	Nuclear Overhauser Effect

Nu	Nucleophile
OAc	Acetate
°C	Degrees Celsius
OTf	Triflate
PCy ₃	Tricyclohexylphosphine
Ph	Phenyl
piv	N-pivaloyl
ppm	Parts per Million
Sia	3-methyl-2-butyl
TBAF	Tetra- <i>n</i> -Butylammonium Fluoride
TBDMS	<i>tert</i> -butyldimethylsilyl
TBDPS	<i>tert</i> -Butyldiphenylsilane
TBS	<i>tert</i> -butyldimethylsilyl
TES	Triethylsilane
Tf ₂ O	Trifluoromethanesulfonic anhydride
TFA	Trifluoroacetic Acid
THF	Tetrahydrofuran
TLC	Thin Layer Chromatography
TMB	Trimethylboroxine
TMS	Trimethylsilane
TMSOK	Potassium Trimethylsilanolate
UV	Ultraviolet Spectroscopy

*BACKGROUND
AND
INTRODUCTION*

CHAPTER ONE

1.1 Palladium Catalyzed Cross-Coupling Reactions

In organic chemistry, cross-coupling reactions of unsaturated (aryl, alkynyl, or alkenyl) carbon centers, catalyzed by transition metals, play a very important role. These types of reactions are becoming very important through their wide applications in organic synthesis, therefore organic chemists attach great importance particularly to study the organometallic mechanisms of these reactions.¹ For example, the Wacker Process is an oxidation of ethylene to acetaldehyde using oxygen and palladium tetrachloride as catalyst;² this process is concerned as an important example for the use of palladium catalysts in the industry. In the last 30 years, palladium catalyzed cross-coupling reactions have been widely used to form carbon-carbon bond in organic synthesis.

The reaction of organic halides (usually aryl/alkenyl halides) with olefins were developed by Heck and co-workers and is also called "Mizoroki-Heck reaction".³ Tsuji and Trost first reported the reaction of π -allyl-(η^3 -allyl)palladium cations with nucleophiles, it is also often referred to as "Trost Allylation or Tsuji-Trost Reaction".⁴ The cross-coupling reactions of organometallic reagents (such as organotin, organoboron and organozinc reagents) with organic halides were particularly developed by Kumada,⁵ Stille,⁶ Suzuki.⁷ In 2010, the nobel prize was awarded jointly to Richard F. Heck, Ei-ichi Negishi and Akira Suzuki for the development of methods for palladium-catalyzed cross-couplings in organic synthesis.

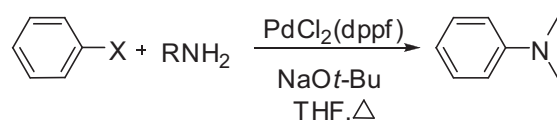
1.2 Types of Palladium Catalyzed Cross-Coupling Reactions

There are many types including palladium catalyzed cross-coupling reactions. Some of them are mentioned here, but not exhaustively.

1.2.1 Buchwald-Hartwig Reaction

The Buchwald-Hartwig reaction is a palladium catalyzed cross-coupling reaction of aryl halides or pseudohalides (for example triflates) with primary or secondary amines as shown below in Scheme 1.1.⁸

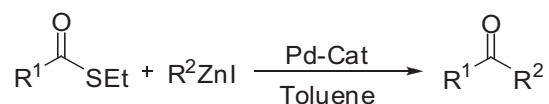
Scheme 1.1 Buchwald-Hartwig reaction



1.2.2 Fukuyama Reaction

The Fukuyama reaction is a palladium catalyzed reaction of organozinc compounds with thioesters to give ketones (Scheme 1.2).⁹

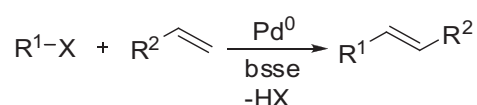
Scheme 1.2 Fukuyama reaction



1.2.3 Heck Reaction

The Heck reaction (also called the Mizoroki-Heck reaction) is a reaction of aryl halides or vinyl halide with activated alkenes in the presence of base as well as using the palladium as catalyst (Scheme 1.3).¹⁰

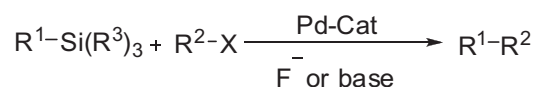
Scheme 1.3 Heck reaction



1.2.4 Hiyama Coupling

The Hiyama coupling is a palladium catalyzed coupling reaction between aryl, alkenyl, alkyl halides or pseudohalides and organosilanes. This reaction is similar to the Suzuki coupling reaction which needs the base or fluoride ion as an activating reagent (Scheme 1.4).^{11,12}

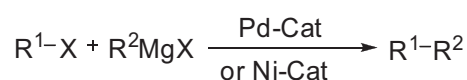
Scheme 1.4 Hiyama coupling



1.2.5 Kumada Reaction

The Kumada reaction is a cross-coupling reaction in organic chemistry between an alkyl or aryl Grignard reagent and an aryl or vinyl halocarbon catalyzed by nickel or palladium (Scheme 1.5).¹³

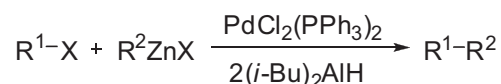
Scheme 1.5 Kumada reaction



1.2.6 Negishi Reaction

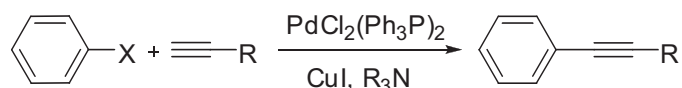
The Negishi reaction is a reaction of various halides (aryl, vinyl, benzyl, or allyl) with organozinc compounds involving the nickel- or palladium catalyst. This reaction is used to synthesize unsymmetrical biaryls (Scheme 1.6).^{14,15}

Scheme 1.6 Negishi reaction

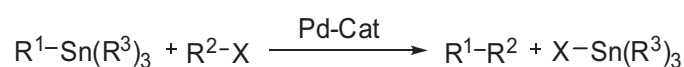


1.2.7 Sonogashira Coupling

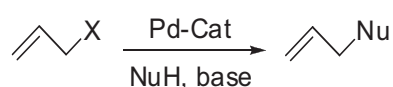
The Sonogashira coupling is a reaction between terminal alkynes with aryl or vinyl halides. This reaction is performed with palladium catalysts, copper(I) as cocatalyst and an amine base (Scheme 1.7).¹⁶

Scheme 1.7 Sonogashira coupling**1.2.8 Stille Coupling**

The Stille coupling is a reaction of organotin compounds with organic halide including sp^2 -hybridized catalyzed by palladium (Scheme 1.8).¹⁷

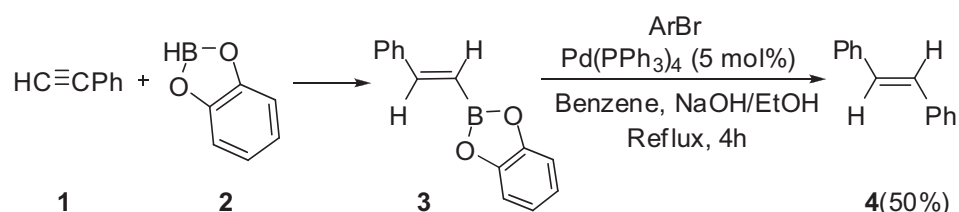
Scheme 1.8 Stille coupling**1.2.9 Tsuji-Trost Reaction**

The Tsuji-Trost reaction is a palladium-catalyzed allylation of nucleophiles such as active methylenes, enolates, amines and phenols, with allylic compounds such as allyl acetates and allyl bromides (Scheme 1.9).¹⁸

Scheme 1.9 Tsuji-Trost reaction**1.3 Suzuki-Miyaura Cross-Coupling Reaction; A Brief History**

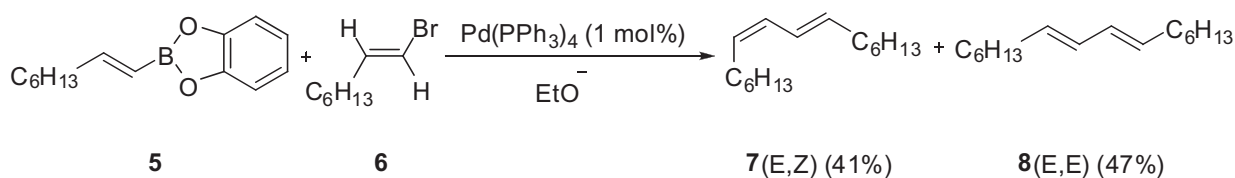
The Suzuki-Miyaura cross-coupling reaction is an extremely versatile methodology for generation of carbon-carbon bonds. This is a reaction of an aryl- or vinyl-boronic acid with an aryl-, vinyl- or an alkyl-halide catalyzed by palladium. It is widely used to synthesize polyolefins, styrenes and substituted biphenyls. The first published reaction was reported in 1979 by Akira Suzuki and co-workers. The reaction of alkyne **1** with borate **2** in benzene using 5 mol% of tetrakis(triphenylphosphine)palladium $\text{Pd}(\text{PPh}_3)_4$ gave (*E*)-1,2-diphenylethene (**4**) in reasonable yields (Scheme 1.10). This reaction was done in presence of base, such as sodium ethoxide in ethanol or sodium hydroxide in ethanol.^{19,20}

Scheme 1.10 The first example of a Suzuki coupling reaction



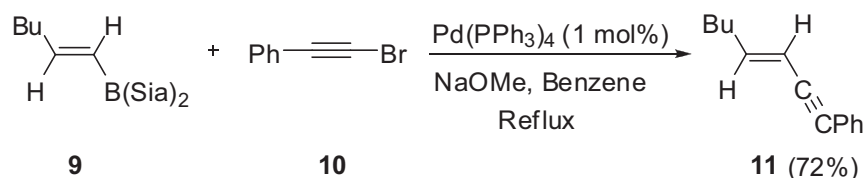
They also applied the same reaction in order to prepare (*E,Z*)-dienes. Although the reactions proceeded smoothly, the results were unsatisfactory because the initially formed (*E,Z*) isomer **7** was isomerized to the more stable (*E,E*) isomer **8** (Scheme 1.11).

Scheme 1.11 Synthesis of **7**, **8**



A novel route for the synthesis of (*E*)-enyne **11** was also reported in the same paper (Scheme 1.12).

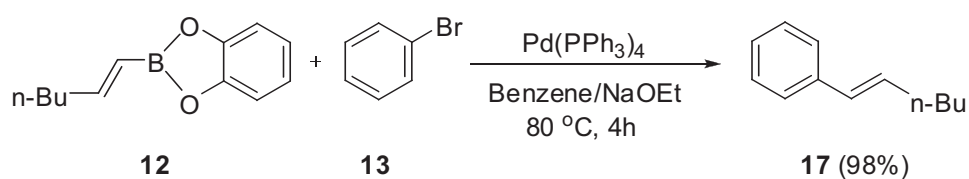
Scheme 1.12 A novel route for the synthesis of **11**



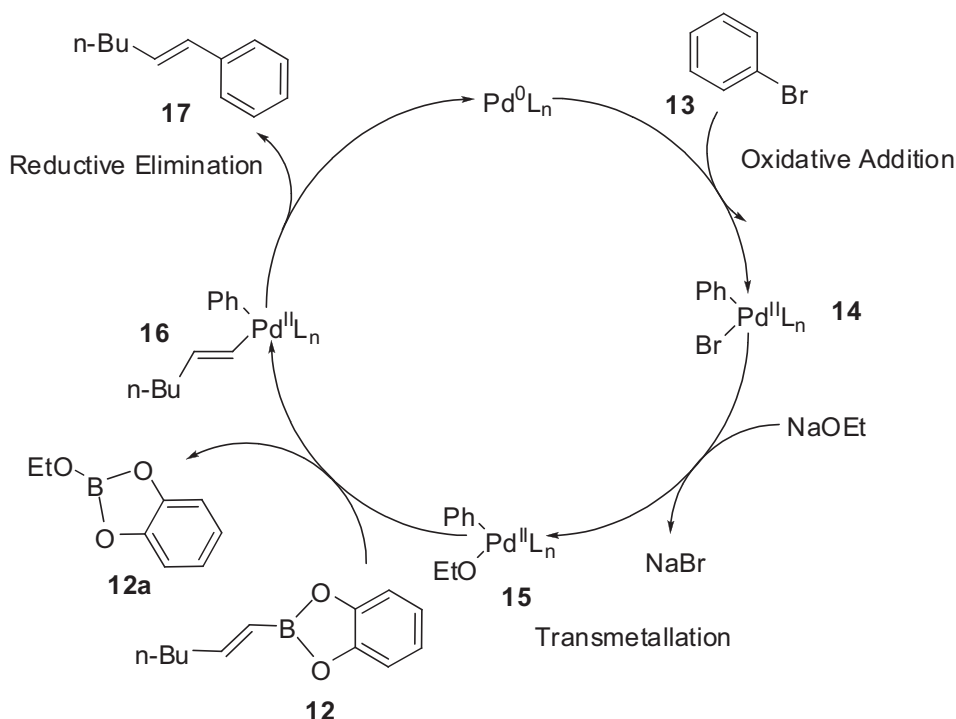
The reaction appears in almost all publications as the name of Suzuki-Miyaura cross-coupling reaction, but it is also often referred to as "Suzuki Coupling".

1.4 Reaction Mechanism

To identify more clearly how a Suzuki coupling reaction occurs, we should keep the following statement (Scheme 1.13) as an example¹⁹ of the coupling and follow the mechanism to understand the coupling how to occur.

Scheme 1.13 Suzuki coupling reaction of boronic ester and bromobenzene**1.4.1 Catalytic Cycle**

The mechanism of the Suzuki coupling reaction is best viewed from the perspective of the palladium catalyst. The catalytic cycle of Suzuki coupling reaction involves three basic steps: Oxidative addition, Transmetalation and Reductive elimination.^{19,21,22} The catalytic cycle for the Suzuki coupling reaction is shown to be that depicted in Figure 1.1. The first step is the oxidative addition of palladium to the halide forming intermediate. Reaction with base gives intermediate **14**, which via transmetalation with the boronate complex **12** forms the organopalladium species **16**. Reductive elimination of the desired product **17** restores the original palladium catalyst.²³

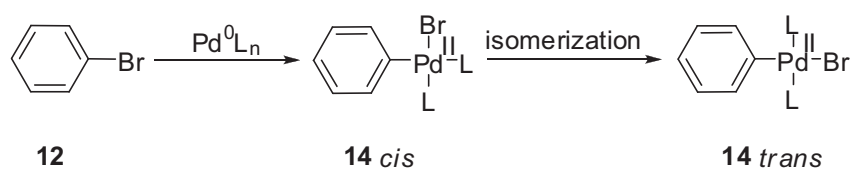
Figure 1.1 Catalytic cycle of Suzuki coupling reaction

The efficiency of palladium originates from its ability, when it is zerovalent, to activate C-X bonds (X=I, Cl, Br, O) by an oxidative addition which provides an organopalladium (II) complex prone to react with nucleophiles.^{24,25} A large variety of palladium(0) catalysts or precursors can be used for this reaction. Palladium(II) complexes along with a reducing agent are also used.²⁶

1.4.2 Oxidative Addition

The first step in Suzuki cross-coupling reaction is oxidative addition of palladium to the halide. Oxidative addition of 1-alkenyl, 1-alkynyl, allyl, benzyl and aryl halides to a Pd(0) complex gives a stable trans- σ -palladium (II) complex (Scheme 1.14).² The reaction proceeds with complete retention of stereochemistry for alkenyl halide and with inversion for allylic and benzylic halides. Oxidative addition is often the rate limiting step in the catalytic cycle. The relative reactivity decreases in the order of I > OTf > Br >> Cl. Aryl and 1-alkenyl halides, activated by the proximity of electron-withdrawing groups, are more reactive to the oxidative addition than those containing donating groups, thus allowing the use of chlorides, such as 3-chloroenones, for the cross-coupling reaction.

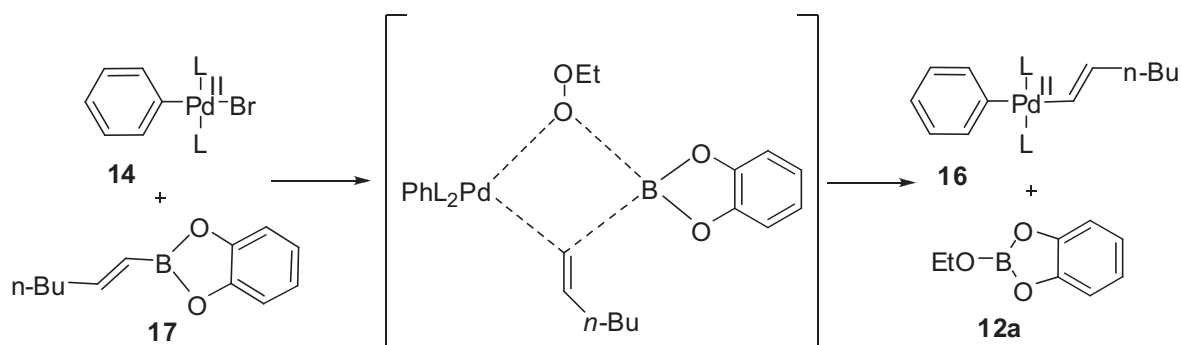
Scheme 1.14 Oxidative addition



1.4.3 Transmetallation Processes

Transmetallation step (Scheme 1.15) between organopalladium(II) complex and organoboron compound does not usually proceed in absence of base, due to low nucleophilicity of the organic group located at the boron atom.²¹ However the nucleophilicity can be enhanced by quaternization of the boron with negatively charged bases giving the corresponding “ate” complex.²⁷ It is reported that such “ate” complexes undergo clean coupling reaction with organic halides.²⁸

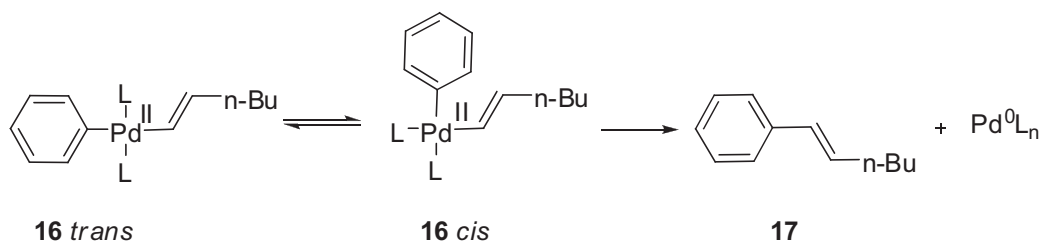
Scheme 1.15 Transmetalation processes



1.4.4 Reductive Elimination

Reductive elimination takes place directly from the *cis*-complex **16**, and *trans*-complex **16** reacts after its isomerization to the corresponding *cis*-complex (Scheme 1.16).²¹ Relative rates of reductive elimination from palladium(II) complexes are diaryl- > (alkyl)aryl- > diethyl- > dimethylpalladium(II).

Scheme 1.16 Reductive elimination

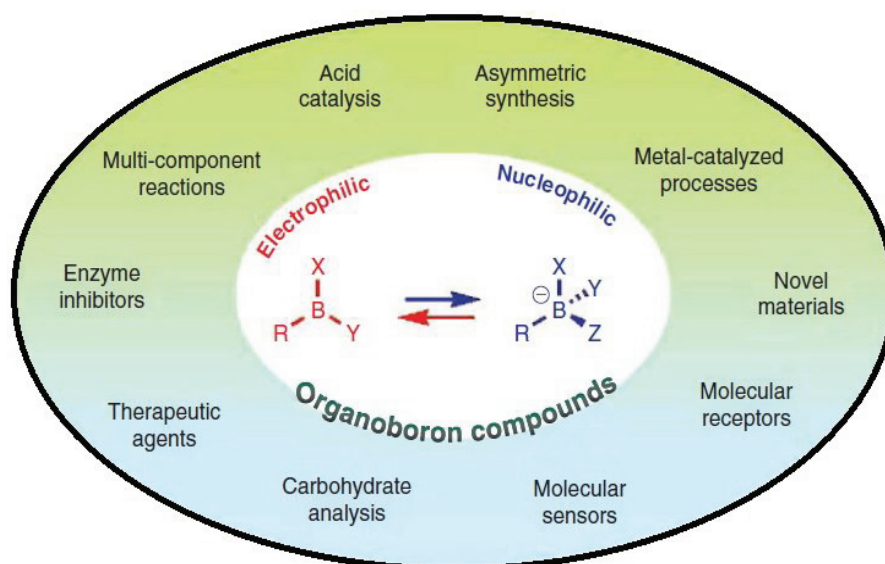


1.5 Organoboron Compounds

For many decades, organic compounds containing boron have been attracted an increased attention. Ever since, their chemical properties and their reactivity aspects had been studied. The discovery of hydroboration opened the door to organoboranes, which are represented among the most widely used reagents and intermediates in organic synthesis including asymmetric reactions. In addition, the previous studies on the chemistry of boron hydrides and carboranes conduce to new classes of compounds with unique structure and reactivity. In spite of this, the stability of organoboron compounds was not discovered until recently. In fact, the lists of organoboron compounds are increased nowadays. In addition to organoboranes,²⁹ now it includes organoboronic acids and boronates,³⁰ and more recently

organotrifluoroborates.³¹⁻³³ As a result, these compounds mentioned hereinabove, have found their way to new and wide applications. For example: molecular receptors, molecular sensors, novel materials, as well as biological probes and pharmaceuticals (Figure 1.2).³³

Figure 1.2 Uses of organoboron compounds³³. The picture was taken from *Aust. J. Chem.* **2007**, *60*, 795-798.

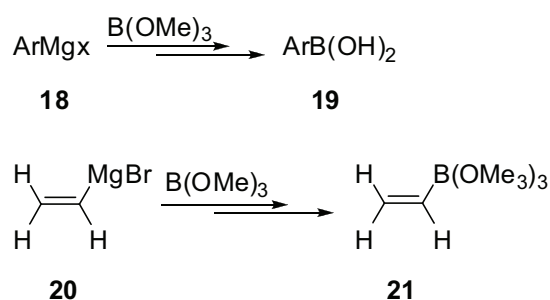


1.5.1 Synthesis of Organoboron Reagents

1.5.1.1 From Organolithium or Magnesium Reagents²¹

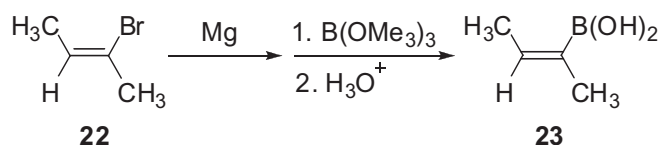
Aryl- and l-alkenylboronic acids or their esters can be prepared by reaction of Grignard reagents or lithium reagents **18**, **20** with trialkyl (Scheme 1.17).³⁴

Scheme 1.17 Synthesis of organoboronic acids from Grignard reagents



In addition to that, a stereocontrolled synthesis of alkenylboronic acids and esters involves the reaction of a (*Z*)- or (*E*)-2-buten-2-ylmagnesium bromide with trimethylborate (Scheme 1.18).³⁵

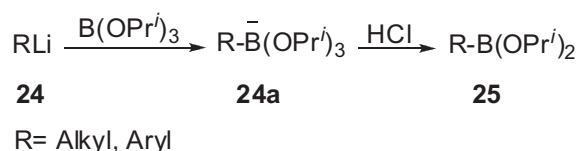
Scheme 1.18 Synthesis of organoboronic acid from trimethyl borate



The disadvantages of application of these procedures include the contamination of small amount of the opposite stereoisomers, or bis-alkylation leading to the boronic acid derivatives and the formation of trialkylboranes.

Brown and co-workers reported the first synthesis of organolithium reagents **24** and triisopropyl borate, followed by acidification with HCl to give directly alkyl-, aryl-, 1-alkynyl-, and 1-alkenylboronic esters **25** in high yields, over 90% (Scheme 1.19).³⁶ Triisopropyl borate is shown to be the best of available alkyl borates to avoid such multiple alkylations of the borates.

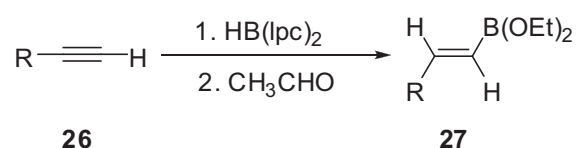
Scheme 1.19 Synthesis of organoboronates from organolithium compounds



1.5.1.2 Hydroboration of Alkenes and Alkynes²¹

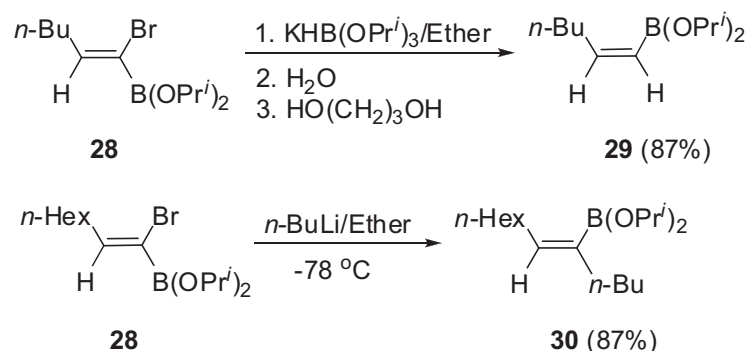
Suzuki and co-workers reported that the hydroboration of propargyl chloride and ethyl propiolate resulted terminal boron derivatives **27** with excellent regiochemistry, whereas the hydroboration with catecholborane or disiamylborane gives an inseparable mixture of internal and terminal boron adducts (Scheme 1.20).³⁷

Scheme 1.20 Hydroboration of alkynes with disiamylborane



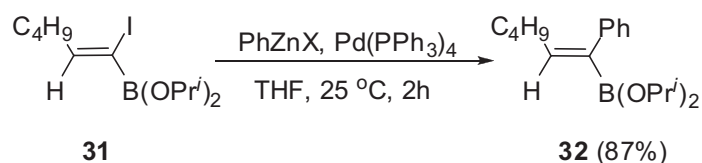
The reaction of 2-(haloalkenyl)boronic esters **28** with $\text{KHB}(\text{OPr}^i)$ or organolithium compounds proceeded with complete inversion of configuration at the sp^2 carbon (Scheme 1.21). The reaction is almost quantitative and highly selective (inversion >99%). Thus, the boron derivatives **29**, **30** synthesized can be directly used for the following cross-coupling reaction without further purification.³⁸⁻⁴²

Scheme 1.21 Hydroboration of alkenes with $\text{KHB}(\text{OPr}^i)$ or with organolithium compounds



The other method is to prepare the stereospecifically (*E*)-1-alkenylboronates by alkylation of **31** with organozinc reagents in the presence of a palladium catalyst (Scheme 1.22).⁴³

Scheme 1.22 Alkylation of alkenes with organozinc reagents

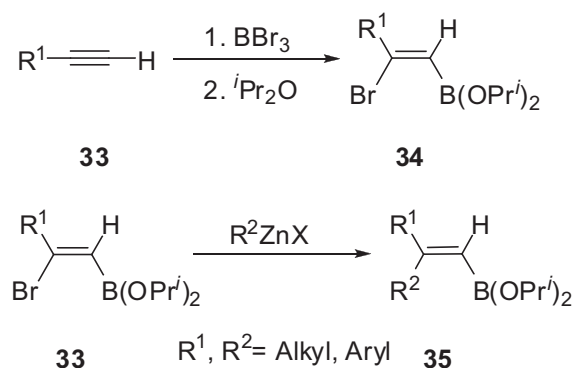


1.5.1.3 Haloboration of Terminal Alkynes²¹

The bromoboration of a terminal alkyne **33** gives β -bromo-1-alkenylboronic esters **34**, followed by palladium-catalyzed displacement of the β -halogen with organozinc reagents which

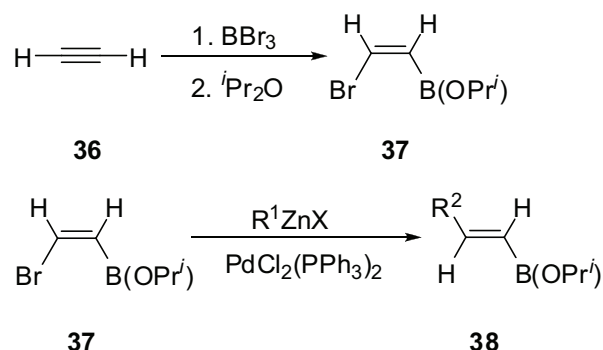
proceeds strictly with retention of configuration.^{44,45} This reaction proceeds via a Markovnikov addition which provides 2,2-diorgano-1-alkenylboronate **35** (Scheme 1.23).

Scheme 1.23 Bromoboration of terminal alkynes



While the addition of borontribromide of acetylene **36** itself results first a *cis* adduct which then isomerizes to the *trans* adduct of (*E*)-1-alkenylborates **37** during its isolation (Scheme 1.24).^{46,47}

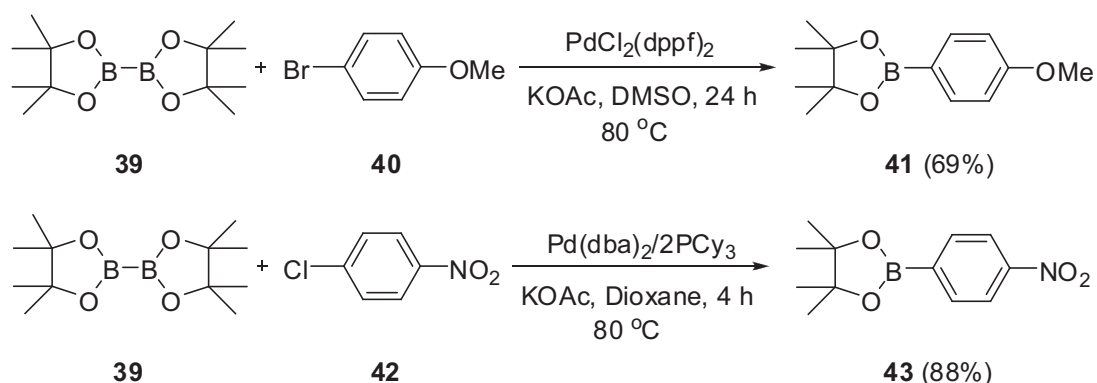
Scheme 1.24 Bromoboration of acetylenes



1.5.1.4 Cross-Coupling Reactions⁴⁸

Miyaura and co-workers were reported the first cross-coupling reactions of aryl halides **40**, **42** with the pinacol ester of diboronate **39** (Scheme 1.25).⁴⁹ KOAc was selected to be a more suitable base for borylation of aryl iodides,⁵⁰ bromides,⁵¹ chlorides^{49a} and triflates.^{52,53} PdCl₂(dppf) is better than Pd(PPh₃)₄ because palladium-triphenylphosphine complexes often resulted in formation of byproducts derived from coupling of the diboron with a phenyl group on triphenylphosphine in the reaction of electron-rich aryl halides.^{49a}

Scheme 1.25 Synthesis of organoboronates by cross-coupling reactions

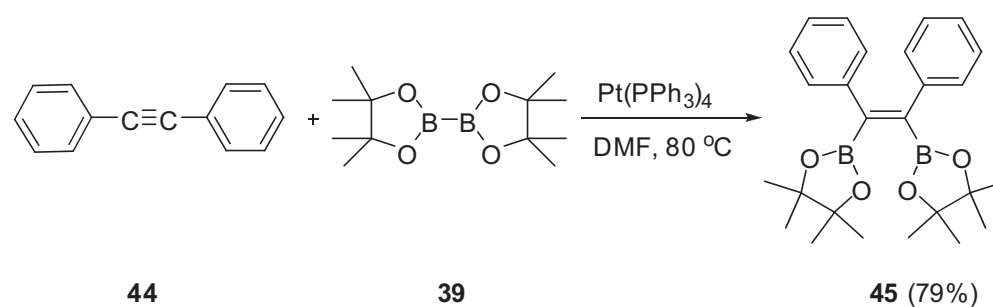


After the first preparation of organoboronic esters, a lot of publications appeared related to synthesis of organoboronic esters by using cross-coupling reactions of aryl halides.⁵⁴⁻⁵⁷

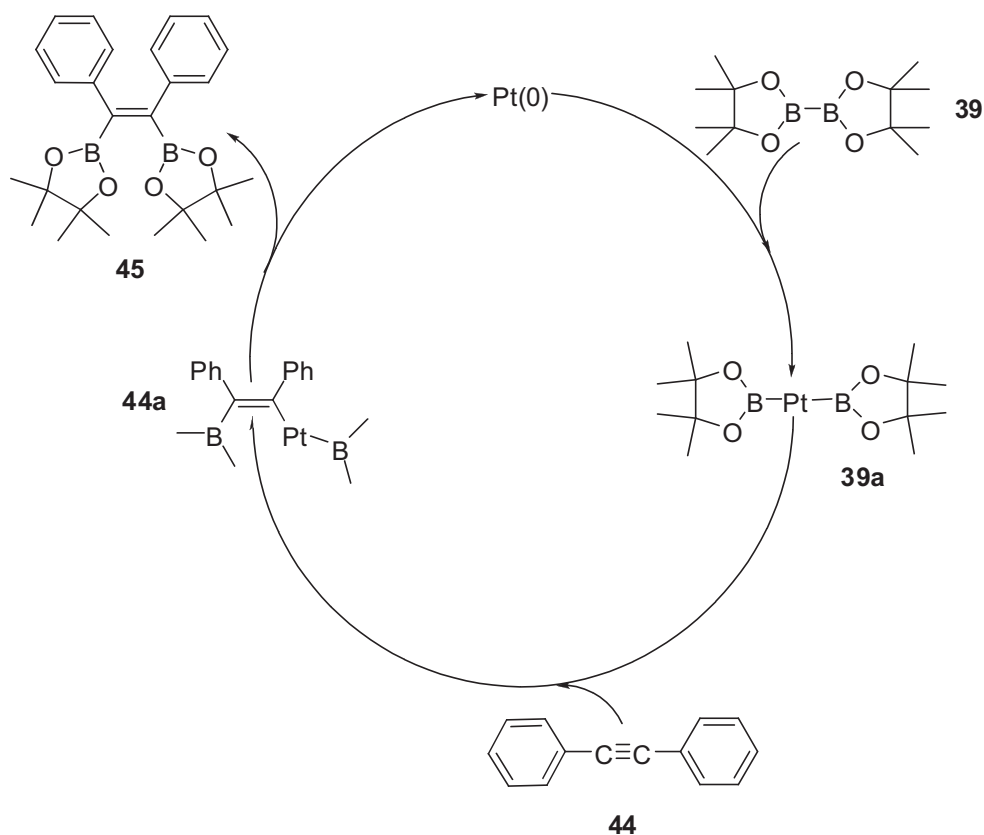
1.5.1.5 Diboration, Silylboration, and Stannylation⁴⁸

Addition reaction of various element-element bonds (B-B, B-Si and B-Sn) to alkenes and alkynes provides polymetallic organic compounds (Scheme 1.26).⁵⁸ Suzuki and co-workers published the first addition reaction of the pinacol ester of diboronate **39** to alkynes **44** using $\text{Pt}(\text{PPh}_3)_4$ as catalyst and DMF as solvent.

Scheme 1.26 Addition of various diboronates bonds to alkynes



They proposed a catalytic cycle for the diboration of alkynes, which involves the oxidative addition of the B-B bond to the platinum(0) complex, the stereospecific insertion of alkyne to the B-Pt bond, and finally the reductive elimination of the bis(boryl)-alkene as outlined in Figure 1.3.

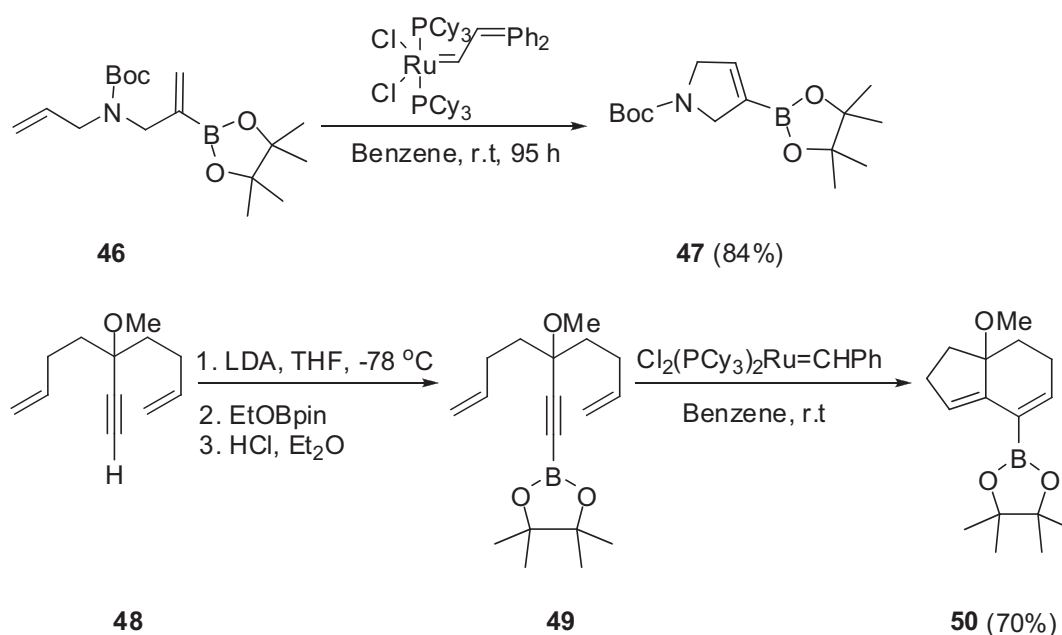
Figure 1.3 Catalytic cycle for the diboration of alkynes

In addition to this reaction, many applications were applied to synthesize boronic acids and esters by using these methods.⁵⁹

1.5.1.6 Olefin Metathesis⁴⁸

Renaud and co-workers reported the synthesis of cyclic 1-alkenylboronic esters **47**, **50** from organoboronic esters **46**, **49** at room temperature by using Grubbs' alkylidene-ruthenium complexes (Scheme 1.27).⁶⁰ Many cyclic alkenylboronic esters have been obtained by using these methods.⁶¹⁻⁶³

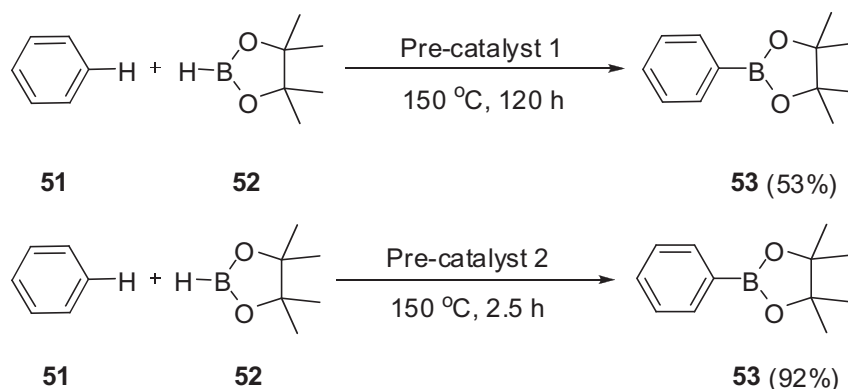
Scheme 1.27 Synthesis of organoboronates by olefin metathesis



1.5.1.7 Aromatic C-H Borylation⁴⁸

Organoboron compounds can be obtained by direct borylation of hydrocarbons.⁵⁸ The first metal-catalyzed reaction of a borane **52** and an arene **51** was reported by Smith and co-workers (Scheme 1.28).⁶⁴ The reaction was performed by using pre-catalyst **1** Cp*Ir(PMe₃)(H)(BPin) (Cp* = η⁵-C₅Me₅) and pre-catalyst **2** Cp*Rh(η⁴-C₆Me₆).⁶⁴ Many reactions have been studied using various catalysts.⁶⁵⁻⁶⁸

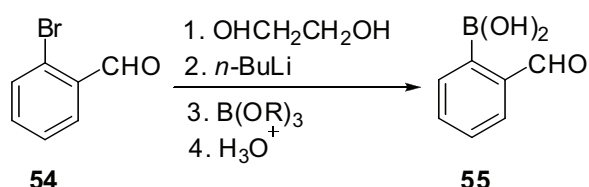
Scheme 1.28 Synthesis of organoboronates by borylation of hydrocarbons



1.5.1.8 Miscellaneous Methods⁴⁸

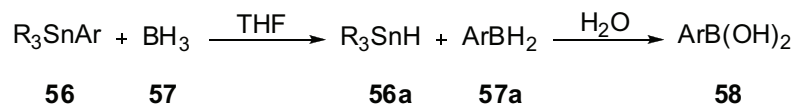
The reaction of Grignard or lithium reagents with boron halides or borates was used for the preparation of 2-formylbezenboronic acid (**55**) in 57 % yield (Scheme 1.29).⁶⁹

Scheme 1.29 Synthesis of organoboron compounds by lithium reagent



The reaction between borane and arylmetallic derivatives leads to arylboronic acids, but in low yields (9-60%). This is due to the formation of other organoborane derivatives. Aryltrialkyltin compound **56** reacts with borane **57** in THF to give mixtures of trialkyltin hydrides **56a** and arylboranes **57a**, which on hydrolysis give the arylboronic acid **58** in high yields (Scheme 1.30).⁷⁰

Scheme 1.30 The reaction between borane and arylmetallic derivatives



1.5.2 The Advantage of Organoboron Compounds

There are many advantages that Organoboron derivatives provide over other organometallic derivatives.^{71,72} They can tolerate a broad range of functional groups, such as organic halides, carbonyl, etc. The electronegativity of boron is about 2.0 which is close to the value of carbon of 2.5 and is higher than the electronegativities of lithium, magnesium, or most of the transition metals which range from 0.86 to 1.75. Therefore the boronic compounds are air-stable and also water tolerant. The starting materials and borate by-products are not toxic.

1.6 Reaction Conditions

1.6.1 The Catalyst

The most commonly used system is Pd(PPh₃)₄, but other palladium sources have been used including Pd^{II} pre-catalysts that are reduced to the active Pd⁰ in situ.⁷³

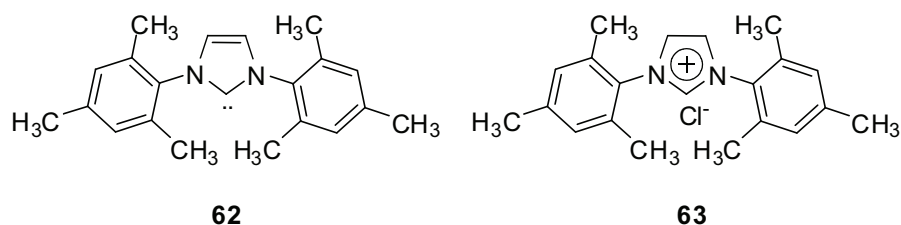
-Pd₂(dba)₃ + PPh₃ **59**

-Pd(OAc)₂ + PPh₃ **60**

-PdCl₂(dppf) (for sp³-sp² couplings) **61**

In addition to that, N-heterocyclic carbenes are also used as an alternative to phosphine ligands. The nucleophilic N-heterocyclic carbene **62** is the active ligand and is formed in situ from **63** (Figure 1.4).⁷⁴

Figure 1.4 N-heterocyclic carbene ligands **62**, **63**

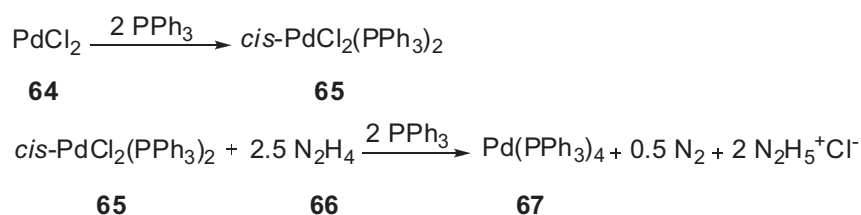


1.6.1.1 Tetrakis(triphenylphosphine)palladium(0) Pd(PPh₃)₄

This compound has the molecular formula Pd[P(C₆H₅)₃]₄, it is light-sensitive, unstable in air, and a coordinatively saturated Pd(0) complex. Sometimes, Pd(PPh₃)₄ is less active as a catalyst, because it is overligated and has too many ligands to allow the coordination of some reactants.⁷⁵

Malatesta and co-workers prepared the catalyst by reduction of chloropalladate **65** with hydrazine **66** in the presence of the phosphine (Scheme 1.31).⁷⁶

Scheme 1.31 Synthesis of 67

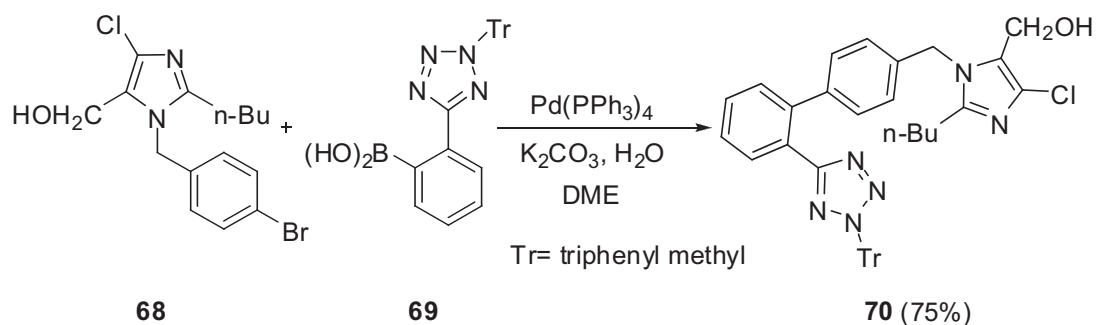


The reaction is proceeding in one pot without isolation and purification of *cis*-PdCl₂(PPh₃)₂ intermediate **64**.⁷⁷ Pd(PPh₃)₄ is widely used as a catalyst for palladium-catalyzed coupling reactions. Most applications include the Heck reaction and Suzuki-Miyaura coupling reaction.

1.6.2 Effect of Base and Water

The synthesis of trityl losartan **70** was studied by Smith and co-workers (Scheme 1.32). The product belongs to a new class of drugs (angiotensin II receptor antagonists) and was developed for the treatment of high blood pressure and heart failure.⁷⁸

Scheme 1.32 Synthesis of 70



They indicated that the Suzuki coupling reaction was efficient when the pK_a of base was close to 10, whereas it failed when the base was a bicarbonate (pK_a close to 6). Considering the pK_a of phenylboronic acid 8.8, phenylboronic acid was transformed into trihydroxyphenylborate (PhB⁻(OH)₃), showing a pH higher than 9. The authors supposed that this anion was the reactive species rather than the neutral boronic acid. Kinetic studies also proved that water and base are required to activate the boronic acid. They assumed that one mol of water and one mol of carbonate are required initially to activate the boronic acid and then to neutralize the produced boric acid.

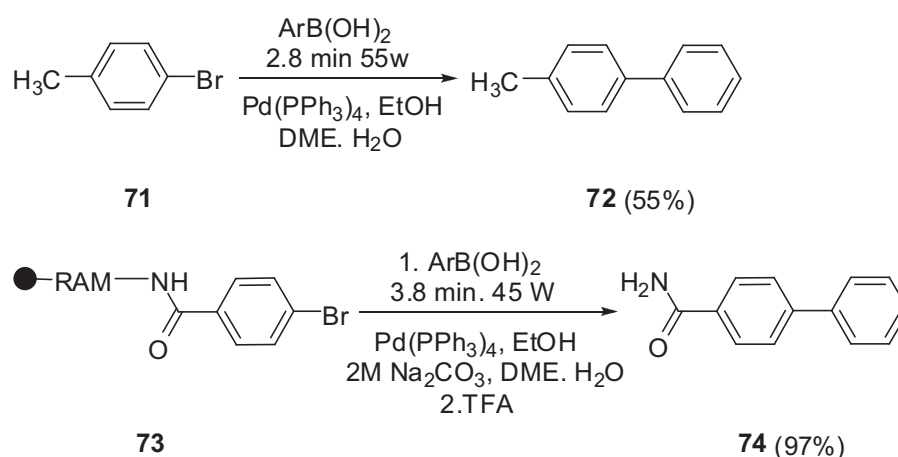
1.6.3 Effect of Solvent

The Suzuki coupling reaction is unrivaled among metal-catalyzed cross-coupling reactions in that it can be run in biphasic (organic/aqueous) or aqueous environments in addition to organic solvents.⁷⁹

1.6.4 Microwave-Assisted Reactions⁴⁸

In 1996, Hallberg and co-workers reported the first application of microwaves to rapid carbon-carbon bond formation (Scheme 1.33).⁸⁰ They confirmed that many metal-catalyzed reactions are completed within a few minutes and full conversion can be achieved in a few minutes. The reactions were carried out in water, ethylene glycol, or DMF, due to the ability of polar solvents to efficiently absorb microwaves irradiation.

Scheme 1.33 Microwave-assisted Suzuki coupling reactions

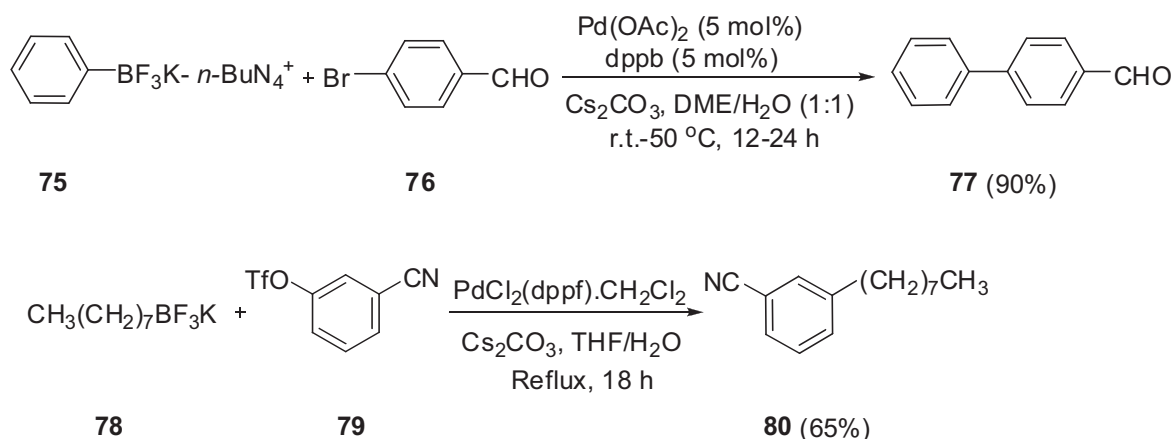


1.6.5 Coupling Reactions of $[\text{RBF}_3]\text{K}$ ⁴⁸

Potassium organotrifluoroborate salts are easily prepared⁸¹ and purified, and thus they are easier to handle compared to the preparation of the corresponding boronic acids. Potassium organotrifluoroborate salts are obtained by treatment of boronic acids with KHF_2 .⁸² Potassium salts are generally insoluble in common organic solvents and require polar solvents such as MeCN and H_2O at high temperatures. Coupling reactions of organotrifluoroborates have several advantages including the simplicity of the preparation of pure and stable crystalline material

compared to the preparation of the corresponding boronic acids. Cross-coupling of arylboronate **75** and alkyl derivatives **78** with organic halides **76**, **79** in the presence of bases resulted in successful coupling (Scheme 1.34).^{82,83}

Scheme 1.34 Coupling reactions of $[\text{RBF}_3]\text{K}$

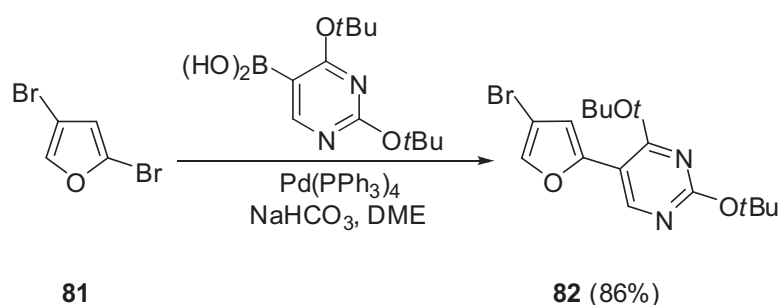


1.7 Site-Selective Suzuki-Miyaura Cross-Coupling Reactions

Recently, site-selective Suzuki coupling reactions became important. Complex compounds can be prepared by successive coupling reactions of substrates containing one, two or more possible reactive sites. The first attack usually occurs at the more electron deficient and less sterically hindered position.^{84,85}

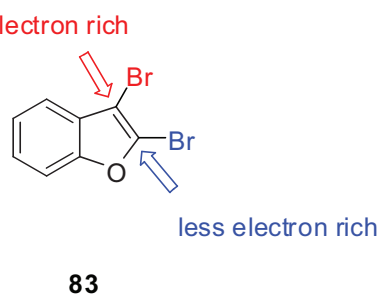
Gronowitz and co-workers were able to convert 2,4-dibromofuran (**81**) into the 4-bromofuran (**82**) in high yield (Scheme 1.35). The electronic difference of the two positions resulted a higher yield and better selectivity as compared to 2,5-dibromofuran.⁸⁶

Scheme 1.35 Site-selective reaction of **81**



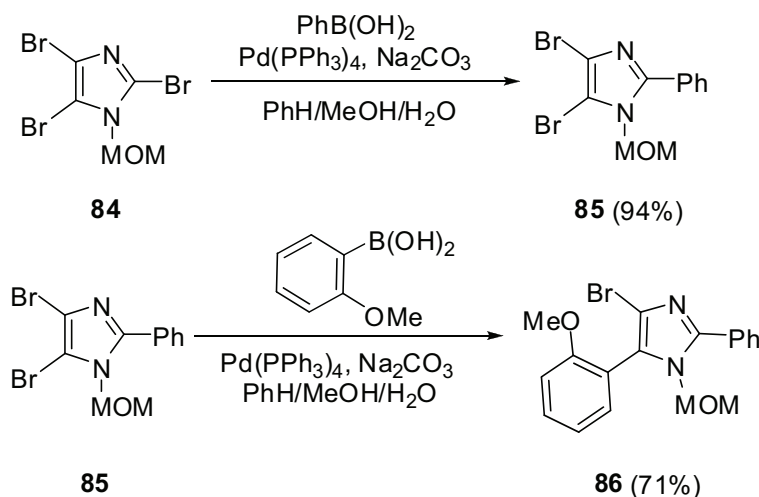
The reaction of 2,3-dibromobenzofuran (**83**) with one equivalent of boronic acids resulted in site-selective formation of 2-aryl-3-bromobenzofurans. The 2-position is less electron rich compared to the 3-position (Figure 1.5).⁸⁷

Figure 1.5 Possible explanation for the site-selectivity of **83**

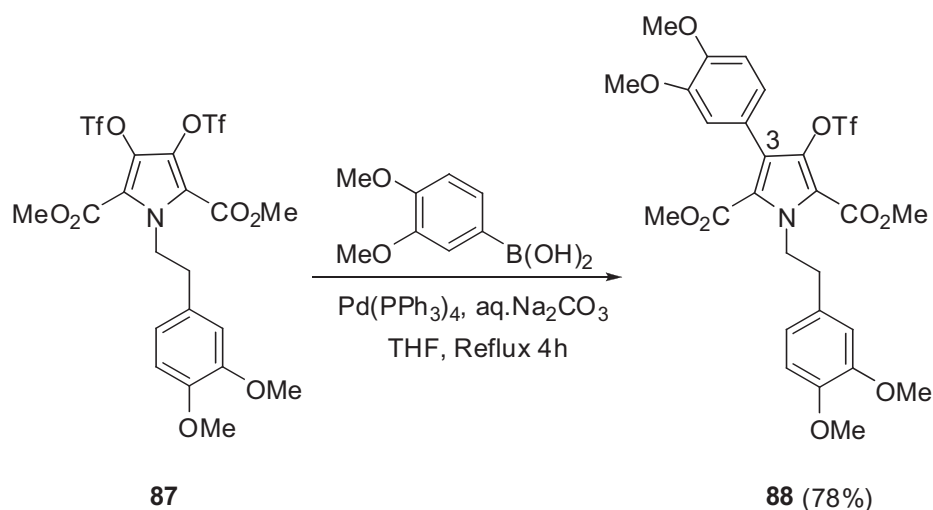


Further studies towards site-selective Suzuki coupling reactions of imidazoles have been confirmed by Ohta and co-workers. Carbon atom C-2 is attacked first and then the second attack occurred at carbon atom C-5 (Scheme 1.36).⁸⁸ Revesz and co-workers used similar Suzuki coupling reactions in order to synthesize potential kinase inhibitors and anti-inflammatory drugs.⁸⁹

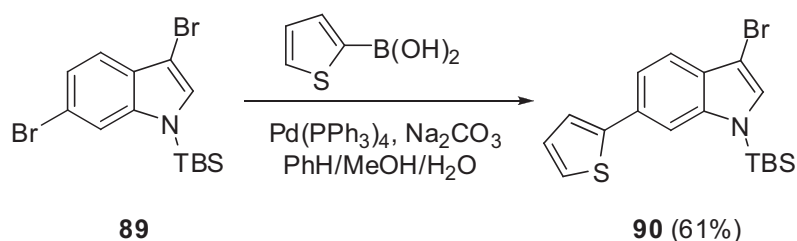
Scheme 1.36 Site-selective reaction of **84**



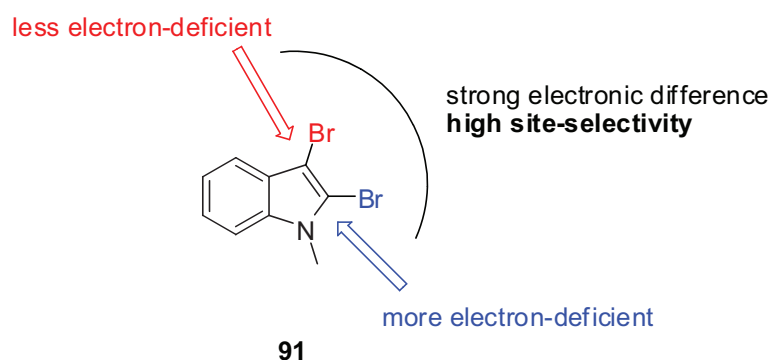
Iwao and co-workers carried out the Suzuki coupling reaction of pyrroles containing two methoxycarbonyl groups at carbon atoms C-2 and C-5 (Scheme 1.37).⁹⁰ The first attack occurred at carbon atom C-3 which can be explained by steric reasons. A further cross-coupling at C-4 is not preferred, due to the large aryl substituent present at carbon atom C-3.

Scheme 1.37 Site-selective reaction of **87**

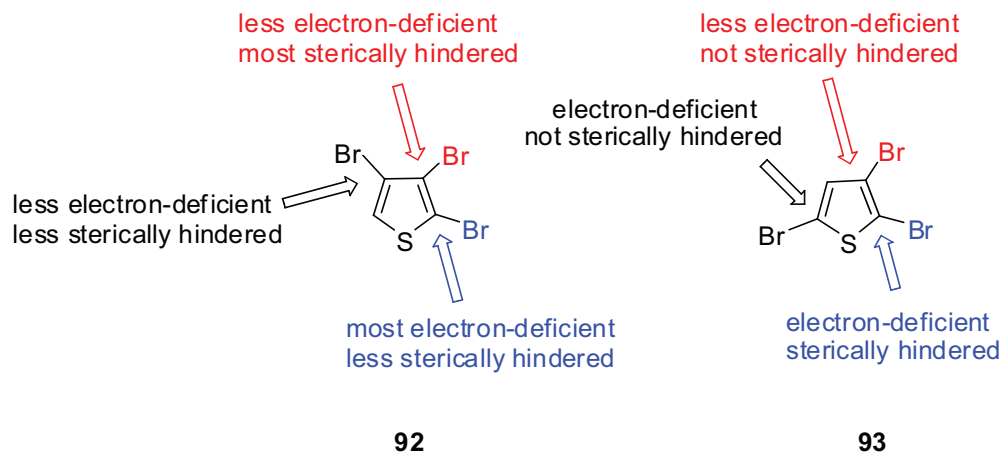
The first attack of N-(TBDMS)-2,6-dibromoindole occurred at carbon atom C-6 (Scheme 1.38). Several boronic acids were used, providing the 6-substituted products in 52-78% yield.⁸⁸

Scheme 1.38 Site-selective reaction of **89**

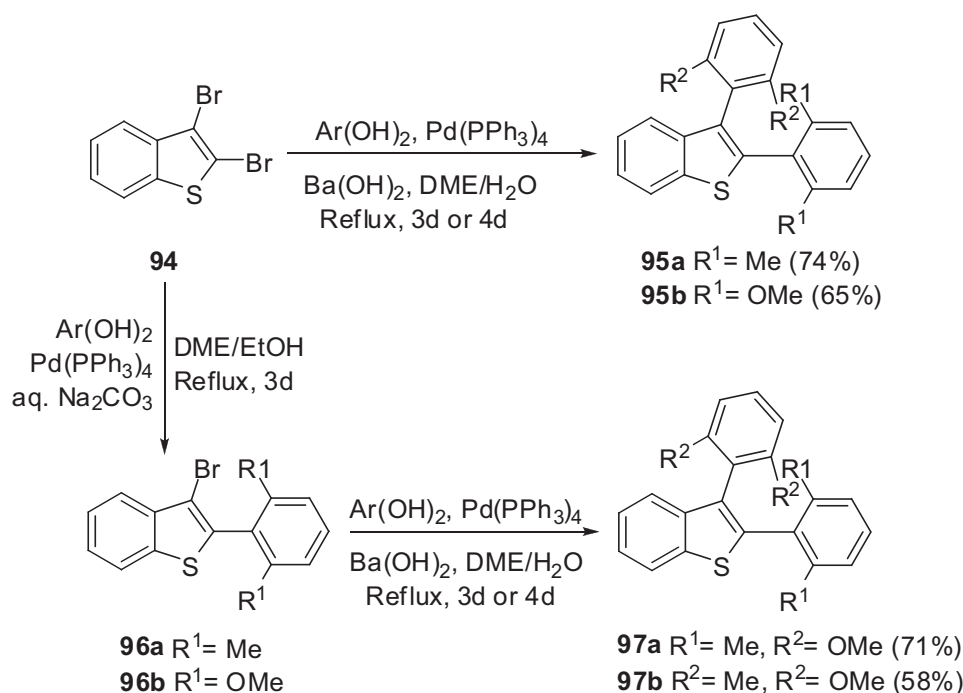
Langer and co-workers showed that the site-selective Suzuki coupling reaction of indole **91** was found to be in favour of the 2-position (Figure 1.6). This is due to the fact that the electronic character of C-2 and C-3 appears to be sufficiently different because site-selective transformations are observed.⁹¹

Figure 1.6 Possible explanation for the site-selectivity of **91**

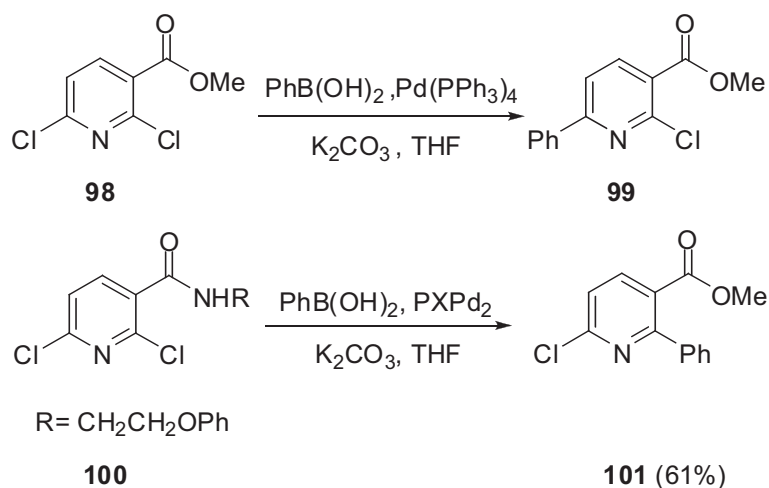
In addition, the substrates 2,3,4-tribromothiophene (**92**) and 2,3,5-tribromothiophene (**93**) showed very good site selectivity. For the **92** the first coupling occurred at the carbon atom C-2 then the second coupling took place at carbon atom C-4. In case of **93** the first coupling preferred to be at carbon atom C-5 and the second at carbon atom C-2 (Figure 1.7). The selectivity can be explained based on the different electronic and steric properties of the three different C–Br bonds of **92** and **93** (Figure 1.7).⁹²

Figure 1.7 Possible explanation for the site-selectivity of **92**, **93**

Guglielmetti and co-workers reported the site-selective Suzuki coupling reaction of 2,3-dibromobenzothiazole (**94**) (Scheme 1.39). They proved that the site-selective attack occurred at position 2 of the 2,3-dibromobenzothiazole (**94**). This reaction was used to synthesize 2,3-diarylbenzo[*b*]thiophenes **95** and **97** substituted by two different aryl rings.⁹³

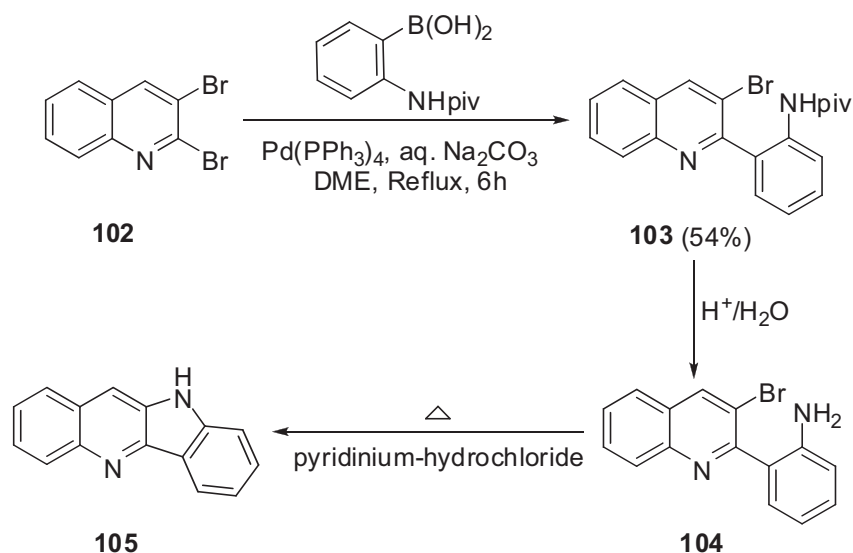
Scheme 1.39 Site-selective reaction of **94**

Corte and co-workers revealed that the site-selective Suzuki coupling reaction can depend on the type of catalyst in the reaction of 2,6-dichloropyridines (**98**) with boronic acids. The substrate reacted with distinct selectivity for 6-position using $\text{Pd}(\text{PPh}_3)_4$ as catalyst. On the other hand, in case of using the pre-catalyst PXPd_2 ($\text{Pd}_2\text{Cl}_4(\text{PtBu}_2\text{Cl})_2$) or $\text{PdCl}_2(\text{dppf})$ preferentially the 2-substituted product **101** was obtained (Scheme 1.40). It was disputed that a chelation is responsible for the observed effect and that the chelation might be enhanced if coordinatively unsaturated $\text{Pd}(0)$ intermediates are generated.⁹⁴

Scheme 1.40 Site-selective reaction of **98**

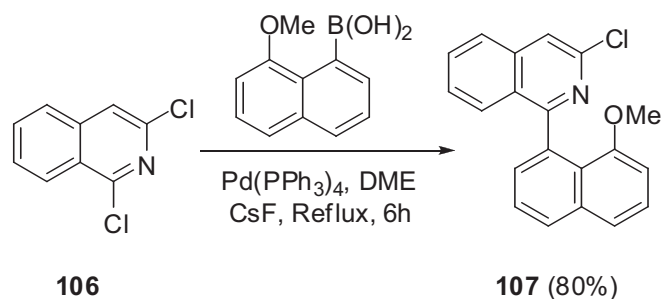
In order to synthesize the quinoline **105**, Timari and co-workers studied a regioselective coupling reaction of 2,3-dibromoquinoline (**102**) with boronic acid taking into consideration the fact that the α -heteroaryl halogen atom is more reactive in such coupling reactions than the β -halogen atom (Scheme 1.41).⁹⁵

Scheme 1.41 Synthesis of **105**



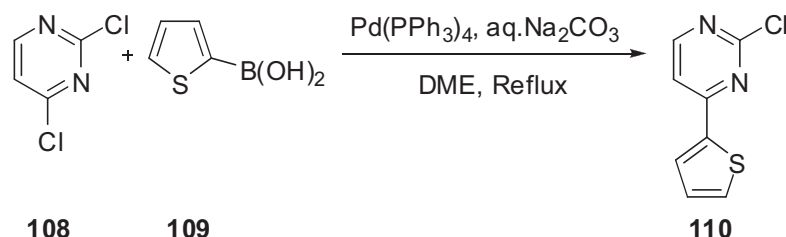
Woodward and co-workers showed that the site-selective Suzuki coupling reaction of 1,3-dichloroisoquinoline (**106**) with boronic acids took place at the 1-position to give **107** (Scheme 1.42).⁹⁶ These reactions were done by using $\text{Pd(PPh}_3)_4$ as a catalyst in the presence of CsF as a base. The carbon atom C-1 is more reactive than carbon atom C-3, due to the ease of oxidative addition at this electrophilic position.

Scheme 1.42 Site-selective reaction of **106**



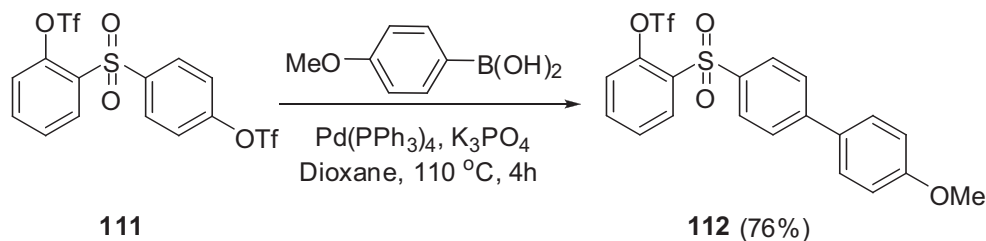
The Site-selective Suzuki coupling reaction of 2,4-dichloropyrimidine (**108**) with 2-thienylboronic acid (**109**) was confirmed by Gronowitz and co-workers (Scheme 1.43).⁹⁷ They proved that the 4-position **110** is more reactive than the 2-position.⁹⁸

Scheme 1.43 Site-selective reaction of **108**



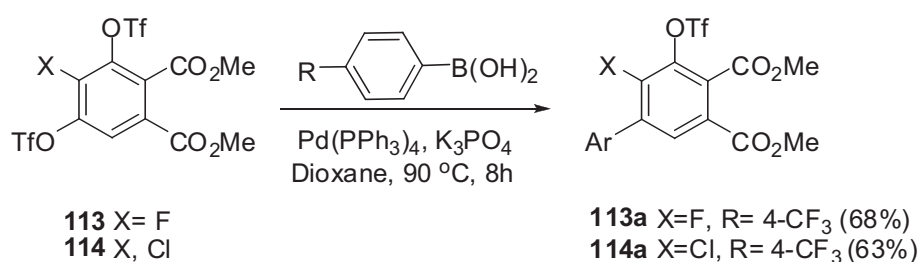
For the reaction of 2,4'-bis(trifluoromethylsulfonyloxy)diphenylsulphone (**111**) with boronic acid derivatives, the Suzuki coupling reactions occurred at carbon atom C-4' **112** (Scheme 1.44).⁹⁹ The oxidative addition of palladium usually occurs first at the most electron-deficient carbon atom. Carbon atoms C-2 and C-4' of the bis(triflate) are expected to be equally electron deficient. The site-selective formation of **112** can be explained by the fact that the carbon atom C-4' is less sterically hindered.

Scheme 1.44 Site-selective reaction of **111**



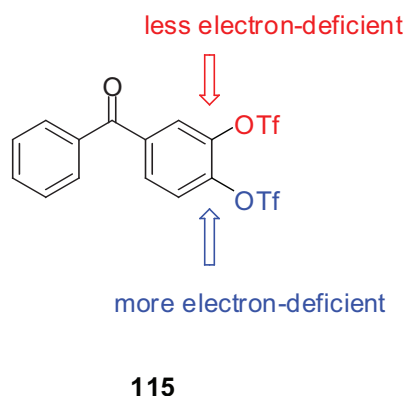
Site-selective reactions of both chloro and fluoro-dihydroxyphthalate derivatives **113**, **114** were also studied by Langer and co-workers. For both derivatives, the site-selective attack took place at C-5 and the formation of the opposite regioisomers was not observed (Scheme 1.45). The site-selectivity can be explained by steric reasons.¹⁰⁰

Scheme 1.45 Site-selective reaction of **113**, **114**



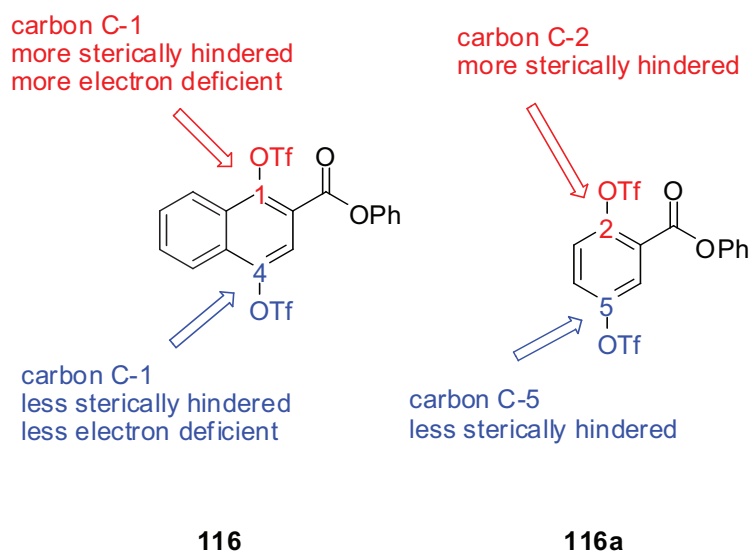
The reaction of the 3,4-bis(triflate) of benzophenone **115** with boronic acid derivatives provided very good site selectivity.¹⁰¹ The first attack occurred at C-4 which is located para to the keto group (Figure 1.8). Carbon C-4 is more electron deficient than C-3 which is located meta to the keto group. Steric parameters have presumably no effect, due to the similar steric environment of carbon atoms C-4 and C-3.

Figure 1.8 Possible explanation for the site-selectivity of **115**



The attack of boronic acids in site-selective Suzuki coupling reactions of the bis(triflate) of phenyl 1,4-dihydroxynaphthoate **116** occurred at the sterically more hindered position C-1 (Figure 1.9). This was confirmed by Langer and co-worker.¹⁰² The reactions are an example of site-selectivity controlled by electronic parameters.

Figure 1.9 Possible explanation for the site-selectivity of **116**



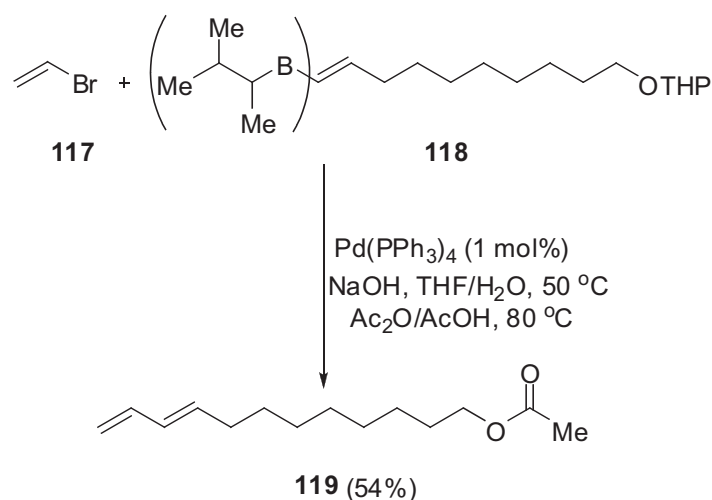
1.8 Applications of Suzuki-Miyaura Cross-Coupling Reactions

Since the Suzuki coupling reaction was discovered by Akira Suzuki and Norio Miyaura it found multiple applications in many areas including total synthesis, pharmaceuticals as well polymer chemistry.

1.8.1 Total Synthesis

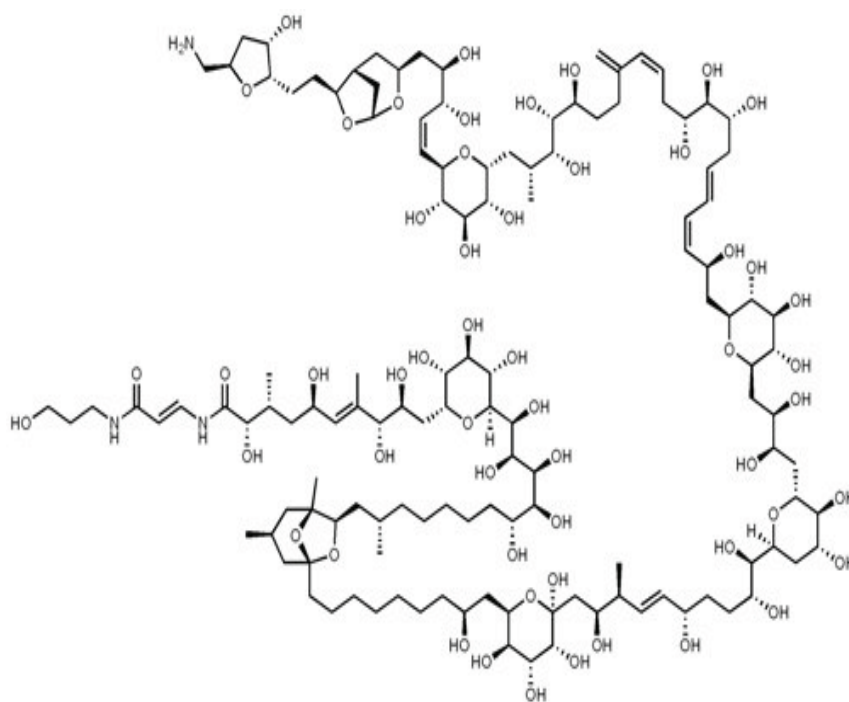
In 1981, Rossi and co-workers reported the first total synthesis of (*E*)-9,11-dodecadien-1-yl acetate **119** which an insect sex pheromone isolated from *Diparopsis castanet* (Scheme 1.46).¹⁰³ The key step in this elegant strategy was the Suzuki coupling reaction. It was prepared using the reaction between vinyl borane (*E*)-120 **118** and vinyl bromide **117**, followed by treatment of the resulting crude product mixture with acetic anhydride in acetic acid in order to convert the tetrahydropyranyl protecting group into the corresponding acetate.

Scheme 1.46 Total synthesis of **119**



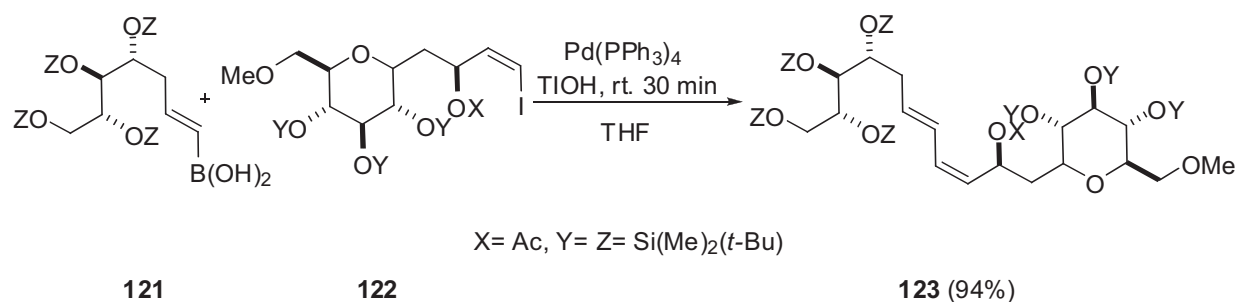
The Palytoxin **120** (Figure 1.10) an extremely poisonous, water-soluble substance from marine coelenterates belonging to the genus *Palythoa*,¹⁰⁴ was originally isolated in 1971 in Hawaii from the seaweed-like coral. Palytoxin is a complex marine natural product containing 71 asymmetric centers, cleaved into several compounds by sodium periodate. Kishi and co-workers first synthesized palytoxin in 1994.¹⁰⁵

Figure 1.10 Structure of (**120**).^{104b} The picture was taken from *Angew. Chem. Int. Ed.* **2005**, *44*, 4442-4489.



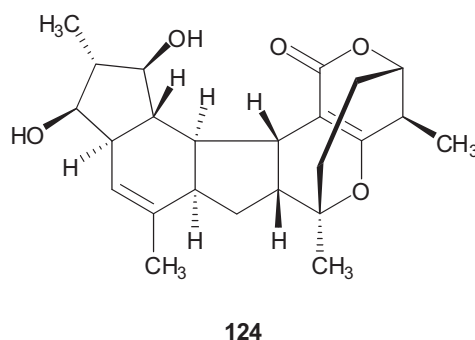
They concluded that the use of TIOH instead of KOH has many advantages. This method can be used in the presence of fragile functional groups as well as with large molecular weights in addition to formation of byproducts is nonexistent (Scheme 1.47).¹⁰⁶

Scheme 1.47 Total synthesis of **120**



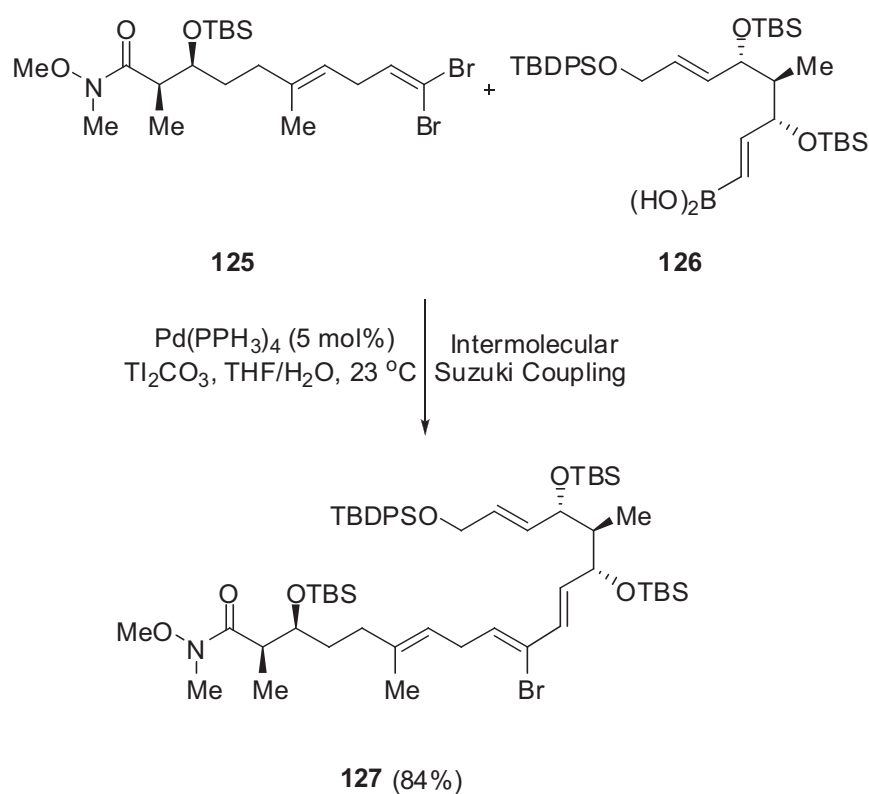
FR182877 **124** (Figure 1.11) is an antibiotic isolated from the fermentation broth of *Streptomyces sp.* No. 9885, in 1998.¹⁰⁷ FR182877 exhibited potent antitumor activities against murine ascitic tumor and solid tumor in vivo.

Figure 1.11 Structure of **124**

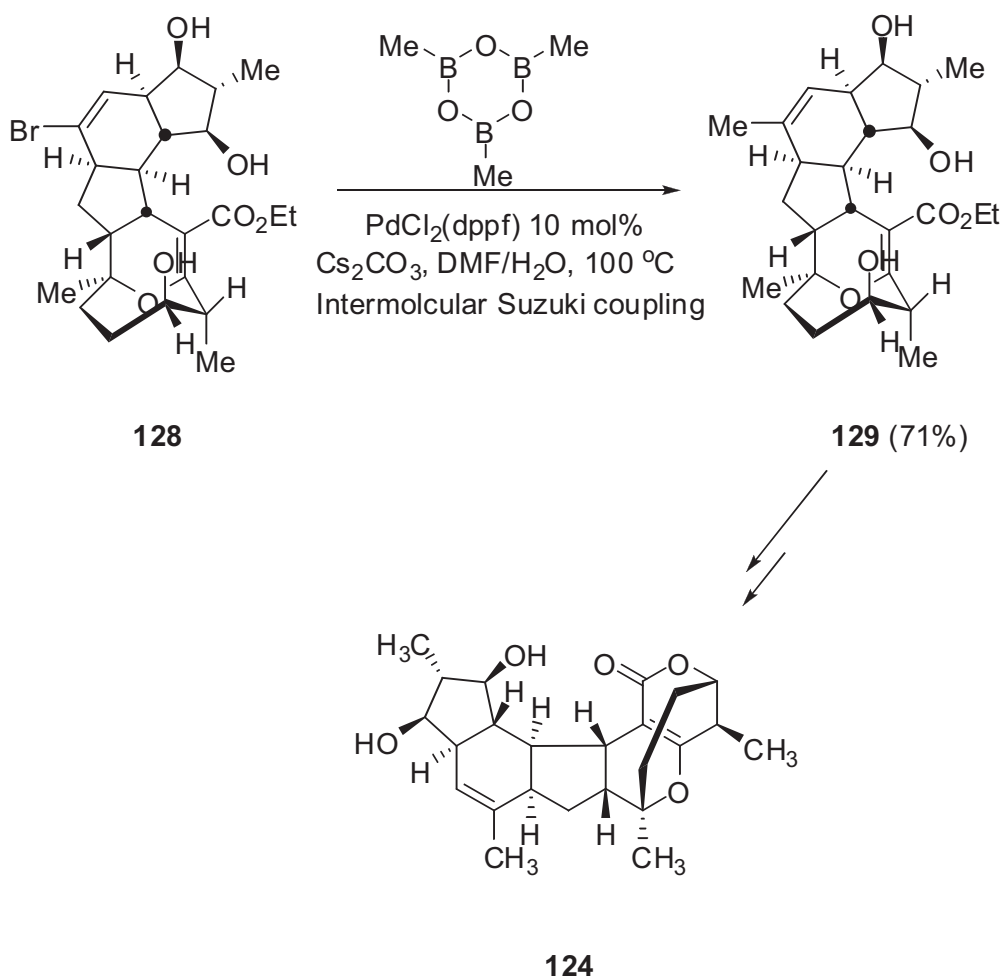


Evans and Starr used the Suzuki coupling reaction between **125** and **126** to prepare regioselective product **127**.¹⁰⁸ They optimized this reaction by using Ti_2CO_3 as a base which gave an excellent yield (84%) (Scheme 1.48).

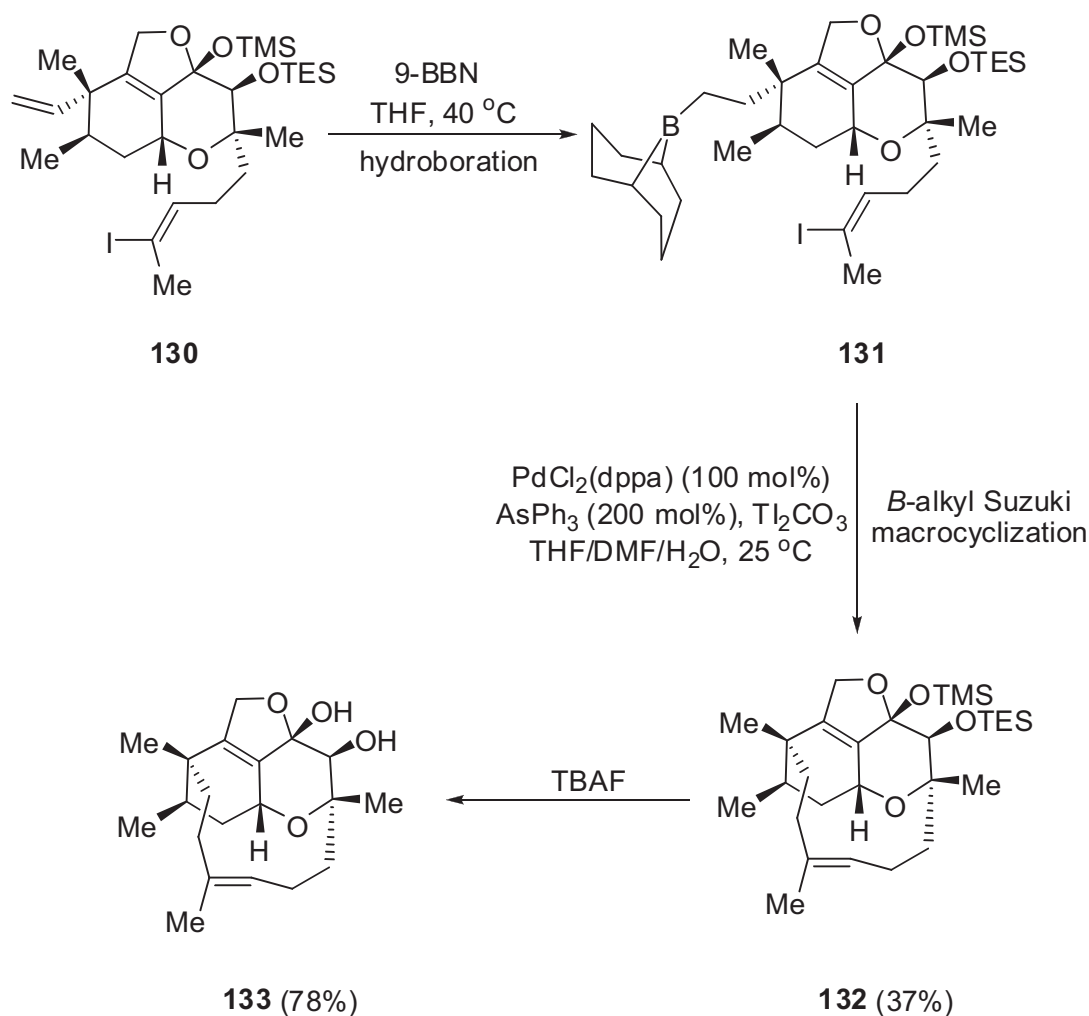
Scheme 1.48 Synthesis of **127**



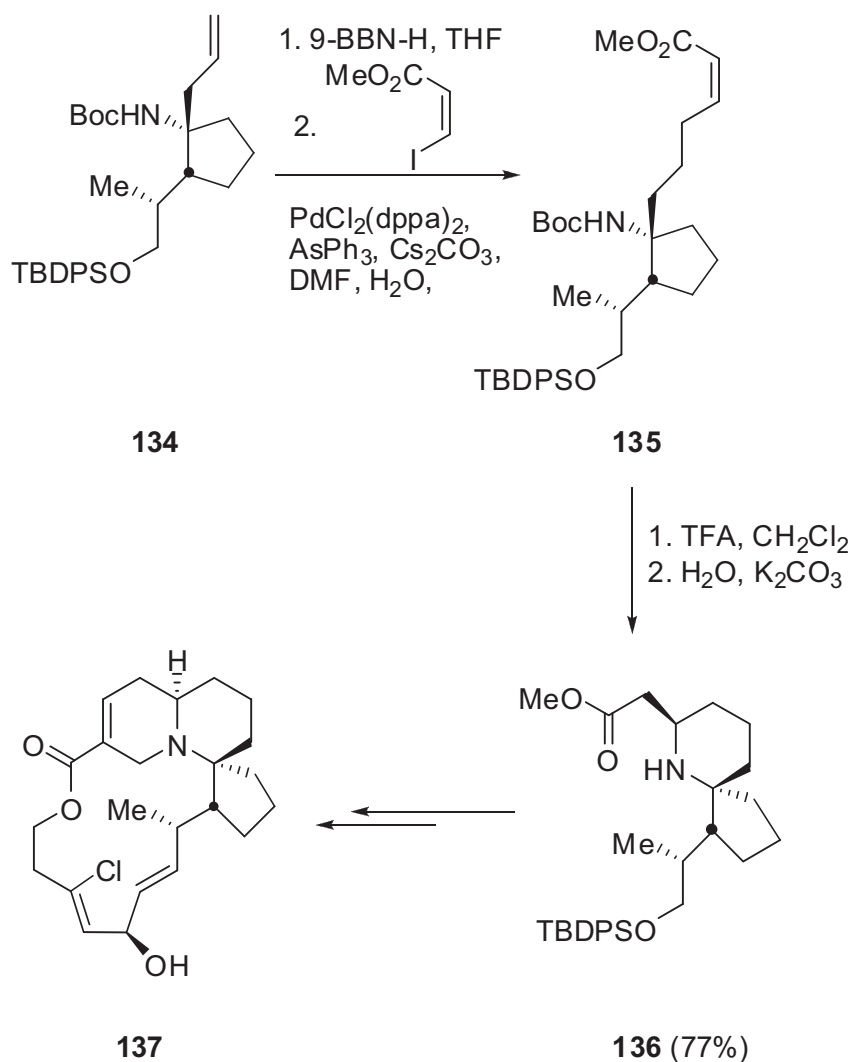
And finally, they utilized the Suzuki methylation in order to convert **128** to **129**. They used TMB as a methylating agent.¹⁰⁹ Saponification of the ethyl ester (TMSOK, THF)¹¹⁰ and lactonization (1-methyl-2-chloropyridinium iodide, NaHCO₃, 62%, 2 steps)¹¹¹ afforded FR182877 (Scheme 1.49).

Scheme 1.49 Total synthesis of **124**

Sugano and co-workers were isolated phomactin A **133**, in the early 1990s.¹¹² The phomactins show biological activity as platelet activating factor (PAF) antagonists. Halcomb and co-workers constructed the phomactin A **133** by using a regioselective hydroboration on the terminal olefin of **130** with 9-BBN to give an intermediate alkyl borane **131**, which cyclized using a modification of Johnson's conditions (Scheme 1.50).¹¹³ The Suzuki coupling reaction proceeded with the sensitive dihydrofuran ring in place. Treatment with TBAF then hydrolyzed both silyl groups to give phomactin A **133**.

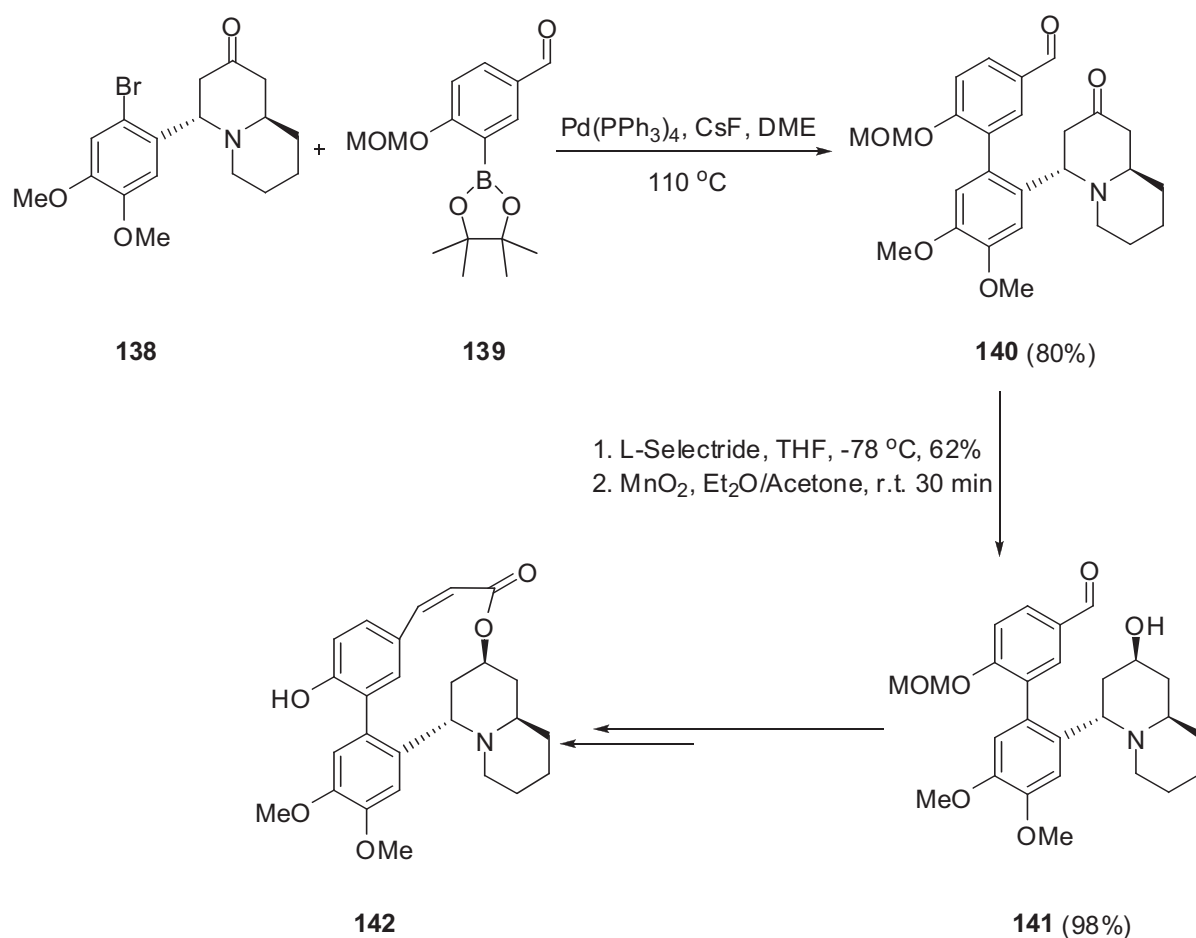
Scheme 1.50 Total synthesis of **133**

Danishefsky and Trauner synthesized (+)-Halichlorine¹¹⁴ **137**, a marine alkaloid recently isolated from the sponge *Halichondria okadai*.¹¹⁵ Hydroboration of the protected amino alkene **134**, followed by palladium-mediated Suzuki coupling reaction with methyl (*Z*)-3-iodoacrylate, afforded the α,β -unsaturated ester **135** (Scheme 1.51). Upon deprotection of the amino function with TFA and subsequent basification, **135** underwent a highly stereoselective intramolecular 1,4-addition to afford piperidine **136** as the only isolated isomer. Intermediate **136** was subsequently converted into the inhibitor (+)-halichlorine **137** in eight steps.

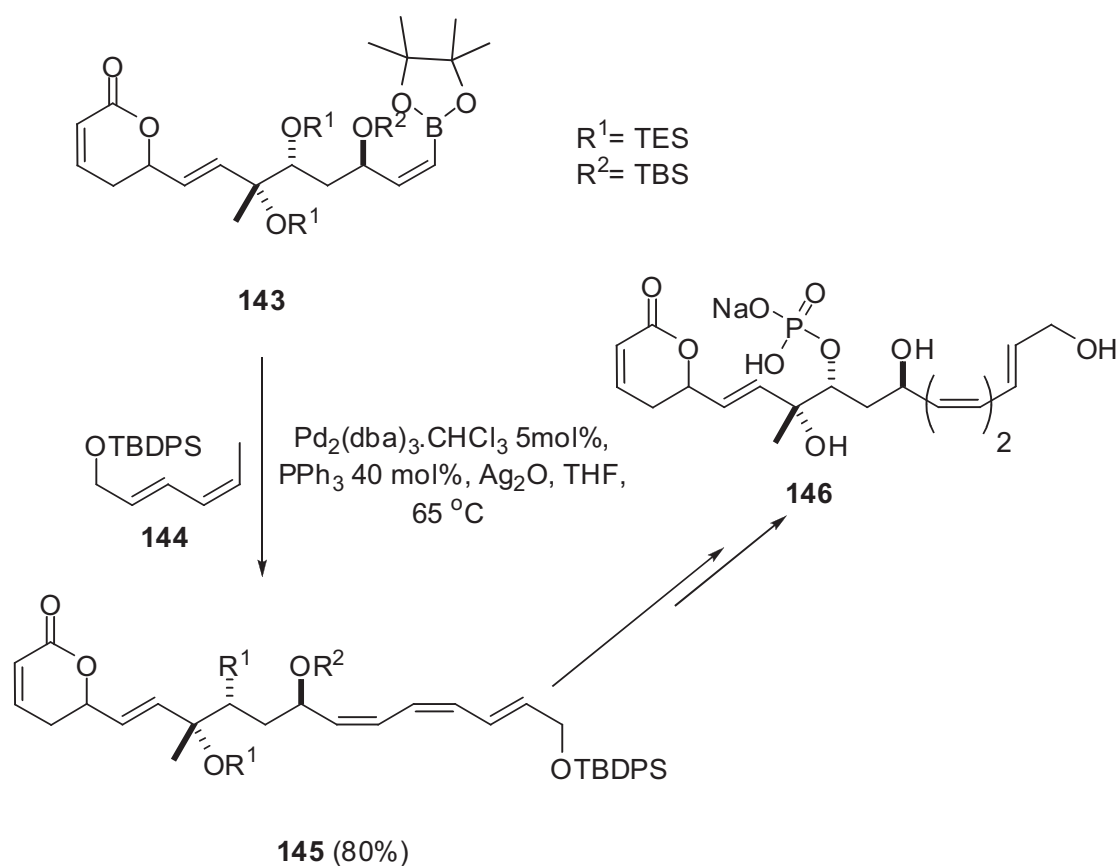
Scheme 1.51 Total synthesis of **137**

Kündig and co-workers prepared vertine **142** in eleven steps including Suzuki coupling reaction and ring-closing metathesis.¹¹⁶ Vertine is classified as a member of the Lythraceae alkaloids isolated in 1962 by Ferris from *Decodon verticillatus* (L.) Ell.¹¹⁷ The reaction between **138** and **139** afforded the product **140** which was isolated as a mixture of two apparent atropisomers in a ratio of 3:1 (Scheme 1.52). To overcome the problem the best choice was choosing L-Selectride as a reducing agent¹¹⁸ to yield a single diastereomer in 62% yield. Aldehyde **141** was obtained by oxidation with MnO₂ in 98% yield.

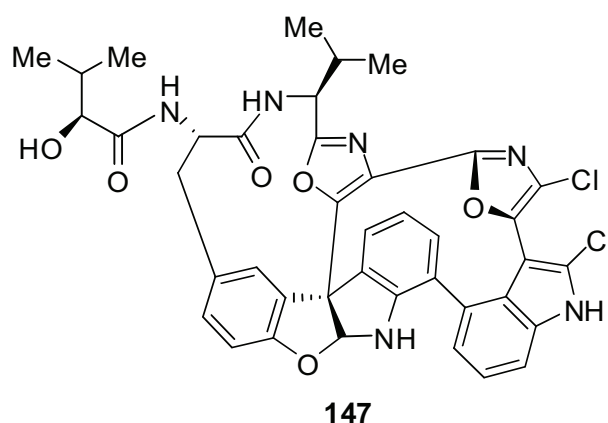
Scheme 1.52 Total synthesis of **142**



Fostriecin **146** is a pyranone-containing natural product isolated from *Streptomyces pulveraceus*.¹¹⁹ Fostriecin has been shown to possess significant in vitro cytotoxic activity against a broad range of cell lines,¹²⁰ such as leukemia, lung cancer, breast cancer, and ovarian cancer and also antitumor activity against leukemia in vivo.¹²¹ O'Doherty and Gao have been recently prepared the Fostriecin in 24 steps starting from enyne.¹²² The reaction of vinyl boronate **143** and vinyl iodide **144** led to (*Z,Z,E*)-triene **145** with excellent alkene stereoselectivity (>20:1) and 80% yield. The reaction has been achieved by using 20% Pd/PPh₃ system (20% Pd₂(dba)₃·CHCl₃/ 80% PPh₃) instead of using the Pd(PPh₃)₄/Ag₂O system which led to no reaction (Scheme 1.53).

Scheme 1.53 Total synthesis of **146**

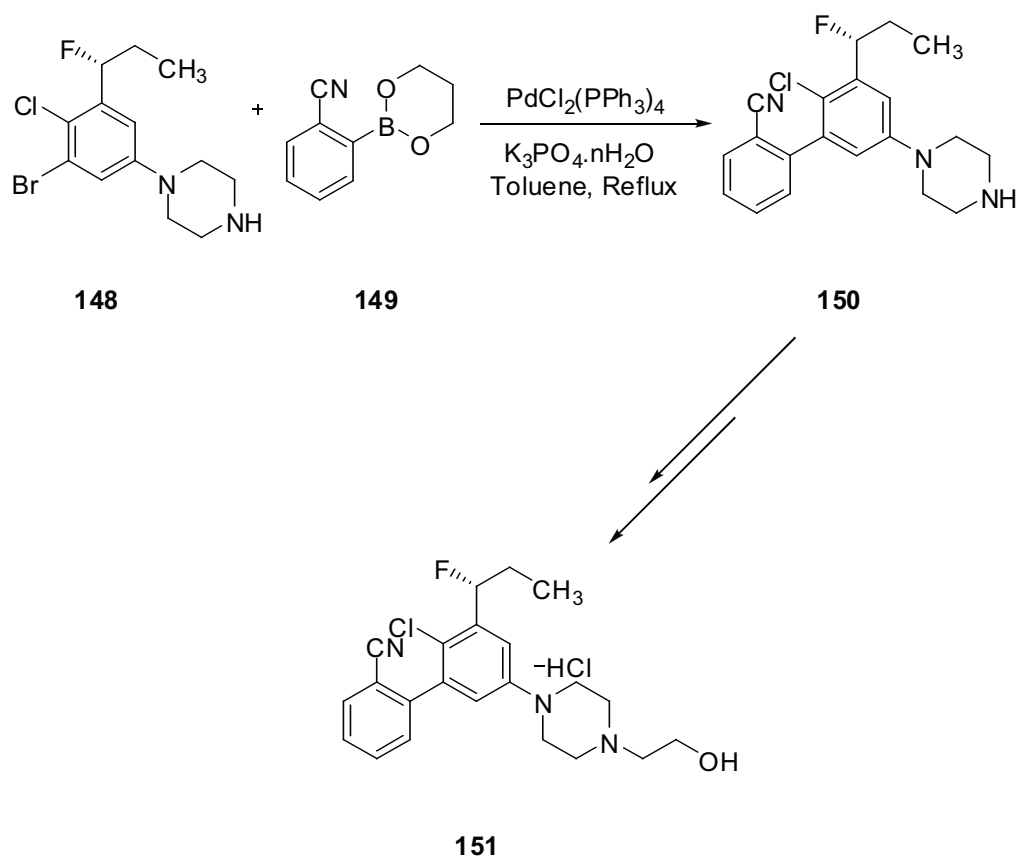
Diazonamide A **147** was isolated from the colonial ascidian *Diazona chinensis* (Figure 1.12).¹²³ Diazonamide A possesses potent in vitro activity against HCT-116 human colon carcinoma and B-16 marine melanoma cancer-cell lines.¹²⁴ Nicolaou and co-workers reported the synthesis of diazonamide A **147** by using also Suzuki coupling reaction.^{125,126}

Figure 1.12 Structures of **147**

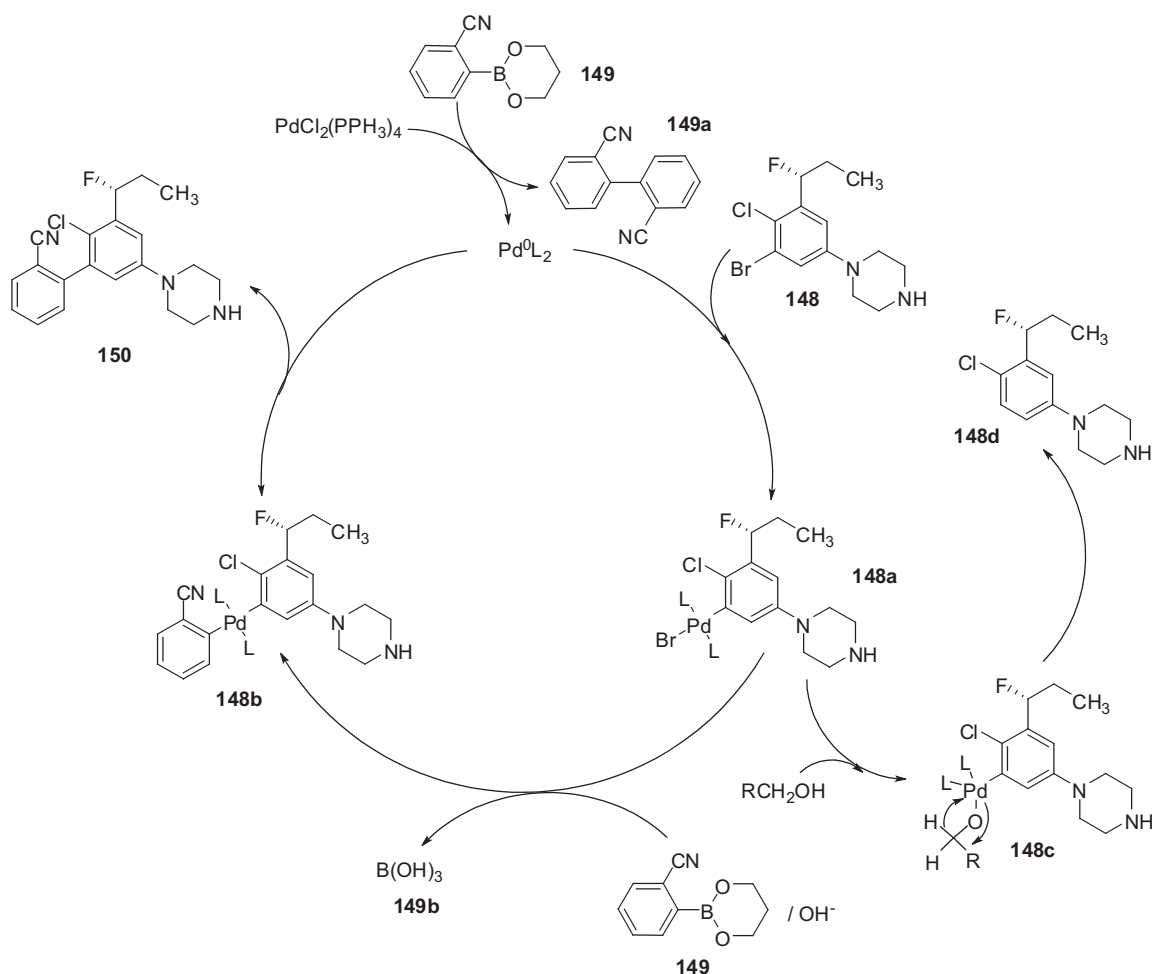
1.8.2 Synthesis of Pharmaceuticals

E2040 **151** is a potent antagonist of D3/D2/5-HT2 receptors being developed for the treatment and amelioration of mental disorders such as aggressive behavior, senile dementia, mental excitation, poriomania, delirium, hallucination, hyperkinesias, schizophrenia, emotional disturbance, depression, neurosis, psychophysiologic disorder and anxiety.¹²⁷ The intermediate **150** was synthesized by Urawa and co-workers at Eisai Co. in Japan.¹²⁸ This reaction was achieved by the Suzuki coupling reaction of optically active **148** with boronate **149** (Scheme 1.54).

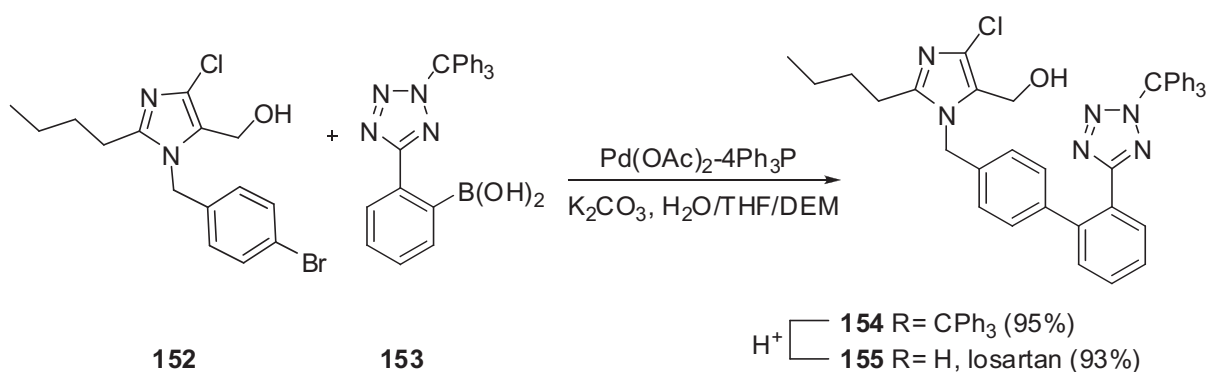
Scheme 1.54 Synthesis of **151**



They proposed mechanism for the Suzuki coupling reaction is shown below in Figure 1.13.

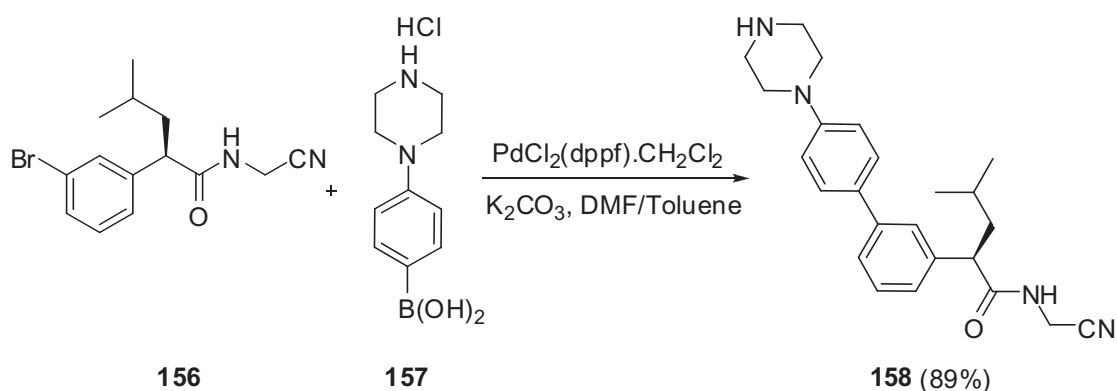
Figure 1.13 Catalytic cycle for the synthesis of **151**

Larsen and co-workers synthesized the angiotensin II receptor antagonist Losartan **155** which is used mainly to treat high blood pressure (hypertension).¹²⁹ The coupling between bromide **152** and boronic acid **153** is catalyzed by a palladium(0) catalyst in the presence of a base at 80 °C (Scheme 1.55).

Scheme 1.55 Synthesis of **155**

The potent cathepsin K inhibitor **158** is used to treat osteoporosis. O'Shea and co-workers reported the synthesis of it by application of the Suzuki coupling reaction.¹³⁰ They optimized the conditions of this coupling and found that the best conditions involve the use of 3 mol% PdCl₂(dppf).CH₂Cl₂ as a catalyst with aqueous K₂CO₃ as a base in 10:1 Toluene/DMF at 80 °C. Under these conditions, the reaction was complete within 2 h to yield **158** in 89% (Scheme 1.56).

Scheme 1.56 Synthesis of **158**



A useful application of the Suzuki coupling reaction is the synthesis of 2-amino-tetralin **161** which is a pharmaceutical ingredient that is useful in the treatment of epilepsy, stroke, and brain or spinal trauma.¹³¹ Coupling of arylbromide **159** with boronic acid **160**, in the presence of K₂CO₃ (Scheme 1.57) and PS-Pd **162** as a catalyst (Figure 1.14).

Scheme 1.57 Synthesis of **161**

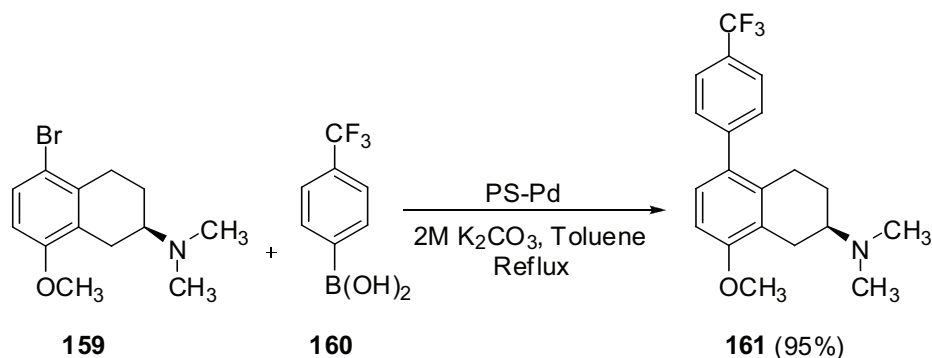
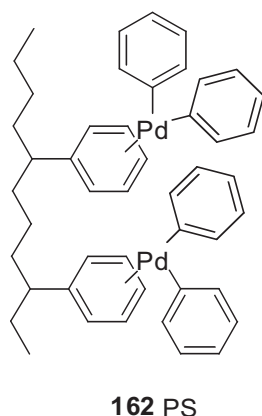


Figure 1.14 Structure of **162**

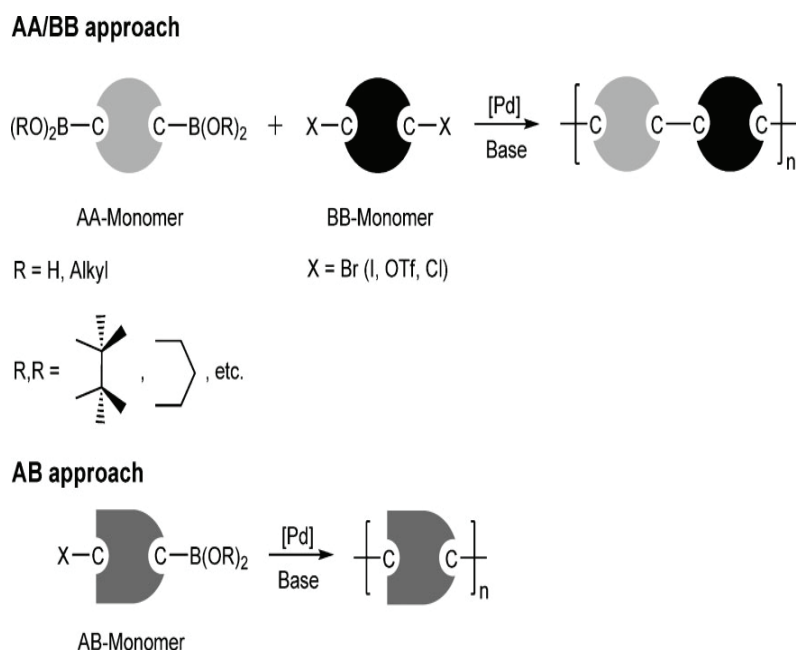
1.8.3 Polymer Synthesis

1.8.3.1 Suzuki Poly-Condensation (SPC)

We can simply identify the Suzuki poly-condensation as a step-growth polymerization of bifunctional aromatic monomers of poly(arylene)s and related polymers.¹³² The required functional groups, boronic acid or esters on the one side and bromide or iodide, on the other, may be present in different monomers (AA/BB approach) or combined in the same monomer (AB approach). Most polymers prepared by this method are poly(paraphenylene)s, which are one of the most important classes of conjugated polymers.^{132,133}

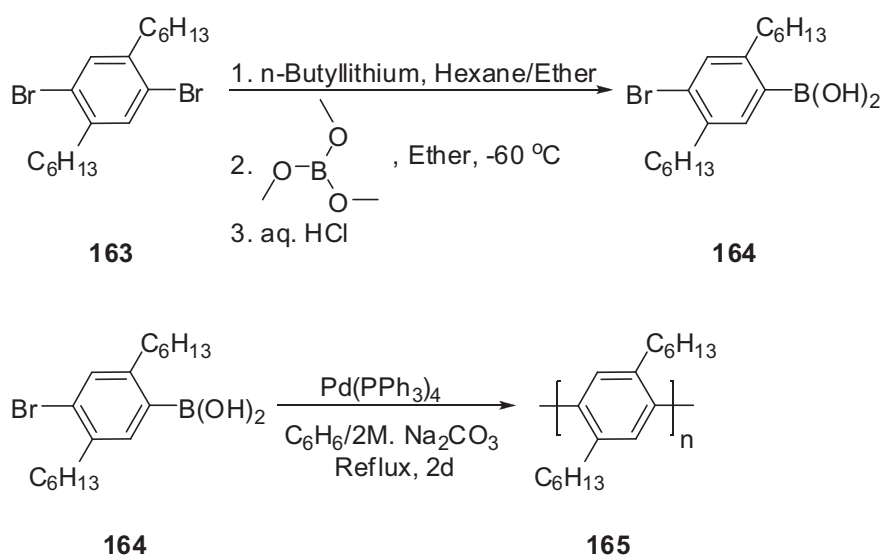
Conjugated polymers have been identified as a fascinating class of novel conductors and semiconductors that have the electrical and optical properties of metals and semiconductors and, in addition, have the processing advantages and mechanical properties of molecular materials. The monomers of types AA and BB are widely used in Suzuki polycondensation. Among the most commonly used monomers of BB type is 2,5-dialkyl-1,4-benzene-bis(boronic) acid.^{134,135} The reaction conditions are like the ones Suzuki reported in his famous original article of 1981.^{21,26,136} The mechanism of SPC is supposed to involve the same steps of oxidative addition, transmetalation, and reductive elimination as for Suzuki cross-coupling. The standard catalyst precursor is Pd(PPh₃)₄.

Scheme 1.58 Suzuki poly-condensation (SPC).^{133b} The picture was taken from *Macromol. Rapid Commun.* **2009**, *30*, 653-687.



Schlüter and co-workers used PSC in order to synthesize poly(para-2,5-di-n-hexylphenylene) (**165**) (Scheme 1.59).¹³⁴ Starting from the suitable monomer 1,4-dibromo-di-2,5-n-hexylbutene¹³⁷ (**163**) which is then converted to boronic acid derivative **164**. The monomer was treated with Pd(PPh₃)₄ under reflux for 2 days to afford poly(para-2,5-di-n-hexylphenylene) (**165**). A large number of poly(paraphenylene)s have been prepared based on this method.¹³⁸⁻¹⁴²

Scheme 1.59 Synthesis of 165



*RESULTS AND
DISCUSSION*

CHAPTER TWO

2.1 Anthraquinones

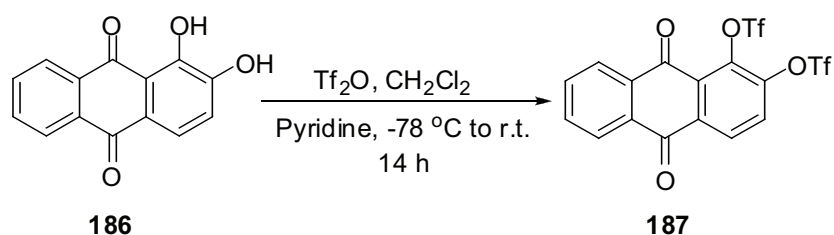
Anthraquinones occur in many naturally occurring bioactive compounds.¹⁴³ For instance, the anthracyclines are important as antitumor agents and antibiotics (e.g., the natural products daunorubicin, adriamycin, and aclarubicin).¹⁴⁴ Anthraquinone containing natural products include chrysophanic acid, vismiaquinone, anthragallol, and questin.¹⁴⁵ Anthraquinone derivatives show a very good antitumor activity against cancer cells.¹⁴⁶ On the other hand, anthraquinones are widely using as antihelminthic¹⁸⁷ as well as inhibitor agents.¹⁴⁸ Many applications of aryl-substituted anthraquinones exist in material sciences, due to their redox,^{149a,b} UV and luminescence properties.^{149c,d} They have also been used as stabilizers of light-modulating fluids.^{149e}

2.1.1 Synthesis of 1,2-Diarylanthraquinones by Site-Selective Suzuki-Miyaura Cross-Coupling Reactions of the Bis(triflate) of Alizarin

The phenol group can be transformed to triflates by treatment with triflic acid anhydride in the presence of pyridine.¹⁵⁰ The triflic anhydride was added at -78 °C and the mixture was allowed to warm to r.t.

My strategy is based on the above mentioned procedure to convert the alizarin **186** into the bis(triflate) of alizarin **187** which was isolated as a yellow solid in 81% yield (Scheme 2.1).

Scheme 2.1 Synthesis of **187**

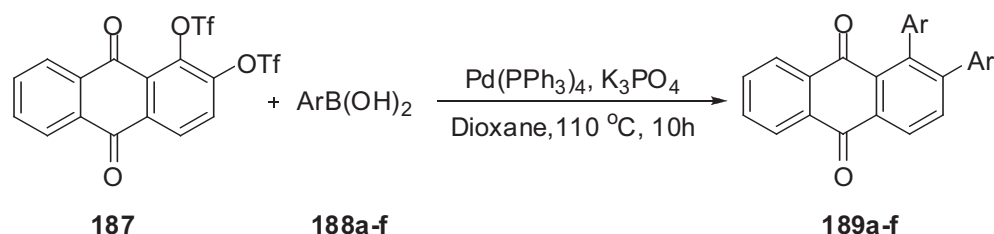


2.1.1.2 Synthesis of 1,2-Diarylanthraquinones **189a-f**

1,2-Diarylanthraquinones **189a-f** were synthesized by using Suzuki coupling reactions of 1,2-bis(trifluoromethylsulfonyloxy)anthraquinone (**187**) and arylboronic acids (2.4 equiv) (Scheme 2.2). The best conditions for the completion of this coupling were the use of Pd(PPh₃)₄

as the catalyst and K_3PO_4 as the base. I have done the Suzuki coupling reactions by using different substituted arylboronic acids including both electron-rich and electron-poor aryl groups. The coupling products were obtained in moderate to very good yields (40-81%).

Scheme 2.2 Synthesis of **189a-f**



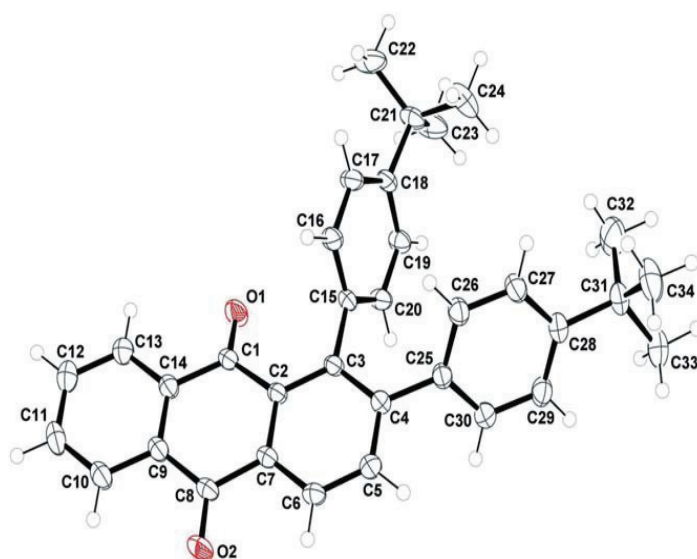
The yield of 1,2-bis(4-methoxyphenyl)anthraquinone (**189b**) was low, due to hydrolysis of **187** to afford a monoarylhydroxyanthraquinone. The best yield was obtained for 1,2-bis(4-chlorophenyl)anthraquinone (**189d**) which resulted in 81% yield. 1,2-Diarylanthraquinones **189e,c,f** were prepared in good yields. 1,2-Bis(4-trifluoromethylphenyl)anthraquinone (**188a**) also gave a good yield (77%) (Table 1).

Table 1 Synthesis of **189a-f**

188	189	Ar	% (189)^a
a	a	4-(F ₃ C)C ₆ H ₄	77
b	b	4-(MeO)C ₆ H ₄	40
c	c	4- <i>t</i> -BuC ₆ H ₄	76
d	d	4-ClC ₆ H ₄	81
e	e	4-MeC ₆ H ₄	77
f	f	4-EtC ₆ H ₄	60

^a Yields of isolated products.

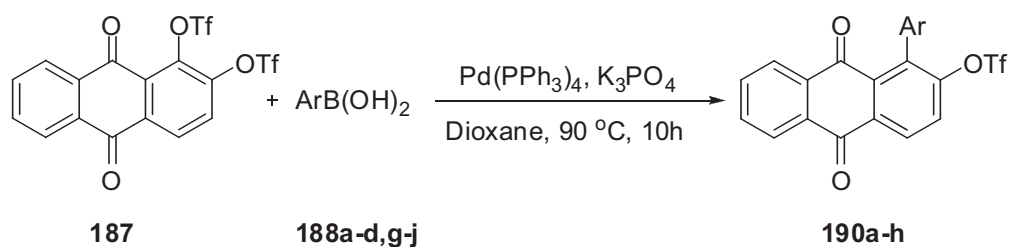
The structure of 1,2-bis(4-*tert*-butylphenyl)anthraquinone (**189c**) was confirmed by X-ray crystal structure analysis as shown below in Figure 2.1. The anthraquinone unit is in plane. The *tert*-butyl-containing aromatic rings are twisted out of plane of the anthraquinone moiety.

Figure 2.1 ORTEP plot of **189c**

2.1.1.3 Site-Selective Synthesis of 1-Aryl-2-(trifluoromethylsulfonyloxy) anthraquinones **190a-h**

The reaction of **187** with one equivalent of arylboronic acids gives rise to the issue of site-selectivity. The conditions of these reactions were optimized in order to get the best yield of 1-aryl-2-(trifluoromethylsulfonyloxy)anthraquinones. The best yields were obtained when $\text{Pd}(\text{PPh}_3)_4$ and K_3PO_4 were used and when the reaction was carried out at 90 °C during 10 h (Scheme 2.3).

Scheme 2.3 Site-selective synthesis of **190a-h**



Arylboronic acids **188d** and **188g** gave the best yields (85 and 84%). Arylboronic acids **188a,h** and **188b,c** were afforded in good yields. Moderate yields were obtained for reactions of **188i,j** (50 and 52%) (Table 2).

Table 2 Synthesis of **190a-h**

188	190	Ar	% (190)^a
a	a	4-(F ₃ C)C ₆ H ₄	74
b	b	4-(MeO)C ₆ H ₄	67
c	c	4- <i>t</i> -BuC ₆ H ₄	61
d	d	4-ClC ₆ H ₄	85
g	e	3-(F ₃ C)C ₆ H ₄	84
h	f	3-(MeO)C ₆ H ₄	79
i	g	4-FC ₆ H ₄	50
j	h	4-(CF ₃ O)C ₆ H ₄	52

^a Yields of isolated products.

The first nucleophilic attack occurred at carbon atom C-1. This can be explained by the π -acceptor effect of the carbonyl group (Figure 2.2). The site-selective formation of **190a-h** can be explained by electronic reasons. The first attack of palladium(0)-catalyzed cross-coupling reactions generally occurs at the electronically more deficient and sterically less hindered position.^{151,152} Position 1 of **187** is sterically more hindered than position 2 (Figure 2.3). However, position 1 (located in β -position to the carbonyl group) is more electron-deficient than position 2. In fact, the ¹H-NMR signals of aromatic protons located at position 1 are generally shifted to lower field compared to the protons located at position 2.¹⁵² In addition, a neighboring group effect by the quinone carbonyl group (chelation of the approaching palladium complex) might play a role. In conclusion, the first attack occurs at the sterically more hindered position, due to electronic reasons.

Figure 2.2 π -Acceptor effect of the carbonyl group

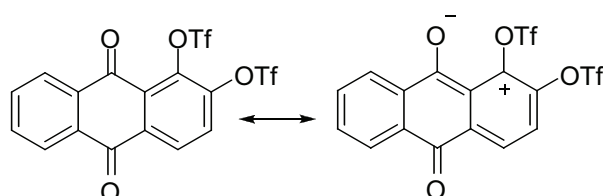
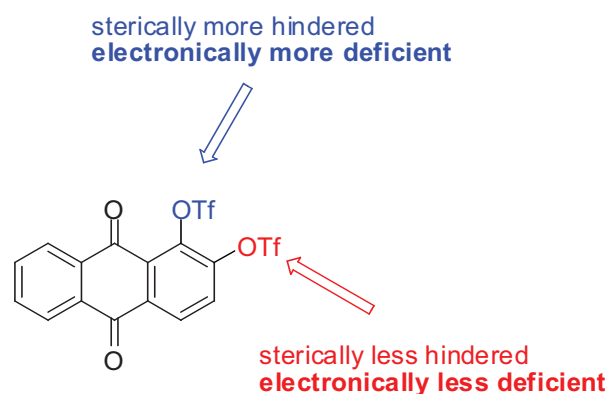
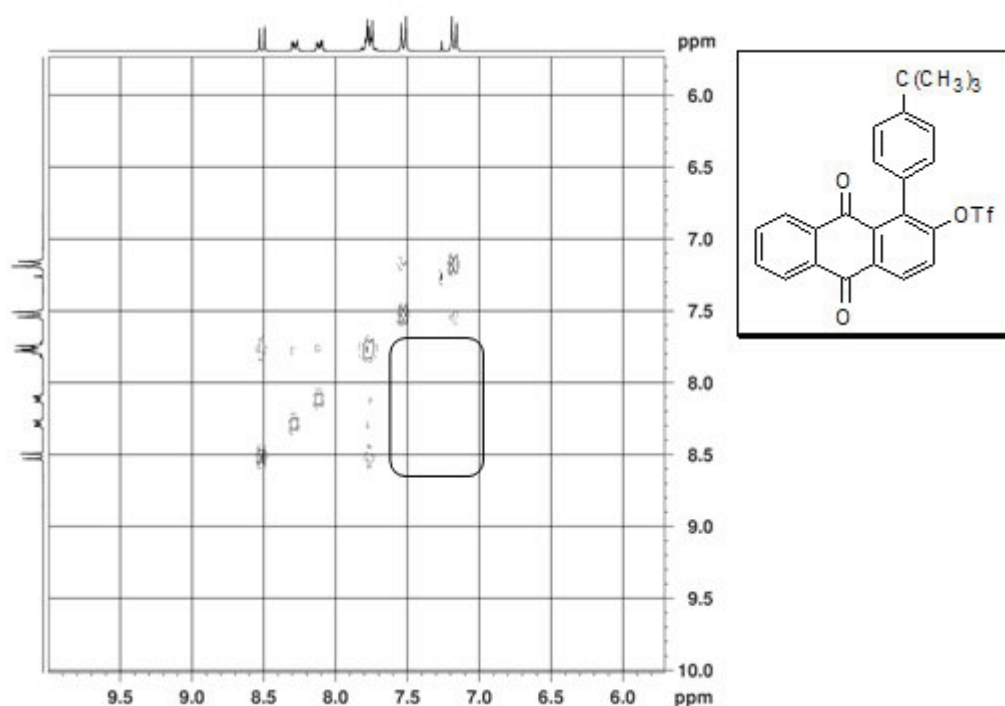


Figure 2.3 Possible explanation for the site-selectivity of **187**

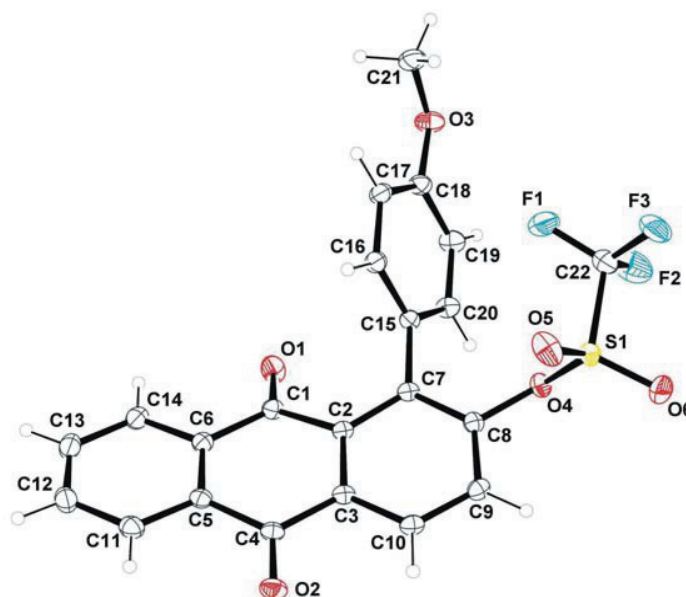


A ^1H , ^1H NOE experiment was used to confirm the structure of compound **190c**. The ^1H , ^1H NOE spectrum does not provide us a real proof for the site-selectivity. The missing correlations give us an indirect hint to the structure of **190c** (Figure 2.4).

Figure 2.4 ^1H , ^1H NOE spectrum of **190c**



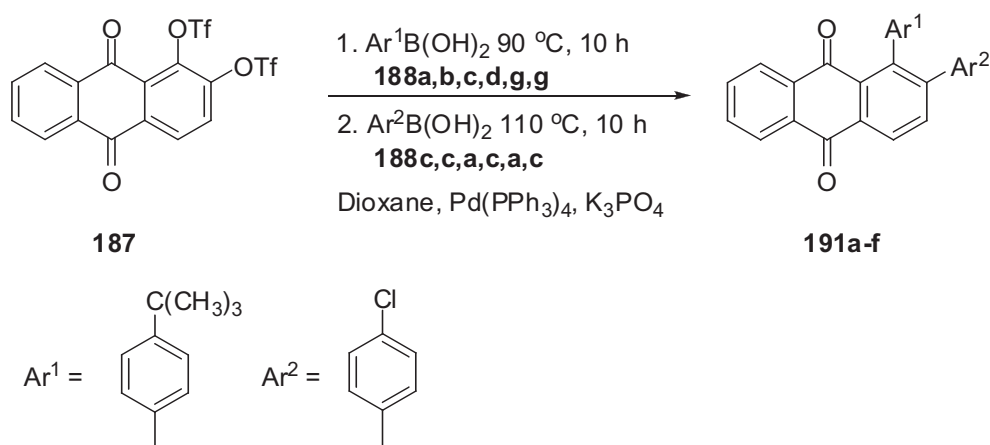
In addition to the ^1H , ^1H NOE experiment, a better proof to the site-selective attack at carbon atom C-1 **190b** was obtained by using X-ray crystal structure analysis (Figure 2.5). The aromatic ring is perpendicular to the anthraquinone system.

Figure 2.5 ORTEP plot of **190b**

2.1.1.4 Synthesis of Unsymmetrical 1,2-Diarylanthraquinones **191a-f**

The possibilities of one-pot Suzuki coupling reactions of **187** with two different arylboronic acids were next studied. The boronic acids were added in a sequential manner. During the optimization, it proved to be important to carry out the first step of the one-pot reaction at 90 °C and the second step at 110 °C (Scheme 2.4).

Scheme 2.4 Site-selective synthesis of unsymmetrical anthraquinones **191a-f**



Products **191a,c,d,e,f** were isolated in moderate yields between 61-68%, except for **191b** which resulted in a moderate yield (50%) (Table 3).

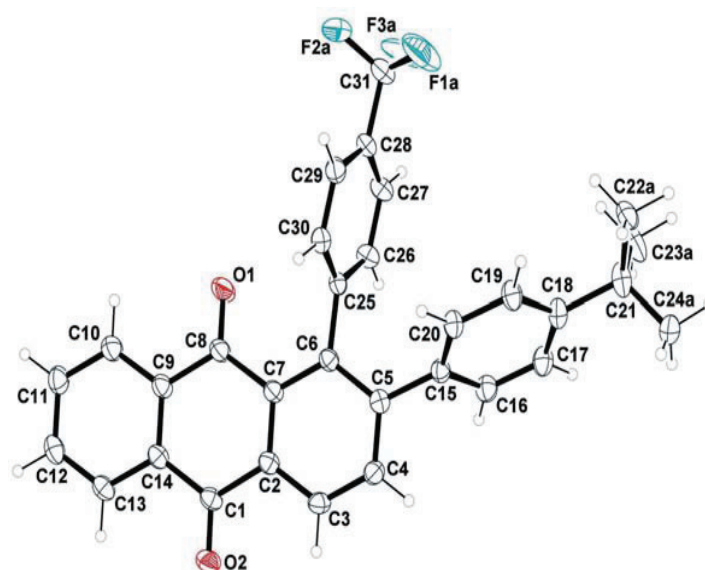
Table 3 Synthesis of 191a-f

188	191	Ar ¹	Ar ²	% (191) ^a
a,c	a	4-(F ₃ C)C ₆ H ₄	4- <i>t</i> -BuC ₆ H ₄	65
b,c	b	4-(MeO)C ₆ H ₄	4- <i>t</i> -BuC ₆ H ₄	50
c,a	c	4- <i>t</i> -BuC ₆ H ₄	4-(CF ₃)C ₆ H ₄	60
d,c	d	4-ClC ₆ H ₄	4- <i>t</i> -BuC ₆ H ₄	61
g,a	e	3-(F ₃ C)C ₆ H ₄	4-(CF ₃)C ₆ H ₄	68
g,c	f	3-(F ₃ C)C ₆ H ₄	4- <i>t</i> -BuC ₆ H ₄	61

^a Yields of isolated products.

For compound **191a** an X-ray crystal structure was measured and the structure was confirmed (Figure 2.6). The aromatic rings are perpendicular to the anthraquinone moiety. Both the CF₃ and the *t*-Bu group are disordered.

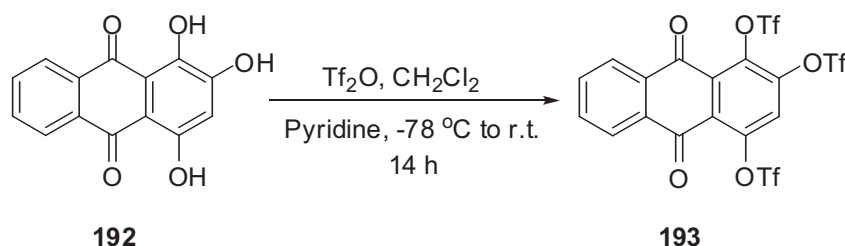
Figure 2.6 ORTEP plot of 191a



2.1.2 Synthesis of 1,2,3-Triarylanthraquinones by Site-Selective Suzuki–Miyaura Cross-coupling Reactions of the Tris(triflate) of Purpurin

The reaction of commercially available purpurin with triflic acid anhydride, in the presence of pyridine, afforded the tris(triflate) of purpurin in 43% yield. The reaction was done at $-78\text{ }^{\circ}\text{C}$ and allowed to warm to r.t. under an inert atmosphere with stirring for 14 h (Scheme 2.5).

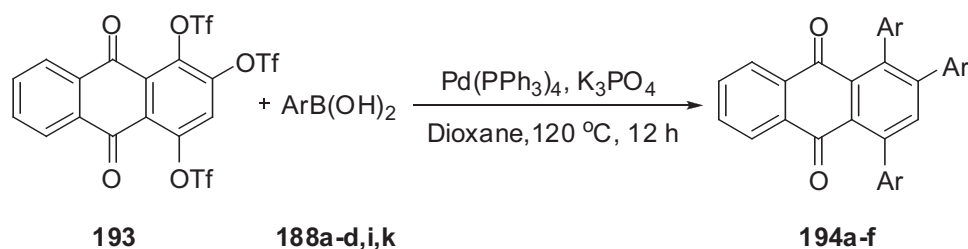
Scheme 2.5 Synthesis of **193**



2.1.2.1 Synthesis of 1,2,3-Triarylanthraquinones **194a-f**

The reaction of the tris(triflate) of purpurin **193** with 4.0 equivalents of boronic acid derivatives afforded 1,2,3-triarylanthraquinones. In the reactions were used $\text{Pd}(\text{PPh}_3)_4$ as the catalyst and K_3PO_4 as the base. The best temperature was $120\text{ }^{\circ}\text{C}$ (Scheme 2.6).

Scheme 2.6 Synthesis of **194a-f**



Arylboronic acids **188c,k** gave very good yields (83 and 86%). Arylboronic acids **188b,d** and **188a,i** provided moderate to good yields (Table 4).

Table 4 Synthesis of 194a-f

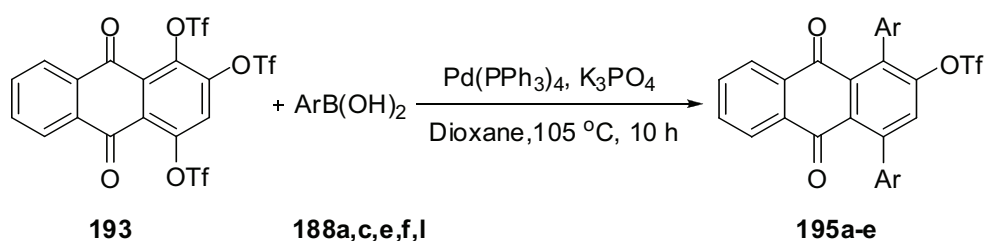
188	194	Ar	% (194) ^a
a	a	4-(F ₃ C)C ₆ H ₄	43
b	b	4-(MeO)C ₆ H ₄	73
c	c	4- <i>t</i> -BuC ₆ H ₄	83
d	d	4-ClC ₆ H ₄	60
i	e	4-FC ₆ H ₄	57
k	f	C ₆ H ₄	86

^a Yields of isolated products.

2.1.2.2 Site-Selective Synthesis of 1,4-Diaryl-2-(trifluoromethylsulfonyloxy)anthraquinones 195a-e

The reaction of the tris(triflate) of purpurin **193** and 2.0 equivalents of arylboronic acids afforded 1,4-diaryl-2-(trifluoromethylsulfonyloxy)anthraquinones **195a-e**. During the optimization, it was proved to be important to carry out the reaction at 105 °C and the reaction had to be stirred for 10 h (Scheme 2.7).

Scheme 2.7 Site-selective synthesis of 195a-e



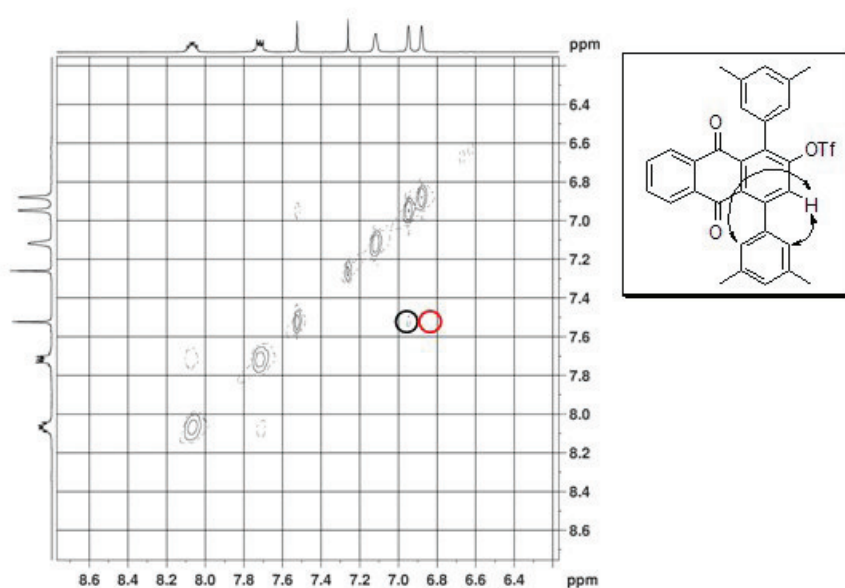
Arylboronic acids **188c,f** afforded the corresponding products in very good yield (83 and 86%). For **188i** a moderate yield was obtained (60%). Moderate yields were observed for **188a,e** (57 and 43%) (Table 5).

Table 5 Synthesis of 195a-e

188	195	Ar	% (195) ^a
a	a	4-(F ₃ C)C ₆ H ₄	61
c	b	4- <i>t</i> -BuC ₆ H ₄	81
e	c	4-MeC ₆ H ₄	51
f	d	4-EtC ₆ H ₄	74
l	e	3,5-MeC ₆ H ₄	60

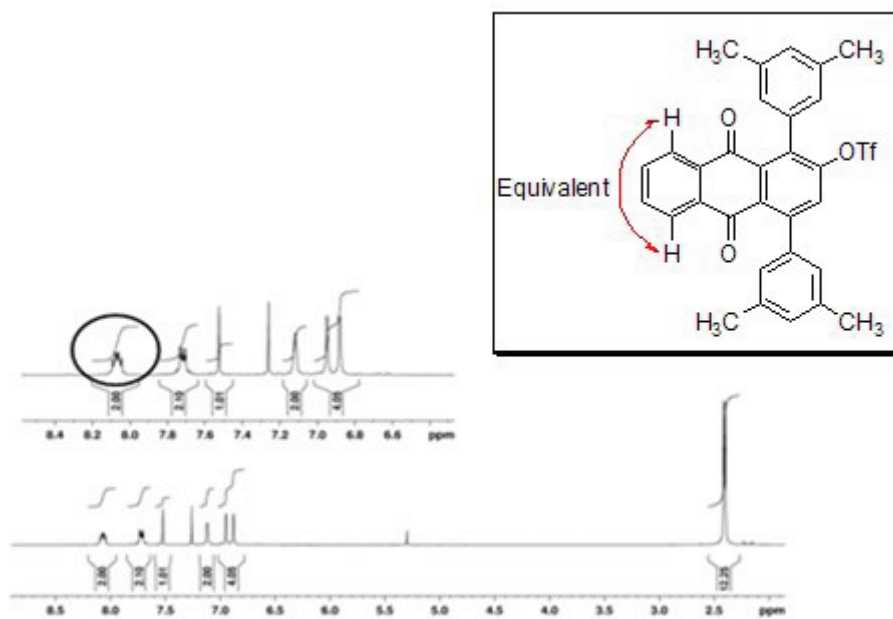
^a Yields of isolated products.

In order to determine the structure of compound **195e**, a ¹H, ¹H NOE experiment was used. The correlation (black circle) shows that the attack of the boronic acid occurred at carbon atom C-4. The missing correlation (red circle) shows that carbon atom C-2 was not attacked (Figure 2.7).

Figure 2.7 ¹H, ¹H NOE spectrum of 195e

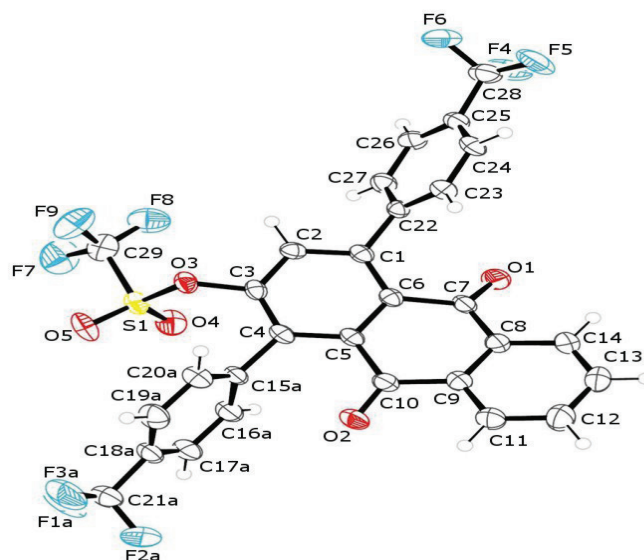
Inspection of the ¹H-NMR shows that the aromatic protons are almost equivalent, which suggests a relatively symmetrical structure containing aryl groups located at carbon atom C-1 and C-4 (Figure 2.8)

Figure 2.8 $^1\text{H-NMR}$ spectrum of **195e**



The structure of **195a** was confirmed by X-ray crystal structure analysis. Both CF_3 containing aromatic rings are perpendicular to the anthraquinone moiety (Figure 2.9).

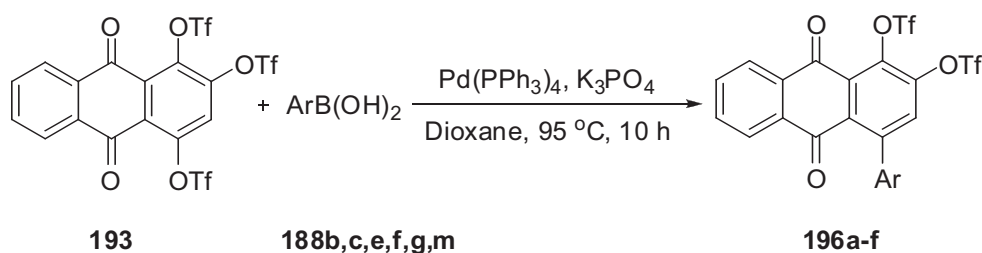
Figure 2.9 ORTEP plot of **195a**



2.1.2.3 Site-Selective Synthesis of 1,2-Bis(trifluoromethylsulfonyloxy)-4-arylanthraquinones **196a-f**

Site-Selective Suzuki-Miyaura coupling reactions were achieved between tris(triflate) of purpurin **193** with 1.0 equivalent of arylboronic acids. The temperature was optimized to be 95 °C and the reaction was allowed to stir for 10 h (Scheme 2.8).

Scheme 2.8 Site-selective synthesis of **196a-f**



Arylboronic acids **188c,d** resulted in moderate yields (61 and 65%). Arylboronic acid **188f** gave 56% yield of product. Arylboronic acids **188b,c,g** gave moderate yields (40, 38 and 40%) (Table 6).

Table 6 Synthesis of **196a-f**

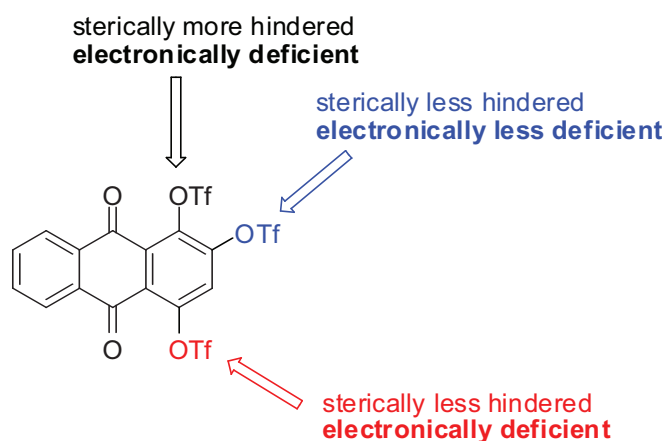
188	196	Ar	% (196)^a
b	a	4-(MeO)C ₆ H ₄	38
c	b	4- <i>t</i> -BuC ₆ H ₄	41
e	c	4-MeC ₆ H ₄	61
f	d	4-EtC ₆ H ₄	65
g	e	3-(F ₃ C)C ₆ H ₄	40
m	f	3-ClC ₆ H ₄	56

^a Yields of isolated products.

The first attack of palladium(0)-catalyzed cross-coupling reactions generally occurs at the electronically more deficient and sterically less hindered position.^{187,188} Position 2 and 4 of **193** are sterically less hindered than position 1 (Figure 2.10). Positions 1 and 4 of **193** are more electron-deficient than position 2. In conclusion, the first attack occurs at the sterically less

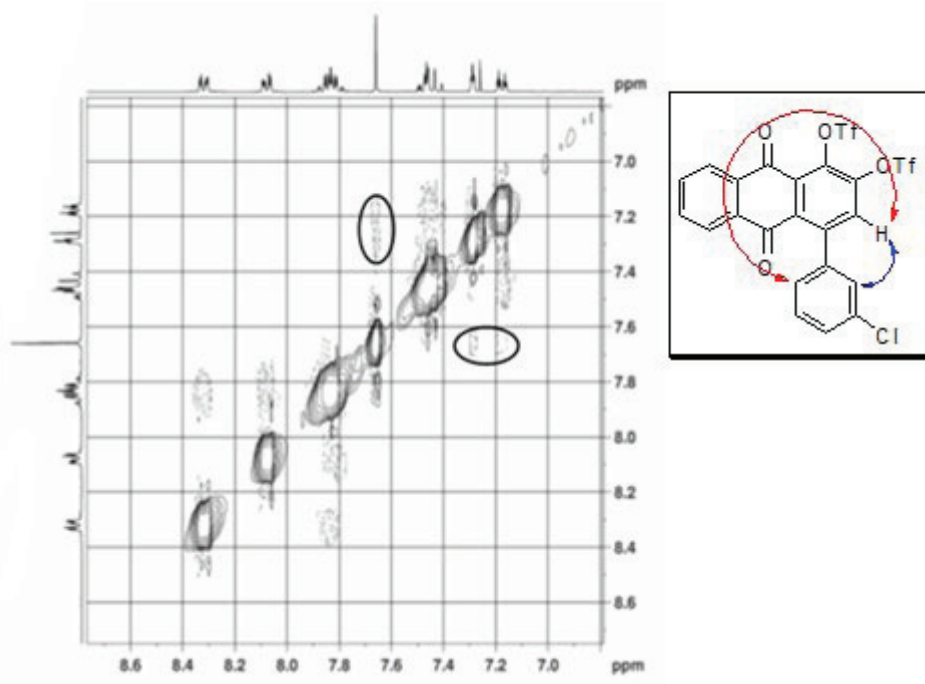
hindered and electronically deficient position 4. The second attack occurs at position 1 which is sterically hindered, but electron deficient. The third attack occurs at position 2 which is not electron deficient and not sterically hindered.

Figure 2.10 Possible explanation for the site-selectivity of **193**



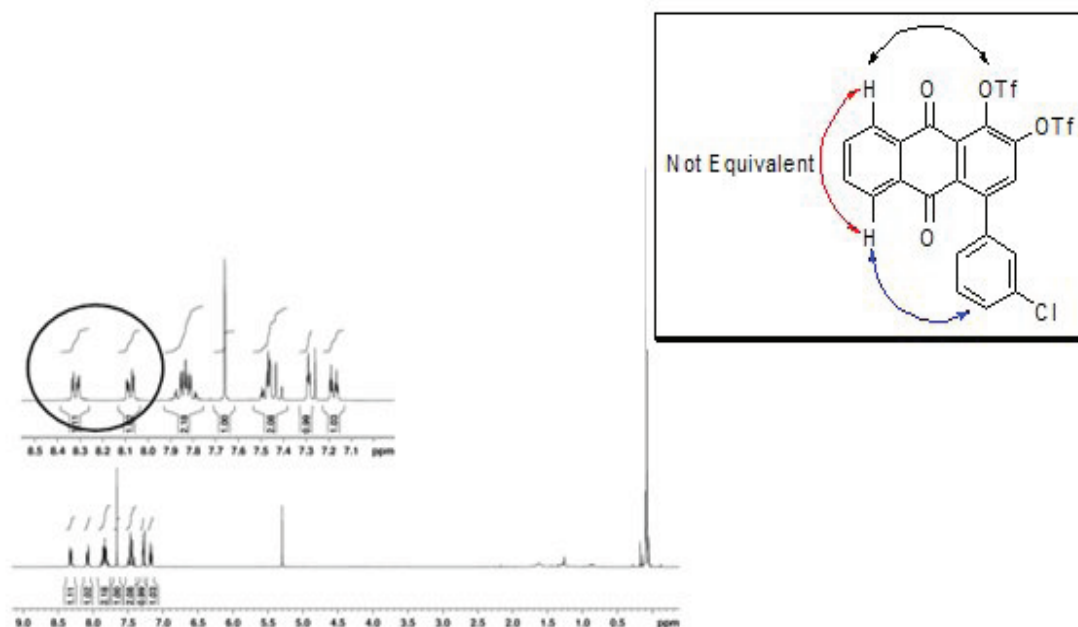
The structure of **196f** was determined by 2D NMR experiments. The ^1H , ^1H NOE correlation shows that the attack of the arylboronic acid occurred at carbon atom C-4 (Figure 2.11).

Figure 2.11 ^1H , ^1H NOE spectrum of **196f**

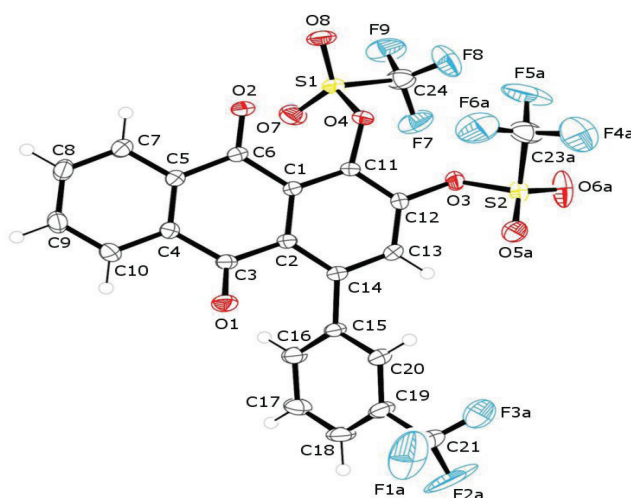


The $^1\text{H-NMR}$ spectrum of **196f** shows that two aromatic protons beside the carbonyl groups are not equivalent to each other, which suggests a relatively unsymmetrical structure containing the aryl groups located at position 4 (Figure 2.12).

Figure 2.12 $^1\text{H-NMR}$ spectrum of **196f**



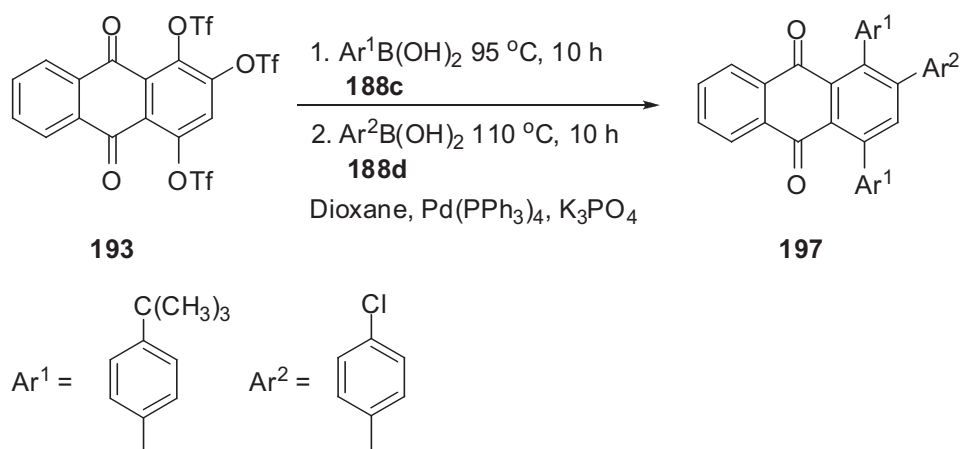
The structure of **196e** was independently confirmed by X-ray crystal structure analysis. The aryl groups are twisted out of plane. The SO_3CF_3 group and the CF_3 group are disordered (Figure 2.13).

Figure 2.13 ORTEP plot of **196e**

2.1.2.4 Synthesis of Unsymmetrical 1,4-Bis(4-*tert*-butylphenyl)-2-(4-chlorophenyl)anthraquinone (**197**)

The one-pot reaction of tris(triflate) of purpurin **193** and different arylboronic acids afforded the 1,4-bis(4-*tert*-butylphenyl)-2-(4-chlorophenyl)anthraquinone (**197**). The first step of the reaction was carried out using 2.0 equivalents of arylboronic acid at 95 °C during 10 h. The second step was carried out at 110 °C during 10 h (Scheme 2.9). 1,4-Bis(4-*tert*-butylphenyl)-2-(4-chlorophenyl)anthraquinone (**197**) was obtained in 45% yield.

Scheme 2.9 Synthesis of unsymmetrical **197**



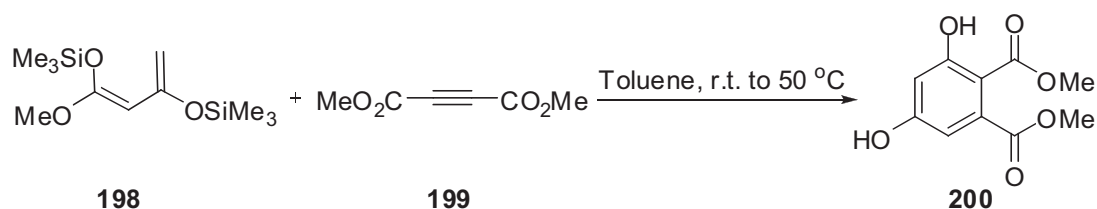
2.2 Hydroxyphthalates

Functionalized hydroxylated benzoates and benzodioates and their derivatives are of great interest as lead structures in pharmaceutical, industrial and agricultural chemistry and constitute valuable synthetic building blocks in synthetic organic chemistry.¹⁵³ Some of these molecules occur in natural products and have interesting pharmacological properties, including analgesic, antipyretic, antimicrobial and fungicidal properties. In addition, they act as inhibitors of some enzymes and as inhibitors for the absorption of steroids, such as, cholesterol and bile acids.¹⁵⁴

2.2.1 Synthesis of Dimethyl 3,5-Dihydroxyphthalates by [4+2]-Cycloaddition and Subsequent Site-Selective Suzuki-Miyaura Cross-Coupling Reactions

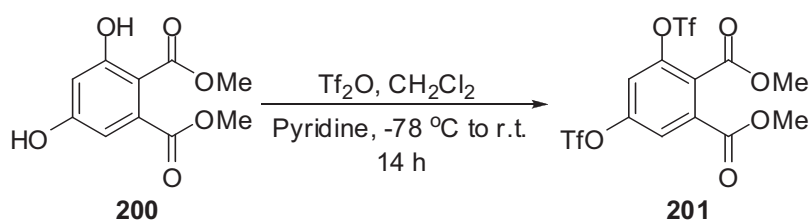
I synthesized dimethyl 3,5-dihydroxyphthalate (**200**) by [4+2]-cycloaddition of 1-methoxy-1,3-bis(trimethylsilyloxy)-1,3-diene with dimethyl acetylenedicarboxylate (DMAD) in 32% yield. DMAD was added at r.t. and the mixture was allowed to stir at 50 °C for 48 h. Toluene was used as the solvent (Scheme 2.10).

Scheme 2.10 Synthesis of **200**



The reaction of dimethyl 3,5-dihydroxyphthalate (**200**) with triflic acid anhydride resulted in formation of dimethyl 3,5-bis(trifluoromethylsulfonyloxy)phthalate (**201**) in good yield (78%) (Scheme 2.11).

Scheme 2.11 Synthesis of **201**



The reaction of dimethyl 3,5-bis(trifluoromethylsulfonyloxy)phthalates (**201**) with 2.4 equivalents of arylboronic acids afforded dimethyl 3,5-diarylphthalates **202a,b** (Table 7). The temperature, which was selected, was 110 °C (8 h). Dioxane was used in this reaction as suitable solvent and the base K₃PO₄ was used (Scheme 2.12).

Scheme 2.12 Synthesis of **202a,b**

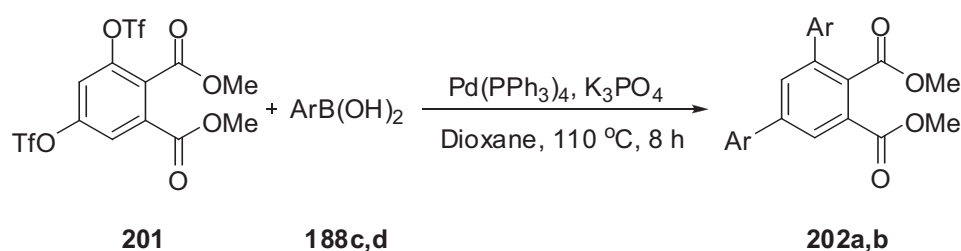


Table 7 Synthesis of **202a,b**

188	202	Ar	% (202)^a
c	a	4- <i>t</i> -BuC ₆ H ₄	91
d	b	4-ClC ₆ H ₄	88

^a Yields of isolated products.

The conditions were optimized for the reaction of dimethyl 3,5-bis(trifluoromethylsulfonyloxy)phthalate (**201**) with 1 equivalent of arylboronic acids (Scheme 2.13). The reaction was carried out at 70 °C during 16 h. As the catalyst, 6 mol% of Pd(PPh₃)₃ was used. Products **203a,b** were isolated in good yields (76 and 71%) (Table 8).

Scheme 2.13 Site-selective synthesis of **203a,b**

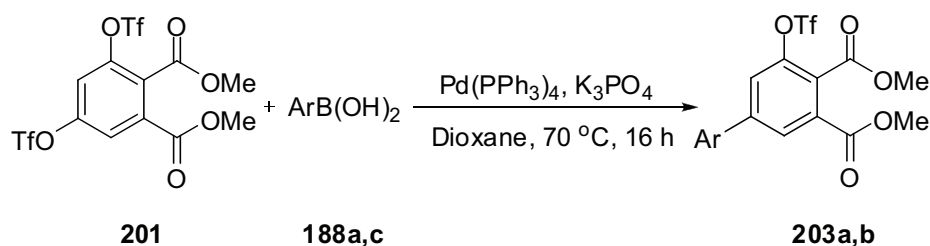
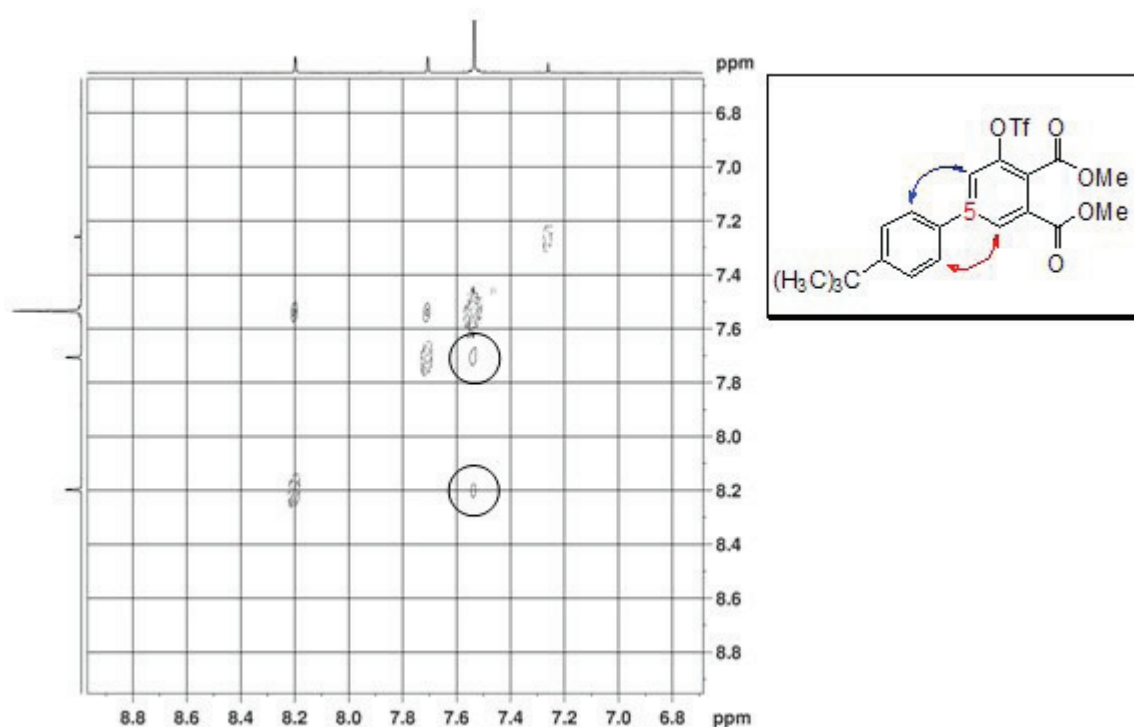


Table 8 Synthesis of **203a,b**

188	203	Ar	% (203) ^a
a	a	4-(F ₃ C)C ₆ H ₄	76
c	b	4- <i>t</i> -BuC ₆ H ₄	71

^a Yields of isolated products.

Based on a ¹H, ¹H NOE experiment for product **203b**, it was confirmed that the first attack of the arylboronic acid occurred at carbon atom C-5 (Figure 2.14). The two protons at carbon atom C-4 and C-6, which appear as doublets at 7.62 and 8.11 ppm with coupling constants $J = 1.62$ Hz, correlate with the aromatic protons which appear as singlets.

Figure 2.14 ¹H, ¹H NOE spectrum of **203b**

2.3 Quinolines

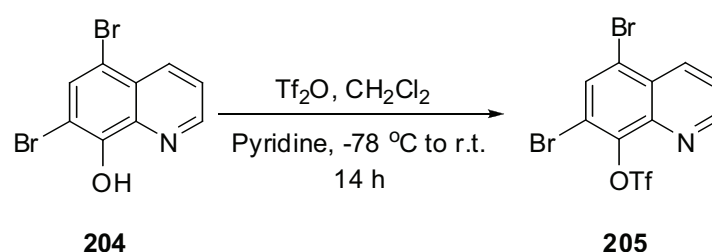
Quinolines are the core for many naturally occurring compounds.¹⁵⁵ They are also very important as pharmacologically active substances. For example, pyrimidinylthiopyrimidinyloxy

quinoline derivatives are active as herbicides, microbicides, and fungicides.¹⁵⁶ Camptothecin is a natural product isolated in 1966 and shows excellent antitumor activity.¹⁵⁷

2.3.1 Synthesis of 5,7-Diaryl-8-(trifluoromethylsulfonyloxy)quinolines by Site-Selective Suzuki-Miyaura Cross-Coupling Reactions

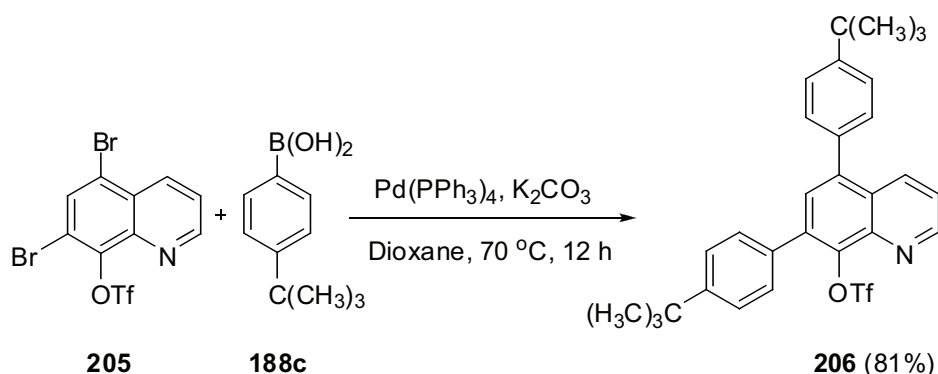
5,7-Dibromo-8-(trifluoromethylsulfonyloxy)quinoline (**205**) was synthesized by reaction of 5,7-dibromo-8-hydroxyquinoline with triflic acid anhydride and afforded product **205** in very good yield (80%) (Scheme 2.14).

Scheme 2.14 Synthesis of **205**



The reaction of **205** with 2.0 equivalent of 4-*tert*-butylphenylboronic acid afforded product **206** in 81% yield (Scheme 2.15). The optimization of the product **206** required to do this reaction at 70 °C and using K₂CO₃ as the base. The first attack occurred at carbon atom C-5 and the second attack occurred at carbon atom C-7.

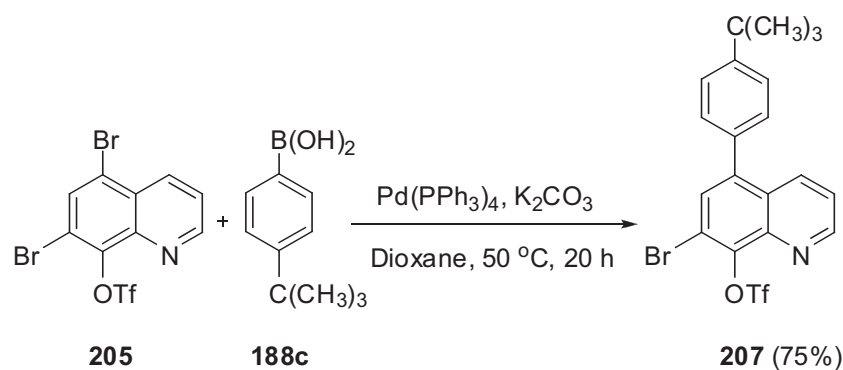
Scheme 2.15 Site-selective synthesis of **206**



The reaction of 5,7-dibromo-8-(trifluoromethylsulfonyloxy)quinoline (**205**) with 1 equivalent of 4-*tert*-butylphenylboronic acid gave 5-(4-*tert*-butylphenyl)-7-bromo-8-

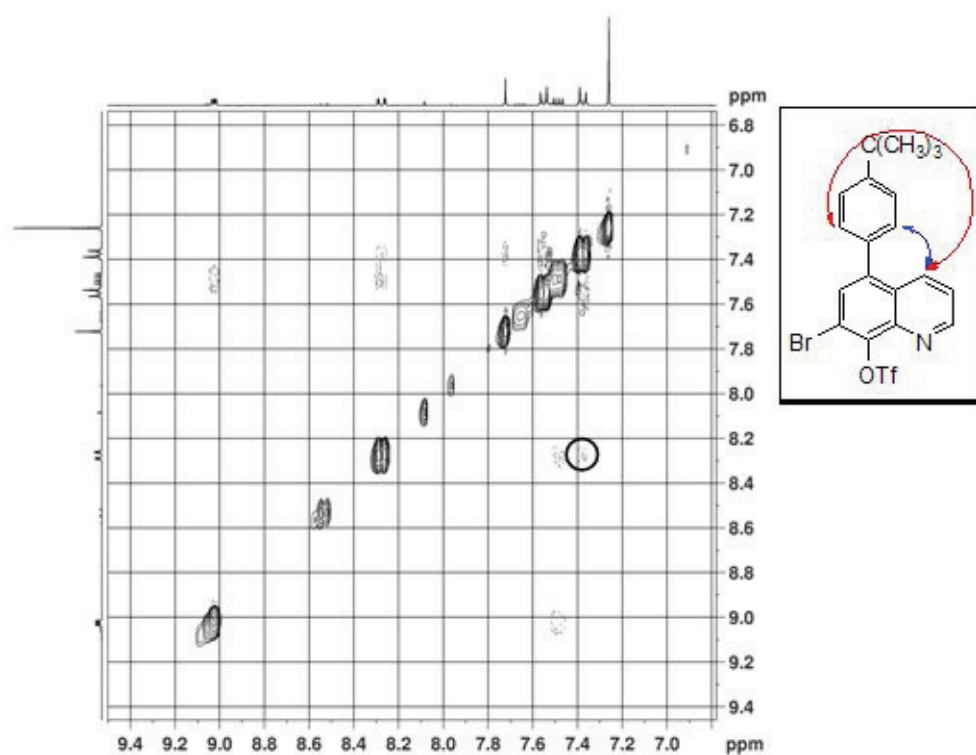
(trifluoromethylsulfonyloxy)quinoline (**207**) in good yield (75%). I carried out this reaction at 50 °C for 20 h. I again used K_2CO_3 as the base (Scheme 2.16). The attack occurred selectively at carbon atom C-5.

Scheme 2.16 Site-selective synthesis of **207**



The structure of compound **207** was confirmed by using 1H , 1H NOE experiments. The *ortho* protons of the 4-*tert*-butylphenyl group correlate with proton H-4 of the quinoline moiety (Figure 2.15).

Figure 2.15 1H , 1H NOE spectrum of **207**



ABSTRACT

In English

Based on the methodology of Suzuki-Miyaura cross-coupling reactions, a wide range of substituted anthraquinones are now readily available including a few examples of phthalates and quinolines. The method provides new possibilities in carbon-carbon bond formation for the preparation of new materials. Due to the importance and useful properties of many anthraquinones, phthalates and quinolines, the chemistry of the bis(triflates) of anthraquinones, phthalates and 5,7-dibromo-8-(trifluoromethylsulfonyloxy)quinoline has been investigated in this thesis. The results for the synthesis and characterization of diarylanthraquinones, diarylphthalates and diarylquinolines are presented in this thesis.

In German

Basierend auf der Methode der Suzuki-Miyaura-Kreuzkupplungsreaktion ist nun eine große Auswahl substituierter Anthrachinone, einschließlich einiger Beispiele für substituierte Phthalate und Chinoline, leicht verfügbar. Die Methode bietet neue Möglichkeiten in der C-C-Bindungsknüpfung, um neue Materialien zu synthetisieren. Wegen der großen Bedeutung und den nützlichen Eigenschaften vieler Anthrachinone, Phthalate und Chinoline wurde die Chemie der Bis(triflate) von Anthrachinonen, Phthalaten und 5,7-Dibrom-8-(trifluormethylsulfonyloxy)chinolinen in der vorliegenden Arbeit untersucht. Die Ergebnisse der Synthese und der Charakterisierung von Diarylanthrachinonen, Diarylphthalaten und Diarylchinonen werden in dieser Arbeit gezeigt und diskutiert.

*EXPERIMENTAL
SECTION*

CHAPTER THREE

3.1 Materials and Methods

3.1.1 General: Equipment, Chemicals and Work Technique

¹H-NMR Spectroscopy

Bruker: AM 250, Bruker ARX 300, Bruker ARX 500; $\delta = 0.00$ ppm for Tetramethylsilane; $\delta = 2.04$ ppm for Acetone d-6; $\delta = 7.26$ ppm for (CDCl₃); 2.50 ppm for d-6 DMSO-; Characterization of the signal fragmentations: s = singlet, d = doublet, dd = double of doublet, ddd = doublet of a double doublet, t = triplet, q = quartet, quint = quintet; sext = Sextet, sept = Septet, m = multiplet, br = broadly. Spectra were evaluated according to first order rule. All coupling constants are indicated as (*J*).

¹³C-NMR Spectroscopy

Bruker: AM 250, (62.9 MHz); Bruker: ARX 300, (75.4 MHz), Bruker: ARX 500, (125 MHz) Ref: 29.84 ± 0.01 ppm and 206.26 ± 0.13 ppm for (CD₃)₂CO. $\delta = 128.00$ ppm for Acetone d-6; $\delta = 77.00$ ppm for CDCl₃. The multiplicity of the carbon atoms was determined by the DEPT 135 and APT technique (APT = Attached Proton Test) and quoted as CH₃, CH₂, CH and C for primary, secondary, tertiary and quaternary carbon atoms. Characterization of the signal fragmentations: quart = quartet the multiplicity of the signals was determined by the DEPT recording technology and/or the APT recording technology.

Mass Spectroscopy (MS)

AMD MS40, AMD 402 (AMD Intectra), Varian MAT CH 7, MAT 731.

High Resolution Mass Spectroscopy (HRMS)

Finnigan MAT 95 or Varian MAT 311; Bruker FT CIR, AMD 402 (AMD Intectra).

Infrared Spectroscopy (IR)

Bruker IFS 66 (FT IR), Nicolet 205 FT IR; Nicolet Protégé 460, Nicolet 360 Smart Orbit (ATR); KBr, KAP, Nujol, and ATR; Abbreviations for signal allocations: w = weak, m = medium, s = strong, br = broad.

Elementary Analysis

LECO CHNS-932, Thermoquest Flash EA 1112.

X-ray Crystal Structure Analysis

Bruker X8Apex Diffractometer with CCD-Kamera (Mo-Ka und Graphit Monochromator, $\lambda = 0.71073 \text{ \AA}$).

Melting Points

Micro heating table HMK 67/1825 Kuestner (Büchi apparatus); Melting points are uncorrected.

Column Chromatography

Chromatography was performed over Merck silica gel 60 (0,063 - 0,200 mm, 70 - 230 mesh) as normal and/or over mesh silica gel 60 (0,040 - 0,063 mm, 200 - 400 mesh) as Flash Chromatography. All solvent were distilled before use.

TLC

Merck DC finished foils silica gel 60 F254 on aluminum foil and Macherey finished foils Alugram® Sil G/UV254. Detection under UV light with 254 nm and/or 366 nm without dipping reagent, as well as with anisaldehyde sulfuric acid reagent (1 mL anisaldehyde consisting in 100 mL stock solution of 85% methanol, 14% acetic acid and 1% sulfuric acid).

Chemicals and Work Technique

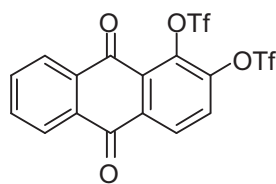
All solvents for using were distilled by standard methods. All reactions were carried out under an inert atmosphere, oxygen and humidity exclusion. All of the chemicals are standard, commercially available from Merck®, Aldrich®, Arcos® and others. The order of the characterized connections effected numerically, but does not correspond to the order in the main part of dissertation.

3.2 Preparative Procedures and Spectroscopic Data

3.3 Synthesis of 1,2-Bis(trifluoromethylsulfonyloxy)anthraquinone (187)

To a solution of 1,2-dihydroxyanthraquinone (**186**) (1.0 equiv) in CH₂Cl₂ (10 mL/mmol) was added pyridine (4.0 equiv) at room temperature under an argon atmosphere. After 10 min, Tf₂O (2.4 equiv) was added at -78 °C. The mixture was allowed to warm up to room temperature and stirred for overnight. The reaction mixture was filtered and the filtrate was concentrated in vacuo. The products of the reaction mixture were isolated by rapid column chromatography (flash silica gel, heptanes/EtOAc).

1,2-Bis(trifluoromethylsulfonyloxy)anthraquinone (187)



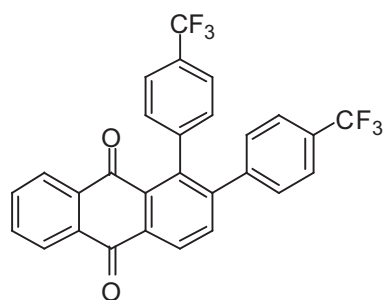
To a solution of **186** (1.0 equiv.) in CH₂Cl₂ (10 mL/mmol) was added pyridine (4.0 equiv.) at room temperature under an argon atmosphere. After 10 min, Tf₂O (2.4 equiv.) was added at -78 °C. The mixture was allowed to warm up to room temperature and stirred for overnight. The reaction mixture was filtered and the filtrate was concentrated in vacuo. The products of the reaction mixture were isolated by rapid column chromatography (flash silica gel, heptanes/EtOAc). Starting with **186** (1.9 g, 8.0 mmol), pyridine (2.6 mL, 32.0 mmol), CH₂Cl₂ (80 mL), Tf₂O (3.2 mL, 19.2 mmol), **187** was isolated as a yellow solid (3.25 g, 81%), mp 152-154 °C. ¹H NMR (300 MHz, CDCl₃): δ = 7.80-7.85 (m, 3H, ArH), 8.23-8.26 (m, 1H, ArH), 8.29-8.32 (m, 1H, ArH), 8.46 (d, *J* = 8.76 Hz, 1H, ArH). ¹³C NMR (75.4 MHz, CDCl₃): δ = 118.5 (q, *J*_{F,C} = 320.9 Hz, CF₃), 118.6 (d, *J*_{F,C} = 320.7 Hz, CF₃), 127.4 (CH), 127.8 (C), 128.0, 128.1, 128.9 (CH), 132.0, 133.7, 134.1 (C), 135.1, 135.2 (CH), 139.2, 145.0 (C), 180.2, 180.5 (CO). ¹⁹F NMR (282 MHz, CDCl₃): δ = -73.4 (q, *J*_F = 3.02, 6.02 Hz, 3F, CF₃), -72.58 (q, *J*_F =

2.84, 5.83 Hz, 3F, CF₃). IR (KBr, cm⁻¹): ν = 1674 (s), 1601, 1587, 1472 (w), 1427 (s), 1330, 1316, 1282, 1249 (w), 1208 (s), 1164, 1150 (m), 1124 (s), 1007, 998, 901, 856 (m), 807 (s), 795, 738 (m), 721, 708 (s), 684, 676, 655, 643 (w), 618, 606 (m), 589, 575, 569 (s), 543, 529 (m). GC-MS (EI, 70 eV): m/z (%) = 504 ([M+H]⁺, 36), 435 (05), 375 (08), 348 (23), 279 (100), 251 (76), 223 (26), 154 (26), 126 (60). HRMS (EI, 70 eV): calcd for C₁₆H₆O₈F₆S₂ [M]⁺: 503.94028, found 503.940108.

3.3.1 General Procedure for Suzuki-Miyaura Reactions

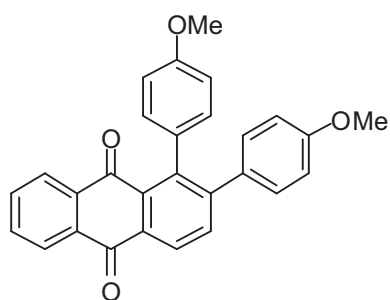
A 1,4-dioxane solution (4 mL per 3 mmol of **187**) of **187**, K₃PO₄, Pd(PPh₃)₄ and arylboronic acid **188** was stirred at 110 °C or 90 °C for 10 h. After cooling to 20 °C, distilled water was added. The organic and the aqueous layers were separated and the latter was extracted with CH₂Cl₂. The combined organic layers were dried (Na₂SO₄), filtered and the filtrate was concentrated in vacuo. The residue was purified by column chromatography.

1,2-Bis(4-trifluoromethylphenyl)anthraquinone (**189a**)



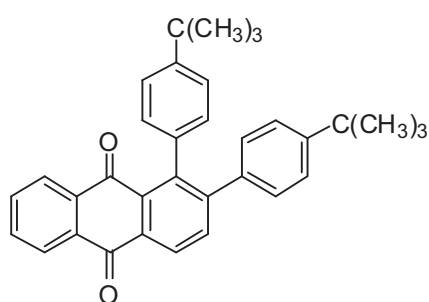
Starting with **187** (250 mg, 0.5 mmol), **188a** (225 mg, 1.2 mmol), Pd(PPh₃)₄ (34 mg, 6 mol-%, 0.03 mmol), K₃PO₄ (320 mg, 1.5 mmol) and 1,4-dioxane (4 mL), **189a** was isolated as a yellow solid (190 mg, 77%), mp 208-210 °C. ¹H NMR (300 MHz, CDCl₃): δ = 7.01-7.07 (m, 4H, ArH), 7.35 (d, J = 8.12 Hz, 2H, ArH), 7.42 (d, J = 8.12 Hz, 2H, ArH), 7.62-7.71 (m, 3H, ArH), 7.95-8.0 (m, 1H, ArH), 8.18-8.21 (m, 1H, ArH), 8.45 (d, J = 8.12 Hz, 1H, ArH). ¹³C NMR (62.9 MHz, CDCl₃): δ = 123.8 (q, $J_{F,C}$ = 272.2 Hz, CF₃), 124.1 (q, $J_{F,C}$ = 272.1 Hz, CF₃), 124.7 (C), 124.7, 124.8, 126.7, 127.4, 127.7 (CH), 128.8 (C), 129.5, 129.7 (CH), 131.5, 132.6 (C), 134.0 (CH), 134.3 (C), 134.4 (CH), 134.5 (C), 135.1 (CH), 140.6, 143.0, 143.2, 147.3 (C), 182.7, 183.3 (CO). ¹⁹F NMR (282 MHz, CDCl₃): δ = -62.69 (s, 3F, CF₃), -62.37 (s, 3F, CF₃). IR (KBr, cm⁻¹): ν = 1670 (m), 1633, 1615, 1580, 1416, 1397 (w), 1324, 1299 (s), 1281, 1261, 1212, 1199 (m), 1158, 1108, 1078, 1061, 1016 (s), 977 (w), 958, 947 (m), 900, 866 (w), 835, 825 (s), 797 (m), 787, 768, 757, 747, 740 (w), 720, 711 (s), 679 (w), 672 (m), 648 (w), 636 (m), 606 (s), 545 (w). GC-MS (EI, 70 eV): m/z (%) = 496 ([M]⁺, 78), 495 (100), 477 (09), 428 (25), 427 (86). HRMS (EI, 70 eV): calcd for C₂₈H₁₃O₂F₆ [M-H]⁺: 495.08143, found 495.081086.

1,2-Bis(4-methoxyphenyl)anthraquinone (**189b**)



Starting with **187** (250 mg, 0.5 mmol), **188b** (180 mg, 1.2 mmol), Pd(PPh₃)₄ (34 mg, 6 mol-%, 0.03 mmol), K₃PO₄ (320 mg, 1.5 mmol) and 1,4-dioxane (4 mL), **189b** was isolated as a red crystal (84 mg, 40%), mp 220-221 °C. ¹H NMR (300 MHz, CDCl₃): δ = 3.66 (s, 3H, OCH₃), 3.71 (s, 3H, OCH₃), 6.61 (d, *J* = 8.76 Hz, 2H, ArH), 6.71 (d, *J* = 8.73 Hz, 2H, ArH), 6.83 (d, *J* = 7.92 Hz, 4H, ArH), 7.60-7.65 (m, 3H, ArH), 7.97-8.0 (m, 1H, ArH), 8.15-8.18 (m, 1H, ArH), 8.30 (d, *J* = 8.07 Hz, 1H, ArH). ¹³C NMR (75.4 MHz, CDCl₃): δ = 54.0 (OCH₃), 54.1 (OCH₃), 112.1, 112.2, 125.4, 126.0, 126.3, 129.4, 129.6 (CH), 130.8, 131.0, 131.4, 131.7 (C), 132.4 (CH), 132.5 (C), 133.0 (CH), 134.0 (C), 134.2 (CH), 140.0, 148.0, 157.1, 157.5 (C), 182.3, 183.0 (CO). IR (KBr, cm⁻¹): ν = 2838 (w), 1671 (s), 1606 (m), 1588, 1550, 1516, 1464, 1451, 1440, 1412, 1394 (w), 1328, 1311 (m), 1297, 1240 (s), 1208, 1107, 1088, 1074 (m), 1027 (s), 977 (w), 954 (s), 858 (w), 840 (m), 828 (s), 811 (w), 800 (s), 767, 749 (w), 727 (m), 718 (s), 697 (m), 669, 649 (w), 640, 601, 588 (m), 537 (s). GC-MS (EI, 70 eV): *m/z* (%) = 420 ([M]⁺, 100), 419 (49), 405 (11), 390 (12), 389 (45), 345 (14), 312 (09). HRMS (EI, 70 eV): calcd for C₂₈H₂₀O₄ [M]⁺: 420.13561, found 420.134505.

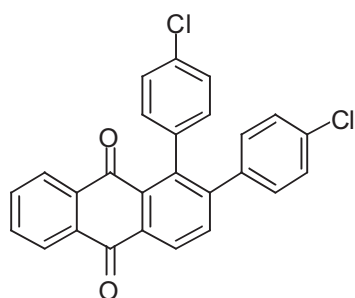
1,2-Bis(4-*tert*-butylphenyl)anthraquinone (**189c**)



Starting with **187** (250 mg, 0.5 mmol), **188c** (213 mg, 1.2 mmol), Pd(PPh₃)₄ (34 mg, 6 mol-%, 0.03 mmol), K₃PO₄ (320 mg, 1.5 mmol) and 1,4-dioxane (4 mL), **189c** was isolated as an orange crystal (180 mg, 76%), mp 234-236 °C. ¹H NMR (300 MHz, CDCl₃): δ = 1.15 (s, 9H, 3CH₃), 1.20 (s, 9H, 3CH₃), 6.75-6.83 (m, 4H, ArH), 7.01-7.14 (m, 4H, ArH), 7.60-7.65 (m, 2H, ArH), 7.71 (d, *J* = 8.01 Hz, 1H, ArH), 8.01-8.03 (m, 1H, ArH), 8.17-8.23 (m, 1H, ArH), 8.34 (d, *J* = 8.05 Hz, 1H, ArH). ¹³C NMR (62.9 MHz, CDCl₃): δ = 31.2 (3CH₃), 31.4 (3CH₃), 34.4, 34.4 (C), 124.2, 124.3, 126.6, 127.0, 127.5, 129.0, 129.0 (CH), 131.3, 132.9 (C), 133.5 (CH), 133.6 (C), 134.1, 134.9 (CH), 135.0, 136.9, 137.2, 142.7, 149.1, 149.8, 149.8 (C), 183.4, 183.7 (CO). IR (KBr, cm⁻¹): ν = 2959 (m), 2901, 2866 (w), 1675 (s), 1663, 1588 (m), 1575, 1566, 1548, 1513, 1475, 1456, 1410, 1394, 1360 (w), 1330, 1315 (m), 1298 (s), 1280, 1262, 1253, 1211, 1199 (m), 1185, 1160 (w), 1113 (m), 1072 (w), 1016 (m),

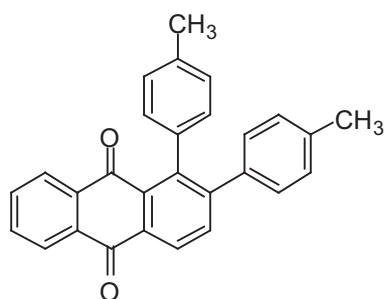
979 (w), 956 (m), 942, 904 (w), 860, 836 (m), 822(s), 795 (m), 774, 768, 755, 745 (w), 719 (s), 690 (m), 682 (w), 662, 645 (m), 587 (s), 568, 559, 543 (m). GC-MS (EI, 70 eV): m/z (%) = 472 ($[M]^+$, 45), 457 (93), 439 (04), 415 (100), 401 (23), 383 (11). HRMS (EI, 70 eV): calcd for $C_{34}H_{32}O_2$ $[M]^+$: 472.23968, found 472.238675.

1,2-Bis(4-chlorophenyl)anthraquinone (189d)



Starting with **187** (250 mg, 0.5 mmol), **188d** (185 mg, 1.2 mmol), $Pd(PPh_3)_4$ (34 mg, 6 mol-%, 0.03 mmol), K_3PO_4 (320 mg, 1.5 mmol) and 1,4-dioxane (4 mL), **189d** was isolated as a yellow solid (174 mg, 81%), mp 208-210 °C. 1H NMR (300 MHz, $CDCl_3$): δ = 6.82-6.87 (m, 4H, ArH), 7.06-7.16 (m, 4H, ArH), 7.61-7.70 (m, 3H, ArH), 7.95-8.02 (m, 1H, ArH), 8.15-8.18 (m, 1H, ArH), 8.34 (d, J = 8.01 Hz, 1H, ArH). ^{13}C NMR (75.4 MHz, $CDCl_3$): δ = 126.7, 127.4, 127.5, 128.1, 128.2, 130.5, 130.7 (CH), 131.6, 132.6, 132.8, 133.6 (C), 133.8 (CH), 134.0 (C), 134.3 (CH), 134.6 (C), 135.1 (CH), 137.9, 138.1, 140.8, 147.7 (C), 183.0, 183.5 (CO). IR (KBr, cm^{-1}): ν = 1673 (s), 1589 (m), 1576, 1551 (w), 1489 (m), 1478, 1451, 1410, 1388 (w), 1326 (m), 1308, 1297, 1267 (s), 1245, 1210 (m), 1181 (w), 1159 (m), 1091 (s), 1070 (m), 1014 (s), 972 (w), 954 (s), 938, 856, 846 (m), 834, 820 (s), 791, 774, 763, 729 (m), 714 (s), 698, 688 (m), 656 (w), 644 (m), 636, 573 (w), 559, 548 (m), 537 (w). GC-MS (EI, 70 eV): m/z (%) = 432 ($[M]^+$, 2x ^{37}Cl , 12), 431 ($[M+H]^+$, ^{37}Cl , 26), 430 ($[M]^+$, ^{37}Cl , 67), 429 ($[M+H]^+$, ^{35}Cl , 91), 428 ($[M]^+$, ^{35}Cl , 93), 427 (100), 395 (30), 394 (24), 393 (91), 357 (17), 300 (26). HRMS (EI, 70 eV): calcd for $C_{26}H_{13}Cl_2O_2$ ($[M-H]^+$, ^{35}Cl): 427.02871, found 427.028111.

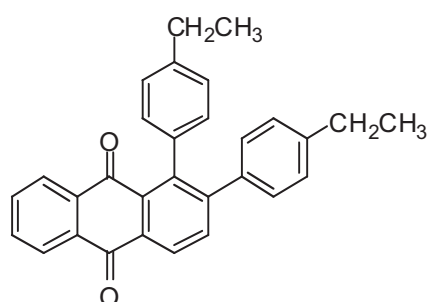
1,2-Bis(4-methylphenyl)anthraquinone (189e)



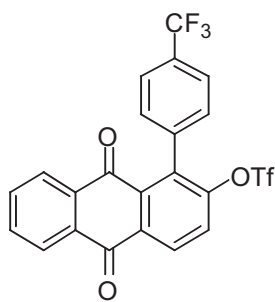
Starting with **187** (250 mg, 0.5 mmol), **188e** (162 mg, 1.2 mmol), $Pd(PPh_3)_4$ (34 mg, 6 mol-%, 0.03 mmol), K_3PO_4 (320 mg, 1.5 mmol) and 1,4-dioxane (4 mL), **189e** was isolated as a yellow solid (149 mg, 77%), mp 218-220 °C. 1H NMR (300 MHz, $CDCl_3$): δ = 2.20 (s, 3H, CH_3), 2.27 (s, 3H, CH_3), 6.82-7.00 (m, 4H, ArH), 6.90 (d, J = 7.86 Hz, 2H, ArH), 6.98 (d, J = 7.88 Hz, 2H, ArH), 7.60-7.70 (m, 3H, ArH), 8.00-8.03 (m, 1H, ArH), 8.18-8.21 (m, 1H, ArH), 8.34 (d, J = 8.01 Hz, 1H, ArH). ^{13}C NMR (75.4 MHz, $CDCl_3$): δ = 21.1 (CH_3), 21.4 (CH_3), 126.5, 127.0, 127.4, 128.4, 128.5, 129.1, 129.3 (CH), 131.8, 132.8, (C), 133.5 (CH), 133.6 (C),

134.1 (CH), 135.1 (C), 135.3 (CH), 136.0, 136.7, 136.8, 137.2, 142.4, 149.2 (C), 183.4, 183.9 (CO). IR (KBr, cm^{-1}): $\nu = 2920, 2851$ (w), 1672, 1662 (s), 1590, 1574, 1548, 1512, 1478, 1445, 1414, 1385 (w), 1327, 1313 (m), 1293, 1278, 1260 (s), 1241, 1208 (m), 1182, 1159, 1112, 1070, 1039 (w), 1018 (m), 965 (w), 952, 939 (m), 896, 854, 832 (w), 811 (s), 794 (m), 762, 749 (w), 723, 713, 701 (s), 669, 650 (w), 642 (m), 595 (w), 580, 549, 540 (m). GC-MS (EI, 70 eV): m/z (%) = 388 ($[\text{M}]^+$, 49), 374 (26), 373 (100), 371 (6). HRMS (EI, (m), 70 eV): calcd for $\text{C}_{28}\text{H}_{20}\text{O}_2$ $[\text{M}]^+$: 388.14578, found 388.144687.

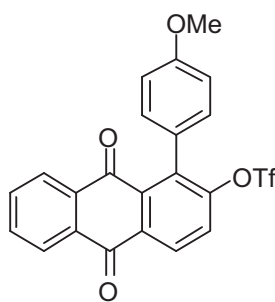
1,2-Bis(4-ethylphenyl)anthraquinone (**189f**)



Starting with **187** (250 mg, 0.5 mmol), **189f** (180 mg, 1.2 mmol), $\text{Pd}(\text{PPh}_3)_4$ (34 mg, 6 mol-%, 0.03 mmol), K_3PO_4 (320 mg, 1.5 mmol) and 1,4-dioxane (4 mL), **189f** was isolated as a brown solid (124 mg, 60%), mp 146-148 °C. ^1H NMR (300 MHz, CDCl_3): $\delta = 1.03$ -1.14 (m, 6H, 2 CH_3), 2.43-2.55 (m, 4H, 2 CH_2), 6.76-6.87 (m, 6H, ArH), 6.95 (d, $J = 8.07$ Hz, 2H, ArH), 7.54-7.64 (m, 3H, ArH), 7.94-8.01 (m, 1H, ArH), 8.11-8.14 (m, 1H, ArH), 8.27 (d, $J = 8.04$ Hz, 1H, ArH). ^{13}C NMR (75.4 MHz, CDCl_3): $\delta = 14.2$ (CH_3), 14.4 (CH_3), 27.3 (CH_2), 27.5 (CH_2), 125.4, 125.8, 126.0 (d, $J = 11.9$ Hz), 126.3, 126.8, 128.1, 128.3 (CH), 130.5, 131.6 (C), 132.3 (CH), 132.5 (C), 133.0 (CH), 134.1 (C), 134.1 (CH), 136.0, 136.3, 141.2, 141.3, 142.0, 148.2 (C), 182.2, 182.6 (CO). IR (KBr, cm^{-1}): $\nu = 2962, 2849$ (w), 1665 (s), 1630 (w), 1589 (m), 1572, 1512, 1478, 1470, 1454, 1434, 1409, 1392, 1358 (w), 1325, 1313 (m), 1294, 1288, 1262 (s), 1210, 1189, 1163, 1156 (m), 1114, 1089 (w), 1073 (m), 1051, 1041, 1017, 974 (w), 951, 943 (m), 889 (w), 871 (m), 832 (s), 791 (m), 761, 738 (w), 712 (s), 694, 669, 648, 583, 553, 533 (m). GC-MS (EI, 70 eV): m/z (%) = 416 ($[\text{M}]^+$, 30), 388 (30), 387 (100), 372 (5), 357 (4). HRMS (EI, 70 eV): calcd for $\text{C}_{30}\text{H}_{24}\text{O}_2$ $[\text{M}]^+$: 416.17708, found 416.176631.

1-(4-Trifluoromethylphenyl)-2-(trifluoromethylsulfonyloxy)anthraquinone (**190a**)

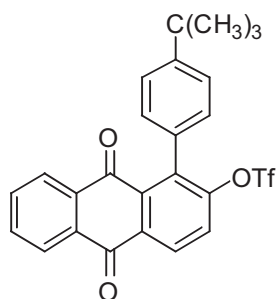
Starting with **187** (250 mg, 0.5 mmol), **188a** (95 mg, 0.5 mmol), Pd(PPh₃)₄ (17 mg, 3 mol-%, 0.015 mmol), K₃PO₄ (160 mg, 0.75 mmol) and 1,4-dioxane (3 mL), **190a** was isolated as a yellow solid (186 mg, 74%), mp 135-136 °C. ¹H NMR (300 MHz, CDCl₃): δ = 7.29 (d, *J* = 8.24 Hz, 2H, ArH), 7.64-7.71 (m, 5H, ArH), 7.94-7.96 (m, 1H, ArH), 8.14-8.17 (m, 1H, ArH), 8.43 (d, *J* = 8.57 Hz, 1H, ArH). ¹³C NMR (75.4 MHz, CDCl₃): δ = 117.0 (q, *J*_{F,C} = 321.0 Hz, CF₃), 123.1 (q, *J*_{F,C} = 271.3 Hz, CF₃), 124.3 (q, *J* = 272.0 Hz), 125.4, 126.0, 126.5, 128.1, 129.1 (CH), 129.2, 129.6, 131.1, 132.2, 133.0 (d, *J* = 1.7 Hz, C), 133.4, 133.7 (CH), 134.7, 136.7 (d, *J* = 1.1 Hz), 151.1 (C), 180.4, 180.8 (CO). ¹⁹F NMR (282 MHz, CDCl₃): δ = -74.03 (s, 3F, CF₃), -62.57 (s, 3F, CF₃). IR (KBr, cm⁻¹): ν = 1674 (s), 1617, 1589, 1572, 1479, 1452, 1433, 1418 (w), 1402 (m), 1326 (s), 1301, 1273 (m), 1249 (w), 1219, 1165, 1125, 1107, 1085, 1061 (s), 1018 (m), 1000 (w), 946 (m), 793, 770, 743 (w), 723, 711 (s), 676, 651 (w), 601 (s), 572, 528 (m). GC-MS (EI, 70 eV): *m/z* (%) = 500 ([M]⁺, 48), 499 (13), 431 (25), 368 (24), 367 (100), 366 (24), 298 (23). HRMS (EI, 70 eV): calcd for C₂₂H₁₀O₅F₆S₁ [M]⁺: 500.01476, found 500.013920.

1-(4-Methoxyphenyl)-2-(trifluoromethylsulfonyloxy)anthraquinone (**190b**)

Starting with **187** (250 mg, 0.5 mmol), **188b** (76 mg, 0.5 mmol), Pd(PPh₃)₄ (17 mg, 3 mol-%, 0.015 mmol), K₃PO₄ (160 mg, 0.75 mmol) and 1,4-dioxane (3 mL), **190b** was isolated as an orange crystal (154 mg, 67%), mp 140-142 °C. ¹H NMR (300 MHz, CDCl₃): δ = 3.82 (s, 3H, OCH₃), 6.94 (d, *J* = 8.76 Hz, 2H, ArH), 7.07 (d, *J* = 8.76 Hz, 2H, ArH), 7.60-7.67 (m, 3H, ArH), 7.96-8.00 (m, 1H, ArH), 8.11-8.14 (m, 1H, ArH), 8.36 (d, *J* = 8.67 Hz, 1H, ArH). ¹³C NMR (75.4 MHz, CDCl₃): δ = 55.2 (OCH₃), 113.8, (CH), 118.2 (q, *J*_{F,C} = 320.4 Hz, CF₃), 125.4 (C), 126.2, 126.8, 127.5, 129.2, 130.0 (CH), 132.3, 133.5 (C), 134.0 (CH), 134.1, 134.5 (C), 134.6 (CH), 137.3, 152.0, 159.6 (C), 182.0, 182.1 (CO). ¹⁹F NMR (282 MHz, CDCl₃): δ = -74.04 (s, 3F, CF₃). IR (KBr, cm⁻¹): ν = 2838 (w), 1671 (s), 1606 (m), 1588, 1550, 1516, 1464, 1451, 1440, 1412, 1394 (w), 1328, 1311 (m), 1297, 1240 (s), 1208, 1107, 1088, 1074 (m), 1027 (s), 977 (w), 954 (s), 858 (w), 840 (m), 828 (s), 811 (w), 800 (s), 767, 749 (w), 727, 718 (s), 697 (m), 669, 649 (w), 640, 601, 588 (m), 537

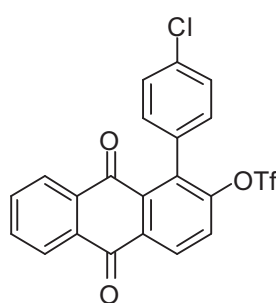
(s). GC-MS (EI, 70 eV): m/z (%) = 462 ($[M]^+$, 55), 330 (23), 329 (100), 314 (17), 286 (11), 202 (14). HRMS (EI, 70 eV): calcd for $C_{22}H_{13}O_6F_3S_1$ $[M]^+$: 462.03794, found 462.037734.

1-(4-*tert*-Butylphenyl)-2-(trifluoromethylsulfonyloxy)anthraquinone (**190c**)



Starting with **187** (250 mg, 0.5 mmol), **188c** (90 mg, 0.5 mmol), $Pd(PPh_3)_4$ (17 mg, 3 mol-%, 0.015 mmol), K_3PO_4 (160 mg, 0.75 mmol) and 1,4-dioxane (3 mL), **190c** was isolated as a yellow crystal (149 mg, 61%), mp 160-162 °C. 1H NMR (250 MHz, $CDCl_3$): δ = 1.31 (s, 9H, 3 CH_3), 7.07 (d, J = 8.4 Hz, 2H, ArH), 7.42 (d, J = 8.51 Hz, 2H, ArH), 7.58-7.67 (m, 3H, ArH), 7.96-8.0 (m, 1H, ArH), 8.11-8.14 (m, 1H, ArH), 8.36 (d, J = 8.81 Hz, 1H, ArH). ^{13}C NMR (75.4 MHz, $CDCl_3$): δ = 31.3 (3 CH_3), 34.7 (C), 118.2 (q, $J_{F,C}$ = 318.5 Hz, CF_3), 125.2, 126.3, 126.9, 127.7, 128.3, 129.3 (CH), 130.5, 132.4, 133.4 (C), 134.1 (CH), 134.1 (C), 134.5 (CH), 134.6, 137.6, 151.2, 151.8 (C), 181.9, 182.0 (CO). ^{19}F NMR (282 MHz, $CDCl_3$): δ = -74.2 (s, 3F, CF_3). IR (KBr, cm^{-1}): ν = 2960, 2930, 2869, 1675, 1665, 1590, 1580, 1573, 1429 (w), 1410 (m), 1362, 1329, 1316, 1297 (w), 1267 (m), 1205 (s), 1165 (m), 1129 (s), 1079, 1040, 1017, 997 (w), 946, 879, 843 (m), 820 (s), 792, 775, 767, 757, 745 (w), 725 (m), 713 (s), 683, 671 (w), 642 (m), 603 (s), 573 (m). GC-MS (EI, 70 eV): m/z (%) = 488 ($[M]^+$, 18), 473 (100), 431 (31), 325 (58), 299 (26), 239 (08). HRMS (EI, 70 eV): calcd for $C_{25}H_{19}O_5F_3S$ $[M]^+$: 488.08998, found 488.090070.

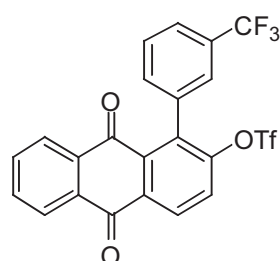
1-(4-Chlorophenyl)-2-(trifluoromethylsulfonyloxy)anthraquinone (**190d**)



Starting with **187** (250 mg, 0.5 mmol), **188d** (78 mg, 0.5 mmol), $Pd(PPh_3)_4$ (17 mg, 3 mol-%, 0.015 mmol), K_3PO_4 (160 mg, 0.75 mmol) and 1,4-dioxane (3 mL), **190d** was isolated by as a yellow solid (199 mg, 85%), mp 160-162 °C. 1H NMR (300 MHz, $CDCl_3$): δ = 7.08-7.11 (m, 2H, ArH), 7.38-7.40 (m, 2H, ArH), 7.62-7.71 (m, 3H, ArH), 7.96-8.00 (m, 1H, ArH), 8.14-8.17 (m, 1H, ArH), 8.41 (d, J = 8.68 Hz, 1H, ArH). ^{13}C NMR (75.4 MHz, $CDCl_3$): δ = 118.1 (q, $J_{F,C}$ = 320.5 Hz, CF_3), 126.3, 127.0, 127.6, 128.7, 129.9, 130.0 (CH), 132.1, 132.3, 133.3, 134.1, 134.2 (C), 134.3 (CH), 134.5 (C), 134.7 (CH), 136.1, 151.4 (C), 181.6, 182.0 (CO). ^{19}F NMR (282 MHz, $CDCl_3$): δ = -73.92 (s, 3F, CF_3). IR (KBr, cm^{-1}): ν = 1676 (s), 1589, 1579, 1570, 1492, 1477, 1453 (w), 1408 (m), 1327, 1314, 1300 (w), 1270 (m), 1253 (w), 1212, 1170, 1132 (s), 1089, 943 (m), 883 (s), 854 (w), 827 (s), 793, 775 (w), 713 (s), 640 (m). GC-MS (EI, 70 eV): m/z (%) = 468 ($[M+H]^+$, ^{37}Cl , 21),

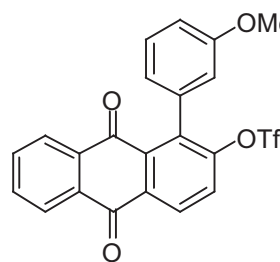
467 ($[M]^+$, ^{37}Cl , 14), 466 ($[M+H]^+$, ^{35}Cl , 53), 465 ($[M]^+$, ^{35}Cl , 09), 431 (09), 335 (32), 334 (25), 333 (100), 332 (14), 298 (35), 297 (15), 270 (19). HRMS (EI, 70 eV): calcd for $\text{C}_{21}\text{H}_{10}\text{Cl}_1\text{F}_3\text{O}_5\text{S}_1$ ($[M]^+$, ^{35}Cl): 465.98841, found 465.987508.

1-(3-Trifluoromethylphenyl)-2-(trifluoromethylsulfonyloxy)anthraquinone (190e)



Starting with **187** (250 mg, 0.5 mmol), **188g** (95 mg, 0.5 mmol), $\text{Pd}(\text{PPh}_3)_4$ (17 mg, 3 mol-%, 0.015 mmol), K_3PO_4 (160 mg, 0.75 mmol) and 1,4-dioxane (3 mL), **190e** was isolated as a yellow solid (209 mg, 84%), mp 115-117 °C. ^1H NMR (300 MHz, CDCl_3): δ = 7.35 (d, J = 7.62 Hz, 1H, ArH), 7.42 (s, 1H, ArH), 7.52 (t, J = 7.76 Hz, 1H, ArH), 7.60-7.73 (m, 4H, ArH), 7.89-7.92 (m, 1H, ArH), 8.08-8.10 (m, 1H, ArH), 8.38 (d, J = 8.64 Hz, 1H, ArH). ^{13}C NMR (62.9 MHz, CDCl_3): δ = 117.0 (q, $J_{\text{F,C}}$ = 320.6 Hz, CF_3), 123.0 (q, $J_{\text{F,C}}$ = 272.2 Hz, CF_3), 124.1 (q, J = 3.8 Hz), 124.6 (q, J = 3.8 Hz), 125.4, 126.0, 126.5, 127.8 (d, J = 4.0 Hz), 129.1 (CH), 129.5, 130.0 (C), 131.2 (CH), 132.2, 133.0 (d, J = 5.5 Hz, C), 133.3 (CH), 133.6 (C), 133.7 (d, J = 4.4 Hz, CH), 134.4, 144.0, 150.2 (C), 180.4, 180.7 (CO). ^{19}F NMR (282 MHz, CDCl_3): δ = -74.10 (s, 3F, CF_3), -62.70 (s, 3F, CF_3). IR (KBr, cm^{-1}): ν = 1673 (s), 1589, 1568, 1492, 1479 (w), 1418, 1308 (m), 1277, 1274 (w), 1250 (m), 1213, 1167, 1121, 1099, 1069 (s), 1001 (w), 955 (m), 883, 839, 804 (s), 770 (w), 727, 712, 702 (s), 689, 652 (w), 628, 598 (s), 572 (m). GC-MS (EI, 70 eV): m/z (%) = 500 ($[M]^+$, 34), 431 (12), 368 (21), 367 (100), 266 (16), 347 (24). HRMS (EI, 70 eV): calcd for $\text{C}_{22}\text{H}_{10}\text{O}_5\text{F}_6\text{S}_1$ $[M]^+$: 500.01476, found 500.015351.

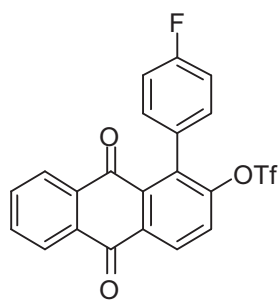
1-(3-Methoxyphenyl)-2-(trifluoromethylsulfonyloxy)anthraquinone (190f)



Starting with **187** (250 mg, 0.5 mmol), **188h** (76 mg, 0.5 mmol), $\text{Pd}(\text{PPh}_3)_4$ (17 mg, 3 mol-%, 0.015 mmol), K_3PO_4 (160 mg, 0.75 mmol) and 1,4-dioxane (3 mL), **190f** was isolated as a yellow solid (183 mg, 79%), mp 115-116 °C. ^1H NMR (300 MHz, CDCl_3): δ = 3.72 (s, 3H, OCH_3), 6.69-6.73 (m, 2H, ArH), 6.91-6.95 (m, 1H, ArH), 7.31 (t, J = 8.76 Hz, 1H, ArH), 7.58-7.66 (m, 3H, ArH), 7.94-8.01 (m, 1H, ArH), 8.10-8.13 (m, 1H, ArH), 8.36 (d, J = 8.70 Hz, 1H, ArH). ^{13}C NMR (62.9 MHz, CDCl_3): δ = 55.2 (OCH_3), 113.8, 114.3 (CH), 118.2 (q, $J_{\text{F,C}}$ = 320.5 Hz, CF_3), 120.8, 126.1, 126.8, 127.5, 129.4, 129.5 (CH), 132.2, 133.3, 134.0 (C), 134.1 (CH), 134.3 (C), 134.6 (CH), 135.0, 137.1, 151.5, 159.5 (C), 181.7, 181.8 (CO). ^{19}F NMR (282 MHz, CDCl_3): δ = -74.02 (s, 3F, CF_3). IR (KBr, cm^{-1}):

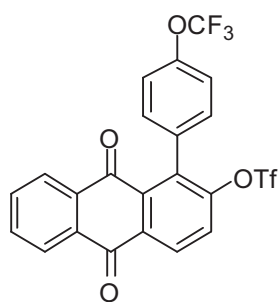
$\nu = 1679$ (m), 1606, 1571, 1488, 1455 (w), 1422 (s), 1327, 1300 (w), 1270 (m), 1250 (w), 1210, 1166, 1152, 1132 (s), 1096, 1076 (w), 1038 (m), 1000 (w), 959 (m), 892, 848 (s), 825, 810, 780, 769 (m), 742 (w), 725 (m), 707, 701 (s), 671 (m), 627, 597 (s), 571 (m). GC-MS (EI, 70 eV): m/z (%) = 462 ($[M]^+$, 40), 330 (21), 329 (100), 314 (28), 298 (10), 286 (14), 202 (13). HRMS (EI, 70 eV): calcd for $C_{22}H_{13}O_6F_3S_1$ $[M]^+$: 462.03794, found 462.038112.

1-(4-Fluorophenyl)-2-(trifluoromethylsulfonyloxy)anthraquinone (**190g**)



Starting with **187** (250 mg, 0.5 mmol), **188i** (70 mg, 0.5 mmol), $Pd(PPh_3)_4$ (17 mg, 3 mol-%, 0.015 mmol), K_3PO_4 (160 mg, 0.75 mmol) and 1,4-dioxane (3 mL), **190g** was isolated as a yellow solid (113 mg, 50%), mp 136-138 °C. 1H NMR (300 MHz, $CDCl_3$): $\delta = 7.11$ -7.14 (m, 4H, ArH), 7.63-7.72 (m, 3H, ArH), 7.97-8.00 (m, 1H, ArH), 8.16-8.20 (m, 1H, ArH), 8.42 (d, $J = 8.70$ Hz, 1H, ArH). ^{13}C NMR (62.9 MHz, $CDCl_3$): $\delta = 115.4$, 115.7 (CH), 118.1 (q, $J_{F,C} = 318.3$ Hz, CF_3), 126.3, 127.0, 127.5 (CH), 129.4 (d, $J_{F,C} = 3.7$ Hz, C), 129.7, 130.4, 130.5 (CH), 132.2, 133.4, 134.1 (C), 134.2 (CH), 134.3 (C), 134.6 (CH), 136.3, 151.5 (C), 162.7 (d, $J_{F,C} = 247.7$ Hz, CF), 181.7, 182.0 (CO). ^{19}F NMR (282 MHz, $CDCl_3$): $\delta = -113.01$ (s, 1F, CF), -74.00 (s, 3F, CF_3). IR (KBr, cm^{-1}): $\nu = 1674$ (m), 1589, 1568, 1510, 1479, 1450 (w), 1420 (m), 1329, 1315, 1298, 1271, 1249 (w), 1206 (s), 1162 (m), 1130 (s), 1096 (m), 1080, 1038, 1015, 999, 974, 945 (w), 879 (s), 856 (m), 832, 809 (s), 770, 752 (w), 729 (m), 717, 708 (s), 681, 669 (w), 646 (m), 637, 621 (w), 603, 578 (s), 541 (m). GC-MS (EI, 70 eV): m/z (%) = 450 ($[M]^+$, 46), 449 (09), 318 (23), 317 (100), 316 (14), 260 (10), 233 (20), 231 (14). HRMS (EI, 70 eV): calcd for $C_{21}H_{10}O_5F_4S_1$ $[M]^+$: 450.01796, found 450.017099.

1-(4-Trifluoromethoxyphenyl)-2-(trifluoromethylsulfonyloxy)anthraquinone (**190h**)



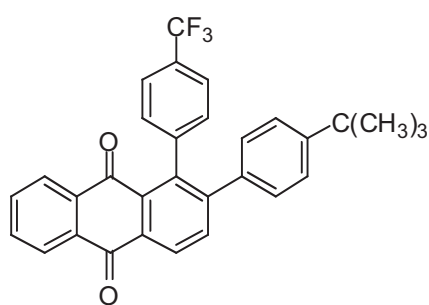
Starting with **187** (250 mg, 0.5 mmol), **188j** (102 mg, 0.5 mmol), $Pd(PPh_3)_4$ (17 mg, 3 mol-%, 0.015 mmol), K_3PO_4 (160 mg, 0.75 mmol) and 1,4-dioxane (3 mL), **190h** was isolated as a yellow solid (135 mg, 52%), mp 108-110 °C. 1H NMR (300 MHz, $CDCl_3$): $\delta = 7.17$ -7.28 (m, 4H, ArH), 7.66-7.70 (m, 3H, ArH), 7.96-8.00 (m, 1H, ArH), 8.16-8.18 (m, 1H, ArH), 8.43 (d, $J = 8.65$ Hz, 1H, ArH). ^{13}C NMR (75.4 MHz, $CDCl_3$): $\delta = 118.1$ (q, $J_{F,C} = 320.6$ Hz, CF_3), 120.5 (q, $J_{F,C} = 257.6$ Hz, OCF_3), 120.8, 126.4, 127.0, 127.6, 129.9, 130.1 (CH), 132.3, 133.3, 134.1, 134.2 (C), 134.3, 134.7 (CH), 135.8,

149.2, 149.3, 151.3 (C), 181.6, 182.0 (CO). ^{19}F NMR (282 MHz, CDCl_3): $\delta = -74.10$ (s, 3F, CF_3), -57.78 (s, 3F, OCF_3). IR (KBr, cm^{-1}): $\nu = 1681$ (m), 1609, 1588, 1570, 1510, 1450 (w), 1425 (m), 1409, 1329, 1315, 1298 (w), 1250, 1204, 1167, 1152, 1131, 1105 (s), 1081 (m), 1038 (w), 1019 (m), 999 (w), 946 (m), 920 (w), 877 (s), 852 (m), 820 (s), 805 (m), 771 (w), 722, 711 (s), 681, 668, 655 (w), 628 (m), 599 (s), 571, 553, 527 (m). GC-MS (EI, 70 eV): m/z (%) = 516 ($[\text{M}]^+$, 43), 431 (10), 384 (22), 383 (100), 382 (13). HRMS (EI, 70 eV): calcd for $\text{C}_{22}\text{H}_{10}\text{O}_6\text{F}_6\text{S}_1$ $[\text{M}]^+$: 416.00968, found 416.010762.

3.3.2 General procedure for the synthesis of 191a-f

The reaction was carried out in a pressure tube. To a dioxane suspension (3 mL) of **187** (0.5 mmol), $\text{Ar}^1\text{B}(\text{OH})_2$ (0.5 mmol) and $\text{Pd}(\text{PPh}_3)_4$ (3 mol-%) was added K_3PO_4 (0.75 mmol), and the resultant solution was degassed by bubbling argon through the solution for 10 min. The mixture was heated at 90 °C under an argon atmosphere for 10 h. The mixture was cooled to 20 °C. $\text{Ar}^2\text{B}(\text{OH})_2$ (0.55 mmol), $\text{Pd}(\text{PPh}_3)_4$ (3 mol-%), K_3PO_4 (0.75 mmol) and dioxane (2 mL) were added. The reaction mixtures were heated under an argon atmosphere for 10 h at 110 °C. They were diluted with H_2O and extracted with CH_2Cl_2 (3×25 mL). The combined organic layers were dried (Na_2SO_4), filtered and the filtrate was concentrated in vacuo. The residue was purified by flash chromatography (flash silica gel, heptanes/EtOAc).

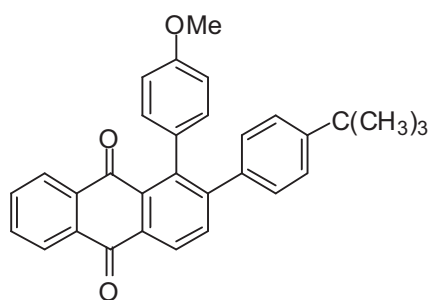
1-(4-Trifluoromethylphenyl)-2-(4-*tert*-butylphenyl)anthraquinone (191a)



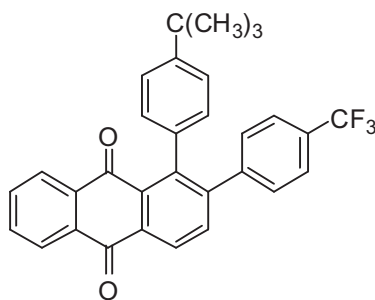
Starting with **187** (252 mg, 0.5 mmol), **188a** (95 mg, 0.5 mmol), $\text{Pd}(\text{PPh}_3)_4$ (17 mg, 3 mol-%, 0.015 mmol), K_3PO_4 (320 mg, 1.5 mmol), 1,4-dioxane (3 mL), and **188c** (98 mg, 0.55 mmol), **191a** was isolated as a yellow crystal (157 mg, 65%), mp 225-227 °C. ^1H NMR (300 MHz, CDCl_3): $\delta = 1.15$ (s, 9H, 3 CH_3), 6.76-6.80 (m, 2H, ArH), 7.03-7.10 (m, 4H, ArH), 7.38 (d, $J = 8.1$ Hz, 2H, ArH), 7.61-7.66 (m, 2H, ArH), 7.70 (d, $J = 8.01$ Hz, 1H, ArH), 7.94-7.98 (m, 1H, ArH), 8.16-8.20 (m, 1H, ArH), 8.36 (d, $J = 8.04$ Hz, 1H, ArH). ^{13}C NMR (75.4 MHz, CDCl_3): $\delta = 31.2$ (3 CH_3), 34.4 (C), 124.3 (q, $J_{\text{F,C}} = 272.3$ Hz, CF_3), 124.4 (dq, $J_{\text{F,C}} = 7.6, 2.2$ Hz), 124.7, 126.7, 127.4, 127.6 (CH), 128.5 (q, $J = 32.8$ Hz, C), 129.0, 129.7 (CH), 131.3, 132.8, 133.6 (C), 133.8, 134.3 (CH), 134.6 (C), 135.4 (CH), 136.3, 140.8, 144.0 (d, $J = 1.7$ Hz), 149.1, 150.5 (C), 183.0, 183.6 (CO). ^{19}F NMR (282 MHz, CDCl_3): $\delta = -62.3$ (s, 3F, CF_3). IR (KBr, cm^{-1}): $\nu = 2962, 2905, 2869$ (w), 1672 (m), 1613, 1588, 1552,

1513, 1462, 1409, 1399, 1363 (w), 1321 (s), 1300, 1278, 1263 (m), 1213, 1186 (w), 1158 (s), 1118 (m), 1105 (s), 1087, 1075, 1059, 1016 (m), 976 (w), 954 (m), 899, 864 (w), 837, 824 (m), 796, 784, 767, 758, 744 (w), 718 (s), 688, 671, 662, 640, 605 (w), 584 (m), 566, 564, 532 (w). GC-MS (EI, 70 eV): m/z (%) = 484 ($[M]^+$, 43), 469 (100), 449 (10), 427 (08), 383 (02), 357 (03). HRMS (EI, 70 eV): calcd for $C_{31}H_{23}O_2F_3$ $[M]^+$: 484.16447, found 484.164850.

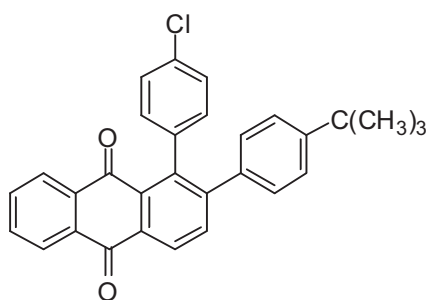
1-(4-Methoxyphenyl)-2-(4-*tert*-butylphenyl)anthraquinone (**191b**)



Starting with **187** (252 mg, 0.5 mmol), **188b** (76 mg, 0.5 mmol), Pd(PPh₃)₄ (17 mg, 3 mol-%, 0.015 mmol), K₃PO₄ (320 mg, 1.5 mmol), 1,4-dioxane (3 mL), and **188c** (98 mg, 0.55 mmol), **191b** was isolated as a red solid (111 mg, 50%), mp 221-222 °C. ¹H NMR (300 MHz, CDCl₃): δ = 1.18 (s, 9H, 3CH₃), 3.71 (s, 3H, OCH₃), 6.70 (d, J = 8.58 Hz, 2H, ArH), 6.84 (d, J = 7.26 Hz, 4H, ArH), 7.10 (d, J = 8.58 Hz, 2H, ArH), 7.58-7.68 (m, 3H, ArH), 7.98-8.01 (m, 1H, ArH), 8.16-8.20 (m, 1H, ArH), 8.32 (d, J = 8.58 Hz, 1H, ArH). ¹³C NMR (62.9 MHz, CDCl₃): δ = 30.2 (3CH₃), 33.4 (C), 54.0 (OCH₃), 112.1, 123.5, 125.4, 125.9, 126.3, 128.1, 129.4 (CH), 130.8, 130.9, 131.7 (C), 132.4 (CH), 132.6 (C), 133.0 (CH), 134.1 (C), 134.2 (CH), 136.1, 141.0, 148.3, 149.0, 157.2 (C), 182.3, 183.0 (CO). IR (KBr, cm⁻¹): ν = 2956, 2865, 2839, 2042, (w), 1671 (s), 1658, 1609, 1586 (w), 1573 (m), 1547 (w), 1513 (m), 1477, 1465, 1451, 1439, 1415, 1405, 1390, 1361 (w), 1329, 1315 (m), 1297, 1277, 1241 (s), 1206 (m), 1176 (s), 1159, 1115 (m), 1088, 1071 (w), 1024 (s), 1014 (m), 977 (w), 953 (m), 941, 931, 901, 859, (w), 836 (m), 823 (s), 795 (m), 767, 752, 747 (w), 718 (s), 686, 661 (w), 648 (m), 634 (w), 597, 578, 569 (m), 540 (s). GC-MS (EI, 70 eV): m/z (%) = 446 ($[M]^+$, 100), 445 (12), 432 (16), 431 (40), 416 (10), 415 (23), 390 (13), 389 (18), HRMS (EI, 70 eV): calcd for $C_{31}H_{26}O_3$ $[M]^+$: 446.18765, found 446.187401.

1-(4-*tert*-Butylphenyl)-2-(4-trifluoromethylphenyl)anthraquinone (**191c**)

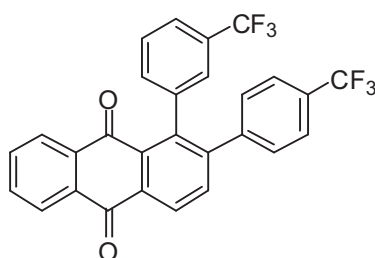
Starting with **187** (252 mg, 0.5 mmol), **188c** (90 mg, 0.5 mmol), Pd(PPh₃)₄ (17 mg, 3 mol-%, 0.015 mmol), K₃PO₄ (320 mg, 1.5 mmol), 1,4-dioxane (3 mL), and **188a** (104 mg, 0.55 mmol), **191c** was isolated as a yellow solid (143 mg, 60%), mp 220-222 °C. ¹H NMR (300 MHz, CDCl₃): δ = 1.20 (s, 9H, 3CH₃), 6.81 (d, *J* = 8.59 Hz, 2H, ArH), 6.98 (d, *J* = 8.12 Hz, 2H, ArH), 7.14 (d, *J* = 8.59 Hz, 2H, ArH), 7.28 (d, *J* = 8.12 Hz, 2H, ArH), 7.60-7.68 (m, 3H, ArH), 8.00-8.02 (m, 1H, ArH), 8.17-8.20 (m, 1H, ArH), 8.36 (d, *J* = 8.12 Hz, 1H, ArH). ¹³C NMR (75.4 MHz, CDCl₃): δ = 30.2 (3CH₃), 33.4 (C), 122.9 (q, *J* = 272.2 Hz, CF₃), 123.3 (q, *J*_{F,C} = 7.4, 3.7 Hz), 123.5, 125.6, 126.1, 126.5 (CH), 127.7 (C), 127.8 (CH), 128.2 (C), 128.7 (CH), 130.4, 131.7 (C), 132.6, 133.2, 133.6 (CH), 133.8, 135.1, 141.5, 142.8 (d, *J* = 1.3 Hz), 146.9, 148.7 (C), 182.1, 182.4 (CO). ¹⁹F NMR (282 MHz, CDCl₃): δ = -62.68 (s, 3F, CF₃). IR (KBr, cm⁻¹): ν = 1674 (s), 1615, 1587, 1576, 1551, 1511, 1461, 1456, 1415, 1393, 1364, 1359 (w), 1323, 1300 (s), 1283, 1258 (m), 1210, 1198, 1184 (w), 1155, 1109 (s), 1085 (m), 1073, 1061, 1014 (s), 978, 967 (w), 956, 941 (m), 903, 861 (m), 837, 823 (s), 796 (m), 780, 766, 753, 739 (w), 720, 714, 700 (s), 678 (w), 646 (m), 632 (w), 605, 585, 563, 545 (m). GC-MS (EI, 70 eV): *m/z* (%) = 485 ([M+H]⁺, 10), 484 ([M]⁺, 29), 470 (34), 469 (100), 428 (22), 427 (65). HRMS (EI, 70 eV): calcd for C₃₁H₂₄F₃O₂ [M+H]⁺: 485.1723, found 485.1713.

1-(4-Chlorophenyl)-2-(4-*tert*-butylphenyl)anthraquinone (**191d**)

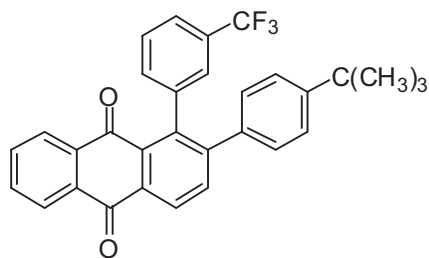
Starting with **187** (252 mg, 0.5 mmol), **188d** (78 mg, 0.5 mmol), Pd(PPh₃)₄ (17 mg, 3 mol-%, 0.015 mmol), K₃PO₄ (320 mg, 1.5 mmol), 1,4-dioxane (3 mL), and **188c** (98 mg, 0.55 mmol), **191d** was isolated as a yellow solid (137 mg, 61%), mp 245-246 °C. ¹H NMR (300 MHz, CDCl₃): δ = 1.30 (s, 9H, 3CH₃), 6.92-7.00 (m, 4H, ArH), 7.21-7.26 (m, 4H, ArH), 7.75-7.82 (m, 3H, ArH), 8.09-8.12 (m, 1H, ArH), 8.30-8.33 (m, 1H, ArH), 8.48 (d, *J* = 7.46 Hz, 1H, ArH). ¹³C NMR (75.4 MHz, CDCl₃): δ = 31.2 (3CH₃), 34.5 (C), 124.7, 126.6, 127.3, 127.4, 128.0, 129.1, 130.7 (CH), 131.6, 132.5, 132.7, 133.6 (C), 133.7, 134.2 (CH), 134.8 (C), 135.5 (CH), 136.6, 138.4, 141.0, 149.1, 150.3 (C), 183.1, 183.8 (CO). IR (KBr, cm⁻¹): ν = 1667 (s), 1588, 1575, 1549, 1513, 1492, 1477, 1461, 1409, 1391, 1360 (w), 1332

(m), 1316 (w), 1298 (m), 1277 (w), 1261 (m), 1247, 1212, 1184, 1159, 1112, 1087, 1071 (w), 1013 (m), 981 (w), 954 (m), 941, 905, 858, 842 (w), 832, 825 (m), 794, 774, 763, 746 (w), 720 (s), 697, 691, 679, 643, 630 (w), 583, 576 (m), 549, 533 (w). GC-MS (EI, 70 eV): m/z (%) = 452 ($[M]^+$, ^{37}Cl , 16), 451 ($[M+H]^+$, ^{35}Cl , 19), 450 ($[M]^+$, ^{35}Cl , 46), 437 (38), 436 (31), 435 (100), 393 (14), 207 (10). HRMS (EI, 70 eV): calcd for $\text{C}_{30}\text{H}_{24}\text{Cl}_2\text{O}_2$ ($[M+H]^+$, ^{35}Cl): 451.1459, found 451.1459.

1-(3-Trifluoromethylphenyl)-2-(4-trifluoromethylphenyl)anthraquinone (191e)



Starting with **187** (252 mg, 0.5 mmol), **188g** (95 mg, 0.5 mmol), $\text{Pd}(\text{PPh}_3)_4$ (17 mg, 3 mol-%, 0.015 mmol), K_3PO_4 (320 mg, 1.5 mmol), 1,4-dioxane (3 mL), and **188a** (104 mg, 0.55 mmol), **191e** was isolated as a yellow solid (169 mg, 68%), mp 255-256 °C. ^1H NMR (300 MHz, CDCl_3): δ = 7.02 (d, J = 8.23 Hz, 2H, ArH), 7.14 (d, 7.65 Hz, 1H, ArH), 7.27-7.45 (m, 5H, ArH), 7.65-7.77 (m, 3H, ArH), 8.00-8.03 (m, 1H, ArH), 8.23-8.26 (m, 1H, ArH), 8.46 (d, J = 8.10 Hz, 1H, ArH). ^{13}C NMR (62.9 MHz, CDCl_3): δ = 122.8 (q, $J_{\text{F,C}}$ = 321.2 Hz, CF_3), 123.1 (q, $J_{\text{F,C}}$ = 272.0 Hz, CF_3), 123.6 (d, J = 4.1 Hz), 124.8 (d, J = 3.7 Hz), 126.2 (d, J = 3.8 Hz), 126.8, 127.4, 127.8, 128.2, 129.7 (CH), 130.0, 130.5, 131.5 (C), 132.5 (CH), 132.6 (C), 134.0 (CH), 134.3 (C), 134.4 (CH), 134.6 (C), 134.9 (CH), 140.1, 140.5, 143.0, 147.6 (C) 182.8, 183.3 (CO). ^{19}F NMR (282 MHz, CDCl_3): δ = -62.79 (s, 3F, CF_3), -62.78 (s, 3F, CF_3). IR (KBr, cm^{-1}): ν = 1669 (s), 1617, 1589, 1574, 1533, 1490, 1432, 1414, 1399 (w), 1328, 1302 (s), 1285, 1263, 1244, 1291, 1212 (w), 1161, 1109, 1081, 1066 (s), 1018 (m), 1002, 981 (w), 961 (m), 923, 893, 863 (w), 849 (m), 836 (w), 825, 805 (m), 792, 767, 752, 746, 725 (w), 712, 706 (s), 686 (w), 675 (m), 655, 629, 605, 567, 542 (w). GC-MS (EI, 70 eV): m/z (%) = 496 ($[M]^+$, 80), 495 (100), 477 (09), 428 (21), 427 (72), 407 (08). HRMS (EI, 70 eV): calcd for $\text{C}_{28}\text{H}_{13}\text{O}_2\text{F}_6$ $[M-H]^+$: 495.08143, found 495.080798.

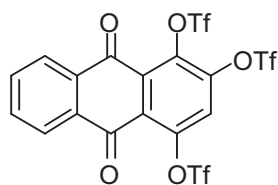
1-(3-Trifluoromethylphenyl)-2-(4-*tert*-butylphenyl)anthraquinone (**191f**)

Starting with **187** (252 mg, 0.5 mmol), **188g** (95 mg, 0.5 mmol), Pd(PPh₃)₄ (17 mg, 3 mol-%, 0.015 mmol), K₃PO₄ (320 mg, 1.5 mmol), 1,4-dioxane (3 mL), and **188c** (98 mg, 0.55 mmol), **191f** was isolated as a yellow solid (148 mg, 61%), mp 227-229 °C. ¹H NMR (300 MHz, CDCl₃): δ = 1.16 (s, 9H, 3CH₃), 6.75 -6.77 (m, 2H, ArH), 7.07-7.10 (m, 3H, ArH), 7.17 (d, *J* = 8.34 Hz, 1H, ArH), 7.27 (t, *J* = 7.68 Hz, 1H, ArH), 7.40 (d, *J* = 7.86 Hz, 1H, ArH), 7.60-7.70 (m, 2H, ArH), 7.73 (d, *J* = 7.86 Hz, 1H, ArH), 7.96-8.00 (m, 1H, ArH), 8.18-8.21 (m, 1H, ArH), 8.37 (d, *J* = 8.04 Hz, 1H, ArH). ¹³C NMR (75.4 MHz, CDCl₃): δ = 30.1 (3CH₃), 33.4 (C), 122.2 (q, *J*_{F,C} = 3.84 Hz, CH), 122.9 (q, *J* = 272.4 Hz, CF₃), 123.6, 125.3 (q, *J* = 3.8 Hz), 125.6, 126.3, 126.5, 126.7, 128.0 (CH), 128.7, 129.1, 130.4, 131.7 (C), 131.9 (CH), 132.6 (C), 132.7, 133.2 (CH), 133.7 (C), 134.2 (CH), 135.2, 139.6 (d, *J* = 9.8 Hz), 148.3, 149.4 (C), 182.0, 182.6 (CO). ¹⁹F NMR (282 MHz, CDCl₃): δ = -62.68 (s, 3F, CF₃). IR (KBr, cm⁻¹): ν = 2957, 2907, 2872, 2134 (w), 1671 (s), 1589, 1574, 1549, 1513, 1479, 1460, 1433, 1407, 1393, 1365 (w), 1329, 1316, 1302 (s), 1279 (m), 1258, 1245 (s), 1211, 1183 (w), 1159, 1116, 1100, 1068 (s), 1017 (m), 1001, 986, 973 (w), 961 (m), 917, 892 (w), 861, 838 (m), 824, 801 (s), 792 (m), 768, 751, 744 (w), 715, 702 (s), 688 (w), 679, 666, 652 (m), 628 (w), 580, 566, 545 (m). GC-MS (EI, 70 eV): *m/z* (%) = 484 ([M]⁺, 43), 470 (33), 469 (100). HRMS (EI, 70 eV): calcd for C₃₁H₂₃O₂F₃ [M]⁺: 484.16447, found 484.164011.

3.4 Synthesis of 1,2,4-Tris(trifluoromethylsulfonyloxy)anthraquinone (**193**)

To a solution of 1,2,4-trihydroxyanthraquinone (**192**) (1.0 equiv) in CH₂Cl₂ (10 mL/mmol) was added pyridine (7.0 equiv) at room temperature under an argon atmosphere. After 10 min, Tf₂O (5.0 equiv) was added at -78 °C. The mixture was allowed to warm up to room temperature and stirred for overnight. The reaction mixture was filtered and the filtrate was concentrated in vacuo. The products of the reaction mixture were isolated by rapid column chromatography (flash silica gel, heptane/EtOAc).

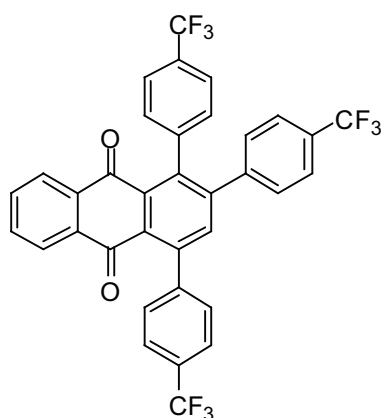
1,2,4-Tris(trifluoromethylsulfonyloxy)anthraquinone (**193**)



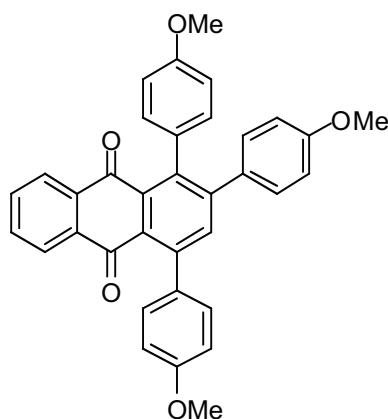
Starting with 1,2,4-trihydroxyanthraquinone **192** (1.00 g, 3.90 mmol), pyridine (2.2 mL, 27.3 mmol), CH₂Cl₂ (40 mL), Tf₂O (3.3 mL, 19.5 mmol), **193** was isolated as a yellow solid (1.10 g, 43%), mp 162-164 °C. ¹H NMR (300 MHz, CDCl₃): δ = 7.66 (s, 1H, ArH), 7.80-7.86 (m, 2H, ArH), 8.22-8.36 (m, 2H, ArH). ¹³C NMR (62.9 MHz, CDCl₃): δ = 118.3 (d, *J*_{F,C} = 313.5 Hz, CF₃), 118.4 (d, *J*_{F,C} = 316.0 Hz, CF₃), 118.6 (d, *J*_{F,C} = 319.0 Hz, CF₃), 123.3 (CH), 126.8 (C), 127.7, 127.8 (CH), 129.6, 132.5, 132.6 (C), 135.5, 135.6 (CH), 138.9, 144.5, 146.6 (C), 178.4, 179.9 (CO). ¹⁹F NMR (282 MHz, CDCl₃): δ = -73.02 (q, *J*_F = 2.82, 5.28 Hz, 3F, CF₃), -72.83 (s, 3F, CF₃), -72.24 (q, *J*_F = 2.73, 5.07 Hz, 3F, CF₃). IR (KBr, cm⁻¹): ν = 3100 (w), 1682 (s), 1589 (m), 1440, 1428 (s), 1310 (m), 1278 (w), 1208, 1182, 1170, 1127 (s), 1071, 1039, 1018 (m), 974 (w), 929, 904, 851, 812, 780, 763 (s), 756, 740 (m), 719 (s), 712, 695, 674 (m), 653, 635 (s), 623 (m), 597, 534 (s). GC-MS (EI, 70 eV): *m/z* (%) = 652 ([M]⁺, 100), 583 (13), 519 (11), 455 (46), 427 (16), 391 (14), 363 (85), 336 (11), 335 (74). HRMS (EI, 70 eV): calcd for C₁₇H₅F₉O₁₁S₃ [M]⁺: 651.88448, found 651.883916.

3.4.1 General Procedure for Suzuki-Miyaura Reactions

A 1,4-dioxane solution (4 mL per 3 mmol of **193**) of **193**, K₃PO₄, Pd(PPh₃)₄ and arylboronic acid **188** was stirred at 110 °C or 90 °C for 10 h. After cooling to 20 °C, distilled water was added. The organic and the aqueous layers were separated and the latter was extracted with CH₂Cl₂. The combined organic layers were dried (Na₂SO₄), filtered and the filtrate was concentrated in vacuo. The residue was purified by column chromatography.

1,2,4-Tris(4-trifluoromethylphenyl)anthraquinone (194a)

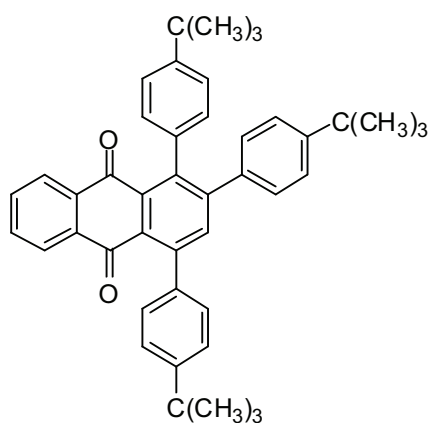
Starting with **193** (100 mg, 0.15 mmol), **188a** (114 mg, 0.6 mmol), Pd(PPh₃)₄ (17 mg, 10 mol-%, 0.015 mmol), K₃PO₄ (159 mg, 0.75 mmol) and 1,4-dioxane (5 mL), **194a** was isolated as a yellow solid (43 mg, 43%), mp 237-238 °C. ¹H NMR (300 MHz, CDCl₃): δ = 7.03-7.12 (m, 4H, ArH), 7.35-7.47 (m, 6H, ArH), 7.48 (s, 1H, ArH), 7.64-7.67 (m, 4H, ArH), 7.94-8.02 (m, 2H, ArH). ¹³C NMR (62.9 MHz, CDCl₃): δ = 123.7 (q, *J*_{F,C} = 272.3 Hz, CF₃), 124.0 (q, *J*_{F,C} = 272.1 Hz, CF₃), 124.2 (q, *J*_{F,C} = 272.1 Hz, CF₃), 124.9 (t, *J* = 3.5 Hz), 125.0, 125.2 (d, *J* = 3.8 Hz), 126.8, 127.0, 128.3 (CH), 128.9 (C), 129.4, 129.6 (CH), 129.8, 130.1, 132.1, 133.4, 133.7, 133.9 (C), 134.1, 134.2, 138.0 (CH), 140.8, 142.4, 143.0, 143.1, 145.4, 146.2 (C), 183.2, 183.7 (CO). ¹⁹F NMR (282 MHz, CDCl₃): δ = -62.77 (s, 3F, CF₃), -62.41 (s, 3F, CF₃), -62.38 (s, 3F, CF₃). IR (KBr, cm⁻¹): ν = 3067, 2929, 2581 (w), 1673 (m), 1616, 1592, 1531, 1407, 1372 (w), 1323 (s), 1285, 1251 (m), 1211 (w), 1167, 1108 (s), 1089 (m), 1081, 1060, 1017 (s), 966 (m), 937, 919, 866 (w), 839 (m), 801, 766, 746 (w), 726 (m), 711, 684, 660, 644, 622, 604, 551, 539 (w). GC-MS (EI, 70 eV): *m/z* (%) = 640 ([M]⁺, 98), 639 (100), 638 (13), 621 (15), 572 (28), 571 (81), 570 (36). HRMS (EI, 70 eV): calcd for C₃₅H₁₆F₉O₂ [M-H]⁺: 639.10011, found 639.099492.

1,2,4-Tris(4-methoxyphenyl)anthraquinone (194b)

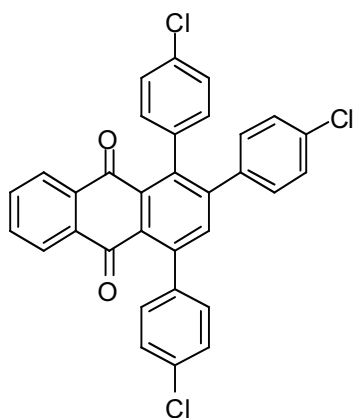
Starting with **193** (100 mg, 0.15 mmol), **188b** (91 mg, 0.6 mmol), Pd(PPh₃)₄ (17 mg, 10 mol-%, 0.015 mmol), K₃PO₄ (159 mg, 0.75 mmol) and 1,4-dioxane (5 mL), **194b** was isolated as an orange solid (59 mg, 73%), mp 240-242 °C. ¹H NMR (300 MHz, CDCl₃): δ = 3.67 (s, 3H, OCH₃), 3.74 (s, 3H, OCH₃), 3.80 (s, 3H, OCH₃), 6.61-6.64 (m, 2H, ArH), 6.72-6.75 (m, 2H, ArH), 6.85-6.90 (m, 6H, ArH), 7.21-7.24 (m, 2H, ArH), 7.49 (s, 1H, ArH), 7.58-7.61 (m, 2H, ArH), 7.93-8.01 (m, 2H, ArH). ¹³C NMR (62.9 MHz, CDCl₃): δ = 55.0 (OCH₃), 55.1 (OCH₃), 55.2 (OCH₃), 113.2, 113.3, 113.6, 126.5, 126.6, 129.3, 130.5, 130.7 (CH), 131.3, 132.1, 132.2 (C), 133.5, 133.6 (CH), 134.0, 134.3, 134.4, 134.5 (C), 138.8 (CH), 141.2, 143.3, 147.5, 158.2, 158.6, 158.9 (C), 184.1, 185.0 (CO). IR (KBr, cm⁻¹): ν = 3318, 3068, 3033, 3012, 2952, 2918, 2849,

2833, 2539 (w), 1665, 1606 (s), 1592, 1575 (m), 1508 (s), 1461, 1454, 1435 (m), 1410, 1368 (w), 1330, 1310 (m), 1289, 1239, 1173 (s), 1107, 1085, 1076 (m), 1027, 1010, 963 (s), 938 (m), 917, 907, 862 (w), 829, 802, 796 (s), 773, 763 (m), 749 (w), 736 (m), 722 (s), 686 (w), 653, 645, 628, 621 (m), 594 (w), 572 (m), 548 (s). GC-MS (EI, 70 eV): m/z (%) = 526 ($[M]^+$, 100), 525 (40), 495 (15), 285 (12). HRMS (EI, 70 eV): calcd for $C_{35}H_{26}O_5$ $[M]^+$: 526.17748, found 526.176367.

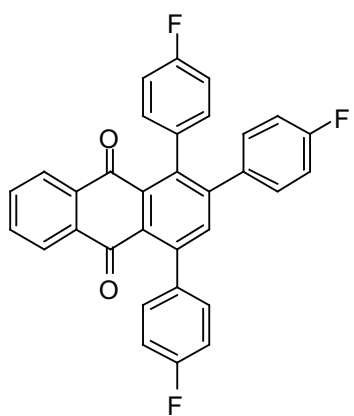
1,2,4-Tris(4-*tert*-butylphenyl)anthraquinone (**194c**)



Starting with **193** (100 mg, 0.15 mmol), **188c** (107 mg, 0.6 mmol), $Pd(PPh_3)_4$ (17 mg, 10 mol-%, 0.015 mmol), K_3PO_4 (159 mg, 0.75 mmol) and 1,4-dioxane (5 mL), **194c** was isolated as an orange solid (77 mg, 83%), mp 244-246 °C. 1H NMR (300 MHz, $CDCl_3$): δ = 1.13 (s, 9H, 3CH₃), 1.20 (s, 9H, 3CH₃), 1.31 (s, 9H, 3CH₃), 6.75-6.76 (m, 2H, ArH), 6.84-6.87 (m, 2H, ArH), 6.99-7.02 (m, 2H, ArH), 7.12-7.15 (m, 2H, ArH), 7.21-7.24 (m, 2H, ArH), 7.36-7.39 (m, 2H, ArH), 7.53 (s, 1H, ArH), 7.55-7.58 (m, 2H, ArH), 7.93-8.03 (m, 2H, ArH). ^{13}C NMR (62.9 MHz, $CDCl_3$): δ = 31.2 (CH₃), 31.4 (CH₃), 31.5 (CH₃), 34.3, 34.4, 34.6, 124.2, 124.4, 125.0, 126.6, 126.8, 127.7, 127.9, 128.6 (C), 129.0 (CH), 131.4 (C), 133.5, 133.5 (CH), 133.6, 134.0, 134.4, 136.8, 137.1 (C), 138.8 (CH), 139.3, 142.0, 143.7, 148.2, 149.1, 149.8 (C), 184.1, 184.6 (CO). IR (KBr, cm^{-1}): ν = 2952 (s), 2902, 2864 (m), 1677, 1669 (s), 1607 (w), 1592 (m), 1574, 1512, 1504, 1475 (w), 1462 (m), 1440, 1392 (w), 1360 (m), 1327 (s), 1309, 1301, 1279, 1266 (m), 1241 (s), 1212, 1201, 1165, 1155 (w), 1114, 1081, 1016, 966 (m), 944, 934, 918, 898, 863 (w), 831 (s), 796 (m), 772, 764, 740 (w), 725 (s), 705, 681 (w), 651, 625 (m), 615 (w), 580 (m), 567 (s), 551 (m). GC-MS (EI, 70 eV): m/z (%) = 604 ($[M]^+$, 31), 590 (11), 589 (24), 548 (14), 547 (33), 532 (03), 490 (04), 287 (11), 69 (06), 57 (100). HRMS (EI, 70 eV): calcd for $C_{44}H_{44}O_2$ $[M]^+$: 604.33358, found 604.33345.

1,2,4-Tris(4-chlorophenyl)anthraquinone (194d)

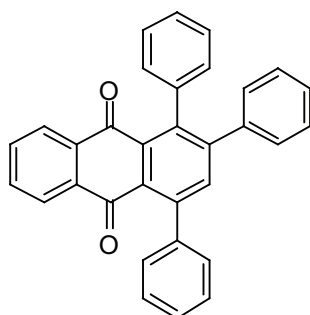
Starting with **193** (100 mg, 0.15 mmol), **188d** (94 mg, 0.6 mmol), Pd(PPh₃)₄ (17 mg, 10 mol-%, 0.015 mmol), K₃PO₄ (159 mg, 0.75 mmol) and 1,4-dioxane (5 mL), **194d** was isolated as a yellow solid (50 mg, 60%), mp 293-295 °C. ¹H NMR (300 MHz, CDCl₃): δ = 6.84-6.92 (m, 4H, ArH), 7.07-7.11 (m, 2H, ArH), 7.18-7.23 (m, 4H, ArH), 7.34-7.38 (m, 2H, ArH), 7.44 (s, 1H, ArH), 7.62-7.65 (m, 2H, ArH), 7.93-8.01 (m, 2H, ArH). ¹³C NMR (75.4 MHz, CDCl₃): δ = 126.7, 126.8, 128.2, 128.2, 128.4, 129.3, 130.5, 130.6 (CH), 131.9, 132.9, 133.5, 133.7, 133.8 (C), 133.9, 134.0 (CH), 134.1, 137.5, 138.0 (C), 138.3 (CH), 141.2, 140.2, 140.7, 142.9, 145.5 (C), 183.8, 184.1 (CO). IR (KBr, cm⁻¹): ν = 3320, 3065, 2923, 2853 (w), 1670 (s), 1650, 1644, 1632 (w), 1591 (m), 1524 (w), 1492 (s), 1470, 1441, 1397, 1370 (w), 1328 (m), 1311 (s), 1282 (m), 1247 (s), 1209, 1158 (w), 1089, 1013, 962 (s), 935, 918, 862 (w), 818 (s), 810, 766 (m), 733 (s), 718 (m), 700, 687, 671, 656 (w), 647 (m), 636, 618, 593 (w), 551 (m). GC-MS (EI, 70 eV): *m/z* (%) = 542 ([M]⁺, 2x ³⁷Cl, 29), 541 ([M+H]⁺, ³⁷Cl, 50), 540 ([M]⁺, ³⁷Cl, 92), 539 ([M+H]⁺, ³⁵Cl, 100), 538 ([M]⁺, ³⁵Cl, 93), 537 (78), 505 (24), 504 (26), 503 (37), 502 (25). HRMS (EI, 70 eV): calcd for C₃₂H₁₇Cl₃O₂ ([M]⁺, ³⁷Cl): 540.02591, found 540.024908, C₃₂H₁₇Cl₃O₂ ([M]⁺, 2x ³⁷Cl): 542.02296, found 542.023142.

1,2,4-Tris(4-fluorophenyl)anthraquinone (194e)

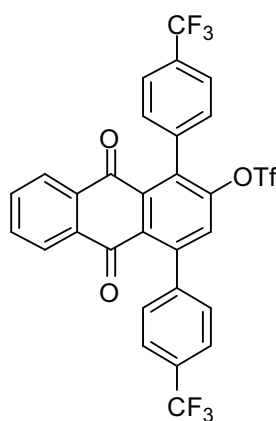
Starting with **193** (100 mg, 0.15 mmol), **188i** (84 mg, 0.6 mmol), Pd(PPh₃)₄ (17 mg, 10 mol-%, 0.015 mmol), K₃PO₄ (159 mg, 0.75 mmol) and 1,4-dioxane (5 mL), **194e** was isolated as an orange crystal (43 mg, 57%), mp 204-206 °C. ¹H NMR (300 MHz, CDCl₃): δ = 6.77-6.83 (m, 2H, ArH), 6.86-6.93 (m, 6H, ArH), 7.04-7.11 (m, 2H, ArH), 7.23-7.27 (m, 2H, ArH), 7.47 (s, 1H, ArH), 7.61-7.64 (m, 2H, ArH), 7.93-8.01 (m, 2H, ArH). ¹³C NMR (62.9 MHz, CDCl₃): δ = 114.7, 114.8, 115.0, 115.1, 115.2, 115.3, 126.6, 126.8, 129.6, 129.7, 130.7, 130.8, 131.0, 131.1 (CH), 131.8, 133.8 (C), 133.8, 133.9 (CH), 133.9, 134.2, 135.2 (d, *J* = 3.3 Hz), 135.5 (d, *J* = 3.6 Hz), 137.7 (d, *J* = 3.6 Hz, C), 138.5 (CH), 140.9, 143.0, 146.9, 161.7 (d, *J*_{F,C} = 246.4 Hz), 161.9 (d, *J*_{F,C} = 248.0 Hz), 162.2 (d, *J*_{F,C}

= 246.6 Hz, CF), 183.7, 184.3 (CO). ^{19}F NMR (282 MHz, CDCl_3): δ = -115.07 (s, F, CF), -114.85 (s, F, CF), -114.14 (s, F, CF). IR (KBr, cm^{-1}): ν = 3069, 3041, 2920, 2852 (w), 1673 (s), 1604 (w), 1592 (m), 1530 (w), 1510 (s), 1442, 1402, 1370 (w), 1328, 1308 (m), 1278 (w), 1245 (m), 1222, 1157 (s), 1092, 1083, 1073, 1014 (w), 963 (m), 945, 927, 866 (w), 829, 817 (s), 804 (m), 786, 766, 745 (w), 734, 721 (m), 709, 701, 686, 658, 650, 642, 624, 617, 587, 560 (w), 551 (m), 534 (w). GC-MS (EI, 70 eV): m/z (%) = 490 ($[\text{M}]^+$, 83), 489 (100), 488 (18), 394 (18). HRMS (EI, 70 eV): calcd for $\text{C}_{32}\text{H}_{17}\text{O}_2\text{F}_3$ $[\text{M}^+]$: 490.11752, found 490.116052.

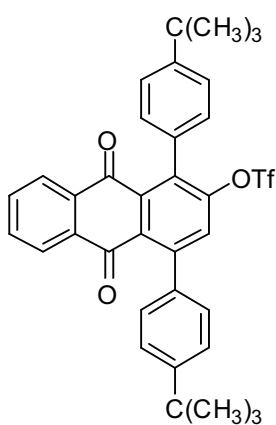
1,2,4-Tris(phenyl)anthraquinone (**194f**)



Starting with **193** (100 mg, 0.15 mmol), **188k** (73 mg, 0.6 mmol), $\text{Pd}(\text{PPh}_3)_4$ (17 mg, 10 mol-%, 0.015 mmol), K_3PO_4 (159 mg, 0.75 mmol) and 1,4-dioxane (5 mL), **194f** was isolated as a yellow solid (58 mg, 86%), mp 228-230 °C. ^1H NMR (300 MHz, CDCl_3): δ = 6.92-7.00 (m, 4H, ArH), 7.06 (t, J = 2.61 Hz, 3H, ArH), 7.16-7.18 (m, 3H, ArH), 7.28-7.38 (m, 5H, ArH), 7.52 (s, 1H, ArH), 7.57-7.60 (m, 2H, ArH), 7.93-8.01 (m, 2H, ArH). ^{13}C NMR (62.9 MHz, CDCl_3): δ = 126.5, 126.6, 126.8, 127.1, 127.2, 127.6, 127.7, 128.0, 128, 129.3, 129.4 (CH), 131.6 (C), 133.6, 133.7 (CH), 133.8, 133.9, 134.4 (C), 138.6 (CH), 139.6, 139.9, 141.8, 142.2, 143.8, 147.7 (C), 183.8, 184.5 (CO). IR (KBr, cm^{-1}): ν = 3329, 3065, 3054, 3022, 2953, 2919, 2850 (w), 1677 (s), 1633 (w), 1590 (m), 1557, 1537, 1524, 1494, 1455, 1443, 1431, 1370 (w), 1322, 1302 (s), 1277 (m), 1243 (s), 1206, 1160 (w), 1085, 1077, 1071 (m), 1034 (w), 1024 (m), 1001, 975 (w), 959 (m), 938, 915, 899, 857, 842, 825 (w), 801, 774, 760, 750, 742 (m), 728 (s), 711 (m), 691 (s), 671 (m), 652 (s), 637, 614, 570 (m), 554 (w), 541 (s). GC-MS (EI, 70 eV): m/z (%) = 436 ($[\text{M}]^+$, 78), 435 (100), 434 (18), 358 (19), 218 (19), 217 (44). HRMS (EI, 70 eV): calcd for $\text{C}_{32}\text{H}_{19}\text{O}_2$ $[\text{M-H}]^+$: 435.13796, found 435.137591.

1,4-Bis(4-trifluoromethylphenyl)-2-(trifluoromethylsulfonyloxy)anthraquinone (195a)

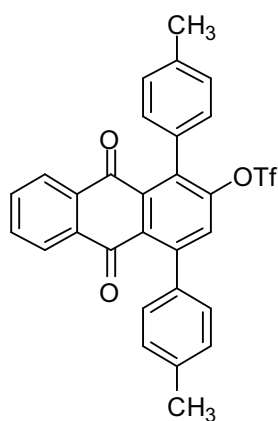
Starting with **193** (100 mg, 0.15 mmol), **188a** (57 mg, 0.3 mmol), Pd(PPh₃)₄ (10 mg, 6 mol-%, 0.009 mmol), K₃PO₄ (96 mg, 0.45 mmol) and 1,4-dioxane (4 mL), **195a** was isolated as an orange solid (61 mg, 61%), mp 168-170 °C. ¹H NMR (300 MHz, CDCl₃): δ = 7.32-7.40 (m, 4H, ArH), 7.48 (s, 1H, ArH), 7.66-7.72 (m, 6H, ArH), 7.94-8.00 (m, 2H, ArH). ¹³C NMR (62.9 MHz, CDCl₃): δ = 118.0 (q, *J*_{F,C} = 320.4 Hz, CF₃), 119.7 (q, *J*_{F,C} = 272.2 Hz, CF₃), 125.4 (t, *J* = 3.8 Hz), 127.0, 127.1, 128.1 (CH), 128.5 (q, *J*_{F,C} = 286.2 Hz, CF₃), 128.9, 129.2 (CH), 129.9, 130.2, 130.4, 132.2, 133.2, 133.3 (C), 134.5, 134.6 (CH), 135.3, 135.7, 137.7, 143.9, 145.6, 149.6 (C), 182.2, 182.2 (CO). ¹⁹F NMR (282 MHz, CDCl₃): δ = -73.86 (s, 3F, CF₃), -62.59 (s, 3F, CF₃), -62.51 (s, 3F, CF₃). IR (KBr, cm⁻¹): ν = 2917 (w), 1675 (m), 1618, 1591, 1541, 1428, 1408 (w), 1321 (s), 1241 (m), 1217 (s), 1190 (w), 1163 (m), 1122, 1108, 1080, 1059 (s), 1040 (w), 1017, 948, 900 (m), 854 (w), 834, 823, 799, 786, 763, 753, 744 (s), 731 (m), 713, 692, 682, 662, 641, 630 (w), 599 (s), 571, 535 (w). GC-MS (EI, 70 eV): *m/z* (%) = 644 ([M]⁺, 100), 643 (68), 625 (11), 576 (14), 575 (48), 512 (21), 511 (56), 510 (29), 509 (13). HRMS (EI, 70 eV): calcd for C₂₉H₁₃F₉O₅S₁ [M]⁺: 644.03345, found 644.03239.

1,4-Bis(4-*tert*-butylphenyl)-2-(trifluoromethylsulfonyloxy)anthraquinone (195b)

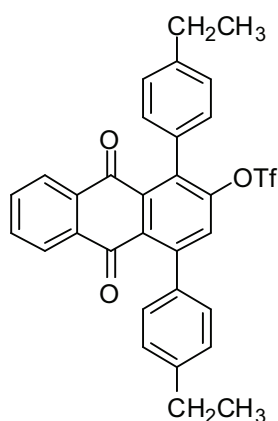
Starting with **193** (100 mg, 0.15 mmol), **188c** (54 mg, 0.3 mmol), Pd(PPh₃)₄ (10 mg, 6 mol-%, 0.009 mmol), K₃PO₄ (96 mg, 0.45 mmol) and 1,4-dioxane (4 mL), **195b** was isolated as a yellow solid (77 mg, 81%), mp 245-247 °C. ¹H NMR (300 MHz, CDCl₃): δ = 0.59 (s, 9H, 3CH₃), 0.60 (s, 9H, 3CH₃), 6.37-6.40 (m, 2H, ArH), 6.46-6.48 (m, 2H, ArH), 6.68-6.74 (m, 4H, ArH), 6.74 (s, 1H, ArH), 6.86-6.90 (m, 2H, ArH), 7.21-7.27 (m, 2H, ArH). ¹³C NMR (62.9 MHz, CDCl₃): δ = 31.3 (3CH₃), 31.4 (3CH₃), 34.7, 34.8 (C), 117.5 (q, *J*_{F,C} = 318.5 Hz, CF₃), 125.2, 125.3, 126.8, 127.0, 127.6, 128.3, 129.5 (CH), 130.8, 132.3, 133.7, 133.8 (C), 133.9, 134.0 (CH), 135.5, 136.5, 137.5, 146.5, 150.1, 150.8, 151.0 (C), 182.8, 182.9 (CO). ¹⁹F NMR (282 MHz, CDCl₃): δ = -74.69 (s, 3F, CF₃). IR (KBr, cm⁻¹): ν = 2965 (m), 2867 (w), 1677 (s), 1590, 1536, 1531, 1513, 1462 (w), 1425 (s), 1404, 1360 (w), 1319 (s), 1268 (m), 1239, 1214 (s), 1177 (m), 1159 (w), 1137, 1115 (s), 1040, 1015, 1004, 977, 966 (w), 947, 900, 844, 825,

812, 803 (s), 776 (w), 746 (m), 732, 722 (s), 699 (w), 686 (m), 661 (w), 642 (m), 608 (s), 597 (m), 566 (s), 528 (m). GC-MS (EI, 70 eV): m/z (%) = 620 ($[M]^+$, 06), 606 (13), 605 (34), 565 (10), 564 (32), 563 (100), 571 (09), 457 (10). HRMS (EI, 70 eV): calcd for $C_{35}H_{31}F_3O_5S$ $[M]^+$: 620.18388, found 620.183785.

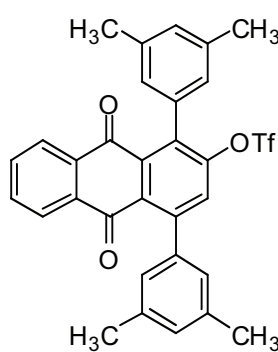
1,4-Bis(4-methylphenyl)-2-(trifluoromethylsulfonyloxy)anthraquinone (**195c**)



Starting with **193** (100 mg, 0.15 mmol), **188e** (41 mg, 0.3 mmol), $Pd(PPh_3)_4$ (10 mg, 6 mol-%, 0.009 mmol), K_3PO_4 (96 mg, 0.45 mmol) and 1,4-dioxane (4 mL), **195c** was isolated as a yellow solid (42 mg, 51%), mp 186-188 °C. 1H NMR (300 MHz, $CDCl_3$): δ = 2.39 (s, 3H, CH_3), 2.40 (s, 3H, CH_3), 7.07-7.10 (m, 2H, ArH), 7.14-7.17 (m, 2H, ArH), 7.22-7.26 (m, 4H, ArH), 7.46 (s, 1H, ArH), 7.59-7.66 (m, 2H, ArH), 7.94-7.98 (m, 2H, ArH). ^{13}C NMR (75.4 MHz, $CDCl_3$): δ = 21.4 (CH_3), 21.5 (CH_3), 118.1 (q, $J_{F,C}$ = 320.7 Hz, CF_3), 126.9, 127.0, 127.8, 128.5, 129.1, 129.2, 129.3 (CH), 130.8, 132.4, 133.7, 133.8 (C), 134.0, 134.1 (CH), 135.5, 136.7, 137.6, 137.8, 137.9, 146.5, 150.1 (C), 182.8, 182.9 (CO). ^{19}F NMR (282 MHz, $CDCl_3$): δ = -73.96 (s, 3F, CF_3). IR (KBr, cm^{-1}): ν = 3022, 2960, 2920, 2860 (w), 1675 (s), 1651, 1592, 1538, 1515, 1446 (w), 1420 (s), 1403, 1379 (w), 1312 (m), 1272, 1261 (w), 1239 (m), 1220, 1205 (s), 1161 (w), 1131 (s), 1037, 1019, 1005, 962 (w), 946, 896 (s), 848 (m), 829, 819, 810, 798 (s), 769 (w), 752 (m), 729 (s), 715 (m), 689, 659, 650, 631 (w), 599 (s), 570, 558, 538, 530 (m). GC-MS (EI, 70 eV): m/z (%) = 536 ($[M]^+$, 85), 535 (23), 523 (10), 522 (26), 521 (100), 404 (10), 403 (48), 402 (33), 401 (20), 389 (18), 388 (77), 387 (61), 386 (27). HRMS (EI, 70 eV): calcd for $C_{29}H_{19}F_3O_5S_1$ $[M]^+$: 536.08998, found 536.090080.

1,4-Bis(4-ethylphenyl)-2-(trifluoromethylsulfonyloxy)anthraquinone (195d)

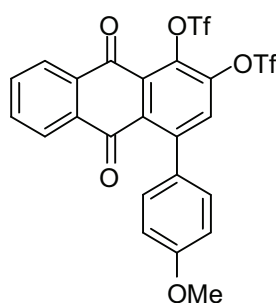
Starting with **193** (100 mg, 0.15 mmol), **188f** (45 mg, 0.3 mmol), Pd(PPh₃)₄ (10 mg, 6 mol-%, 0.009 mmol), K₃PO₄ (96 mg, 0.45 mmol) and 1,4-dioxane (4 mL), **195d** was isolated as a yellow solid (64 mg, 74%), mp 142-144 °C. ¹H NMR (300 MHz, CDCl₃): δ = 1.24 (t, *J* = 7.62 Hz, 3H, CH₃), 1.26 (t, *J* = 7.60 Hz, 3H, CH₃), 2.70 (q, *J* = 15.18, 7.59 Hz, 4H, 2CH₂), 7.08-7.12 (m, 2H, ArH), 7.17-7.20 (m, 2H, ArH), 7.24-7.28 (m, 4H, ArH), 7.47 (s, 1H, ArH), 7.60-7.63 (m, 2H, ArH), 7.94-7.99 (m, 2H, ArH). ¹³C NMR (75.4 MHz, CDCl₃): δ = 15.2 (CH₃), 15.3 (CH₃), 28.6 (CH₂), 28.7 (CH₂), 118.1 (q, *J*_{F,C} = 320.1 Hz, CF₃), 126.9, 127.0, 127.8, 127.9, 128.2, 128.5, 129.4 (CH), 131.0, 132.4, 133.7, 133.8 (C), 134.0, 134.1 (CH), 135.5, 136.7, 137.8, 143.9, 144.2, 146.6, 150.1 (C), 182.8, 182.9 (CO). ¹⁹F NMR (282 MHz, CDCl₃): δ = -74.01 (s, 3F, CF₃). IR (KBr, cm⁻¹): ν = 3024, 2962, 2932, 2874 (w), 1677 (s), 1641, 1610, 1591, 1536, 1514, 1460 (w), 1427 (s), 1410, 1373 (w), 1320, 1311 (m), 1260 (w), 1206 (s), 1173, 1160 (w), 1133 (s), 1050, 1038 (w), 1018 (m), 1005, 977 (w), 946, 899 (s), 846 (m), 823, 802 (s), 766 (w), 752 (m), 729 (s), 703, 688, 663, 642 (m), 631 (w), 599, 569 (s), 541 (m). GC-MS (EI, 70 eV): *m/z* (%) = 564 ([M]⁺, 43), 563 (11), 537 (11), 536 (32), 535 (100), 403 (17), 402 (50), 401 (28), 387 (16), 386 (11), 374 (25), 373 (86). HRMS (EI, 70 eV): calcd for C₃₁H₂₃F₃O₅S₁ [M]⁺: 564.12128, found 564.121848.

1,4-Bis(3,5-dimethylphenyl)-2-(trifluoromethylsulfonyloxy)anthraquinone (195e)

Starting with **193** (100 mg, 0.15 mmol), **188i** (45 mg, 0.3 mmol), Pd(PPh₃)₄ (10 mg, 6 mol-%, 0.009 mmol), K₃PO₄ (96 mg, 0.45 mmol) and 1,4-dioxane (4 mL), **195e** was isolated as a yellow solid (52 mg, 60%), mp 211-213 °C. ¹H NMR (300 MHz, CDCl₃): δ = 2.31 (s, 6H, 2CH₃), 2.32 (s, 6H, 2CH₃), 6.79 (b, 2H, ArH), 6.86 (b, 2H, ArH), 7.03 (b, 2H, ArH), 7.44 (s, 1H, ArH), 7.61-7.64 (m, 2H, ArH), 7.96-7.99 (m, 2H, ArH). ¹³C NMR (75.4 MHz, CDCl₃): δ = 21.4 (2CH₃), 21.4 (2CH₃), 118.1 (q, *J*_{F,C} = 320.2 Hz, CF₃), 125.5, 126.2, 126.9, 127.0, 129.1, 129.6, 129.8 (CH), 132.2, 133.7, 133.7, 133.8 (C), 134.0, 134.1 (CH), 135.3, 136.8, 137.7, 137.9, 140.5, 146.7, 149.9 (C), 182.7, 182.8 (CO). ¹⁹F NMR (282 MHz, CDCl₃): δ = -74.51 (s, 3F, CF₃). IR (KBr, cm⁻¹): ν = 3005, 2916, 2861 (w), 1674 (s), 1593, 1537, 1442, 1427 (w), 1405 (m), 1371 (w),

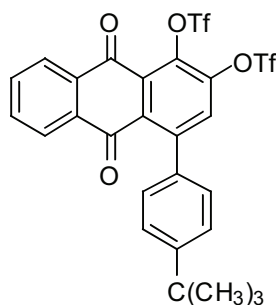
1331, 1294 (m), 1267 (w), 1240 (m), 1206 (s), 1173, 1162 (m), 1134, 1026, 1010 (s), 968 (m), 920, 898, 883 (w), 848, 814, 796 (s), 771, 752 (w), 729, 723 (s), 708 (w), 692, 648, 631, 604 (s), 570, 552, 530 (m). GC-MS (EI, 70 eV): m/z (%) = 564 ($[M]^+$, 66), 550 (22), 549 (80), 432 (14), 431 (49), 430 (21), 417 (34), 416 (86), 415 (36), 402 (16), 401 (57), 387 (14), 215 (14), 208 (100), 207 (15). HRMS (EI, 70 eV): calcd for $C_{31}H_{23}F_3O_5S$ $[M]^+$: 564.12128, found 564.122443.

1,2-Bis(trifluoromethylsulfonyloxy)-4-(4-methoxyphenyl)anthraquinone (196a)



Starting with **193** (100 mg, 0.15 mmol), **188b** (23 mg, 0.15 mmol), $Pd(PPh_3)_4$ (5 mg, 3 mol-%, 0.0045 mmol), K_3PO_4 (48 mg, 0.225 mmol) and 1,4-dioxane (3 mL), **196a** was isolated as a red solid (36 mg, 38%), mp 87-88 °C. 1H NMR (300 MHz, $CDCl_3$): δ = 3.82 (s, 3H, OCH_3), 6.91-6.93 (m, 1H, ArH), 6.94-6.96 (m, 1H, ArH), 7.13-7.14 (m, 1H, ArH), 7.16-7.18 (m, 1H, ArH), 7.59 (s, 1H, ArH), 7.69-7.78 (m, 2H, ArH), 7.99-8.01 (m, 1H, ArH), 8.21-8.24 (m, 1H, ArH). ^{13}C NMR (62.9 MHz, $CDCl_3$): δ = 55.3 (OCH_3), 114.0 (CH), 115.9 (q, $J_{F,C}$ = 318.4 Hz, CF_3), 121.0 (q, $J_{F,C}$ = 320.2 Hz, CF_3), 127.2, 127.4, 129.2 (CH), 129.3 (C), 131.1 (CH), 131.2, 131.9, 132.9, 133.4 (C), 134.5, 135.0 (CH), 138.1, 143.1, 146.2, 159.9 (C), 181.1, 181.4 (CO). ^{19}F NMR (282 MHz, $CDCl_3$): δ = -73.33 (q, J_F = 5.33, 2.45 Hz, 3F, CF_3), -72.56 (q, J_F = 5.70, 2.79 Hz, 3F, CF_3). IR (KBr, cm^{-1}): ν = 2961, 2916, 2840 (w), 1680 (s), 1607, 1593, 1579, 1513 (w), 1432 (s), 1323 (m), 1303 (w), 1243, 1204, 1177, 1168, 1126 (s), 1044, 1030 (m), 1013, 996 (s), 905 (w), 865, 830, 805, 784, 760, 723 (s), 684, 654, 644, 622 (m), 593, 579 (s), 534 (m). GC-MS (EI, 70 eV): m/z (%) = 610 ($[M+H]^+$, 100), 479 (10), 478 (27), 477 (82), 385 (10), 346 (12), 345 (24), 317 (28), 316 (93), 315 (10). HRMS (EI, 70 eV): calcd for $C_{23}H_{12}F_6O_9S_2$ $[M]^+$: 609.98214, found 609.981630.

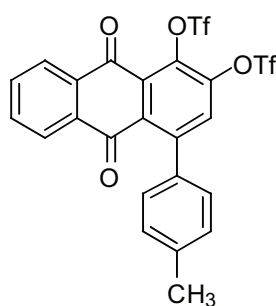
1,2-Bis(trifluoromethylsulfonyloxy)-4-(4-*tert*-butylphenyl)anthraquinone (196b)



Starting with **193** (100 mg, 0.15 mmol), **188c** (27 mg, 0.15 mmol), $Pd(PPh_3)_4$ (5 mg, 3 mol-%, 0.0045 mmol), K_3PO_4 (48 mg, 0.225 mmol) and 1,4-dioxane (3 mL), **196b** was isolated as a yellow solid (40 mg, 41%), mp 80-81 °C. 1H NMR (300 MHz, $CDCl_3$): δ = 1.33 (s, 9H, 3 CH_3), 7.13-7.17 (m, 2H, ArH), 7.41-7.44 (m, 2H, ArH), 7.60 (s, 1H, ArH), 7.69-7.78 (m, 2H, ArH), 7.99-8.02 (m, 1H, ArH), 8.22-8.25 (m, 1H, ArH). ^{13}C NMR (62.9 MHz, $CDCl_3$): δ = 30.31 (3 CH_3), 33.75 (C), 115.0 (q, $J_{F,C}$ = 319.4

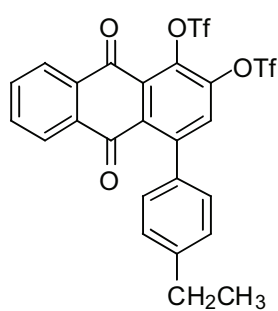
Hz, CF₃), 120.0 (q, $J_{F,C} = 321.7$ Hz, CF₃), 124.5, 126.2, 126.4, 126.5 (CH), 128.2 (C), 130.2 (CH), 131.0, 132.0, 132.4 (C), 133.5, 134.0 (CH), 135.1, 137.2, 142.1, 145.5, 150.5 (C), 180.1, 180.3 (CO). ¹⁹F NMR (282 MHz, CDCl₃): $\delta = 73.32$ (q, $J_F = 5.31, 2.52$ Hz, 3F, CF₃), -72.56 (q, $J_F = 6.09, 2.97$ Hz, 3F, CF₃). IR (KBr, cm⁻¹): $\nu = 2963$ (m), 2870 (w), 1684 (s), 1594, 1577 (w), 1436 (s), 1364 (w), 1325 (m), 1303 (w), 1245, 1218 (s), 1169 (w), 1135 (s), 1105, 1045, 1018, 1000, 906 (w), 870 (m), 839 (w), 806 (m), 783, 763, 727, 703, 685, 655, 644, 624 (w), 598 (m), 575 (w). GC-MS (EI, 70 eV): m/z (%) = 636 ([M]⁺, 53), 623 (12), 622 (27), 621 (90), 581 (14), 580 (27), 579 (100), 447 (26). HRMS (EI, 70 eV): calcd for C₂₆H₁₈F₆O₈S₂ [M]⁺: 636.03418, found 636.033895.

1,2-Bis(trifluoromethylsulfonyloxy)-4-(4-methylphenyl)anthraquinone (**196c**)



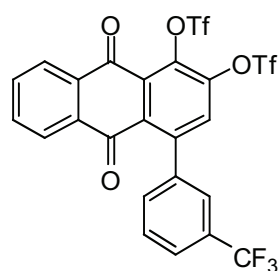
Starting with **193** (100 mg, 0.15 mmol), **188e** (20 mg, 0.15 mmol), Pd(PPh₃)₄ (5 mg, 3 mol-%, 0.0045 mmol), K₃PO₄ (48 mg, 0.225 mmol) and 1,4-dioxane (3 mL), **196c** was isolated as a yellow solid (56 mg, 61%), mp 79-80 °C. ¹H NMR (300 MHz, CDCl₃): $\delta = 2.37$ (s, 3H, CH₃), 7.09-7.11 (m, 2H, ArH), 7.20-7.23 (m, 2H, ArH), 7.58 (s, 1H, ArH), 7.67-7.76 (m, 2H, ArH), 7.97-8.00 (m, 1H, ArH), 8.20-8.23 (m, 1H, ArH). ¹³C NMR (62.9 MHz, CDCl₃): $\delta = 21.36$ (CH₃), 113.4 (q, $J_{F,C} = 318.8$ Hz, CF₃), 123.6 (q, $J_{F,C} = 319.1$ Hz, CF₃), 127.2, 127.4, 127.6 (CH), 128.3 (C), 129.3, 131.1 (CH), 132.0, 132.9, 133.4 (C), 134.6, 135.0 (CH), 136.2, 138.3, 138.4, 143.1, 146.5 (C), 181.1, 181.3 (CO). ¹⁹F NMR (282 MHz, CDCl₃): $\delta = -73.33$ (q, $J_F = 5.13, 2.34$ Hz, 3F, CF₃), -72.58 (d, $J_F = 2.88$ Hz, 3F, CF₃). IR (KBr, cm⁻¹): $\nu = 3070, 3027, 2924, 2871$ (w), 1680 (s), 1593, 1578, 1513 (w), 1432 (s), 1322 (m), 1303 (w), 1243 (m), 1203 (s), 1168 (m), 1126 (s), 1044, 1021, 1015 (w), 998 (m), 946, 905 (w), 865, 818, 805 (s), 783, 760 (m), 723 (s), 708, 684, 645, 627 (w), 593, 576 (s), 532 (w). GC-MS (EI, 70 eV): m/z (%) = 594 ([M+H]⁺, 17), 579 (14), 461 (19), 369 (10), 330 (19), 329 (32), 316 (10), 315 (45), 301 (19), 300 (31), 215 (31), 64 (100), 48 (58). HRMS (EI, 70 eV): calcd for C₂₃H₁₂F₆O₈S₂ [M]⁺: 593.98723, found 593.985244.

1,2-Bis(trifluoromethylsulfonyloxy)-4-(4-ethylphenyl)anthraquinone (196d)



Starting with **193** (100 mg, 0.15 mmol), **188f** (22 mg, 0.15 mmol), Pd(PPh₃)₄ (5 mg, 3 mol-%, 0.0045 mmol), K₃PO₄ (48 mg, 0.225 mmol) and 1,4-dioxane (3 mL), **196d** was isolated as an orange solid (61 mg, 65%), mp 101-103 °C. ¹H NMR (300 MHz, CDCl₃): δ = 1.25 (t, *J* = 7.65 Hz, CH₃), 2.69 (q, *J* = 14.94, 7.62 Hz, 2H, CH₂), 7.12-7.15 (m, 2H, ArH), 7.24-7.26 (m, 2H, ArH), 7.59 (s, 1H, ArH), 7.68-7.77 (m, 2H, ArH), 7.98-8.01 (m, 1H, ArH), 8.21-8.24 (m, 1H, ArH). ¹³C NMR (75.4 MHz, CDCl₃): δ = 15.2 (CH₃), 28.6 (CH₂), 113.2 (q, *J*_{F,C} = 321.0 Hz, CF₃), 121.7 (q, *J*_{F,C} = 321.0 Hz, CF₃), 126.2, 126.4, 126.7, 127.0 (CH), 128.2, 130.1 (C), 131.0 (CH), 131.9, 132.4 (C), 133.5, 134.0 (CH), 135.4, 137.3, 142.1, 143.6, 145.5 (C), 180.1, 180.3 (CO). ¹⁹F NMR (282 MHz, CDCl₃): δ = -73.32 (q, *J*_F = 5.31, 2.76 Hz, 3F, CF₃), -72.56 (q, *J*_{CF} = 6.09, 2.94 Hz, 3F, CF₃). IR (KBr, cm⁻¹): ν̄ = 3075, 3027, 2965, 2931, 2874 (w), 1681 (s), 1611, 1593, 1577, 1512 (w), 1433 (s), 1323 (m), 1303 (w), 1243 (m), 1205 (s), 1168 (m), 1128 (s), 1044 (w), 1015, 998 (m), 905 (w), 865 (s), 826 (m), 803 (s), 783, 760, 754 (m), 723 (s), 684, 654, 645, 626 (w), 594 (s), 533 (w). GC-MS (EI, 70 eV): *m/z* (%) = 608 ([M]⁺, 32), 581 (11), 580 (20), 579 (85), 475 (14), 447 (14), 383 (12), 382 (12), 354 (25), 344 (13), 343 (23), 316 (18), 315 (100), 314 (36), 313 (14). HRMS (EI, 70 eV): calcd for C₂₄H₁₄F₆O₈S₂ [M]⁺: 608.00288, found 608.003921.

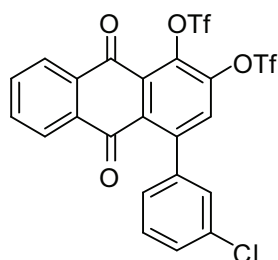
1,2-Bis(trifluoromethylsulfonyloxy)-4-(3-trifluoromethylphenyl)anthraquinone (196e)



Starting with **193** (100 mg, 0.15 mmol), **188g** (28 mg, 0.15 mmol), Pd(PPh₃)₄ (5 mg, 3 mol-%, 0.0045 mmol), K₃PO₄ (48 mg, 0.225 mmol) and 1,4-dioxane (3 mL), **196e** was isolated as a yellow crystal (40 mg, 40%), mp 169-171 °C. ¹H NMR (300 MHz, CDCl₃): δ = 7.41 (d, *J* = 7.71 Hz, 1H, ArH), 7.47 (b, 1H, ArH), 7.54 (d, *J* = 7.80 Hz 1H, ArH), 7.59 (s, 1H, ArH), 7.68-7.71 (m, 1H, ArH), 7.73-7.81 (m, 2H, ArH), 7.97-8.00 (m, 1H, ArH), 8.23-8.26 (m, 1H, ArH). ¹³C NMR (62.9 MHz, CDCl₃): δ = 117.5 (q, *J*_{F,C} = 321.3 Hz, CF₃), 121.2 (q, *J*_{F,C} = 272.3 Hz, CF₃), 123.5 (d, *J* = 3.8 Hz), 124.2 (d, *J* = 3.7 Hz), 126.3, 126.6 (CH), 127.3 (q, *J*_{F,C} = 265.5 Hz, CF₃), 128.0 (CH), 128.4 (C), 129.8 (d, *J* = 5.1 Hz), 129.9, 130.3, 131.0 (C), 131.9, 132.0, 133.9, 134.2 (CH), 138.0, 138.8, 142.4, 143.3 (C), 179.8, 179.9 (CO). ¹⁹F NMR (282 MHz, CDCl₃): δ = -73.25 (q, *J*_F = 5.78, 2.84 Hz, 3F, CF₃), -72.48 (q, *J*_F = 5.16, 2.25 Hz, 3F, CF₃), -62.59 (s, 3F, CF₃). IR (KBr, cm⁻¹): ν̄ = 2954, 2923, 2852 (w), 1690

(m), 1676 (s), 1612, 1593, 1578, 1570, 1489 (w), 1446, 1429 (s), 1412 (m), 1389, 1334 (w), 1306, 1242, 1208, 1180, 1163, 1118, 1049, 1071, 1046, 1007 (s), 927, 909 (w), 879, 841 (s), 828 (m), 811, 802, 782 (s), 773 (w), 759, 741, 724, 717, 701, 680 (s), 657, 650, 624 (m), 603, 591, 571 (s), 530 (m). GC-MS (EI, 70 eV): m/z (%) = 647 ($[M]^+$, 17), 579 (10), 516 (15), 515 (49), 451 (29), 424 (25), 423 (100), 395 (13), 384 (26), 383 (50), 312 (12), 355 (37), 354 (71). HRMS (EI, 70 eV): calcd for $C_{23}H_9F_9O_8S_2$ $[M]^+$: 647.95896, found 647.958459.

1,2-Bis(trifluoromethylsulfonyloxy)-4-(3-chlorophenyl)anthraquinone (196f)



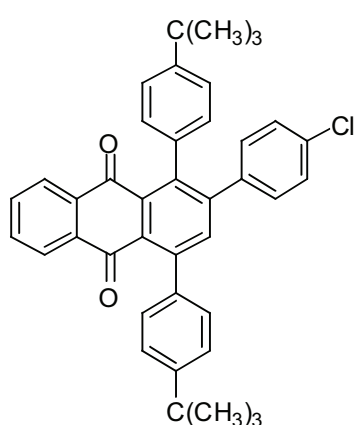
Starting with **193** (100 mg, 0.15 mmol), **188m** (23 mg, 0.15 mmol), $Pd(PPh_3)_4$ (5 mg, 3 mol-%, 0.0045 mmol), K_3PO_4 (48 mg, 0.225 mmol) and 1,4-dioxane (3 mL), **196f** was isolated as a yellow crystal (53 mg, 56%), mp 78-80 °C. 1H NMR (300 MHz, $CDCl_3$): δ = 6.58 (dt, J = 7.17, 1.65 Hz, 1H, ArH), 6.68-6.70 (m, 1H, ArH), 6.81-6.90 (m, 2H, ArH), 7.06 (s, 1H, ArH), 7.19-7.28 (m, 2H, ArH), 7.47-7.50 (m, 1H, ArH), 7.71-7.74 (m, 1H, ArH). ^{13}C NMR (62.9 MHz, $CDCl_3$): δ = 114.0 (q, $J_{F,C}$ = 316.2 Hz, CF_3), 120.0 (q, $J_{F,C}$ = 320.2 Hz, CF_3), 124.8, 126.3, 126.5, 126.6, 127.5 (CH), 128.3 (C), 128.8, 129.8 (CH), 130.9, 131.9, 132.0 (C), 133.5 (CH), 133.8 (C), 134.1 (CH), 137.8, 139.8, 142.2, 143.5 (C), 179.8, 179.9 (CO). ^{19}F NMR (282 MHz, $CDCl_3$): δ = -73.90 (q, J_F = 4.99, 2.85 Hz, 3F, CF_3), -73.11 (q, $J_{F,C}$ = 5.53, 2.99 Hz, 3F, CF_3). IR (KBr, cm^{-1}): ν = 3070, 2961 (w), 1680 (s), 1592, 1577 (w), 1433 (s), 1323 (m), 1303 (w), 1244, 1205 (s), 1169 (m), 1127, 1093, 1080 (s), 1045 (m), 1008, 876, 837, 799, 784, 761, 711, 689, 654 (s), 623 (m), 593, 572 (s), 535 (m). GC-MS (EI, 70 eV): m/z (%) = 617 ($[M]^+$, $2x$ ^{37}Cl , 07), 616 ($[M+H]^+$, ^{37}Cl , 32), 615 ($[M]^+$, ^{37}Cl , 24), 614 ($[M+H]^+$, ^{35}Cl , 82), 613 ($[M]^+$, ^{35}Cl , 16), 579 (15), 483 (12), 482 (12), 481 (29), 446 (16), 382 (18), 355 (18), 354 (100), 350 (12), 349 (20). HRMS (EI, 70 eV): calcd for $C_{22}H_9Cl_1F_6O_8S_2$ ($[M]^+$, ^{35}Cl): 613.93261, found 613.932573. calcd for $C_{22}H_9Cl_1F_6O_8S_2$ ($[M]^+$, ^{37}Cl): 615.92966, found 615.931303.

3.4.2 General Procedure for the Synthesis of 197

The reaction was carried out in a pressure tube. To a dioxane suspension (4 mL) of **193** (100 mg, 0.15 mmol), $Ar^1B(OH)_2$ (0.3 mmol) and $Pd(PPh_3)_4$ (6 mol-%) was added K_3PO_4 (96 mg, 0.45 mmol), and the resultant solution was degassed by bubbling argon through the solution for 10 min. The mixture was heated at 95 °C under an argon atmosphere for 10 h. The

mixture was cooled to 20 °C. Ar²B(OH)₂ (0.15 mmol), Pd(PPh₃)₄ (3 mol-%), K₃PO₄ (48 mg, 0.225 mmol) and dioxane (2 mL) were added. The reaction mixtures were heated under an argon atmosphere for 10 h at 110 °C. They were diluted with H₂O and extracted with CH₂Cl₂ (3 × 25 mL). The combined organic layers were dried (Na₂SO₄), filtered and the filtrate was concentrated in vacuo. The residue was purified by flash chromatography (flash silica gel, EtOAc/heptanes).

1,4-Bis(4-*tert*-butylphenyl)-2-(4-chlorophenyl)anthraquinone (**197**)



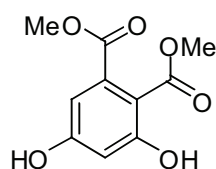
Starting with **193** (100 mg, 0.15 mmol), **188c** (54 mg, 0.3 mmol), Pd(PPh₃)₄ (17 mg, 10 mol-%, 0.015 mmol), K₃PO₄ (143 mg, 0.675 mmol) and 1,4-dioxane (5 mL), and **188d** (23 mg, 0.15 mmol), **197** was isolated as a yellow solid (40 mg, 45%), mp 288-290 °C. ¹H NMR (300 MHz, CDCl₃): δ = 1.25 (s, 9H, 3CH₃), 1.32 (s, 9H, 3CH₃), 6.80-6.83 (m, 2H, ArH), 6.84-6.88 (m, 2H, ArH), 6.98-7.01 (m, 2H, ArH), 7.17-7.24 (m, 4H, ArH), 7.39-7.41 (m, 2H, ArH), 7.48 (s, 1H, ArH), 7.58-7.62 (m, 2H, ArH), 7.94-8.01 (m, 2H, ArH). ¹³C NMR (62.9 MHz, CDCl₃): δ = 31.3 (3CH₃), 31.4 (3CH₃), 34.5, 34.6 (C), 124.7, 125.1, 126.6, 126.8, 127.6, 127.8 (CH), 128.2 (C), 128.9, 130.7 (CH), 131.8, 133.1 (C), 133.5, 133.6 (CH), 133.9, 134.4, 136.5, 138.2 (C), 138.6 (CH), 139.0, 141.7, 143.8, 146.5, 149.5, 150.0 (C), 183.9, 184.5 (CO). IR (KBr, cm⁻¹): ν = 3076, 3025 (w), 2958 (m), 2902, 2865 (w), 1677 (s), 1591 (m), 1523, 1512, 1490, 1471, 1462, 1443, 1423, 1400, 1358 (w), 1329, 1306, 1269, 1248, 1217 (m), 1158, 1137, 1115 (w), 1092 (m), 1039 (w), 1013 (m), 964, 946, 935, 915, 899, 863, 846, 836 (w), 822 (s), 800 (m), 768, 746 (w), 730 (s), 721 (m), 697, 669, 658, 647, 631, 621, 608 (w), 575, 568 (m), 531 (w). GC-MS (EI, 70 eV): *m/z* (%) = 585 ([M+H]⁺, ³⁷Cl, 08), 584 ([M]⁺, ³⁷Cl, 22), 583 ([M+H]⁺, ³⁵Cl, 22), 582 ([M]⁺, ³⁵Cl, 46), 581 (10), 570 (15), 569 (30), 568 (40), 567 (63), 566 (10), 565 (10), 528 (20), 527 (44), 526 (56), 525 (100), 524 (11), 513 (10), 512 (23), 511 (27), 510 (43). HRMS (EI, 70 eV): calcd for C₄₀H₃₅ClO₂ [M]⁺: 582.23201, found 582.231833.

3.5 Synthesis of Dimethyl 3,5-dihydroxyphthalate (**200**)

To a solution of Diene **198** (1 equiv) in toluene (0.5 mL/mmol) was added to DMAD **199** (1.5 equiv) at -78 °C. The mixture was allowed to warm to 50 °C during 48 h with stirring.

To the mixture were added hydrochloric acid (10%) and dichloromethane (10 mL/2 mmol). The organic and the aqueous layer were separated and the latter was extracted with CH₂Cl₂. The combined organic layers were dried (Na₂SO₄), filtered and the filtrate was concentrated in vacuo. The residue was purified by column chromatography (flash silica gel, heptanes/EtOAc).

Dimethyl 3,5-dihydroxyphthalate (**200**)

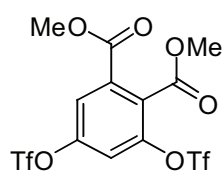


Starting with **198** (5.0 g, 19.19 mmol), Toluene (5 mL), **199** (4.1 g, 3.5 mL, 43.2 mmol), **200** was isolated as colorless solid (1.45 g, 33%), mp 127-129 °C. ¹H-NMR (300 MHz, CDCl₃): δ = 3.80 (s, 3H, OCH₃), 3.81 (s, 3H, OCH₃), 6.34 (d, *J* = 2.35 Hz, 1H, ArH), 6.40 (d, *J* = 2.35 Hz, 1H, ArH), 6.95 (s, 1H, OH), 10.89 (s, 1H, OH). ¹³C-NMR (62.9 MHz, CDCl₃): δ = 52.6 (OCH₃), 53.0 (OCH₃), 102.6 (C), 104.8, 108.1 (CH), 137.1, 161.4, 163.6 (C), 169.0, 170.2 (CO). IR (KBr, cm⁻¹): ν = 3201 (m), 3074, 3007, 2954, 2851 (w), 1726 (w), 1690 (m), 1667, 1621 (s), 1586 (m), 1567, 1536, 1515 (w), 1493 (m), 1435 (s), 1383, 1337 (m), 1302, 1238, 1195, 1182, 1165 (s), 1108, 1024, 994, 948, 917, 865, 855, 850 (m), 833 (w), 799, 782 (m), 724, 703 (s), 643, 615, 578, 543 (m). GC-MS (EI, 70 eV): *m/z* (%) = 226 ([M]⁺ 34), 195 (46), 194 (42), 164 (14), 137 (12), 136 (100), 135 (17). HRMS (EI, 70 eV): calcd for C₁₀H₁₀O₆ [M]⁺: 226.04719, found 226.046991.

3.5.1 Synthesis of Dimethyl 3,5-bis(trifluoromethylsulfonyloxy)phthalate (**201**)

To a solution of **200** (1.0 equiv) in CH₂Cl₂ (10 mL/mmol) was added pyridine (4.0 equiv) at room temperature under an argon atmosphere. After 10 min, Tf₂O (2.4 equiv) was added at -78 °C. The mixture was allowed to warm up to room temperature and stirred for overnight. The reaction mixture was filtered and the filtrate was concentrated in vacuo. The products of the reaction mixture were isolated by rapid column chromatography (flash silica gel, heptanes/EtOAc).

Dimethyl 3,5-bis(trifluoromethylsulfonyloxy)phthalate (**201**)

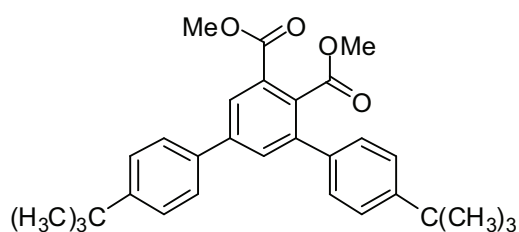


Starting with **200** (1.76 g, 7.8 mmol), pyridine (2.5 mL, 31.2 mmol), CH₂Cl₂ (80 mL), Tf₂O (3.15 mL, 18.74 mmol), **201** was isolated as viscous red oil (3.00 g, 78%). ¹H-NMR (300 MHz, CDCl₃): δ = 3.87 (s, 3H, OCH₃), 3.93 (s, 3H, OCH₃), 7.43 (d, *J* = 2.34 Hz, 1H, ArH), 7.86 (d, *J* = 2.34 Hz, 1H, ArH). ¹³C-NMR (62.9 MHz, CDCl₃): δ = 53.5 (OCH₃), 53.6 (OCH₃), 118.3 (q, *J*_{F,C} = 320.6 Hz, CF₃), 118.6 (q, *J*_{F,C} = 321.1 Hz, CF₃), 119.2, 122.8 (CH), 129.3, 132.3, 146.4, 149.2 (C), 162.7, 163.2 (CO). ¹⁹F NMR (282 MHz, CDCl₃): δ = -72.25 (d, *J*_F = 2.34 Hz, 3F, CF₃), -73.23 (d, *J*_F = 2.25 Hz, 3F, CF₃). IR (KBr, cm⁻¹): ν = 3102, 3011, 2960, 2904, 2848 (w), 1737 (s), 1610, 1587, 1476 (w), 1428, 1298, 1245, 1205, 1125 (s), 1082, 1002 (m), 980 (s), 954, 913 (m), 878 (w), 841 (m), 818, 791 (s), 772 (w), 755 (s), 743 (m), 700, 676, 639 (w), 597 (s). GC-MS (EI, 70 eV): *m/z* (%) = 490 ([M+H]⁺ 07), 461 (11), 460 (14), 459 (100), 395 (11), 268 (14). HRMS (EI, 70 eV): calcd for C₁₂H₈F₆O₁₀S₂ [M]⁺: 489.94576, found 489.945970.

3.5.2 General Procedure for Suzuki-Miyaura Reactions

A 1,4-dioxane solution (4 mL per 3 mmol of **201**) of **201**, K₂CO₃, Pd(PPh₃)₄ and arylboronic acid **188** was stirred at 110 °C or 90 °C for 10 h. After cooling to 20 °C, distilled water was added. The organic and the aqueous layers were separated and the latter was extracted with CH₂Cl₂. The combined organic layers were dried (Na₂SO₄), filtered and the filtrate was concentrated in vacuo. The residue was purified by column chromatography.

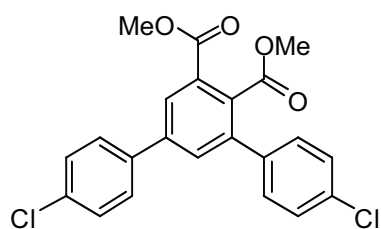
Dimethyl 3,5-bis(4-*tert*-butylphenyl)phthalate (**202a**)



Starting with **201** (200 mg, 0.40 mmol), **188c** (171 mg, 0.96 mmol), Pd(PPh₃)₄ (28 mg, 6 mol%, 0.024 mmol), K₃PO₄ (255 mg, 1.2 mmol) and 1,4-dioxane (4 mL), **202a** was isolated as colorless oil (171 mg, 91%). ¹H-NMR (300 MHz, CDCl₃): δ = 1.24 (s, 18H, 6CH₃), 3.60 (s, 3H, OCH₃), 3.81 (s, 3H, OCH₃), 7.24-7.66 (m, 8H, ArH), 8.10 (s, 1H, ArH), 8.11 (s, 1H, ArH). ¹³C-NMR (62.9 MHz, CDCl₃): δ = 30.2, 30.2 (6CH₃), 33.5, 33.5 (2C), 51.2, 51.5 (OCH₃), 124.2, 124.8, 125.8, 126.0, 127.2 (CH), 127.6 (C), 131.5 (CH), 132.0, 135.1, 135.3, 140.0, 140.9, 149.7, 150.3 (C), 165.2, 168.4 (CO). IR (KBr, cm⁻¹): ν = 3030 (w), 2951, 2903, 2867 (m), 2255, 1911 (w), 1726 (s), 1600, 1514, 1460 (w), 1431 (m), 1393, 1362

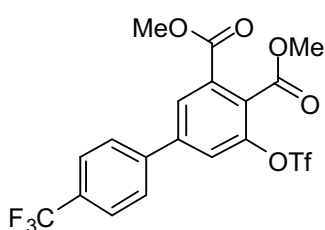
(w), 1343 (m), 1264, 1242, 1199 (s), 1176 (m), 1122, 1067 (s), 1056 (m), 1016, 976, 963 (w), 906 (m), 874, 854 (w), 832 (s), 805 (w), 793 (m), 775 (w), 729 (s), 707 (m), 696, 647, 625 (w), 589, 555 (m). GC-MS (EI, 70 eV): m/z (%) = 458 ($[M]^+$, 44), 444 (31), 443 (100), 214 (10). HRMS (EI, 70 eV): calcd for $C_{30}H_{34}O_4$ $[M]^+$: 458.24516, found 458.244023.

Dimethyl 3,5-bis(4-chlorophenyl)phthalate (**202b**)



Starting with **201** (200 mg, 0.40 mmol), **188d** (150 mg, 0.96 mmol), $Pd(PPh_3)_4$ (28 mg, 6 mol%, 0.024 mmol), K_3PO_4 (255 mg, 1.2 mmol) and 1,4-dioxane (4 mL), **202b** was isolated as colorless oil (150 mg, 88%). 1H -NMR (300 MHz, $CDCl_3$): δ = 3.62 (s, 3H, OCH_3), 3.84 (s, 3H, OCH_3), 7.26-7.36 (m, 6H, ArH), 7.44-7.47 (m, 2H, ArH), 7.57 (d, J = 1.86 Hz, 1H, ArH), 8.09 (d, J = 1.86 Hz, 1H, ArH). ^{13}C -NMR (62.9 MHz, $CDCl_3$): δ = 52.5 (OCH_3), 52.7 (OCH_3), 127.5, 128.4, 128.6 (CH), 129.1 (C), 129.2, 129.9, 132.2 (CH), 133.6, 134.3, 134.6, 137.3, 137.5, 140.1, 141.1 (C), 165.8, 168.8 (CO). IR (KBr, cm^{-1}): ν = 3067, 3030, 2997, 2949, 2840 (w), 1723 (s), 1601 (w), 1494 (m), 1458 (w), 1430 (m), 1398, 1380 (w), 1341 (m), 1269, 1241 (s), 1199, 1175 (m), 1119, 1090, 1066 (s), 1054 (m), 1012 (s), 973, 960, 904, 872, 845 (w), 825 (s), 806 (w), 792 (m), 772 (w), 755 (m), 729 (s), 705, 692, 646, 633, 618, 566 (w). GC-MS (EI, 70 eV): m/z (%) = 418 ($[M]^+$, $2 \times ^{37}Cl$, 07), 417 ($[M+H]^+$, ^{37}Cl , 09), 416 ($[M]^+$, ^{37}Cl , 40), 415 ($[M+H]^+$, ^{35}Cl , 14), 414 ($[M]^+$, ^{35}Cl , 60), 387 (12), 386 (14), 385 (67), 384 (23), 383 (100), 226 (15). HRMS (EI, 70 eV): calcd for $C_{22}H_{16}Cl_2O_4$ ($[M]^+$, ^{35}Cl): 414.04202, found 414.041035.

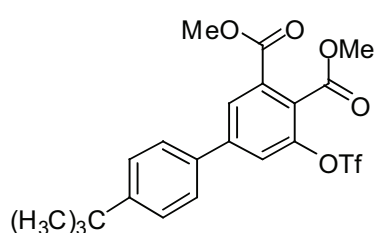
Dimethyl 3-(trifluoromethylsulfonyloxy)-5-(4-trifluoromethylphenyl)phthalate (**203a**)



Starting with **201** (200 mg, 0.40 mmol), **188a** (76 mg, 0.40 mmol), $Pd(PPh_3)_4$ (18 mg, 4 mol%, 0.016 mmol), K_3PO_4 (127 mg, 0.6 mmol) and 1,4-dioxane (3 mL), **203a** was isolated as colorless solid (152 mg, 76%), mp 103-104 °C. 1H -NMR (300 MHz, $CDCl_3$): δ = 3.88 (s, 3H, OCH_3), 3.92 (s, 3H, OCH_3), 7.61-7.68 (m, 4H, ArH), 7.72 (d, J = 1.56 Hz, 1H, ArH), 8.14 (d, J = 1.56 Hz, 1H, ArH). ^{13}C -NMR (62.9 MHz, $CDCl_3$): δ = 53.2, 53.3 (OCH_3), 118.4 (q, J_{FC} = 320.5 Hz, CF_3), 122.0 (C), 123.8 (CH), 125.6 (C), 126.3 (d, J = 3.76 Hz), 127 (CH), 128.2 (C), 128.3 (CH), 131.5, 140.8, 143.3, 146.5 (C), 164.3, 164.4 (CO). ^{19}F NMR (282 MHz, $CDCl_3$): δ = -73.46 (s, 3F, CF_3), -62.77 (s, 3F, CF_3). IR

(KBr, cm^{-1}): $\nu = 3088, 3009, 2956, 2923, 2815$ (w), 1738 (m), 1728 (s), $1613, 1562, 1481$ (w), 1427 (s), 1394 (w), $1324, 1292$ (s), 1260 (w), 1246 (m), $1206, 1163, 1142, 1115, 1098, 1069, 1055$ (s), 1016 (m), 992 (s), 952 (w), 920 (m), $897, 870$ (w), 842 (m), $823, 804, 791$ (s), 772 (m), 758 (s), 742 (m), $671, 663, 637$ (w), 599 (s), 568 (w). GC-MS (EI, 70 eV): m/z (%) = 486 ($[\text{M}]^+$, 43), 456 (17), 455 (100), 264 (830), 263 (12). HRMS (EI, 70 eV): calcd for $\text{C}_{18}\text{H}_{12}\text{F}_6\text{O}_7\text{S}_1$ $[\text{M}^+]$: 486.02024, found 486.020205.

Dimethyl 3-(trifluoromethylsulfonyloxy)-5-(4-*tert*-butylphenyl)phthalate (203b)

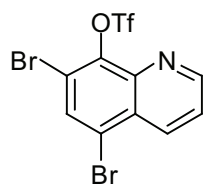


Starting with **201** (200 mg, 0.40 mmol), **188c** (71 mg, 0.40 mmol), $\text{Pd}(\text{PPh}_3)_4$ (18 mg, 4 mol%, 0.016 mmol), K_3PO_4 (127 mg, 0.6 mmol) and 1,4-dioxane (3 mL), **203b** was isolated as colorless oil (139 mg, 71%). $^1\text{H-NMR}$ (300 MHz, CDCl_3): $\delta = 1.28$ (s, 9H, 3CH_3), 3.86 (s, 3H, OCH_3), 3.91 (s, 3H, OCH_3), 7.45 (s, 4H, ArH), 7.62 (d, $J = 1.62$ Hz, 1H, ArH), 8.11 (d, $J = 1.62$ Hz, 1H, ArH). $^{13}\text{C-NMR}$ (62.9 MHz, CDCl_3): $\delta = 31.2$ (3CH_3), 34.7 (C), $53.0, 53.1$ (OCH_3), 118.5 (q, $J_{\text{F,C}} = 320.3$ Hz, CF_3), $123.2, 126.2$ (CH), 126.8 (C), $126.9, 127.9$ (CH), $131.2, 134.4, 144.8, 146.5, 152.6$ (C), $165.8, 168.8$ (CO). $^{19}\text{F NMR}$ (282 MHz, CDCl_3): $\delta = -73.57$ (s, 3F, CF_3). IR (KBr, cm^{-1}): $\nu = 3033$ (w), 2955 (m), $2906, 2870$ (w), 1731 (s), 1612 (m), $1573, 1553, 1521, 1479$ (w), 1425 (s), 1318 (m), $1267, 1245, 1206, 1156, 1135, 1115$ (s), $1093, 1057$ (m), 997 (s), 959 (w), 925 (s), $890, 872$ (w), 834 (m), $820, 804, 789$ (s), $765, 749$ (m), $704, 664, 640$ (w), 602 (s), $571, 551$ (m). GC-MS (EI, 70 eV): m/z (%) = 474 ($[\text{M}]^+$, 23), 460 (22), 459 (100). HRMS (EI, 70 eV): calcd for $\text{C}_{21}\text{H}_{21}\text{F}_3\text{O}_7\text{S}_1$ $[\text{M}^+]$: 474.09546, found 474.095709.

3.6 Synthesis of 5,7-Dibromo-8-(trifluoromethylsulfonyloxy)quinoline (205)

To a solution of **204** (1.0 equiv) in CH_2Cl_2 (10 mL/mmol) was added pyridine (7.0 equiv) at room temperature under an argon atmosphere. After 10 min, TF_2O (5.0 equiv) was added at -78 °C. The mixture was allowed to warm up to room temperature and stirred for overnight. The reaction mixture was filtered and the filtrate was concentrated in vacuo. The products of the reaction mixture were isolated by rapid column chromatography (flash silica gel, heptanes/EtOAc).

5,7-Dibromo-8-(trifluoromethylsulfonyloxy)quinoline (205)

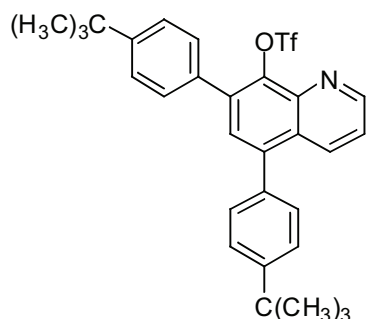


Starting with **204** (1.00 g, 3.30 mmol), pyridine (0.7 mL, 8.25 mmol), CH₂Cl₂ (40 mL), Tf₂O (0.7 mL, 3.96 mmol), **205** was isolated as colorless solid (1.15 g, 80%), mp 119-120 °C. ¹H-NMR (300 MHz, CDCl₃): δ = 7.54 (dd, *J* = 8.61, 4.23 Hz, 1H, ArH), 8.00 (s, 1H, ArH), 8.44 (dd, *J* = 8.58, 7.05 Hz, 1H, ArH), 8.97 (dd, *J* = 4.23, 2.67 Hz, 1H, ArH). ¹³C-NMR (62.9 MHz, CDCl₃): δ = 117.6 (d, *J*_{F,C} = 320.9 Hz, CF₃), 114.9, 120.5 (C), 122.6 (CH), 126.8 (C), 132.3, 134.7 (CH), 140.8, 143.0 (C), 151 (CH). ¹⁹F NMR (282 MHz, CDCl₃): δ = -72.36 (s, 3F, CF₃). IR (KBr, cm⁻¹): ν = 3084, 2961, 2919, 2850, 1599, 1584, 1555, 1472, 1449 (w), 1420, 1405 (m), 1347, 1334, 1291, 1249 (w), 1229 (m), 1202, 1179, 1129, 1057 (s), 1035, 962, 933 (w), 873 (m), 825, 809, 784 (s), 765 (m), 692 (s), 641 (m), 609, 601, 584 (s), 584, 553, 546 (m). GC-MS (EI, 70 eV): *m/z* (%) = 435 ([M+H]⁺, ⁸¹Br, 26), 433 ([M+H]⁺, ⁷⁹Br, 13), 304 (49), 303 (10), 302 (100), 276 (37), 275 (07), 274 (73), 272 (39). HRMS (EI, 70 eV): calcd for C₁₀H₅Br₂F₃N₁O₃S₁ ([M+H]⁺, ⁷⁹Br): 433.8304, found 433.8299, calcd for C₁₀H₅Br₂F₃N₁O₃S₁ ([M+H]⁺, ⁸¹Br): 435.8283, 435.8283.

3.6.1 General Procedure for Suzuki–Miyaura Reactions

A 1,4-dioxane solution (4 mL per 3 mmol of **205**) of **205**, K₂CO₃, Pd(PPh₃)₄ and arylboronic acid **188** was stirred at 110 °C or 90 °C for 10 h. After cooling to 20 °C, distilled water was added. The organic and the aqueous layers were separated and the latter was extracted with CH₂Cl₂. The combined organic layers were dried (Na₂SO₄), filtered and the filtrate was concentrated in vacuo. The residue was purified by column chromatography.

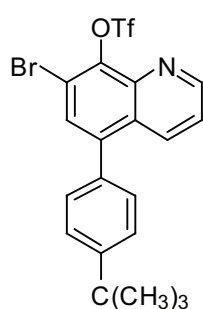
5,7-Bis(4-*tert*-butylphenyl)-8-(trifluoromethylsulfonyloxy)quinoline (206)



Starting with **205** (100 mg, 0.22 mmol), **188c** (78 mg, 0.44 mmol), Pd(PPh₃)₄ (15 mg, 6 mol%, 0.0132 mmol), K₂CO₃ (2 mL), and 1,4-dioxane (3 mL), **206** was isolated as colorless solid (101 mg, 81%), mp 150-152 °C. ¹H-NMR (300 MHz, CDCl₃): δ = 1.30 (s, 9H, 3CH₃), 1.33 (s, 9H, 3CH₃), 7.33-7.36 (m, 2H, ArH), 7.40 (dd, *J* = 8.61, 4.23 Hz, 1H, ArH), 7.45-7.48 (m, 6H, ArH), 7.54 (s, 1H, ArH), 8.24 (dd, *J* = 8.55, 7.11 Hz, 1H, ArH), 8.99 (dd, *J* = 4.05, 2.67 Hz, 1H, ArH). ¹³C-NMR (62.9 MHz, CDCl₃): δ = 31.2, 31.35 (6CH₃), 34.7 (C), 118.5 (q, *J*_{F,C} = 320.5 Hz, CF₃), 121.9, 125.4, 125.6 (CH), 126.9 (C), 129.3, 129.6

(CH), 132.3 (C), 134.0, 134.5 (CH), 134.8, 135.0, 140.3, 141.7, 142.1 (C), 151.0 (CH), 151.3, 151.9 (C). ^{19}F NMR (282 MHz, CDCl_3): $\delta = -75.06$ (s, 3F, CF_3). IR (KBr, cm^{-1}): $\nu = 3037$ (w), 2952, 2924, 2903, 2866 (m), 1619, 1596, 1568, 1555, 1513, 1485, 1454 (w), 1416 (s), 1392 (m), 1363, 1342, 1311, 1266, 1241 (w), 1220, 1203 (s), 1170, 1153 (m), 1135 (s), 1106, 1097, 1065 (w), 1043, 1034, 1021, 1014 (m), 968, 940, 922, 900, 880 (w), 849 (m), 838, 828, 793 (s), 774, 763, 755, 747, 723, 706, 687, 665, 642, 631 (w), 607, 597 (s), 577, 563, 555, 540, 529 (w). GC-MS (EI, 70 eV): m/z (%) = 541 ($[\text{M}]^+$, 04), 353 (22), 352 (100), 336 (14). HRMS (EI, 70 eV): calcd for $\text{C}_{30}\text{H}_{30}\text{F}_3\text{N}_1\text{O}_3\text{S}_1$ $[\text{M}]^+$: 541.18930, found 541.188400.

5-(4-*tert*-Butylphenyl)-7-bromo-8-(trifluoromethylsulfonyloxy)quinoline (207)



Starting with **205** (100 mg, 0.22 mmol), **188c** (39 mg, 0.22 mmol), $\text{Pd}(\text{PPh}_3)_4$ (8 mg, 3 mol%, 0.0066 mmol), K_2CO_3 (1 mL), and 1,4-dioxane (2 mL), **207** was isolated as colorless solid (85 mg, 75%), mp 111-113 °C. ^1H -NMR (300 MHz, CDCl_3): $\delta = 1.33$ (s, 9H, 3 CH_3), 7.28-7.32 (m, 2H, ArH), 7.41 (dd, $J = 8.64, 4.17$ Hz, 1H, ArH), 7.45-7.50 (m, 2H, ArH), 7.65 (s, 1H, ArH), 8.20 (dd, $J = 8.61, 6.99$ Hz, 1H, ArH), 8.95 (dd, $J = 4.17, 2.58$ Hz, 1H, ArH). ^{13}C -NMR (62.9 MHz, CDCl_3): $\delta = 30.31$ (3 CH_3), 33.75 (C), 114.4 (q, $J_{F,C} = 320.5$ Hz, CF_3), 121.3, 124.7 (CH), 126.0 (C), 128.5, 129.6 (CH), 132.8 (C), 133.8 (CH), 140.3, 140.8, 142.3 (C), 150.3 (CH), 150.8, 151.2 (C). ^{19}F NMR (282 MHz, CDCl_3): $\delta = -72.49$ (s, 3F, CF_3). IR (KBr, cm^{-1}): $\nu = 2956$ (m), 2922 (s), 2852 (m), 1743, 1728, 1693, 1665, 1630, 1602, 1589, 1515 (w), 1462, 1451 (m), 1426 (s), 139, 1376, 1307, 1261 (w), 1241 (m), 1209 (s), 1183 (m), 1136 (s), 1103 (w), 1055 (s), 1034 (w), 1019, 942, 881, 865 (w), 832 (s), 788, 766, 754, 746, 720, 697, 684, 644, 619, 613 (w), 599 (s), 565, 541 (w). HRMS (EI, 70 eV): calcd for $\text{C}_{20}\text{H}_{18}\text{BrF}_3\text{N}_1\text{O}_3\text{S}_1$ ($[\text{M}+\text{H}]^+$, ^{79}Br): 488.0137, found 488.0145, calcd for $\text{C}_{20}\text{H}_{18}\text{BrF}_3\text{N}_1\text{O}_3\text{S}_1$ ($[\text{M}+\text{H}]^+$, ^{81}Br): 490.0118, found 490.0129.

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*X-Ray Crystallography
Reports*

APPENDIX

Crystal Data and Structure Refinement for Compound 189c

Identification code	is_a14	
Empirical formula	C ₃₄ H ₃₂ O ₂	
Formula weight	472.60	
Temperature	173 (2) K	
Wavelength	0.71073 Å	
Crystal system	Triclinic	
Space group (H.-M.)	<i>P</i> -1	
Space group (Hall)	-P1	
Unit cell dimensions	$a = 9.106 (6) \text{ \AA}$	$\alpha = 105.943 (11)^\circ$
	$b = 10.813 (6) \text{ \AA}$	$\beta = 93.339 (13)^\circ$
	$c = 14.071 (8) \text{ \AA}$	$\gamma = 97.190 (16)^\circ$
Volume	1315.4 (13) Å ³	
Z	2	
Density (calculated)	1.193 Mg m ⁻³	
Absorption coefficient	0.07 mm ⁻¹	
F(000)	504	
Crystal size	0.74 × 0.57 × 0.37 mm	
Θ range for data collection	θ = 6.4-59.9°	
Index ranges	-11 ≤ h ≤ 11, -14 ≤ k ≤ 14, -18 ≤ l ≤ 18	
Reflections collected	23152	
Independent reflections	5994 [R(int) = 0.037]	

Completeness to $\Theta = 29.82^\circ$	99.2%
Absorption correction	Semi-empirical from equivalents
Max. and min. transmission	0.978 and 0.948
Refinement method	Full-matrix least-squares on F ²
Data/ restraints / parameters	5175/0/331
Goodness-of-fit on F ²	1.097
Final R indices [$I > 2\sigma(I)$]	R1 = 0.0555, wR2 = 0.1476
R indices (all data)	R1 = 0.0482, wR2 = 0.1398
Largest diff. peak and hole	0.336 and -0.294 e \AA^{-3}

Crystal Data and Structure Refinement for Compound 190b

Identification code	is_a17	
Empirical formula	C ₂₂ H ₁₃ F ₃ O ₆ S	
Formula weight	462.38	
Temperature	173 (2) K	
Wavelength	0.71073 Å	
Crystal system	Triclinic	
Space group (H.-M.)	<i>P</i> -1	
Space group (Hall)	-P 1	
Unit cell dimensions	$a = 10.2281 (4) \text{ \AA}$	$\alpha = 85.020 (2)^\circ$
	$b = 10.8657 (4) \text{ \AA}$	$\beta = 87.467 (2)^\circ$
	$c = 19.2816 (7) \text{ \AA}$	$\gamma = 67.002 (2)^\circ$
Volume	1964.98 (13) Å ³	
Z	4	
Density (calculated)	1.563 Mg m ⁻³	
Absorption coefficient	0.23 mm ⁻¹	
F(000)	944	
Crystal size	0.60 × 0.35 × 0.08 mm ³	
Θ range for data collection	θ = 4.7-60.5°	
Index ranges	-14 ≤ h ≤ 14, -15 ≤ k ≤ 14, -20 ≤ l ≤ 27	
Reflections collected	42358	
Independent reflections	11784 [R(int) = 0.025]	

Completeness to $\Theta = 29.82^\circ$	98.6%
Absorption correction	Semi-empirical from equivalents
Max. and min. transmission	0.982 and 0.873
Refinement method	Full-matrix least-squares on F2
Data / restraints / parameters	5175/0/579
Goodness-of-fit on F2	1.064
Final R indices [$I > 2\sigma(I)$]	R1 = 0.0598, wR2 = 0.1145
R indices (all data)	R1 = 0.0412, wR2 = 0.1067
Largest diff. peak and hole	0.39 and -0.36 e \AA^{-3}

Crystal Data and Structure Refinement for Compound 191a

Identification code	is_a24	
Empirical formula	C ₃₁ H ₂₃ F ₃ O ₂	
Formula weight	484.49	
Temperature	173(2) K	
Wavelength	0.71073 Å	
Crystal system	Triclinic	
Space group (H.-M.)	<i>P</i> $\bar{1}$	
Space group (Hall)	-P 1	
Unit cell dimensions	<i>a</i> = 9.0823 (18) Å	α = 76.95 (3)°
	<i>b</i> = 11.869 (2) Å	β = 88.73 (3)°
	<i>c</i> = 12.460 (3) Å	γ = 73.54 (3)°
Volume	1253.6 (4) Å ³	
Z	2	
Density (calculated)	1.284 Mg m ⁻³	
Absorption coefficient	0.09 mm ⁻¹	
F(000)	504	
Crystal size	0.38 × 0.37 × 0.07 mm	
Θ range for data collection	θ = 4.7-55.4°	
Index ranges	-11 ≤ <i>h</i> ≤ 11, -14 ≤ <i>k</i> ≤ 15, -16 ≤ <i>l</i> ≤ 16	
Reflections collected	21238	
Independent reflections	5706 [R(int) = 0.0245]	

Completeness to $\Theta = 29.82^\circ$	98.9%
Absorption correction	Semi-empirical from equivalents
Max. and min. transmission	0.993 and 0.965
Refinement method	Full-matrix least-squares on F2
Data / restraints / parameters	3766/0/87
Goodness-of-fit on F2	1.093
Final R indices [$I > 2\sigma(I)$]	R1 = 0.0860, wR2 = 0.1480
R indices (all data)	R1 = 0.0499, wR2 = 0.1332
Largest diff. peak and hole	0.31 and -0.21 e \AA^{-3}

Crystal Data and Structure Refinement for Compound 195a

Identification code	is_a136	
Empirical formula	C ₂₉ H ₁₃ F ₉ O ₅ S	
Formula weight	651.78	
Temperature	173 (2) K	
Wavelength	0.71073 Å	
Crystal system	Monoclinic	
Space group (H.-M.)	P 21/n	
Space group (Hall)	-P 2yn	
Unit cell dimensions	$a = 14.4439 (7) \text{ \AA}$	$\alpha = 90.00^\circ$
	$b = 11.2736 (5) \text{ \AA}$	$\beta = 101.911 (2)^\circ$
	$c = 33.9566 (16) \text{ \AA}$	$\gamma = 90.00^\circ$
Volume	5410.3 (4) Å ³	
Z	8	
Density (calculated)	1.600 Mg m ⁻³	
Absorption coefficient	0.239 mm ⁻¹	
F(000)	2621	
Crystal size	0.60 × 0.17 × 0.09 mm ³	
Θ range for data collection	θ = 1.91-24.98°	
Index ranges	-17 ≤ h ≤ 17, -13 ≤ k ≤ 13, -40 ≤ l ≤ 40	
Reflections collected	39066	
Independent reflections	9445 [R(int) = 0.0495]	

Completeness to $\Theta = 29.82^\circ$	99.4%
Absorption correction	Semi-empirical from equivalents
Max. and min. transmission	0.9788 and 0.8698
Refinement method	Full-matrix least-squares on F ²
Data / restraints / parameters	6265/7/846
Goodness-of-fit on F ²	1.049
Final R indices [$I > 2\sigma(I)$]	R1 = 0.0934, wR2 = 0.1228
R indices (all data)	R1 = 0.0517, wR2 = 0.1228
Largest diff. peak and hole	0.380 and -0.395 e \AA^{-3}

Crystal Data and Structure Refinement for Compound 196e

Identification code	is_a106	
Empirical formula	C ₂₃ H ₉ F ₉ O ₈ S ₂	
Formula weight	648.42	
Temperature	173 (2) K	
Wavelength	0.71073 Å	
Crystal system	Triclinic	
Space group (H.-M.)	P -1	
Space group (Hall)	-P 1	
Unit cell dimensions	$a = 8.5921 (2) \text{ \AA}$	$\alpha = 79.2310 (10)^\circ$
	$b = 11.1466 (3) \text{ \AA}$	$\beta = 80.2880 (10)^\circ$
	$c = 13.0127 (3) \text{ \AA}$	$\gamma = 85.0560 (10)^\circ$
Volume	1204.84 (5) Å ³	
Z	2	
Density (calculated)	1.787 Mg m ⁻³	
Absorption coefficient	0.342 mm ⁻¹	
F(000)	648	
Crystal size	0.34 × 0.18 × 0.14 mm ³	
Θ range for data collection	θ = 2.24-30.00°	
Index ranges	-15 ≤ h ≤ 15, -12 ≤ k ≤ 12, -16 ≤ l ≤ 18	
Reflections collected	26483	
Independent reflections	6942 [R(int) = 0.0279]	

Completeness to $\Theta = 29.82^\circ$	98.7%
Absorption correction	Semi-empirical from equivalents
Max. and min. transmission	0.9537 and 0.8927
Refinement method	Full-matrix least-squares on F ²
Data / restraints / parameters	5429/0/462
Goodness-of-fit on F ²	1.027
Final R indices [$I > 2\sigma(I)$]	R1 = 0.0655, wR2 = 0.1174
R indices (all data)	R1 = 0.0469, wR2 = 0.1079
Largest diff. peak and hole	0.587 and -0.476 e \AA^{-3}

*ABOUT THE
AUTHOR*

Name	Ahmed Salem Ahmed Mahal
Date of Birth	Sept. 06, 1976
Place of Birth	Mosul, Iraq
Nationality	Iraqi
Professional Qualifications	
1991-1994	Al-Resala Secondary School, Mosul, Iraq
1994-1998	B.Sc. in Chemistry, University of Mosul, Iraq
2001-2004	M.Sc. in Chemistry, Al al-Bayt University, Jordan
2007-2011	Ph.D. in Chemistry, University of Rostock, Germany Thesis Title: Synthesis of Functionalized Anthraquinones, Phthalates and Quinolines by Site-Selective Suzuki-Miyaura Cross-Coupling Reactions
Employment Details	
2006- Now	Assistant Lecturer, University of Mosul, Iraq
Teaching Duties	
03/2006-05/2007	1. Practical Inorganic Chemistry, Chemistry Laboratories 2 ^{ed} Class, Department of Chemistry, University of Mosul, Iraq 2. Practical Inorganic Chemistry, Chemistry Laboratories 3 rd Class, Department of Chemistry, University of Mosul, Iraq
Scholarships	
2001-2004	Ministry of Higher Education and Scientific Research Fellowship (Iraq), Al al-Bayt University, Jordan
2007-2011	German Academic Exchange Service (DAAD) Fellowship, University of Rostock, Germany

Research Interest

1. Total Synthesis of Natural Products
2. New Synthetic Methods for Organic Synthesis
3. Catalysts
4. Medicinal Chemistry
5. Asymmetric Synthesis

Membership in Societies

1. Membership in Iraqi Chemists Union, Iraq, 1998
2. Member of the Gesellschaft Deutscher Chemiker GDCh (German Chemical Society) and its division: Liebig-Vereinigung für Organische Chemie (Liebig-Union for Organic Chemistry), 2008
3. IUPAC Sponsored Affiliate Member, 2010

*LIST OF
PUBLICATION*

1. **Ahmed Mahal.**; Alexander Villinger.; Peter Langer. Synthesis of 1,2-Diaryl-anthraquinones by Site-Selective Suzuki-Miyaura Reactions of the Bis(triflate) of Alizarin. *Synlett* **2010**, 2010, 1085-1088.

2. **Ahmed Mahal.**; Alexander Villinger.; Peter Langer. *Site-Selective Arylation of Alizarin and Purpurin based on Suzuki-Miyaura Cross-Coupling Reaction. Eur. J. Org. Chem*, **2011**. *accepted*.

*DECLARATION/
ERKLÄRUNG*

Here by I declare that this work has so far neither submitted to the Faculty of Mathematics and Natural Sciences at the University of Rostock nor to any other scientific Institution for the purpose of doctorate. Furthermore, I declare that I have written this work by myself and that I have not used any other sources, other than mentioned earlier in this work.

Hiermit erkläre ich, daß diese Arbeit bisher von mir weder an der Mathematisch-Naturwissenschaftlichen Fakultät der Universität Rostock noch einer anderen wissenschaftlichen Einrichtung zum Zwecke der Promotion eingereicht wurde.

Ferner erkläre ich, dass ich diese Arbeit selbständig verfasst und keine anderen als die darin angegebenen Hilfsmittel benutzt habe

I hereby apply irrevocably to take oral examination in the form of a private viva voce and a public presentation.

Ahmed Mahal