

ETHYLENE-BASED POLYMERS

REFERENCE TO RELATED APPLICATIONS

The present application claims the benefit of U.S. Provisional Application No. 62/018,863, filed June 30, 2014, and incorporated herein by reference.

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BACKGROUND

Ethylene-based polymers, such as, polyethylene is known for use in the manufacture of a wide variety of articles. The polyethylene polymerization process can be varied, in a number of ways to produce a wide variety of resultant polyethylene resins, having different physical properties that render the various resins suitable for use in different applications. It is generally known that ethylene-based polymers can be produced in solution phase loop reactors, in which ethylene monomer, and optionally one or more alpha olefin comonomers, typically having from 3 to 10 carbon atoms, are circulated in the presence of one or more catalyst systems, under pressure, around a loop reactor, by a circulation pump. The ethylene monomers, and optionally one or more comonomers, are present in a liquid diluent, such as an alkane or isoalkane. Hydrogen may also be added to the reactor. The catalyst systems for producing ethylene-based polymers may typically comprise a chromium-based catalyst system, a Ziegler Natta catalyst system, and/or a molecular (either metallocene or non-metallocene) catalyst system. Despite the research efforts in developing ethylene-based polymers, there is still a need for new ethylene-based polymers having improved properties. These needs have been met by the following invention.

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SUMMARY

The instant disclosure provides an ethylene-based polymer comprising the following properties:

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- a) a ZSVR value from 1.2 to 2.6,
- b) a MWD from 1.5 to 2.8, and
- c) a tan delta (0.1 rad/s; 190°C) from 5.0 to 50.

In one aspect, there is provided an ethylene-based polymer comprising the following properties:

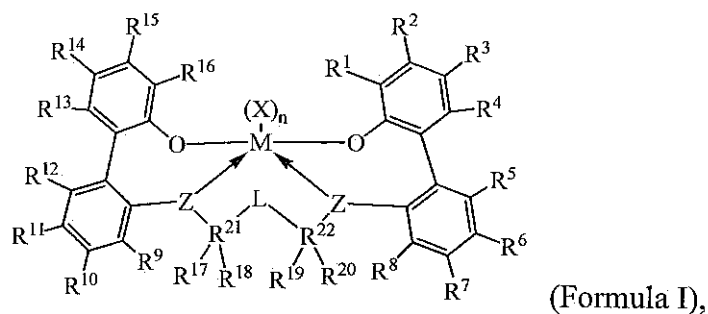
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- a) a zero-shear viscosity ratio (ZSVR) value from 1.2 to 2.6,
- b) a molecular weight distribution (MWD or Mw/Mn) from 1.5 to 2.8,
- c) a tan delta (0.1 rad/s; 190°C) from 5.0 to 50, and
- d) a melt index (I₂) from 0.93 to 1.05 g/10 min.

In another aspect, there is provided a process for producing the ethylene-based polymer as defined herein comprising polymerizing at least ethylene, in the presence of at least one catalyst system comprising the reaction product of the following:

A) at least one cocatalyst; and

B) a procatalyst comprising a metal-ligand complex of Formula (I):



wherein:

M is titanium, zirconium, or hafnium, each independently being in a formal oxidation state of +2, +3, or +4; and n is an integer from 0 to 3, and wherein when n is 0, X is absent; and

Each X, independently, is a (C₁-C₄₀)hydrocarbyl, a (C₁-C₄₀)heterohydrocarbyl, or a halide, and wherein each X, independently, is a monodentate ligand that is neutral, monoanionic, or dianionic; or

wherein two Xs are taken together to form a bidentate ligand that is neutral, monoanionic, or dianionic; and

wherein X and n are chosen, in such a way, that the metal-ligand complex of Formula (I) is, overall, neutral; and

Each Z, independently, is an oxygen atom, a sulfur atom, -N[(C₁-C₄₀)hydrocarbyl]-, or -P[(C₁-C₄₀)hydrocarbyl]-; and

L is a substituted or unsubstituted (C₁-C₄₀)hydrocarbylene, or a substituted or unsubstituted (C₁-C₄₀)heterohydrocarbylene, and

wherein, for L, the (C₁-C₄₀)hydrocarbylene has a portion that comprises a 1-carbon atom to 10-carbon atom linker backbone linking R²¹ and R²² in Formula (I) (to which L is bonded), or

wherein, for L, the (C₁-C₄₀)heterohydrocarbylene has a portion that comprises a 1-atom to 10-atom linker backbone linking R²¹ and R²² in Formula (I), wherein each of the 1 to 10 atoms of the 1-atom to 10-atom linker backbone of the (C₁-C₄₀)heterohydrocarbylene, independently,

is one of the following: i) a carbon atom, ii) a heteroatom, wherein each heteroatom independently is -O- or -S-, or iii) a substituent selected from -S(O)-, -S(O)₂-, -Si(R^C)₂-,

-Ge(R^C)₂-, -P(R^C)-, or -N(R^C)-, and wherein each R^C is, independently, a substituted or unsubstituted (C₁-C₃₀)hydrocarbonyl, or a substituted or unsubstituted (C₁-C₃₀) heterohydrocarbonyl; and

R²¹ and R²² are each, independently, C or Si; and

5 R¹ through R²⁰ are each, independently, selected from the group consisting of the following: a substituted or unsubstituted (C₁-C₄₀)hydrocarbonyl, a substituted or unsubstituted (C₁-C₄₀)heterohydrocarbonyl, -Si(R^C)₃, -Ge(R^C)₃, -P(R^C)₂, -N(R^C)₂, -OR^C, -SR^C, -NO₂, -CN, -CF₃, -S(O)R^C, -S(O)₂R^C, -N=C(R^C)₂, -OC(O)R^C, -C(O)OR^C, -N(R)C(O)R^C, -C(O)N(R^C)₂, a halogen atom, and a hydrogen atom; and wherein each R^C is independently a
10 substituted or unsubstituted (C₁-C₃₀)hydrocarbonyl, or a substituted or unsubstituted (C₁-C₃₀) heterohydrocarbonyl; and

wherein, when R¹⁷ is a hydrogen atom, then R¹⁸ is a substituted or unsubstituted (C₁-C₄₀)hydrocarbonyl, a substituted or unsubstituted (C₁-C₄₀)heterohydrocarbonyl, -Si(R^C)₃, -Ge(R^C)₃, -P(R^C)₂, -N(R^C)₂, -OR^C, -SR^C, -NO₂, -CN, -CF₃, -S(O)R^C, -S(O)₂R^C,
15 -N=C(R^C)₂, -OC(O)R^C, -C(O)OR^C, -N(R)C(O)R^C, -C(O)N(R^C)₂, a halogen atom, or a hydrogen atom; and wherein each R^C is independently a substituted or unsubstituted (C₁-C₃₀)hydrocarbonyl, or a substituted or unsubstituted (C₁-C₃₀) heterohydrocarbonyl; or

wherein, when R¹⁸ is a hydrogen atom, then R¹⁷ is a substituted or unsubstituted (C₁-C₄₀)hydrocarbonyl, a substituted or unsubstituted (C₁-C₄₀)heterohydrocarbonyl, -Si(R^C)₃,
20 -Ge(R^C)₃, -P(R^C)₂, -N(R^C)₂, -OR^C, -SR^C, -NO₂, -CN, -CF₃, -S(O)R^C, -S(O)₂R^C, -N=C(R^C)₂, -OC(O)R^C, -C(O)OR^C, -N(R)C(O)R^C, -C(O)N(R^C)₂, a halogen atom, or a hydrogen atom; and wherein each R^C is independently a substituted or unsubstituted (C₁-C₃₀)hydrocarbonyl, or a substituted or unsubstituted (C₁-C₃₀) heterohydrocarbonyl; and/or

wherein, when R¹⁹ is a hydrogen atom, then R²⁰ is a substituted or unsubstituted
25 (C₁-C₄₀)hydrocarbonyl, a substituted or unsubstituted (C₁-C₄₀)heterohydrocarbonyl, -Si(R^C)₃, -Ge(R^C)₃, -P(R^C)₂, -N(R^C)₂, -OR^C, -SR^C, -NO₂, -CN, -CF₃, -S(O)R^C, -S(O)₂R^C, -N=C(R^C)₂, -OC(O)R^C, -C(O)OR^C, -N(R)C(O)R^C, -C(O)N(R^C)₂, a halogen atom, or a hydrogen atom; and wherein each R^C is independently a substituted or unsubstituted (C₁-C₃₀)hydrocarbonyl, or a substituted or unsubstituted (C₁-C₃₀) heterohydrocarbonyl; or

wherein, when R^{20} is a hydrogen atom, then R^{19} is a substituted or unsubstituted (C_1-C_{40}) hydrocarbyl, a substituted or unsubstituted (C_1-C_{40}) heterohydrocarbyl, $-Si(R^C)_3$, $-Ge(R^C)_3$, $-P(R^C)_2$, $-N(R^C)_2$, $-OR^C$, $-SR^C$, $-NO_2$, $-CN$, $-CF_3$, $-S(O)R^C$, $-S(O)_2R^C$, $-N=C(R^C)_2$, $-OC(O)R^C$, $-C(O)OR^C$, $-N(R)C(O)R^C$, $-C(O)N(R^C)_2$, a halogen atom, or a hydrogen atom; and wherein each R^C is independently a substituted or unsubstituted (C_1-C_{30}) hydrocarbyl, or a substituted or unsubstituted (C_1-C_{30}) heterohydrocarbyl; and

wherein, for Formula I, two or more of R^1 through R^{22} , optionally, may form one or more ring structures, and wherein each ring structure has from 3 to 50 atoms in the ring, excluding any hydrogen atoms; and

wherein, for Formula I, one or more hydrogen atoms may optionally be substituted with one or more deuterium atoms.

In another aspect, there is provided a composition comprising the ethylene-based polymer as defined herein.

In another aspect, there is provided an article comprising at least one component formed from the composition as defined above.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 depicts conventional GPC profiles for an inventive (Inventive 9 = Inventive 11) and two comparative (Comparative 3 and Comparative 4) ethylene-based polymers.

Figure 2 depicts CEF (Crystallization Elution Fractionation – Comonomer Distribution) profiles for an inventive (Inventive 9 = Inventive 11) and two comparative (Comparative 3 and Comparative 4) ethylene-based polymers.

Figure 3 depicts Tan Delta profiles for one inventive (Inventive 9 = Inventive 11) and two comparative (Comparative 3 and Comparative 4) ethylene-based polymers.

DETAILED DESCRIPTION OF THE INVENTION

As discussed above, the invention provides an ethylene-based polymer comprising the following properties:

- a) a ZSVR value from 1.2 to 2.6,
- b) a MWD from 1.5 to 2.8, and
- c) a tan delta (0.1 rad/s; 190°C) from 5.0 to 50.

An ethylene-based polymer may comprise a combination of two or more embodiments as described herein.

The MWD (= Mw/Mn) is measured according to conventional GPC method as described below.

In one embodiment, the ethylene-based polymer has the following properties: d) a melt index (I2) less than 0.9 g/10 min, further less than, or equal to, 0.8 g/10 min, further less than, or equal to, 0.6 g/10 min; and a tan delta (0.1 rad/s; 190°C) greater than 5.0, further greater than 6.0, further greater than 7.0. In a further embodiment, the ethylene-based polymer has a melt index greater than, or equal to, 0.05, further greater than, or equal to, 0.1.

In one embodiment, the ethylene-based polymer has the following properties: e) a melt index (I2) greater than, or equal to, 0.9 g/10 min, and a tan delta (0.1 rad/s; 190°C) greater than 15, further greater than 20, further greater than 25; and a ZSVR value from 1.3 to 2.6, further from 1.3 to 2.5, further from 1.3 to 2.3. In a further embodiment, the ethylene-based polymer has a melt index less than, or equal to, 10, further less than, or equal to, 5.0, further less than, or equal to, 2.0.

In one embodiment, the ethylene-based polymer is an ethylene/alpha-olefin interpolymer.

In one embodiment, the ethylene-based polymer has a density from 0.885 to 0.940 g/cc, further from 0.890 to 0.930 g/cc, further from 0.892 to 0.920 g/cc (1 cc = 1 cm³).

In one embodiment, the ethylene-based polymer has a melt index (I2) from 0.05 to 500 g/10 min, further from 0.05 to 100 g/10 min, further 0.1 to 50 g/10 min, further from 0.1 to 20 g/10 min, further from 0.1 to 5 g/10 min, further from 0.1 to 2 g/10 min.

In one embodiment, the ethylene-based polymer has a tan delta (0.1 rad/s; 190°C) from 5.0 to 50, further from 7.0 to 45, further from 8.0 to 45.

In one embodiment, the ethylene-based polymer has a single peak in the CEF-Comonomer Distribution, at a temperature from 60°C to 100°C, further from 60°C to 95°C.

In one embodiment, the ethylene-based polymer has a CEF profile that has a single peak with a peak width at 25% peak height less than 30°C (30 degrees C), less than 25°C (25 degrees C), less than 20°C (20 degrees C), most preferably less than 15°C (15 degrees C).

In one embodiment, the ethylene-based polymer has a single peak in the CEF-Comonomer Distribution, at a temperature from 60°C to 100°C, and wherein the peak has a peak width at 25% peak height less than 30°C (30 degrees C), less than 25°C (25 degrees C), less than 20°C (20 degrees C), most preferably less than 15°C (15 degrees C).

In one embodiment, the ethylene-based polymer has a single peak in the CEF-Comonomer Distribution, at a temperature from 60°C to 95°C, and wherein the peak has a peak width at 25% peak height less than 30°C (30 degrees C), less than 25°C (25 degrees C), less than 20°C (20 degrees C), most preferably less than 15°C (15 degrees C).

An inventive ethylene-based polymer may comprise a combination of two or more embodiments described herein.

The invention also provides a composition comprising an inventive ethylene-based polymer as described herein.

An inventive composition may comprise a combination of two or more embodiments described herein.

The invention also provides an article comprising at least one component formed from an inventive composition.

An inventive article may comprise a combination of two or more embodiments described herein.

Ethylene-based polymers

The term, “ethylene-based polymer,” as used herein, refers to a polymer that comprises, in polymerized form, a majority amount of ethylene monomer (based on the weight of the polymer), and optionally may comprise one or more comonomers. Trace amounts of impurities (for example, catalyst residues) may be incorporated into and/or within the polymer

The inventive ethylene based polymers, for example homopolymers (employed to refer to polymers prepared from only one type of monomer, with the understanding that trace amounts of impurities can be incorporated into the polymer structure), interpolymers, or copolymers, of ethylene, and optionally one or more comonomers, such as α -olefins, have a zero shear viscosity

ratio (ZSVR) in the range from 1.2 to 2.6; or in the alternative, from 1.2 to 2.5; or in the alternative, from 1.3 to 2.6; or in the alternative, from 1.3 to 2.6; or in the alternative, from 1.3 to 2.3; or in the alternative, from 1.3 to 2.2; or in the alternative, from 1.3 to 2.1.

The term “ethylene-based interpolymers,” as used herein, refers to a polymer that comprises a majority amount of polymerized ethylene monomer (based on weight of the polymer), and at least one comonomer, for example, and α -olefin.

The term “ethylene-based copolymer,” as used herein, refers to a polymer that comprises a majority amount of polymerized ethylene monomer (based on weight of the polymer), and one comonomer (e.g., an α -olefin), as the only two monomer types.

The term “ethylene/ α -olefin interpolymers,” as used herein, refers to an interpolymers that comprises a majority amount of polymerized ethylene monomer (based on the weight of the interpolymers) and at least one α -olefin.

The term, “ethylene/ α -olefin copolymer,” as used herein, refers to a copolymer that comprises a majority amount of polymerized ethylene monomer (based on the weight of the copolymer), and an α -olefin, as the only two monomer types.

In one embodiment, the inventive ethylene-based polymers, for example homopolymers, interpolymers, or copolymers, of ethylene, and optionally one or more comonomers, such as α -olefins, have a density in the range from 0.885 to 0.940 g/cm³. All individual values and subranges from 0.885 to 0.940 g/cm³ are included herein and disclosed herein; for example, the density can be from a lower limit of 0.885, 0.888, 0.890 or 0.894 g/cm³, to an upper limit of 0.940, 0.938, 0.935, 0.932, 0.930, 0.928, 0.925, 0.922, 0.920, 0.918, 0.915, 0.912, 0.910, or 0.905 g/cm³.

In one embodiment, the inventive ethylene-based polymers, for example homopolymers, interpolymers, or copolymers, of ethylene, and optionally one or more comonomers, such as α -olefins, have a molecular weight distribution (M_w/M_n) (measured according to the conventional GPC method) in the range from 1.5 to 2.8; for example, the molecular weight distribution (M_w/M_n) may be in the range from 1.5 to 2.7; or in the alternative, the molecular weight distribution (M_w/M_n) may be in the range from 1.5 to 2.6; or in the alternative, from 1.6 to 2.7; or in the alternative, from 1.6 to 2.6; or in the alternative, from 1.6 to 2.5; or in the alternative, from 1.7 to 2.7; or in the alternative, from 1.7 to 2.6; or in the alternative, from 1.7 to 2.5; or in the alternative, from 1.7 to 2.2.

In one embodiment, the inventive ethylene-based polymers, for example homopolymers, interpolymers, or copolymers, of ethylene, and optionally one or more comonomers, such as α -olefins, have a weight average molecular weight (M_w) in the range from equal to, or greater than,

20,000 g/mole, for example, in the range from 20,000 to 350,000 g/moles, further from 50,000 to 300,000 g/mole, further from 80,000 to 250,000 g/mole, further from 90,000 to 200,000 g/mole.

In one embodiment, the inventive ethylene-based polymers, for example homopolymers, interpolymers, or copolymers, of ethylene, and optionally one or more comonomers, such as α -olefins, have a melt index (I_2) in the range from 0.05 to 500 g/10 minutes. All individual values and subranges from 0.05 to 500 g/10 minutes are included herein and disclosed herein; for example, the melt index (I_2) can be from a lower limit of 0.05, 0.1, 0.5, 0.2, 0.5, 1, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 10, 15, 20, 30, 40, 50, 60, 80, 90, 100, or 150 g/10 minutes, to an upper limit of 0.9, 1, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 10, 15, 20, 30, 40, 50, 60, 80, 90, 100, 200, or 500 g/10 minutes.

In one embodiment, the inventive ethylene-based polymers, for example homopolymers, interpolymers, or copolymers, of ethylene, and optionally one or more comonomers, such as α -olefins, have a melt flow ratio (I_{10}/I_2) in the range of from 5.0 to 10. All individual values and subranges from 5 to 10 are included herein and disclosed herein; for example, the melt flow ratio (I_{10}/I_2) can be from a lower limit of 5.0, 5.2, 5.3, 5.4 or 5.5, to an upper limit of 7.0, 7.5, 7.8, 8.0, 8.2, 8.5, 9.0, or 10.

In one embodiment, the ethylene-based polymers, for example homopolymers, interpolymers, or copolymers, of ethylene, and optionally one or more comonomers, such as α -olefins, have a long chain branching frequency in the range of from 0 to 3 long chain branches (LCB) per 1000C.

In one embodiment, the inventive ethylene-based polymers, for example homopolymers, interpolymers, or copolymers, of ethylene, and optionally one or more comonomers, such as α -olefins, may further comprise at least 0.01 parts by weight of metal residues and/or metal oxide residues remaining from the inventive catalyst system per one million parts of the inventive ethylene based polymers. The metal residues and/or metal oxide residues remaining from the catalyst system in the inventive ethylene based polymers may be measured by X-ray fluorescence (XRF), which is calibrated to reference standards.

The inventive ethylene-based polymers, such as interpolymers or copolymers of ethylene, and optionally one or more comonomers, such as α -olefins, may comprise less than 48 percent by weight of units derived from one or more α -olefin comonomers, based on the weight of the polymer. All individual values and subranges from less than 48 weight percent are included herein and disclosed herein; for example, the inventive ethylene based polymers may comprise from less than 37 percent by weight of units derived from one or more α -olefin comonomers; or in the alternative, less than 30 percent by weight of units derived from one or more α -olefin

comonomers; or in the alternative, less than 23 percent by weight of units derived from one or more α -olefin comonomers; and at least 0 percent by weight of units derived by α -olefin comonomers; or in the alternative, at least 1.3 percent by weight of units derived by α -olefin comonomers; or in the alternative, at least 2.8 percent by weight of units derived by α -olefin comonomers; or in the alternative, at least 9.5 percent by weight of units derived by α -olefin comonomers.

In one embodiment, the ethylene-based polymer is an ethylene/alpha-olefin interpolymer, and further an ethylene/alpha-olefin copolymer. Suitable alpha-olefins are described below.

The inventive ethylene-based polymers, such as interpolymers or copolymers of ethylene, and optionally one or more comonomers, such as α -olefins, may comprise less than 20 percent by moles of units derived from one or more α -olefin comonomers, based on the total moles of polymerized monomer units in the polymer. All individual values and subranges from less than 20 mole percent are included herein and disclosed herein; for example, the inventive ethylene based polymers may comprise from less than 13 percent by moles of units derived from one or more α -olefin comonomers; or in the alternative, from less than 9.5 percent by moles of units derived from one or more α -olefin comonomers; or in the alternative, from less than 7.0 percent by moles of units derived from one or more α -olefin comonomers; and at least 0 percent by moles of units derived by α -olefin comonomers; or in the alternative, at least 0.3 percent by moles of units derived by α -olefin comonomers; or in the alternative, at least 0.7 percent by moles of units derived by α -olefin comonomers; or in the alternative, at least 2.5 percent by moles of units derived by α -olefin comonomers.

The α -olefin comonomers typically have no more than 20 carbon atoms. For example, the α -olefin comonomers may preferably have 3 to 10 carbon atoms, and more preferably 3 to 8 carbon atoms. Exemplary α -olefin comonomers include, but are not limited to, propylene, 1-butene, 1-pentene, 1-hexene, 1-heptene, 1-octene, 1-nonene, 1-decene, and 4-methyl-1-pentene. The one or more α -olefin comonomers may, for example, be selected from the group consisting of propylene, 1-butene, 1-hexene, and 1-octene; or in the alternative, from the group consisting of 1-hexene and 1-octene.

In one embodiment, the inventive ethylene-based polymers, for example homopolymers, interpolymers or copolymers, of ethylene, and optionally one or more comonomers, such as α -olefins, may comprise at least 52 percent by weight of units derived from ethylene, based on the weight of the polymer. All individual values and subranges from at least 52 weight percent are included herein and disclosed herein; for example, the inventive ethylene based polymers may comprise at least 63 percent by weight of units derived from ethylene; or in the alternative, at

least 70 percent by weight of units derived from ethylene; or in the alternative, at least 77 percent by weight of units derived from ethylene; or in the alternative, at least 85 percent by weight of units derived from ethylene; and at most 100 percent by weight of units derived by ethylene; or in the alternative, at most 98.7 percent by weight of units derived by ethylene; or in the alternative, at most 97.2 percent by weight of units derived by ethylene; or in the alternative, at most 90.5 percent by weight of units derived by ethylene,

The inventive ethylene-based polymers, for example homopolymers, interpolymers or copolymers, of ethylene, and optionally one or more comonomers, such as α -olefins, may further comprise one or more additives. Such additives include, but are not limited to, antistatic agents, color enhancers, dyes, lubricants, pigments, primary antioxidants, secondary antioxidants, processing aids, UV stabilizers, and combinations thereof. The inventive ethylene based polymers may contain any amounts of additives. The inventive ethylene-based polymers may comprise from about 0 to about 10 percent, further from 0.1 to 10 percent, by the combined weight of such additives, based on the weight of the inventive ethylene based polymers and the one or more additives. The inventive ethylene-based polymers may further comprise fillers, which may include, but are not limited to, organic or inorganic fillers. Such fillers, e.g., calcium carbonate, talc, $\text{Mg}(\text{OH})_2$, can be present in levels from about 0 to about 20 percent, further from 1 to 20 percent, based on the weight of the inventive ethylene-based polymers and the one or more additives and/or fillers. The inventive ethylene-based polymers may further be blended with one or more polymers to form a blend.

The inventive ethylene-based polymer may comprise a combination of two or more embodiments as described herein.

The inventive ethylene-based polymers are preferably produced using solution polymerization processes, using one or more reactors, such as loop reactors, isothermal reactors, stirred tank reactors, batch reactors in parallel, series, and/or any combinations thereof.

In general, the solution phase polymerization process occurs in one or more well-stirred reactors such as one or more loop reactors or one or more spherical isothermal reactors at a temperature in the range of from 120°C to 300 °C; for example, from 120 or 130 or 135 or 140 or 145 or 150 or 155 or 160°C, to 150 or 155 or 165 or 170 or 175 or 180 or 185 or 190 or 195 or 200 or 205 or 210 or 215 or 220 or 230 or 240 or 250°C; and at pressures in the range of from 300 to 1500 psi; for example, from 400 to 750 psi. The solution phase polymerization process also occurs in one or more well-stirred reactors, such as one or more loop reactors, or one or more spherical isothermal reactors, with a reactor ethylene exit concentration in the range of from 18 g/L to 1 g/L; for example, from 18 or 16 or 14 or 12 or 10 or 8 or 6 g/L, to 11 or 9 or 7

or 5 or 3 or 1 g/L. The residence time in solution phase polymerization process is typically in the range from 2 to 30 minutes; for example, from 10 to 20 minutes. Ethylene, one or more solvents, one or more catalyst systems, e.g., a catalyst system comprising the procatalyst of Formula I, optionally one or more cocatalysts, and optionally one or more comonomers are fed continuously to the one or more reactors. Exemplary solvents include, but are not limited to, isoparaffins. For example, such solvents are commercially available under the name ISOPAR E from ExxonMobil Chemical Co., Houston, Texas. The resultant mixture of the ethylene based polymer and solvent is then removed from the reactor, and the ethylene based polymer is isolated. Solvent is typically recovered via a solvent recovery unit, i.e., heat exchangers and vapor liquid separator drum, and is then recycled back into the polymerization system.

In one embodiment, the ethylene based polymer may be produced, via solution polymerization, in a dual reactor system, for example, a dual loop reactor system, wherein ethylene, and optionally one or more α -olefins, are polymerized in the presence of the catalyst system comprising the procatalyst of Formula I, as described herein, and optionally one or more cocatalysts. In one embodiment, the ethylene based polymer may be produced via solution polymerization, in a dual reactor system, for example a dual loop reactor system, wherein ethylene, and optionally one or more α -olefins, are polymerized in the presence of the catalyst system, comprising the procatalyst of Formula I, as described herein, and optionally one or more other catalysts. The catalyst system, as described herein, can be used in the first reactor, or second reactor, optionally in combination with one or more other catalysts. In one embodiment, the ethylene based polymer may be produced via solution polymerization in a dual reactor system, for example a dual loop reactor system, wherein ethylene, and optionally one or more α -olefins, are polymerized in the presence of the catalyst system, comprising the procatalyst of Formula I, as described herein, in both reactors.

The procatalyst comprising the metal-ligand complex of Formula I may be activated, to form an active catalyst composition, by combination with one or more cocatalysts, as described herein, for example, a cation forming cocatalyst, a strong Lewis acid, or a combination thereof. Suitable cocatalysts for use include polymeric or oligomeric aluminoxanes, especially methyl aluminoxane, as well as inert, compatible, noncoordinating, ion forming compounds. Exemplary suitable cocatalysts include, but are not limited to modified methyl aluminoxane (MMAO), bis(hydrogenated tallow alkyl)methyl, tetrakis(pentafluorophenyl)borate(1-) amine, triethyl aluminum (TEA), and combinations thereof.

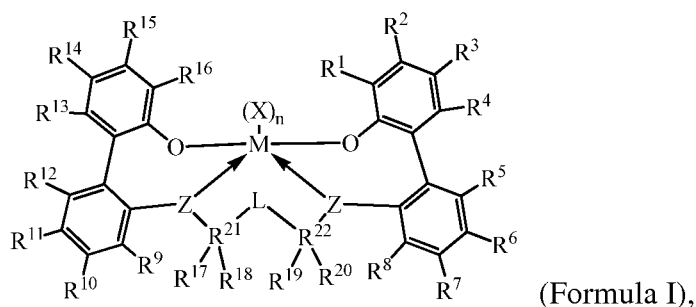
In another embodiment, the inventive ethylene based polymers, for example homopolymers, interpolymers, or copolymers, of ethylene, and optionally one or more

comonomers, such as α -olefins, may be produced via solution polymerization in a single reactor system, for example a single loop reactor system, wherein ethylene, and optionally one or more α -olefins, are polymerized in the presence of one or more catalyst systems.

As discussed above, in one embodiment, the ethylene-based polymer is formed by a process comprising polymerizing at least ethylene, in the presence of at least one catalyst system comprising the reaction product of the following:

A) at least one cocatalyst; and

B) a procatalyst comprising a metal-ligand complex of Formula (I):



wherein:

M is titanium, zirconium, or hafnium, each independently being in a formal oxidation state of +2, +3, or +4; and n is an integer from 0 to 3, and wherein when n is 0, X is absent; and

Each X, independently, is a (C₁-C₄₀)hydrocarbyl, a (C₁-C₄₀)heterohydrocarbyl, or a halide, and wherein each X, independently, is a monodentate ligand that is neutral, monoanionic, or dianionic; or

wherein two Xs are taken together to form a bidentate ligand that is neutral, monoanionic, or dianionic; and

wherein X and n are chosen, in such a way, that the metal-ligand complex of Formula (I) is, overall, neutral; and

Each Z independently is an oxygen atom, a sulfur atom, -N[(C₁-C₄₀)hydrocarbyl]-, or -P[(C₁-C₄₀)hydrocarbyl]-; and

L is a substituted or unsubstituted (C₁-C₄₀)hydrocarbylene, or a substituted or unsubstituted (C₁-C₄₀)heterohydrocarbylene, and

wherein, for L, the (C₁-C₄₀)hydrocarbylene has a portion that comprises a 1-carbon atom to 10-carbon atom linker backbone linking R²¹ and R²² in Formula (I) (to which L is bonded), or

wherein, for L, the (C₁-C₄₀)heterohydrocarbylene has a portion that comprises a 1-atom to 10-atom linker backbone linking R²¹ and R²² in Formula (I), wherein each of the 1 to 10 atoms of the 1-atom to 10-atom linker backbone of the (C₁-C₄₀)heterohydrocarbylene, independently,

is one of the following: i) a carbon atom, ii) a heteroatom, wherein each heteroatom independently is -O- or -S-, or iii) a substituent selected from -S(O)-, -S(O)₂-, -Si(R^C)₂-, -Ge(R^C)₂-, -P(R^C)-, or -N(R^C)-, and wherein each R^C is, independently, a substituted or unsubstituted (C₁-C₃₀)hydrocarbyl, or a substituted or unsubstituted (C₁-C₃₀) heterohydrocarbyl; and

R²¹ and R²² are each, independently, C or Si; and

R¹ through R²⁰ are each, independently, selected from the group consisting of the following: a substituted or unsubstituted (C₁-C₄₀)hydrocarbyl, a substituted or unsubstituted (C₁-C₄₀)hetero-hydrocarbyl, -Si(R^C)₃, -Ge(R^C)₃, -P(R^C)₂, -N(R^C)₂, -OR^C, -SR^C, -NO₂, -CN, -CF₃, -S(O)R^C, -S(O)₂R^C, -N=C(R^C)₂, -OC(O)R^C, -C(O)OR^C, -N(R)C(O)R^C, -C(O)N(R^C)₂, a halogen atom, and a hydrogen atom; and wherein each R^C is independently a substituted or unsubstituted (C₁-C₃₀)hydrocarbyl, or a substituted or unsubstituted (C₁-C₃₀) heterohydrocarbyl; and

wherein, when R¹⁷ is a hydrogen atom, then R¹⁸ is a substituted or unsubstituted (C₁-C₄₀)hydrocarbyl, a substituted or unsubstituted (C₁-C₄₀)heterohydrocarbyl, -Si(R^C)₃, -Ge(R^C)₃, -P(R^C)₂, -N(R^C)₂, -OR^C, -SR^C, -NO₂, -CN, -CF₃, -S(O)R^C, -S(O)₂R^C, -N=C(R^C)₂, -OC(O)R^C, -C(O)OR^C, -N(R)C(O)R^C, -C(O)N(R^C)₂, a halogen atom, or a hydrogen atom; and wherein each R^C is independently a substituted or unsubstituted (C₁-C₃₀)hydrocarbyl, or a substituted or unsubstituted (C₁-C₃₀) heterohydrocarbyl; or

wherein, when R¹⁸ is a hydrogen atom, then R¹⁷ is a substituted or unsubstituted (C₁-C₄₀)hydrocarbyl, a substituted or unsubstituted (C₁-C₄₀)heterohydrocarbyl, -Si(R^C)₃, -Ge(R^C)₃, -P(R^C)₂, -N(R^C)₂, -OR^C, -SR^C, -NO₂, -CN, -CF₃, -S(O)R^C, -S(O)₂R^C, -N=C(R^C)₂, -OC(O)R^C, -C(O)OR^C, -N(R)C(O)R^C, -C(O)N(R^C)₂, a halogen atom, or a hydrogen atom; and wherein each R^C is independently a substituted or unsubstituted (C₁-C₃₀)hydrocarbyl, or a substituted or unsubstituted (C₁-C₃₀) heterohydrocarbyl; and/or

wherein, when R¹⁹ is a hydrogen atom, then R²⁰ is a substituted or unsubstituted (C₁-C₄₀)hydrocarbyl, a substituted or unsubstituted (C₁-C₄₀)heterohydrocarbyl, -Si(R^C)₃, -Ge(R^C)₃, -P(R^C)₂, -N(R^C)₂, -OR^C, -SR^C, -NO₂, -CN, -CF₃, -S(O)R^C, -S(O)₂R^C, -N=C(R^C)₂, -OC(O)R^C, -C(O)OR^C, -N(R)C(O)R^C, -C(O)N(R^C)₂, a halogen atom, or a

hydrogen atom; and wherein each R^C is independently a substituted or unsubstituted (C_1 - C_{30})hydrocarbyl, or a substituted or unsubstituted (C_1 - C_{30}) heterohydrocarbyl; or

wherein, when R^{20} is a hydrogen atom, then R^{19} is a substituted or unsubstituted (C_1 - C_{40})hydrocarbyl, a substituted or unsubstituted (C_1 - C_{40})heterohydrocarbyl, $-\text{Si}(R^C)_3$, $-\text{Ge}(R^C)_3$, $-\text{P}(R^C)_2$, $-\text{N}(R^C)_2$, $-\text{OR}^C$, $-\text{SR}^C$, $-\text{NO}_2$, $-\text{CN}$, $-\text{CF}_3$, $-\text{S}(\text{O})R^C$, $-\text{S}(\text{O})_2R^C$, $-\text{N}=\text{C}(R^C)_2$, $-\text{OC}(\text{O})R^C$, $-\text{C}(\text{O})\text{OR}^C$, $-\text{N}(\text{R})\text{C}(\text{O})R^C$, $-\text{C}(\text{O})\text{N}(R^C)_2$, a halogen atom, or a hydrogen atom; and wherein each R^C is independently a substituted or unsubstituted (C_1 - C_{30})hydrocarbyl, or a substituted or unsubstituted (C_1 - C_{30}) heterohydrocarbyl; and

wherein, for Formula I, two or more of R^1 through R^{22} , optionally, may form one or more ring structures, and wherein each ring structure has from 3 to 50 atoms in the ring, excluding any hydrogen atoms; and

wherein, for Formula I, one or more hydrogen atoms may optionally be substituted with one or more deuterium atoms.

The procatalyst of Formula I may comprise a combination of two or more embodiments as described herein.

As used herein, $R1 = R^1$, $R2 = R^2$, $R3 = R^3$, and so forth. As known in the art, O is oxygen, S is sulfur, Si is silicon, and so forth.

In one embodiment, for Formula I, when R^{17} is a hydrogen atom, then R^{18} is a substituted or unsubstituted (C_1 - C_{40})hydrocarbyl, a substituted or unsubstituted (C_1 - C_{40})heterohydrocarbyl, $-\text{Si}(R^C)_3$, $-\text{Ge}(R^C)_3$, $-\text{P}(R^C)_2$, $-\text{N}(R^C)_2$, $-\text{OR}^C$, $-\text{SR}^C$, $-\text{NO}_2$, $-\text{CN}$, $-\text{CF}_3$, $-\text{S}(\text{O})R^C$, $-\text{S}(\text{O})_2R^C$, $-\text{N}=\text{C}(R^C)_2$, $-\text{OC}(\text{O})R^C$, $-\text{C}(\text{O})\text{OR}^C$, $-\text{N}(\text{R})\text{C}(\text{O})R^C$, $-\text{C}(\text{O})\text{N}(R^C)_2$, or a halogen atom; and wherein each R^C is independently a substituted or unsubstituted (C_1 - C_{30})hydrocarbyl, or a substituted or unsubstituted (C_1 - C_{30}) heterohydrocarbyl; or

wherein, when R^{18} is a hydrogen atom, then R^{17} is a substituted or unsubstituted (C_1 - C_{40})hydrocarbyl, a substituted or unsubstituted (C_1 - C_{40})heterohydrocarbyl, $-\text{Si}(R^C)_3$, $-\text{Ge}(R^C)_3$, $-\text{P}(R^C)_2$, $-\text{N}(R^C)_2$, $-\text{OR}^C$, $-\text{SR}^C$, $-\text{NO}_2$, $-\text{CN}$, $-\text{CF}_3$, $-\text{S}(\text{O})R^C$, $-\text{S}(\text{O})_2R^C$, $-\text{N}=\text{C}(R^C)_2$, $-\text{OC}(\text{O})R^C$, $-\text{C}(\text{O})\text{OR}^C$, $-\text{N}(\text{R})\text{C}(\text{O})R^C$, $-\text{C}(\text{O})\text{N}(R^C)_2$, or a halogen atom; and wherein each R^C is independently a substituted or unsubstituted (C_1 - C_{30})hydrocarbyl, or a substituted or unsubstituted (C_1 - C_{30}) heterohydrocarbyl; and/or

wherein, when R^{19} is a hydrogen atom, then R^{20} is a substituted or unsubstituted (C_1 - C_{40})hydrocarbyl, a substituted or unsubstituted (C_1 - C_{40})heterohydrocarbyl, $-\text{Si}(R^C)_3$,

$-\text{Ge}(\text{R}^{\text{C}})_3$, $-\text{P}(\text{R}^{\text{C}})_2$, $-\text{N}(\text{R}^{\text{C}})_2$, $-\text{OR}^{\text{C}}$, $-\text{SR}^{\text{C}}$, $-\text{NO}_2$, $-\text{CN}$, $-\text{CF}_3$, $-\text{S}(\text{O})\text{R}^{\text{C}}$, $-\text{S}(\text{O})_2\text{R}^{\text{C}}$, $-\text{N}=\text{C}(\text{R}^{\text{C}})_2$, $-\text{OC}(\text{O})\text{R}^{\text{C}}$, $-\text{C}(\text{O})\text{OR}^{\text{C}}$, $-\text{N}(\text{R})\text{C}(\text{O})\text{R}^{\text{C}}$, $-\text{C}(\text{O})\text{N}(\text{R}^{\text{C}})_2$, or a halogen atom; and wherein each R^{C} is independently a substituted or unsubstituted (C_1 - C_{30})hydrocarbyl, or a substituted or unsubstituted (C_1 - C_{30}) heterohydrocarbyl; or

wherein, when R^{20} is a hydrogen atom, then R^{19} is a substituted or unsubstituted (C_1 - C_{40})hydrocarbyl, a substituted or unsubstituted (C_1 - C_{40})heterohydrocarbyl, $-\text{Si}(\text{R}^{\text{C}})_3$, $-\text{Ge}(\text{R}^{\text{C}})_3$, $-\text{P}(\text{R}^{\text{C}})_2$, $-\text{N}(\text{R}^{\text{C}})_2$, $-\text{OR}^{\text{C}}$, $-\text{SR}^{\text{C}}$, $-\text{NO}_2$, $-\text{CN}$, $-\text{CF}_3$, $-\text{S}(\text{O})\text{R}^{\text{C}}$, $-\text{S}(\text{O})_2\text{R}^{\text{C}}$, $-\text{N}=\text{C}(\text{R}^{\text{C}})_2$, $-\text{OC}(\text{O})\text{R}^{\text{C}}$, $-\text{C}(\text{O})\text{OR}^{\text{C}}$, $-\text{N}(\text{R})\text{C}(\text{O})\text{R}^{\text{C}}$, $-\text{C}(\text{O})\text{N}(\text{R}^{\text{C}})_2$, or a halogen atom; and wherein each R^{C} is independently a substituted or unsubstituted (C_1 - C_{30})hydrocarbyl, or a substituted or unsubstituted (C_1 - C_{30}) heterohydrocarbyl.

In one embodiment, for Formula I, each Z is an oxygen atom.

In one embodiment, for Formula I, R^{21} and R^{22} are each C (carbon).

In one embodiment, each X is, independently, a (C_1 - C_{40})hydrocarbyl, a (C_1 - C_{40})heterohydrocarbyl, or a halide. In a further embodiment both X groups are the same.

In one embodiment, each X is, independently, a (C_1 - C_{40})hydrocarbyl, or a halide. In a further embodiment both X groups are the same.

In one embodiment, each X is, independently, a (C_1 - C_{40})hydrocarbyl. In a further embodiment both X groups are the same.

In one embodiment, each X is, independently, a (C_1 - C_3)alkyl, further ethyl or methyl, and further methyl. In a further embodiment both X groups are the same.

In one embodiment, for Formula I, L is selected from the following: $-\text{CH}_2\text{CH}_2\text{CH}_2-$, $-\text{CH}_2\text{CH}_2-$ or $-\text{CH}_2-$; and further $-\text{CH}_2\text{CH}_2-$ or $-\text{CH}_2-$, and further $-\text{CH}_2-$.

In one embodiment, for Formula I, each (C_1 - C_{40})hydrocarbyl, and each (C_1 - C_{40})heterohydrocarbyl is not substituted.

In one embodiment, for Formula I, at least one (C_1 - C_{40})hydrocarbyl, and/or at least one (C_1 - C_{40})heterohydrocarbyl is/are, independently, substituted with at least one R^{S} substituent, and wherein each R^{S} substituent is, independently, selected from the following: a halogen atom, a polyfluoro substituent, a perfluoro substituent, $\text{F}_3\text{C}-$, $\text{FCH}_2\text{O}-$, $\text{F}_2\text{HCO}-$, $\text{F}_3\text{CO}-$, $(\text{R}^{\text{C}})_3\text{Si}-$, $(\text{R}^{\text{C}})_3\text{Ge}$, $(\text{R}^{\text{C}})\text{O}-$, $(\text{R}^{\text{C}})\text{S}-$, $(\text{R}^{\text{C}})\text{S}(\text{O})-$, $(\text{R}^{\text{C}})\text{S}(\text{O})_2-$, $(\text{R}^{\text{C}})_2\text{P}-$, $(\text{R}^{\text{C}})_2\text{N}-$, $(\text{R}^{\text{C}})_2\text{C}=\text{N}-$, $\text{NC}-$, $(\text{R}^{\text{C}})\text{C}(\text{O})\text{O}-$, $(\text{R}^{\text{C}})\text{OC}(\text{O})-$, $(\text{R}^{\text{C}})\text{C}(\text{O})\text{N}(\text{R}^{\text{C}})-$, or $(\text{R}^{\text{C}})_2\text{NC}(\text{O})-$; and wherein each R^{C} is

independently a substituted or unsubstituted (C₁-C₃₀)hydrocarbyl, or a substituted or unsubstituted (C₁-C₃₀) heterohydrocarbyl.

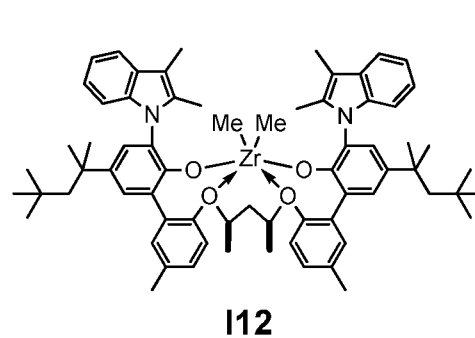
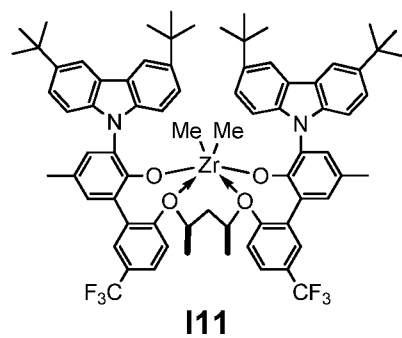
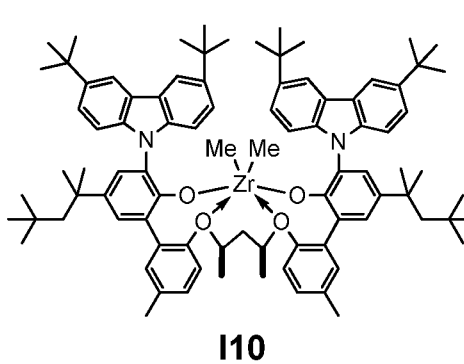
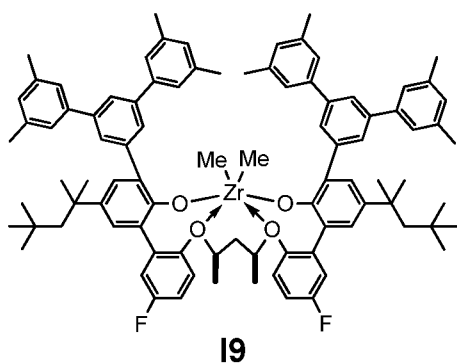
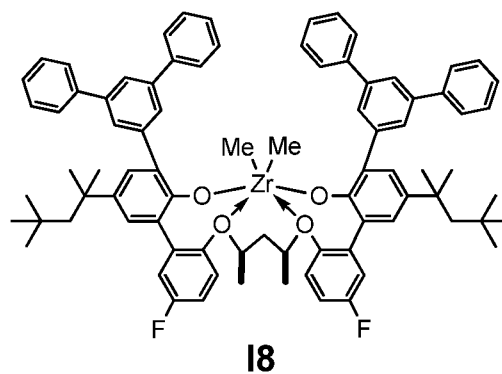
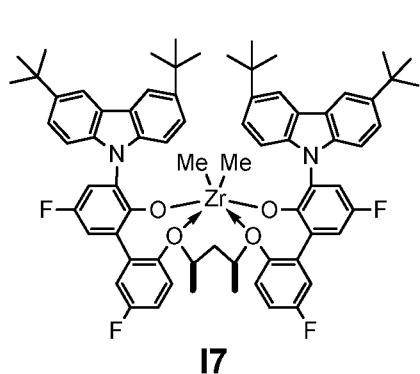
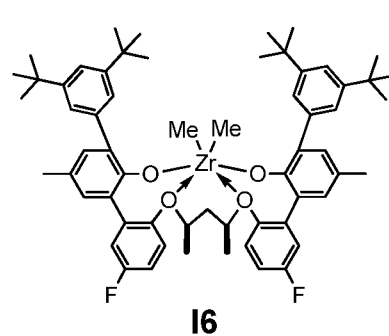
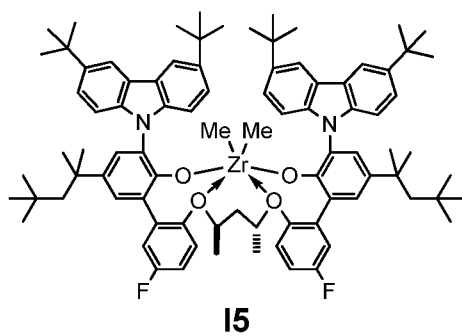
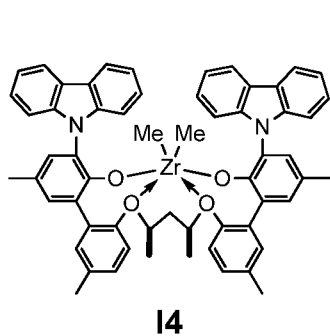
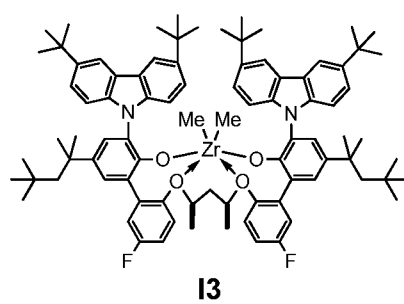
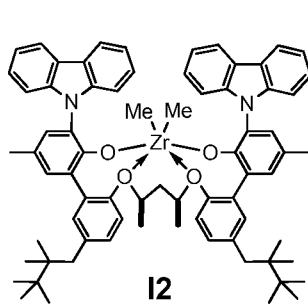
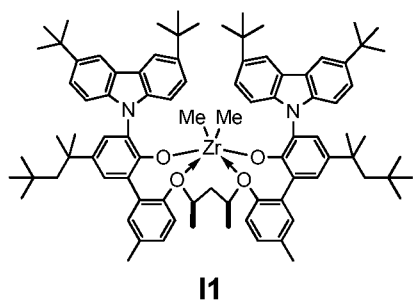
In one embodiment, for Formula I, each (C₁-C₄₀)hydrocarbyl, and each (C₁-C₄₀)heterohydrocarbyl are, independently, substituted with at least one R^S substituent, and wherein each R^S substituent is, independently, selected from the following: a halogen atom, a polyfluoro substituent, a perfluoro substituent, F₃C-, FCH₂O-, F₂HCO-, F₃CO-, (R^C)₃Si-, (R^C)₃Ge-, (R^C)O-, (R^C)S-, (R^C)S(O) -, (R^C)S(O)₂-, (R^C)₂P-, (R^C)₂N-, (R^C)₂C=N-, NC-, (R^C)C(O)O-, (R^C)OC(O) -, (R^C)C(O)N(R^C) -, or (R^C)₂NC(O)-; and wherein each R^C is independently a substituted or unsubstituted (C₁-C₃₀)hydrocarbyl, or a substituted or unsubstituted (C₁-C₃₀) heterohydrocarbyl.

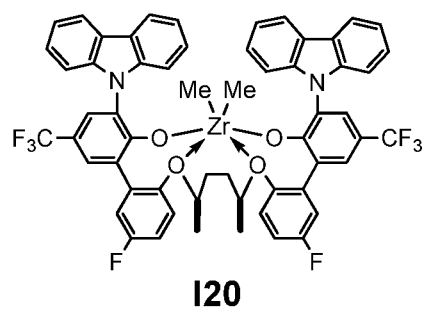
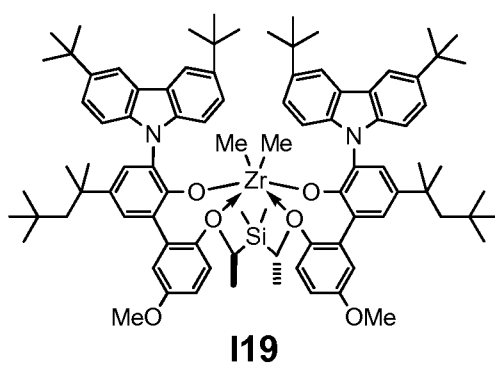
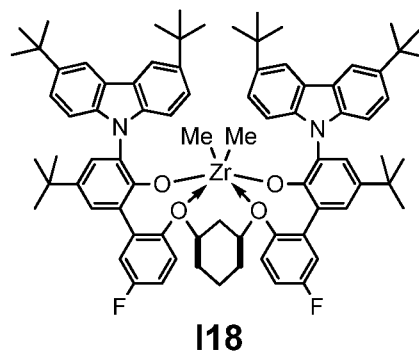
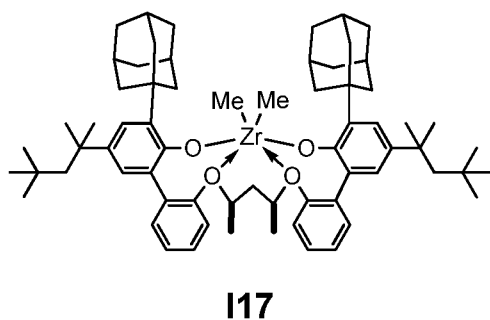
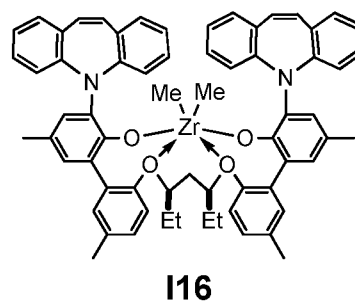
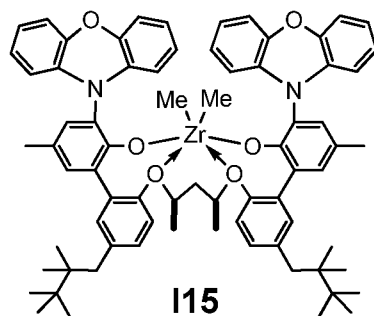
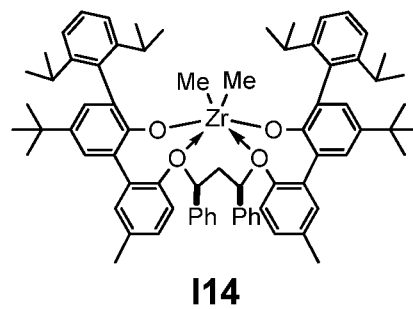
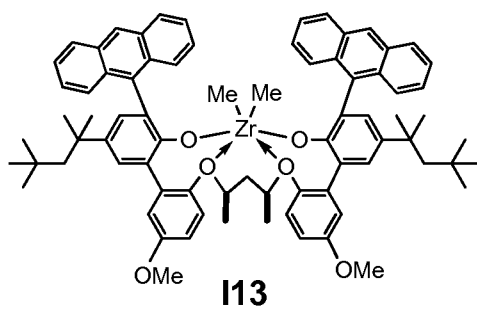
In one embodiment, two or more of R¹ to R²² do not form one or more ring structures.

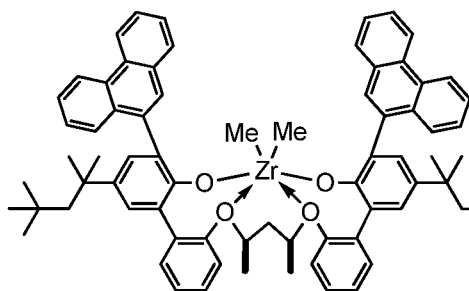
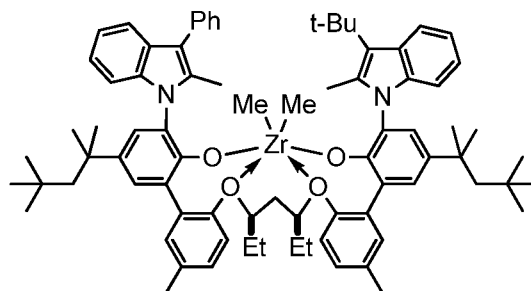
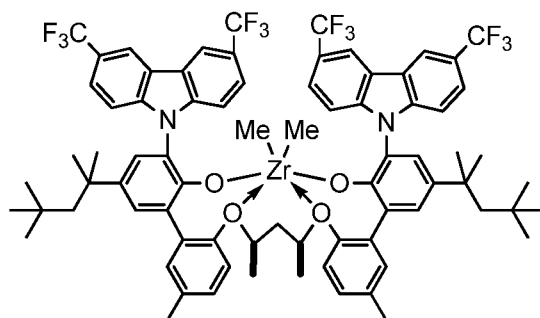
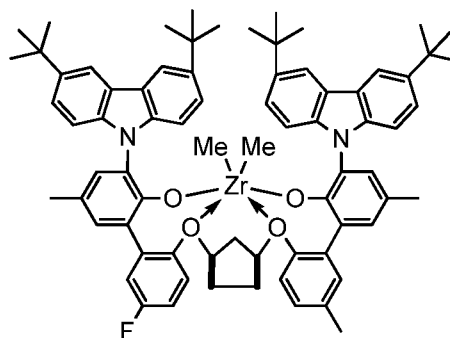
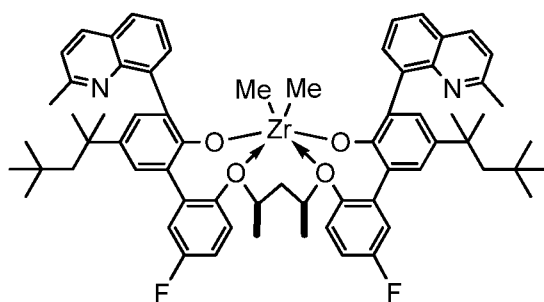
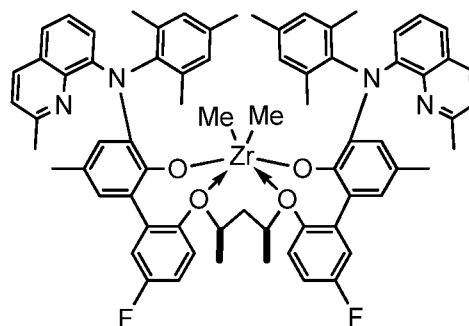
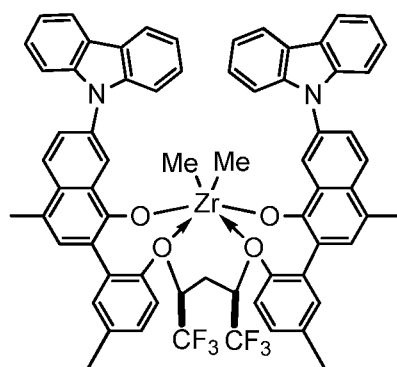
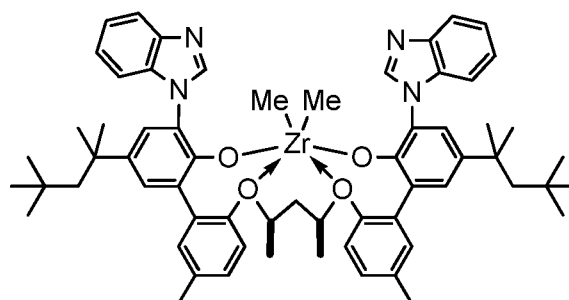
In one embodiment, Formula I does not contain one or more deuterium atoms.

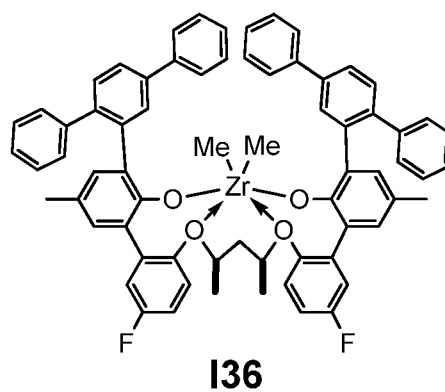
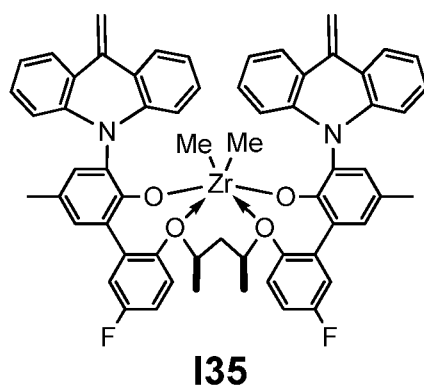
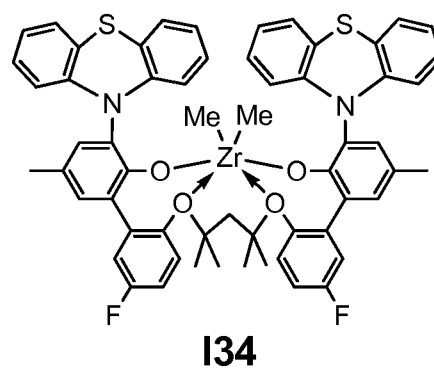
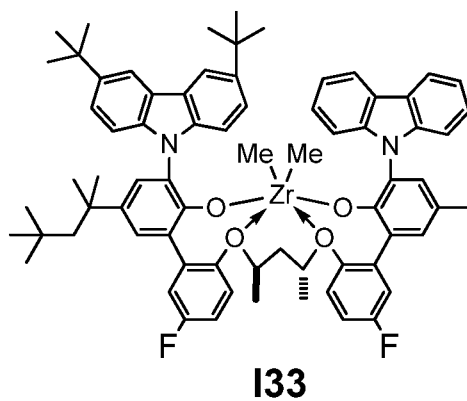
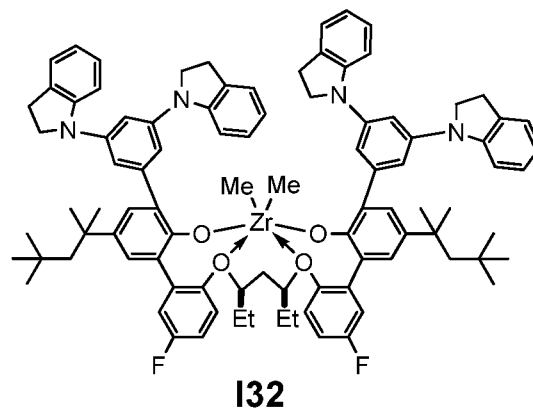
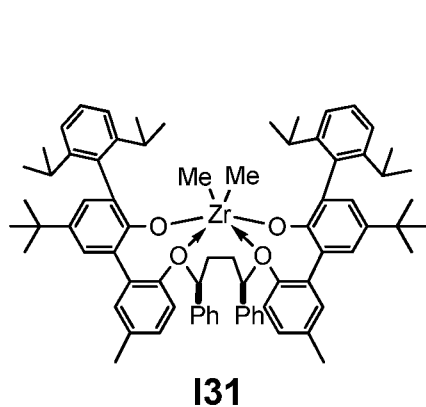
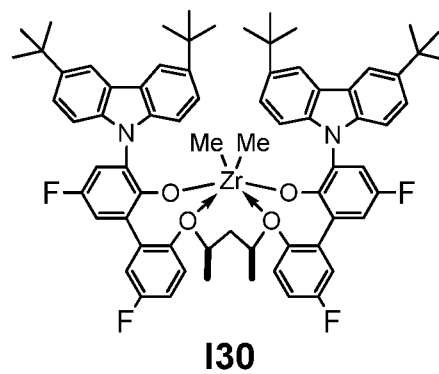
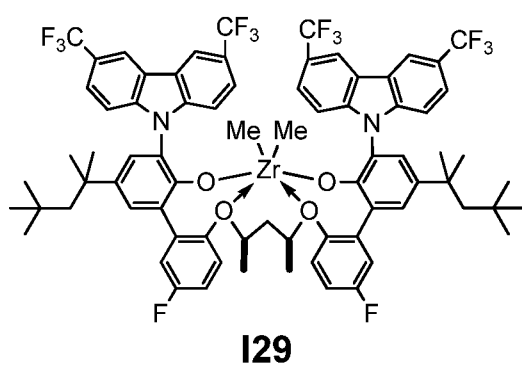
In one embodiment, for Formula I, the procatalyst is selected from the group consisting of the following I1 through I76:

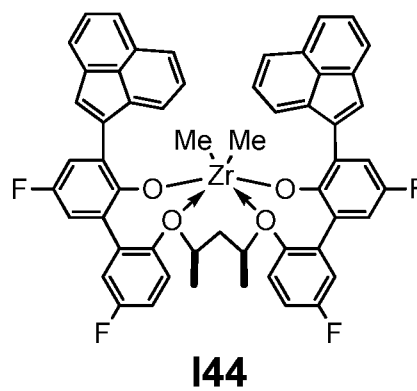
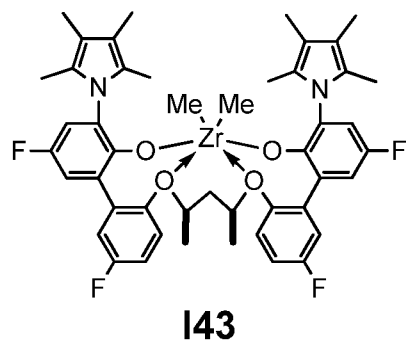
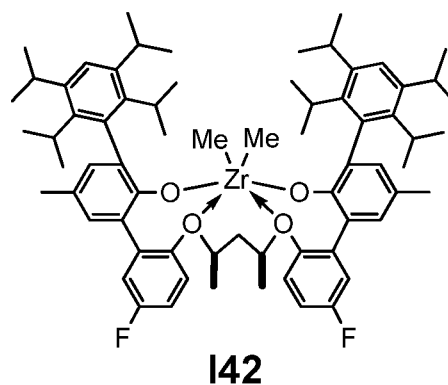
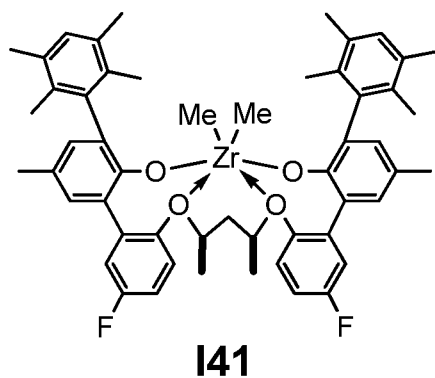
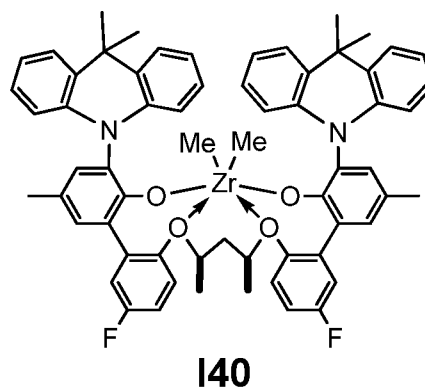
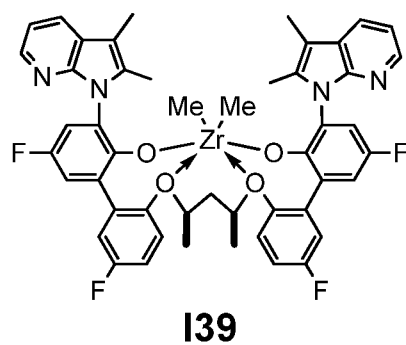
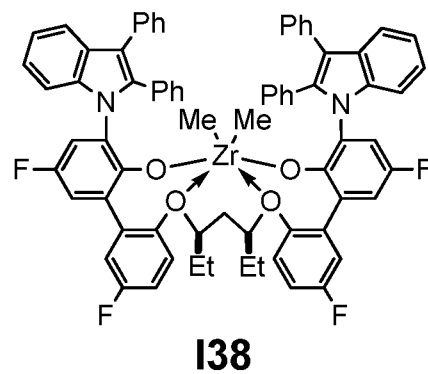
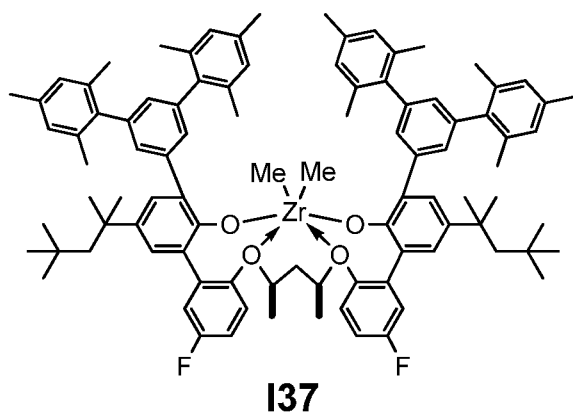
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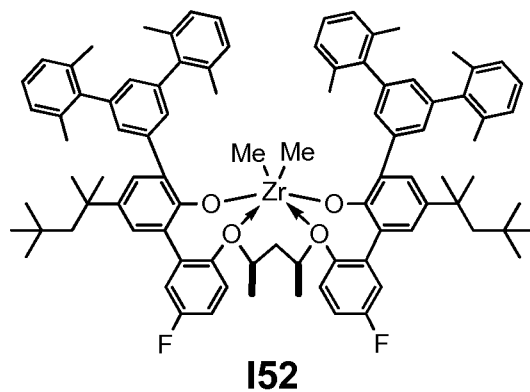
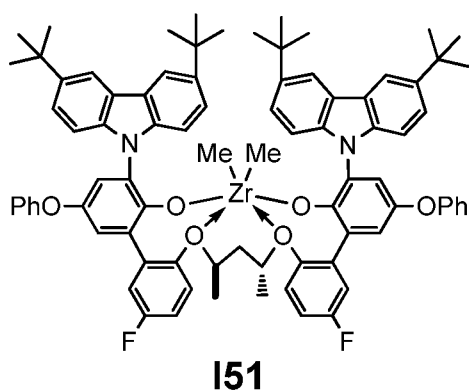
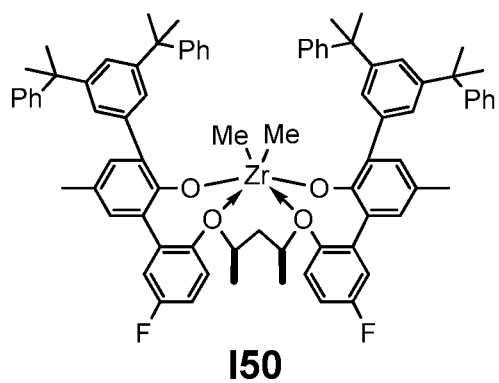
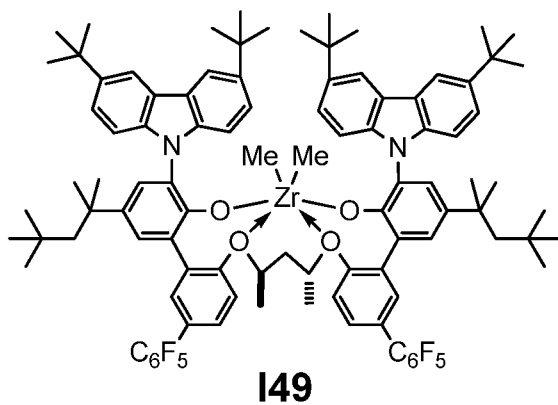
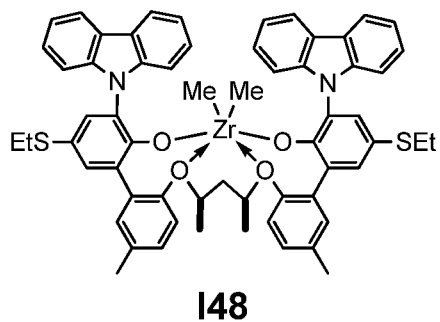
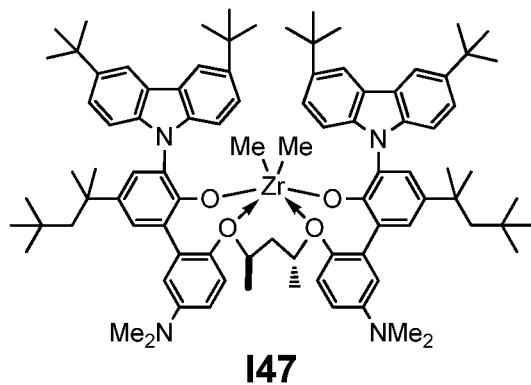
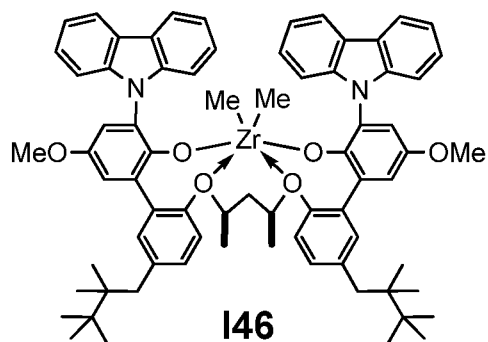
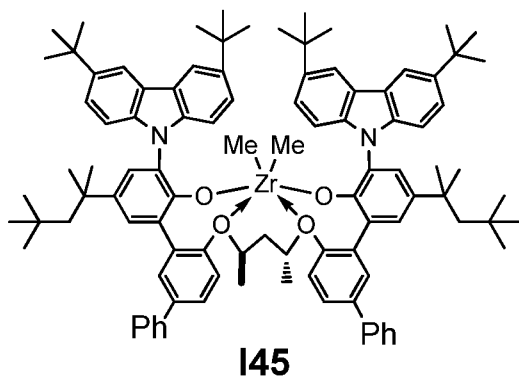


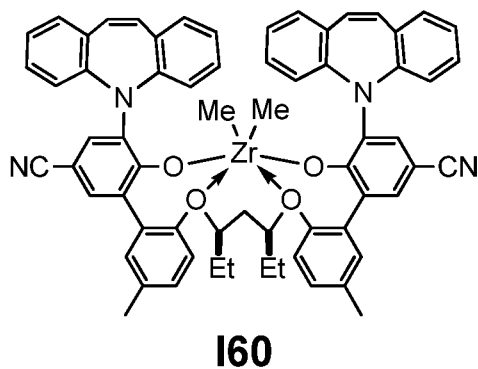
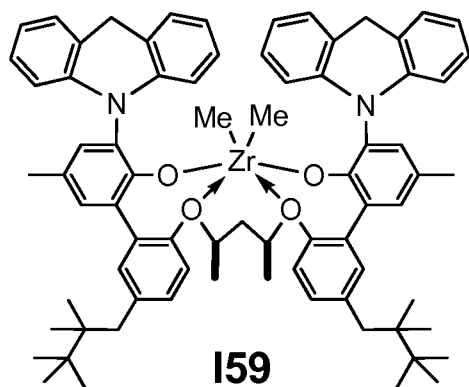
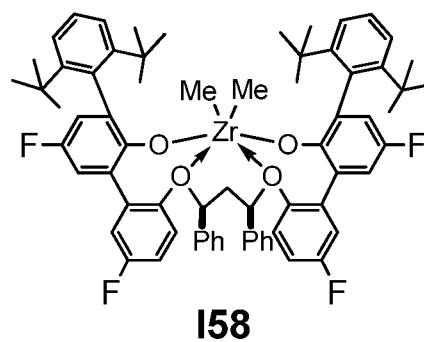
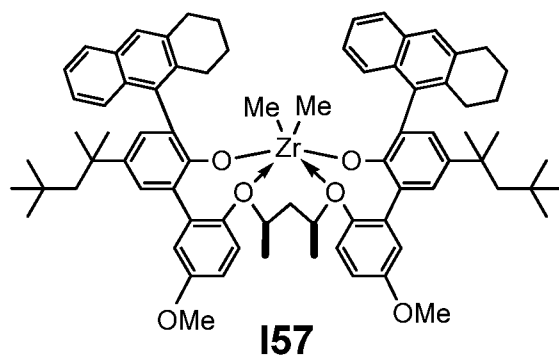
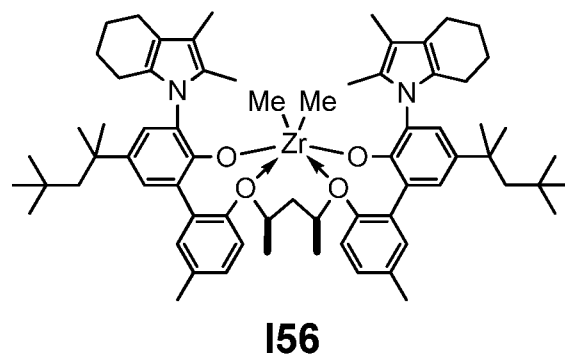
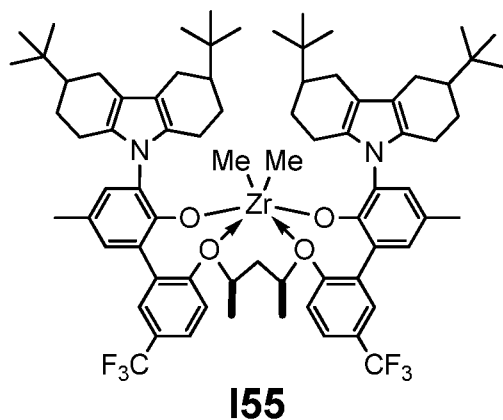
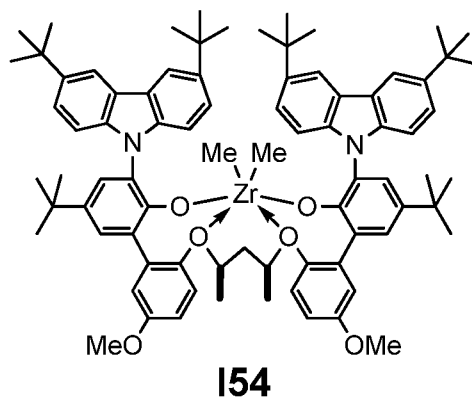
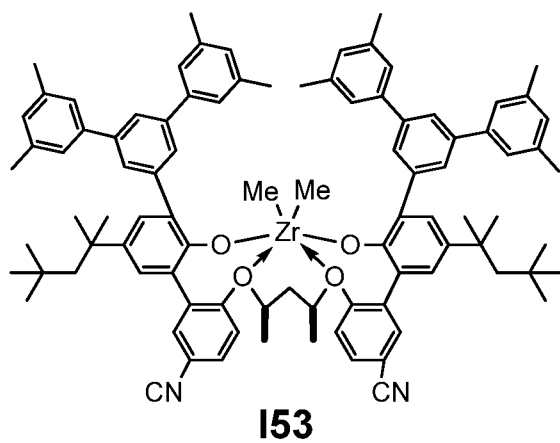


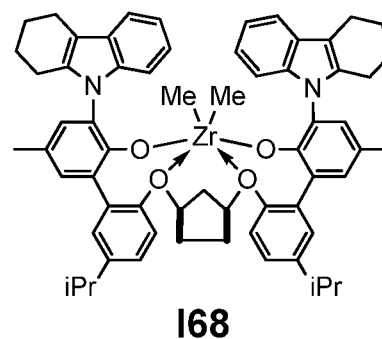
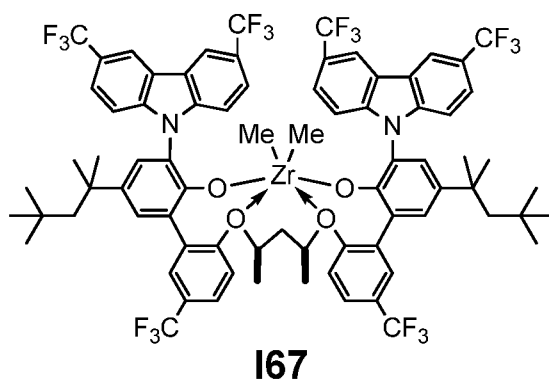
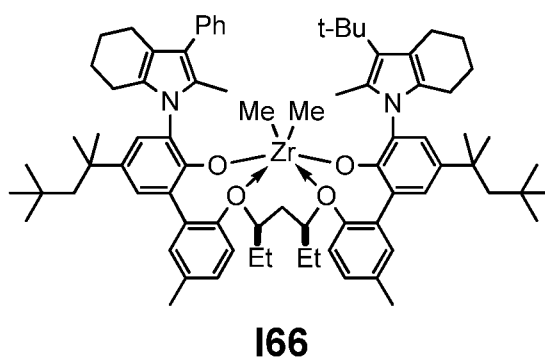
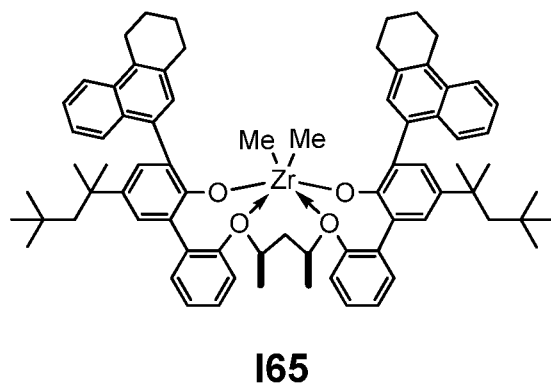
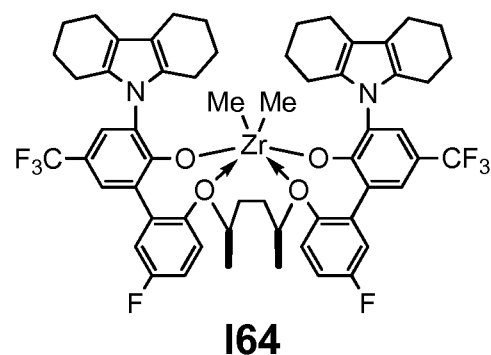
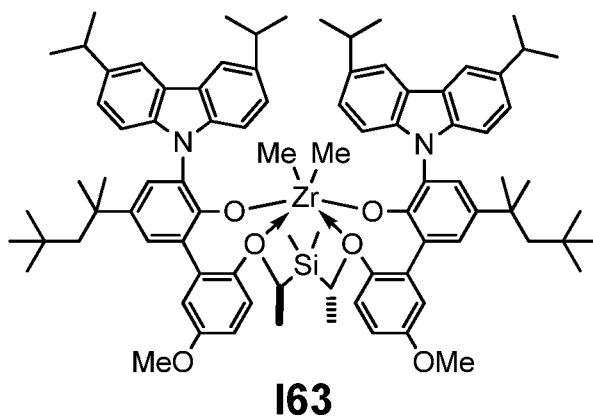
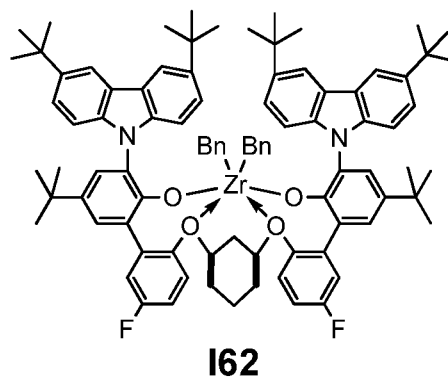
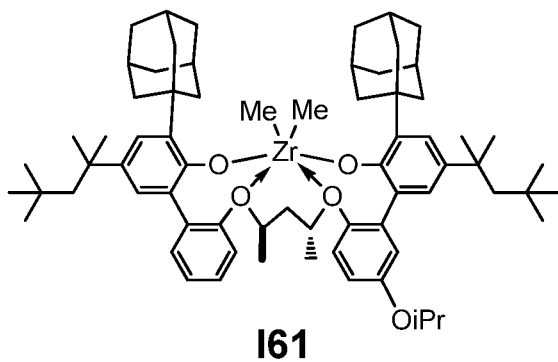
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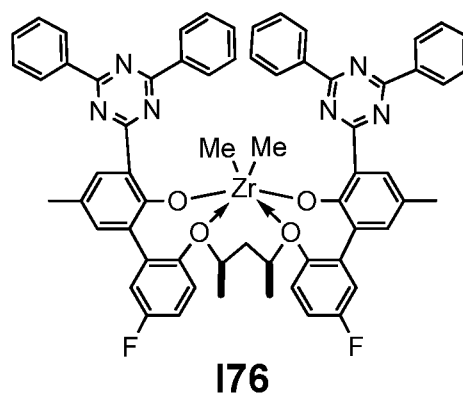
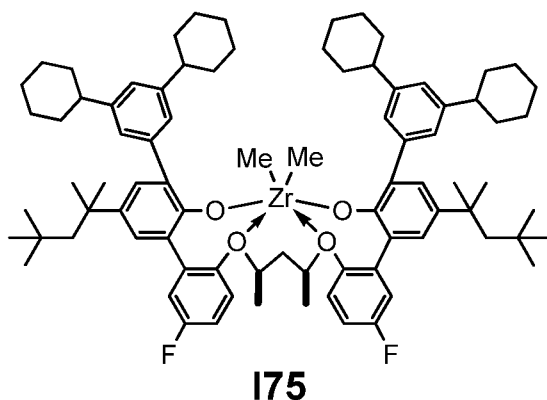
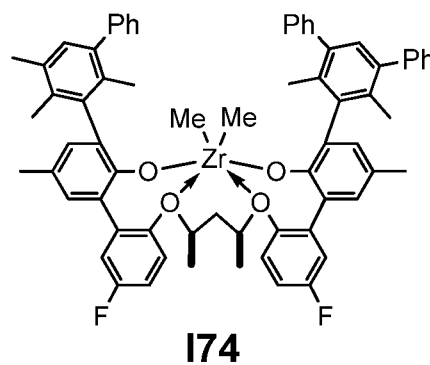
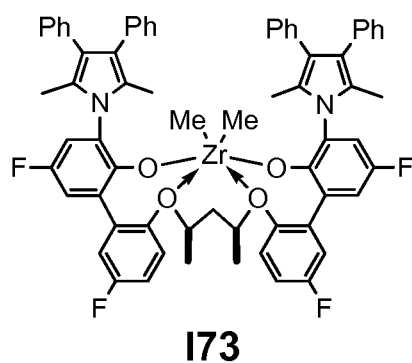
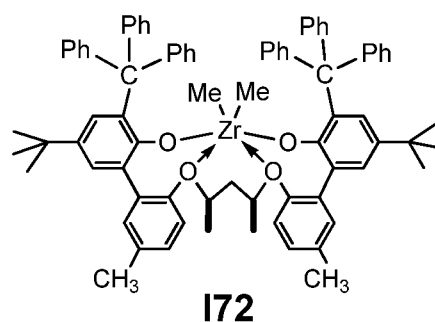
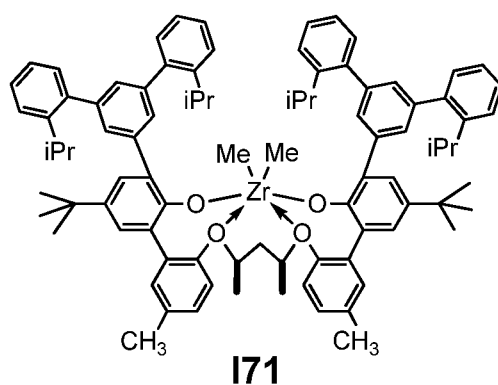
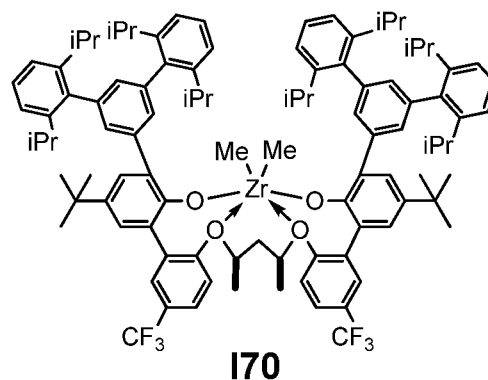
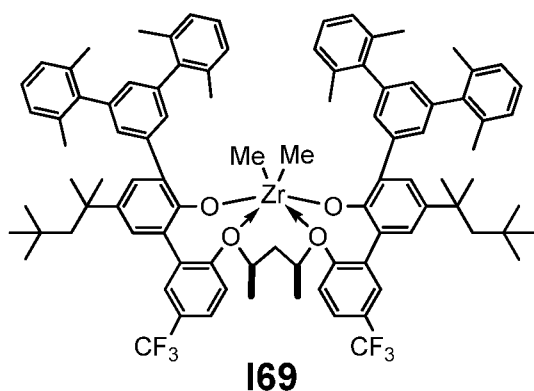












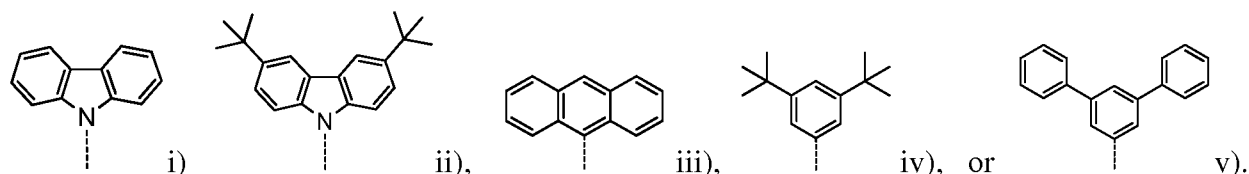
In a further embodiment, for Formula I, the procatalyst is selected from the group consisting of the following: from I1 through I20, further from I1 to I12, further from I1 to I6.

In one embodiment, for Formula I, R^2 , R^4 , R^5 , R^7 , R^8 , R^9 , R^{10} , R^{12} , R^{13} and R^{15} are each hydrogen.

In one embodiment, for Formula I, M is zirconium or hafnium; n is 2; each X, independently, is a (C₁-C₄₀)hydrocarbyl, a (C₁-C₄₀)hetero-hydrocarbyl, or a halide; and R², R⁴, R⁵, R⁷, R⁸, R⁹, R¹⁰, R¹², R¹³ and R¹⁵ are each hydrogen.

In one embodiment, for Formula I, M is zirconium; and each Z is an oxygen atom.

In one embodiment, for Formula I, R¹ and R¹⁶ are each independently selected from the following i) through v):



In a further embodiment, both R¹ and R¹⁶ are the same. In each of structures 1) through v), the dashed line (---) indicated the point of attachment to the remainder structure of Formula I.

In one embodiment, for Formula I, R¹ and R¹⁶ are each independently selected from the following i) through ii). In a further embodiment, both R¹ and R¹⁶ are the same.

In one embodiment, for Formula I, R¹⁷ or R¹⁸ is a hydrogen atom, and the other is a substituted or unsubstituted (C₁-C₄₀)hydrocarbyl, a substituted or unsubstituted (C₁-C₄₀)heterohydrocarbyl, -Si(R^C)₃, -Ge(R^C)₃, -P(R^C)₂, -N(R^C)₂, -OR^C, -SR^C, -NO₂, -CN, -CF₃, -S(O)R^C, -S(O)₂R^C, -N=C(R^C)₂, -OC(O)R^C, -C(O)OR^C, -N(R)C(O)R^C, -C(O)N(R^C)₂, or a halogen atom; and wherein each R^C is independently a substituted or unsubstituted (C₁-C₃₀)hydrocarbyl, or a substituted or unsubstituted (C₁-C₃₀) heterohydrocarbyl. In a further embodiment, R¹⁹ or R²⁰ is a hydrogen atom, and the other is a substituted or unsubstituted (C₁-C₄₀)hydrocarbyl, a substituted or unsubstituted (C₁-C₄₀)heterohydrocarbyl, -Si(R^C)₃, -Ge(R^C)₃, -P(R^C)₂, -N(R^C)₂, -OR^C, -SR^C, -NO₂, -CN, -CF₃, -S(O)R^C, -S(O)₂R^C, -N=C(R^C)₂, -OC(O)R^C, -C(O)OR^C, -N(R)C(O)R^C, -C(O)N(R^C)₂, or a halogen atom; and wherein each R^C is independently a substituted or unsubstituted (C₁-C₃₀)hydrocarbyl, or a substituted or unsubstituted (C₁-C₃₀) heterohydrocarbyl.

In one embodiment, R¹⁷ or R¹⁸ is hydrogen, and the other is an unsubstituted hydrocarbyl. In a further embodiment, R¹⁹ or R²⁰ is hydrogen, and the other is an unsubstituted hydrocarbyl.

In one embodiment, for Formula I, R¹⁷, R¹⁸, R¹⁹ and R²⁰ are each, independently, an unsubstituted (C₁-C₄₀)hydrocarbyl. In a further embodiment, R¹⁷, R¹⁸, R¹⁹ and R²⁰ are each, independently, an unsubstituted (C₁-C₃₀)hydrocarbyl, further an unsubstituted

(C₁-C₂₀)hydrocarbyl, further an unsubstituted (C₁-C₁₀)hydrocarbyl, further an unsubstituted (C₁-C₅)hydrocarbyl, and further an unsubstituted (C₁-C₃)hydrocarbyl.

In one embodiment, for Formula I, R³ and R¹⁴ are each, independently, an unsubstituted (C₁-C₄₀)hydrocarbyl. In a further embodiment, R³ and R¹⁴ are each, independently, an unsubstituted (C₁-C₃₀)hydrocarbyl, further an unsubstituted (C₁-C₂₀)hydrocarbyl, further an unsubstituted (C₁-C₁₀)hydrocarbyl, further an unsubstituted (C₁-C₅)hydrocarbyl, and further an unsubstituted (C₁-C₃)hydrocarbyl.

In one embodiment, for Formula I, R⁶ and R¹¹ are each, independently, an unsubstituted (C₁-C₄₀)hydrocarbyl or a halogen. In a further embodiment, R⁶ and R¹¹ are each, independently, an unsubstituted (C₁-C₃₀)hydrocarbyl, further an unsubstituted (C₁-C₂₀)hydrocarbyl, further an unsubstituted (C₁-C₁₀)hydrocarbyl, further an unsubstituted (C₁-C₅)hydrocarbyl, and further an unsubstituted (C₁-C₃)hydrocarbyl. In another embodiment, for Formula I, R⁶ and R¹¹ are each, independently a halogen, and further Cl or F, and further F.

In another embodiment, the instant invention provides a catalyst system comprising procatalyst comprising a metal-ligand complex of Formula I, as described above and one or more co-catalysts.

When used to describe certain carbon atom-containing chemical groups (e.g., (C₁-C₄₀)alkyl), the parenthetical expression (C₁-C₄₀) can be represented by the form “(C_x-C_y),” which means that the unsubstituted version of the chemical group comprises from a number x carbon atoms to a number y carbon atoms, wherein each x and y independently is an integer as described for the chemical group.

The term “substituted,” as used herein, with respect to a chemical compound, refers to a substituent that comprises at least one heteroatom (for example, O, S, N, P, etc.). Substituents include, but are not limited to, the R^S substituents, as noted above, as the following: a halogen atom, a polyfluoro substituent, a perfluoro substituent, F₃C-, FCH₂O-, F₂HCO-, F₃CO-, (R^C)₃Si-, (R^C)₃Ge-, (R^C)O-, (R^C)S-, (R^C)S(O)-, (R^C)S(O)₂-, (R^C)₂P-, (R^C)₂N-, (R^C)₂C=N-, NC-, (R^C)C(O)O-, (R^C)OC(O)-, (R^C)C(O)N(R^C)-, and (R^C)₂NC(O)-; wherein R^C is described above.

The term “unsubstituted,” as used herein, with respect to a chemical compound, refers to the lack of a substituent that comprises at least one heteroatom (for example, O, S, N, P, etc.).

The term “hydrocarbyl,” as used herein, refers to a monovalent (monoradical or radical) chemical group containing only hydrogen and carbon atoms.

The term “substituted hydrocarbyl,” as used herein, refers to a hydrocarbyl, in which at least one hydrogen atom is substituted with a substituent that comprises at least one heteroatom.

The term “heterohydrocarbyl,” as used herein, refers to a hydrocarbyl, in which at least one carbon atom, or CH group, or CH₂ group, is substituted with a heteroatom or a chemical group containing at least one heteroatom. Heteroatoms include, but are not limited to, O, N, P and S.

The term “substituted heterohydrocarbyl,” as used herein, refers to a heterohydrocarbyl in which at least one hydrogen atom is substituted with a substituent that comprises at least one heteroatom.

The term “hydrocarbylene,” as used herein, refers to a divalent (diradical) chemical group containing only hydrogen and carbon atoms.

The term “substituted hydrocarbylene,” as used herein, refers to a hydrocarbylene, in which at least one hydrogen atom is substituted with a substituent that comprises at least one heteroatom.

The term “heterohydrocarbylene,” as used herein, refers to a hydrocarbylene, in which at least one carbon atom, or CH group, or CH₂ group, is substituted with a heteroatom or a chemical group containing at least one heteroatom. Heteroatoms include, but are not limited to, O, N, P and S.

The term “substituted heterohydrocarbylene,” as used herein, refers to a heterohydrocarbylene, in which at least one hydrogen atom is substituted with a substituent that comprises at least one heteroatom.

In some embodiments, each of the chemical groups (e.g., X, L, R¹ through R²², etc.) of the metal-ligand complex of Formula (I) may be unsubstituted (for example, without use of a substituent R^S). In other embodiments, at least one of the chemical groups of the metal-ligand complex of Formula (I) independently contain one or more of the substituents (for example, R^S). Preferably, accounting for all chemical groups, there are not more than a total of 20 R^S, more preferably not more than a total of 10 R^S, and still more preferably not more than a total of 5 R^S in the metal-ligand complex of Formula (I). Where the invention compound contains two or more substituents R^S, each R^S independently is bonded to a same or different atom.

As used herein, the term “(C₁-C₄₀)hydrocarbyl” refers to hydrocarbon radical of from 1 to 40 carbon atoms. Each hydrocarbon radical independently may be aromatic (6 carbon atoms or more) or non-aromatic, saturated or unsaturated, straight chain or branched chain, cyclic (including mono- and poly-cyclic, fused and non-fused polycyclic, including bicyclic or acyclic, or a combination of two or more thereof; and each hydrocarbon radical independently is the same

as, or different from, another hydrocarbon radical, respectively. Each hydrocarbon radical may be optionally substituted with one or more R^S substituents, as defined above. A “(C₁-C₃₀)hydrocarbyl” is similarly defined, as discussed above for the “(C₁-C₄₀)hydrocarbyl.”

Preferably, a (C₁-C₄₀)hydrocarbyl is independently a (C₁-C₄₀)alkyl, or a (C₃-C₄₀)cycloalkyl. More preferably, each of the aforementioned (C₁-C₄₀)hydrocarbyl groups independently has a maximum of 20 carbon atoms (i.e., (C₁-C₂₀)hydrocarbyl), and still more preferably a maximum of 12 carbon atoms. Further, the (C₁-C₄₀)hydrocarbyl is optionally substituted with one or more R^S substituents, as defined above.

As used herein, the term “(C₁-C₄₀)hydrocarbylene” refers to a hydrocarbon diradical of from 1 to 40 carbon atoms. Each hydrocarbon diradical independently may be aromatic (6 carbon atoms or more) or non-aromatic, saturated or unsaturated, straight chain or branched chain, cyclic (including mono- and poly-cyclic, fused and non-fused polycyclic, including bicyclic or acyclic, or a combination of two or more thereof; and each hydrocarbon diradical independently is the same as, or different from, another hydrocarbon diradical, respectively. Further the hydrocarbon radical may be optionally substituted with one or more R^S substituents, as defined above.

Preferably, a (C₁-C₄₀)hydrocarbylene independently is a (C₃-C₂₀)cycloalkyl-(C₁-C₂₀)alkylene, (C₆-C₄₀)aryl, or (C₆-C₂₀)aryl-(C₁-C₂₀)alkylene. More preferably, each of the aforementioned (C₁-C₄₀)hydrocarbylene groups independently has a maximum of 20 carbon atoms (i.e., (C₁-C₂₀)hydrocarbyl), and still more preferably a maximum of 12 carbon atoms. The (C₁-C₄₀)hydrocarbylene may be optionally substituted with one or more R^S substituents, as defined above.

The term “(C₁-C₄₀)heterohydrocarbyl” refers to a heterohydrocarbon radical of from 1 to 40 carbon atoms. Each heterohydrocarbon independently may comprise one or more heteroatoms O; S; S(O); S(O)₂; Si(R^C)₂; Ge(R^C)₂; P(R^P); and N(R^N), wherein independently each R^C is unsubstituted (C₁-C₁₈)hydrocarbyl, each R^P is unsubstituted (C₁-C₁₈)hydrocarbyl; and each R^N is unsubstituted (C₁-C₁₈)hydrocarbyl. Each (C₁-C₄₀)heterohydrocarbyl independently may be saturated or unsaturated, straight chain or branched chain, cyclic (including mono- and poly-cyclic, fused and non-fused polycyclic) or acyclic, or a combination of two or more thereof; and each is respectively the same as or different from another. A “(C₁-

C₃₀)heterohydrocarbyl” is similarly defined, as discussed above for the “(C₁-C₄₀)heterohydrocarbyl.”

The term “(C₁-C₄₀)heterohydrocarbylene refers to a heterohydrocarbon diradical of from 1 to 40 carbon atoms. Each heterohydrocarbon independently may comprise one or more heteroatoms O; S; S(O); S(O)₂; Si(R^C)₂; Ge(R^C)₂; P(R^P); and N(R^N), wherein independently each R^C is unsubstituted (C₁-C₁₈)hydrocarbyl, each R^P is unsubstituted (C₁-C₁₈)hydrocarbyl; and each R^N is unsubstituted (C₁-C₁₈). Each (C₁-C₄₀)heterohydrocarbylene independently is unsubstituted or substituted (for example, by one or more R^S), aromatic or non-aromatic, saturated or unsaturated, straight chain or branched chain, cyclic (including mono- and polycyclic, fused and non-fused polycyclic) or acyclic, or a combination of two or more thereof; and each is respectively the same as or different from another.

Preferably, the (C₁-C₄₀)heterohydrocarbyl independently is (C₁-C₄₀)heteroalkyl, (C₁-C₄₀)hydrocarbyl-O-, (C₁-C₄₀)hydrocarbyl-S-, (C₁-C₄₀)hydrocarbyl-S(O)-, (C₁-C₄₀)hydrocarbyl-S(O)₂-, (C₁-C₄₀)hydrocarbyl-Si(R^C)₂-, (C₁-C₄₀)hydrocarbyl-Ge(R^C)₂-, (C₁-C₄₀)hydrocarbyl-N(R^N)-, (C₁-C₄₀)hydrocarbyl-P(R^P)-, (C₂-C₄₀)heterocycloalkyl.

Preferably, the (C₁-C₄₀)heterohydrocarbylene independently is (C₂-C₁₉)heterocycloalkyl-(C₁-C₂₀)alkylene, (C₃-C₂₀)cycloalkyl-(C₁-C₁₉)heteroalkylene, (C₂-C₁₉)heterocycloalkyl-(C₁-C₂₀)heteroalkylene, (C₁-C₄₀)heteroaryl, (C₁-C₁₉)heteroaryl-(C₁-C₂₀)alkylene, (C₆-C₂₀)aryl-(C₁-C₁₉)heteroalkylene, or (C₁-C₁₉)heteroaryl-(C₁-C₂₀)heteroalkylene.

The term “halogen atom” means fluorine atom (F), chlorine atom (Cl), bromine atom (Br), or iodine atom (I) radical. Preferably each halogen atom independently is the Br, F, or Cl radical, and more preferably the F or Cl radical. The term “halide” means fluoride (F⁻), chloride (Cl⁻), bromide (Br⁻), or iodide (I⁻) anion.

Preferably, there are no O-O, S-S, or O-S bonds, other than O-S bonds in an S(O) or S(O)₂ diradical functional group, in the metal-ligand complex of Formula (I). More preferably, there are no O-O, N-N, P-P, N-P, S-S, or O-S bonds, other than O-S bonds in an S(O) or S(O)₂ diradical functional group, in the metal-ligand complex of Formula (I).

The term “saturated” means lacking carbon-carbon double bonds, carbon-carbon triple bonds, and (in heteroatom-containing groups) carbon-nitrogen, carbon-phosphorous, and carbon-silicon double bonds.

The term “unsaturated” means containing one or more carbon-carbon double bonds, carbon-carbon triple bonds, and (in heteroatom-containing groups) carbon-nitrogen, carbon-phosphorous, and/or carbon-silicon double bonds.

M is titanium, zirconium, or hafnium. In one embodiment, M is zirconium or hafnium, and in another embodiment M is hafnium. In another embodiment, M is zirconium. In some embodiments, M is in a formal oxidation state of +2, +3, or +4. In some embodiments, n is 0, 1, 2, or 3. Each X independently is a monodentate ligand that is neutral, monoanionic, or dianionic; or two Xs are taken together to form a bidentate ligand that is neutral, monoanionic, or dianionic. X and n are chosen in such a way that the metal-ligand complex of Formula (I) is, overall, neutral. In some embodiments each X independently is the monodentate ligand. In one embodiment, when there are two or more X monodentate ligands, each X is the same. In some embodiments the monodentate ligand is the monoanionic ligand. The monoanionic ligand has a net formal oxidation state of -1. Each monoanionic ligand may independently be hydride, (C₁-C₄₀)hydrocarbyl carbanion, (C₁-C₄₀)heterohydrocarbyl carbanion, halide, nitrate, HC(O)O⁻, (C₁-C₄₀)hydrocarbylC(O)O⁻, HC(O)N(H)⁻, (C₁-C₄₀)hydrocarbyl-C(O)N(H)⁻, (C₁-C₄₀)hydrocarbylC(O)N((C₁-C₂₀)hydrocarbyl)⁻, R^KR^LB⁻, R^KR^LN⁻, R^KO⁻, R^KS⁻, R^KR^LP⁻, or R^MR^KR^LSi⁻, wherein each R^K, R^L, and R^M independently is hydrogen, (C₁-C₄₀)hydrocarbyl, or (C₁-C₄₀)heterohydrocarbyl, or R^K and R^L are taken together to form a (C₂-C₄₀)hydrocarbylene or (C₁-C₄₀)heterohydrocarbylene and R^M is as defined above.

In some embodiments, at least one monodentate ligand of X independently is the neutral ligand. In one embodiment, the neutral ligand is a neutral Lewis base group that is R^XNR^KR^L, R^KOR^L, R^KSR^L, or R^XPR^KR^L, wherein each R^X independently is hydrogen, (C₁-C₄₀)hydrocarbyl, [(C₁-C₁₀)hydrocarbyl]₃Si, [(C₁-C₁₀)hydrocarbyl]₃Si(C₁-C₁₀)hydrocarbyl, or (C₁-C₄₀)heterohydrocarbyl and each R^K and R^L independently is as defined above.

In some embodiments, each X is a monodentate ligand that independently is a halogen atom, unsubstituted (C₁-C₂₀)hydrocarbyl, unsubstituted (C₁-C₂₀)hydrocarbylC(O)O⁻, or R^KR^LN⁻ wherein each of R^K and R^L independently is an unsubstituted (C₁-C₂₀)hydrocarbyl. In some embodiments each monodentate ligand X is a chlorine atom, (C₁-C₁₀)hydrocarbyl (e.g., (C₁-C₆)alkyl or benzyl), unsubstituted (C₁-C₁₀)hydrocarbylC(O)O⁻, or R^KR^LN⁻ wherein each of R^K and R^L independently is an unsubstituted (C₁-C₁₀)hydrocarbyl.

In some embodiments, there are at least two X and the two X are taken together to form the bidentate ligand. In some embodiments the bidentate ligand is a neutral bidentate ligand. In one embodiment, the neutral bidentate ligand is a diene of formula $(R^D)_2C=C(R^D)-C(R^D)=C(R^D)_2$, wherein each R^D independently is H, unsubstituted (C_1-C_6) alkyl, phenyl, or naphthyl. In some embodiments the bidentate ligand is a monoanionic-mono(Lewis base) ligand. The monoanionic-mono(Lewis base) ligand may be a 1,3-dionate of formula (D): $R^E-C(O^-)=CH-C(=O)-R^E$ (D), wherein each R^D independently is H, unsubstituted (C_1-C_6) alkyl, phenyl, or naphthyl. In some embodiments the bidentate ligand is a dianionic ligand. The dianionic ligand has a net formal oxidation state of -2. In one embodiment, each dianionic ligand independently is carbonate, oxalate (i.e., $^{-}O_2CC(O)O^{-}$), (C_2-C_{40}) hydrocarbylene dicarbanion, (C_1-C_{40}) hetero-hydrocarbylene dicarbanion, or sulfate.

As previously mentioned, number and charge (neutral, monoanionic, dianionic) of X are selected depending on the formal oxidation state of M such that the metal-ligand complex of Formula (I) is, overall, neutral.

In some embodiments, each X is the same, wherein each X is methyl; ethyl; 1-propyl; 2-propyl; 1-butyl; 2,2,-dimethylpropyl; trimethylsilylmethyl; phenyl; benzyl; or chloro. In some embodiments n is 2 and each X is the same.

In some embodiments, at least two X are different. In some embodiments, n is 2 and each X is a different one of methyl; ethyl; 1-propyl; 2-propyl; 1-butyl; 2,2,-dimethylpropyl; trimethylsilylmethyl; phenyl; benzyl; and chloro.

The integer n indicates number of X. In one embodiment, n is 2 or 3, and at least two X independently are monoanionic monodentate ligands, and a third X, if present, is a neutral monodentate ligand. In some embodiments n is 2, at two X are taken together to form a bidentate ligand. In some embodiments, the bidentate ligand is 2,2-dimethyl-2-silapropene-1,3-diyl or 1,3-butadiene.

In some embodiments, each Z independently is O, S, $-N[(C_1-C_{40})\text{hydrocarbyl}]^{-}$, or $-P[(C_1-C_{40})\text{hydrocarbyl}]^{-}$. In some embodiments, each Z is different. In some embodiments, one Z is O, and one Z is $-N(CH_3)^{-}$. In some embodiments, one Z is O, and one Z is S. In some embodiments, one Z is S, and one Z is $-N[(C_1-C_{40})\text{hydrocarbyl}]^{-}$ (e.g., $-N(CH_3)^{-}$). In some embodiments, each Z is the same. In some embodiments, each Z is O. In some embodiments, each Z is S. In some embodiments, each Z is $-N[(C_1-C_{40})\text{hydrocarbyl}]^{-}$ (e.g., $-N(CH_3)^{-}$). In

some embodiments, at least one, and in some embodiments each Z is $-P[(C_1-C_{40})\text{hydrocarbyl}]$ - (e.g., $-P(CH_3)-$).

In some embodiments, L is selected from the following: $-CH_2-$, $-CH_2CH_2-$, $-CH_2CH_2CH_2-$; $-CH(CH_3)CH_2CH(CH_3)-$; $-CH(CH_3)CH(CH_3)CH(CH_3)-$; $-CH_2C(CH_3)_2CH_2-$; 1,3-cyclopentane-diyl; or 1,3-cyclohexane-diyl. In some embodiments L comprises the 4-carbon atom linker backbone (e.g., L is $-CH_2CH_2CH_2CH_2-$; $-CH_2C(CH_3)_2C(CH_3)_2CH_2-$; 1,2-bis(methylene)cyclohexane; or 2,3-bis(methylene)-bicyclo[2.2.2]octane). In some embodiments, L comprises the 5-carbon atom linker backbone (e.g., L is $-CH_2CH_2CH_2CH_2CH_2-$ or 1,3-bis(methylene)cyclohexane). In some embodiments, L comprises the 6-carbon atom linker backbone (e.g., L is $-CH_2CH_2CH_2CH_2CH_2CH_2-$ or 1,2-bis(ethylene)cyclohexane).

Process for Producing Procatalyst

In some embodiments, the ligands of the invention may be prepared using known procedures. Specifically, the ligands of the invention may be prepared using a variety of synthetic routes, depending on the variation desired in the ligand. In general, building blocks are prepared that are then linked together with a bridging group. Variations in the R group substituents can be introduced in the synthesis of the building blocks.

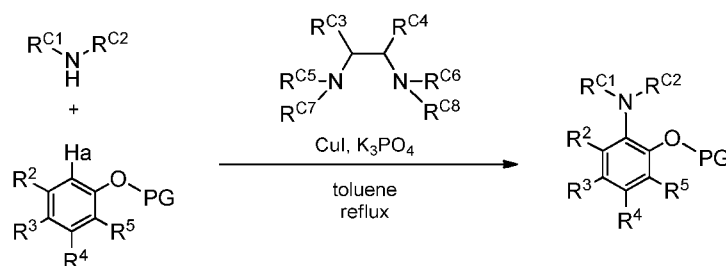
Variations in the bridge can be introduced with the synthesis of the bridging group. Specific ligands within the scope of this invention may be prepared according to the general schemes shown below, where building blocks are first prepared, and then coupled together. There are several different ways to use these building blocks. In one embodiment, generally, each of the optionally substituted phenyl rings is prepared as a separate building block. The desired optionally substituted phenyls are then combined into bi-phenyl building blocks, which are then bridged together. In another embodiment, the optionally substituted phenyl building blocks are bridged together, and then additional, optionally substituted phenyl building blocks are added to form the bridged bi-aryl structures. The starting materials or reagents used are generally commercially available, or are prepared via routine synthetic means.

In the schemes below, the term ligand refers to the organic precursor to the pro-catalyst. The pro-catalyst is derived from a reaction of the ligand with a suitable metallic (titanium, zirconium, or hafnium) precursor. Common abbreviations are listed in the key system as follows: **LG** : generic leaving group; **PG** : generic protecting group, common examples include:



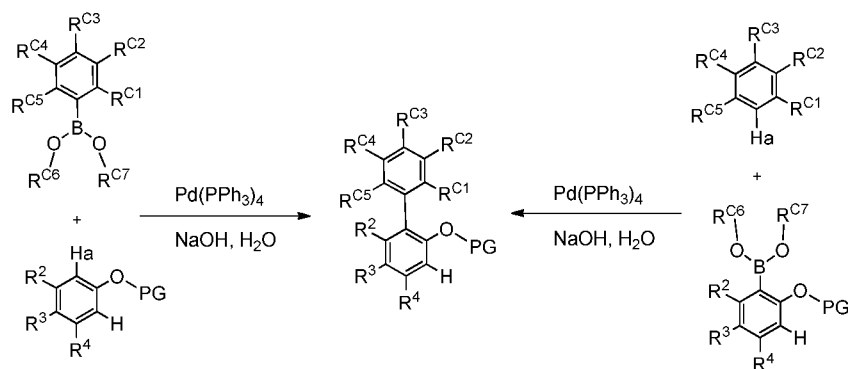
R, L, M, Z, X : as defined above; **Ha** : halide, most commonly Br or I; **Me** : methyl; **Et** : ethyl; **Ph** : phenyl; ***i*-Pr** : *iso*-propyl; ***t*-Bu** : *tert*-butyl; ***t*-Oct** : *tert*-octyl; **Ts** : toluene sulfonate; **THF** : tetrahydrofuran; **Et₂O** : diethyl ether; **DMF** : dimethylformamide; **EtOAc** : ethyl acetate; **DIAD** : diisopropyl azodicarboxylate; **GC** : gas chromatography; **LC** : liquid chromatography; **TLC** : thin layer chromatography; **NMR** : nuclear magnetic resonance; **PTSA** : *para*-toluene sulfonic acid; **NIS** : *N*-iodosuccinimide

1a. Preparation of 2-substituted protected phenols (protocol 1, carbon-nitrogen coupling).



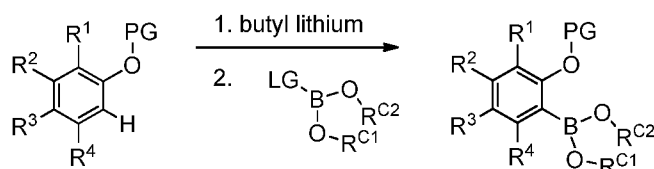
A three-neck, round-bottomed flask, in a glove box, is charged with the desired protected phenol (approximately 1.0 equivalents), the desired aryl-nitrogen compound or nitrogen heterocyclic (approximately 0.6 equivalents), K₃PO₄ (approximately 2.1 equivalents), anhydrous CuI (approximately 0.03 equivalents), dried toluene (approximately 2 mL per mmol of phenol), and an appropriate *N,N'*-disubstituted diamine (approximately 0.08 equivalents). The reaction mixture is then heated under reflux. The reaction progress can be monitored by a suitable technique (e.g. GC/MS, NMR spectroscopy, TLC), and, in some cases, additional anhydrous CuI (approximately 0.03 equivalents) and *N,N'*-disubstituted diamine (approximately 0.08 equivalents) is added to the mixture, and heating under reflux continued, until such a time, when the conversion is observed to be complete. The reaction is then allowed to cool to room temperature, and filtered through a small silica plug, washed with THF, and concentrated, to give the crude product. This crude material can be purified by either recrystallization or flash chromatography on silica gel.

1b. Preparation of 2-substituted protected phenols (protocol 2, carbon-carbon coupling).

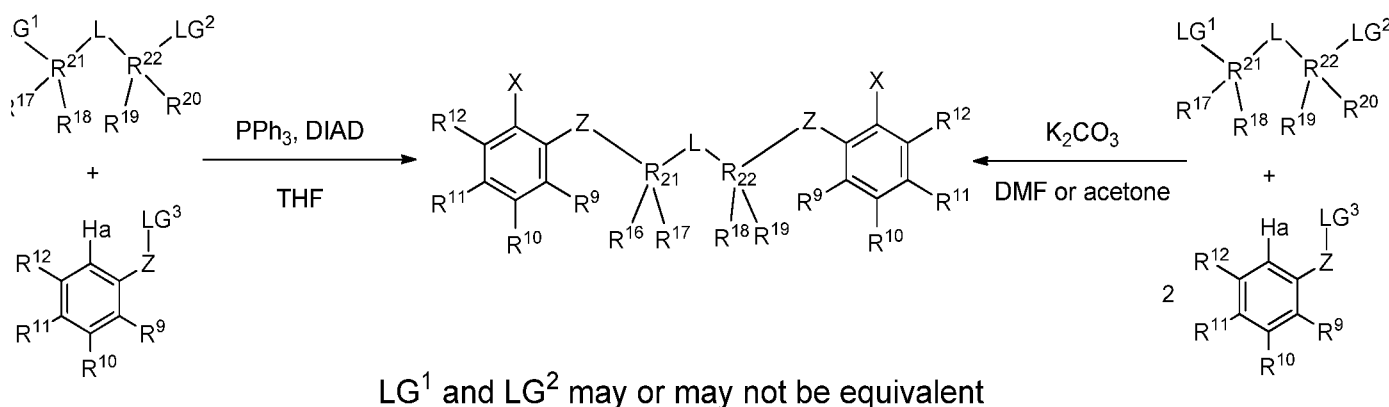


A three-neck, round-bottomed flask, placed under a nitrogen atmosphere, is charged with approximately equimolar quantities of the aryl halide and the borylated aryl compound, NaOH (approximately 6 equivalents relative to aryl halide), Pd(PPh₃)₄ (approximately 0.02 equivalents relative to aryl halide), degassed toluene (approximately 5 mL per mmol of aryl halide), and degassed water (approximately 1 mL per mmol of aryl halide). The system is nitrogen-sparged, and the contents are then heated to 110°C for approximately 24 hours. The reaction is cooled, and the volatiles removed under vacuum. The residue is taken up in Et₂O, washed with brine, dried over anhydrous magnesium sulfate, filtered through a pad of silica gel, and then concentrated. This crude material can be purified by either recrystallization or flash chromatography on silica gel.

2. Preparation of borylated 2-substituted protected phenols:



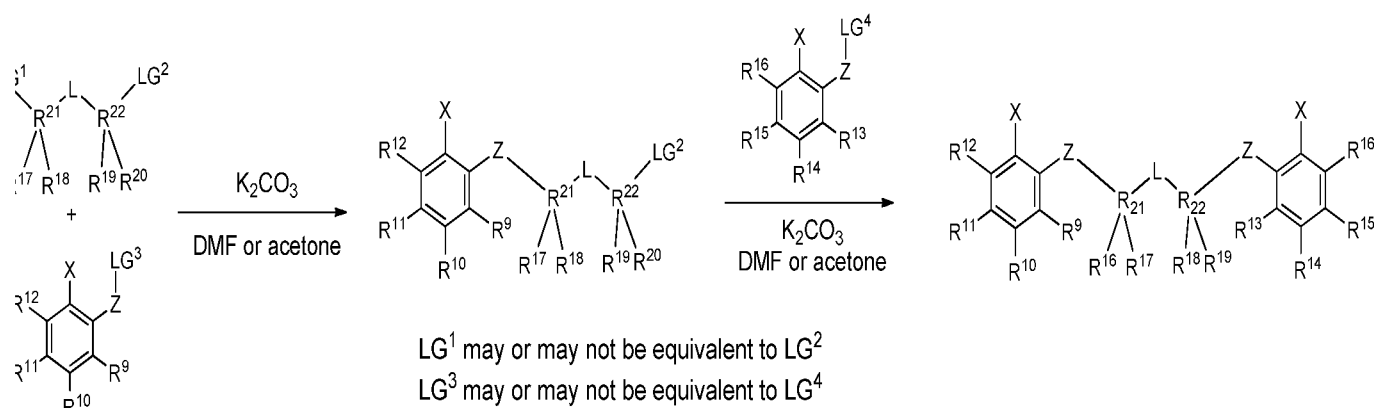
To an oven dried, three-neck, round-bottomed flask, under nitrogen atmosphere, is added the desired protected phenol (approximately 1.0 equivalents) and dry THF (approximately 6 mL per mmol of protected phenol). This solution was cooled to approximately 0-10°C (ice-water bath), and 2.5 M *n*-butyl lithium in hexanes (approximately 2.2 equivalents) is added slowly. After stirring for approximately 4 hours, the desired boronic ester or boronic acid (approximately 2.2 equivalents) is added slowly. The mixture is stirred for one hour at approximately 0-10°C, before allowing the reaction to warm to room temperature, and then stirred for approximately 18 hours. To the reaction mixture is added cold, saturated aqueous sodium bicarbonate (approximately 6 mL per mmol of protected phenol). The mixture is extracted with several portions of methylene chloride. The organic phases are combined, and washed with cold saturated aqueous sodium bicarbonate, brine, then dried over anhydrous magnesium sulfate, filtered, and concentrated to give the crude product. Purification can be accomplished by recrystallization from a suitable solvent (e.g., acetonitrile, toluene, hexane, or methanol).

3a. Preparation of symmetrical bridging fragments.

Mitsunobu-type: An oven, dried three-neck, round-bottomed flask, equipped with an addition funnel, is placed under nitrogen atmosphere, and charged with the desired aryl halide (approximately 1.0 equivalents), the desired connecting unit (containing the L moiety and the R¹⁷-R²² groups, approximately 0.45 equivalents), triphenylphosphine (approximately 1.0 equivalents), and THF (approximately 1.0 mL per mmol of aryl halide). The addition funnel is then charged with DIAD (approximately 1.0 equivalents) and THF (approximately 0.5 mL per mmol of aryl halide). The contents in the flask are cooled to approximately 2-5°C, in an ice-water bath, and the DIAD solution in the addition funnel is added, at such a rate, to maintain the reaction temperature at 2-5°C. The resulting mixture is stirred at 2-5°C for an additional one hour, subsequent to the DIAD addition, then allowed to warm up to ambient temperature, and stirred overnight. The volatiles are removed under vacuum, and the resulting residue is extracted with alkane solvent, and sequentially washed with 1M NaOH, water, 1N HCl, and water. The organic portion is collected, and dried under vacuum. Purification can be accomplished by recrystallization from a suitable solvent (e.g. acetonitrile, toluene, hexane, or methanol), or column chromatography on silica gel.

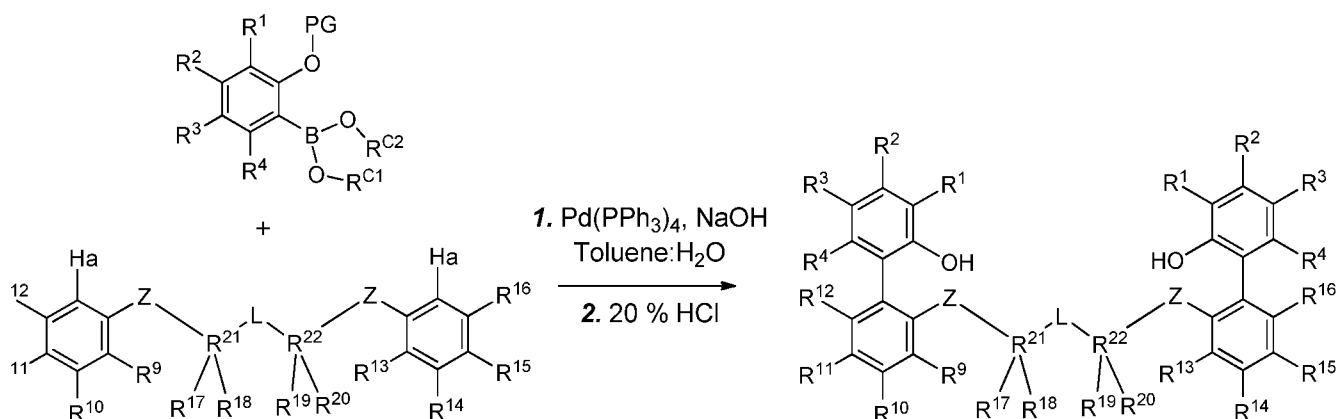
S_N2-type: To a solution of the desired aryl halide (approximately 1.0 equivalents) and desired connecting unit (containing the L moiety and the R¹⁷-R²² groups, approximately 0.45 equivalents), in acetone (approximately 7.0 mL per mmol of aryl halide), is added K₂CO₃ (approximately 2.5 equivalents). The reaction mixture is then heated under reflux for approximately 36 hours. The resulting suspension is then cooled, filtered, and concentrated under vacuum. Purification can be accomplished by recrystallization from a suitable solvent (e.g. acetonitrile, toluene, hexane, or methanol), or column chromatography on silica gel.

3b. Preparation of unsymmetrical bridging fragments.



To a solution of the desired aryl halide (approximately 1.0 equivalents) and desired connecting unit (containing the L moiety and the R¹⁷-R²² groups, approximately 1.5 equivalents), in acetone (approximately 7.0 mL per mmol of aryl halide,) is added K₂CO₃ (approximately 2.5 equivalents). The reaction mixture is then heated under reflux for approximately 36 hours. The resulting suspension is then cooled, filtered, and concentrated under vacuum. Purification can be accomplished at this stage by recrystallization from a suitable solvent (e.g. acetonitrile, toluene, hexane, or methanol), or column chromatography on silica gel. The obtained material is then subjected to an analogous sequential reaction, by combining it with another aryl halide (approximately 1.0 equivalents), and K₂CO₃ (approximately 2.5 equivalents), in acetone (approximately 7.0 mL per mmol of aryl halide), and heating under reflux. The resulting suspension is then cooled, filtered, and concentrated under vacuum. Purification can be accomplished recrystallization from a suitable solvent (e.g. acetonitrile, toluene, hexane, or methanol), or column chromatography on silica gel.

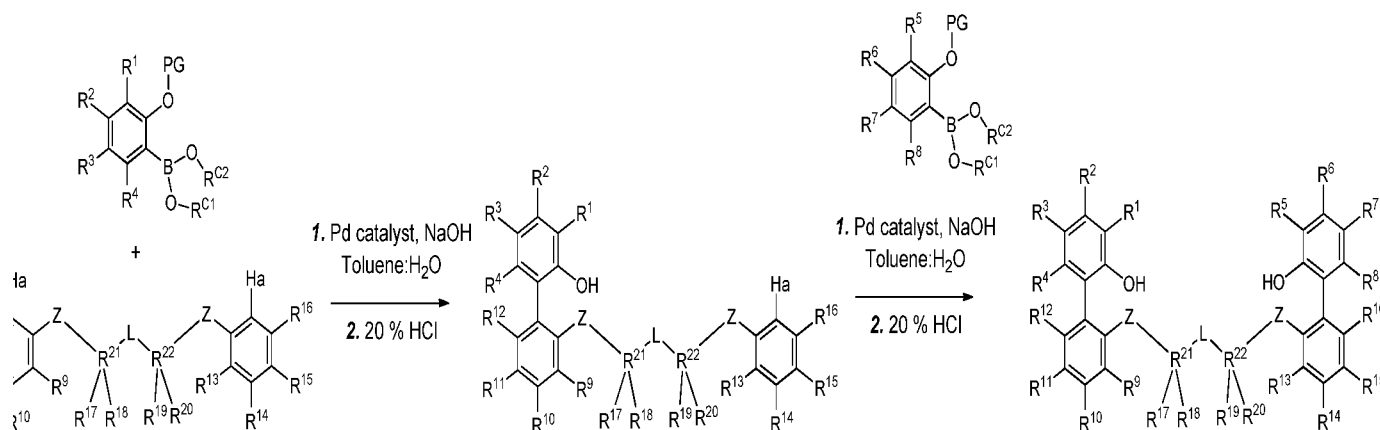
5a. Preparation of ligand (simultaneous double Suzuki reaction).



To an oven dried, three-neck, round-bottomed flask, under nitrogen atmosphere, is added the bis-arylhalide (approximately 1.0 equivalents) and the borylated protected phenol (approximately 2.2 equivalents) dissolved in toluene (approximately 5 mL per mmol of bis-

arylhalide), under a nitrogen atmosphere with stirring. To this, is added, NaOH (approximately 1.0 equivalents) dissolved in water, (approximately 10 mL per mmol of NaOH), followed by quick addition of Pd(PPh₃)₄ (approximately 0.04 equivalents), and the reaction heated to 88 °C. The course of the reaction can be monitored via LC. When deemed complete, the reaction vessel is cooled to ambient temperature, and the stirring halted. The caustic layer is removed from the resulting bisphasic mixture, and a 20% aqueous HCl solution is added (approximately 1.5 mL per mmol of bis-arylhalide) to the remaining organic portion. The resulting mixture is heated under reflux for approximately 8 hours. The reactor is cooled to ambient temperature, the aqueous layer removed, and the organic layer washed with brine, and then dried over MgSO₄. This mixture is filtered, and concentrated, to provide the crude product, which can be purified by recrystallization from a suitable solvent (e.g. acetonitrile, toluene, hexane, or methanol), or column chromatography on silica gel.

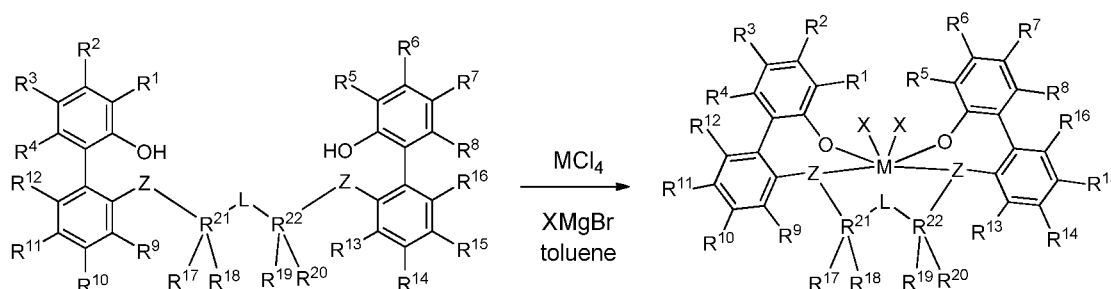
5b. Preparation of ligand (sequential Suzuki reactions).



To an oven dried, three-neck, round-bottomed flask, under nitrogen atmosphere, is added the bis-arylhalide (approximately 1.0 equivalents) and the borylated protected phenol (approximately 1.0 equivalents) dissolved in toluene (approximately 5 mL per mmol of bis-arylhalide), under a nitrogen atmosphere with stirring. To this is added, NaOH (approximately 1.0 equivalents) dissolved in water, (approximately 10 mL per mmol of NaOH), followed by quick addition of a suitable palladium catalyst (approximately 0.04 equivalents), and the reaction is heated to 88 °C. The course of the reaction can be monitored via LC. When deemed complete, the reaction vessel is cooled to ambient temperature, and the second borylated protected phenol (approximately 1.0 equivalents), and a suitable palladium catalyst (approximately 0.04 equivalents). The reaction is heated to 88 °C, and the course of the reaction can be again be monitored via LC. When deemed complete, the reaction vessel is cooled to ambient temperature, and the stirring halted. The caustic layer is removed from the resulting bisphasic mixture, and a

20% aqueous HCl solution is added (approximately 1.5 mL per mmol of bis-arylhalide) to the remaining organic portion. The resulting mixture is heated under reflux for approximately 8 hours. The reactor is cooled to ambient temperature, the aqueous layer removed, and the organic layer washed with brine, and then dried over MgSO_4 . This mixture is filtered, and concentrated, to provide the crude product, which can be purified by recrystallization from a suitable solvent (e.g. acetonitrile, toluene, hexane, or methanol), or column chromatography on silica gel.

7. Preparation of pro-catalyst.



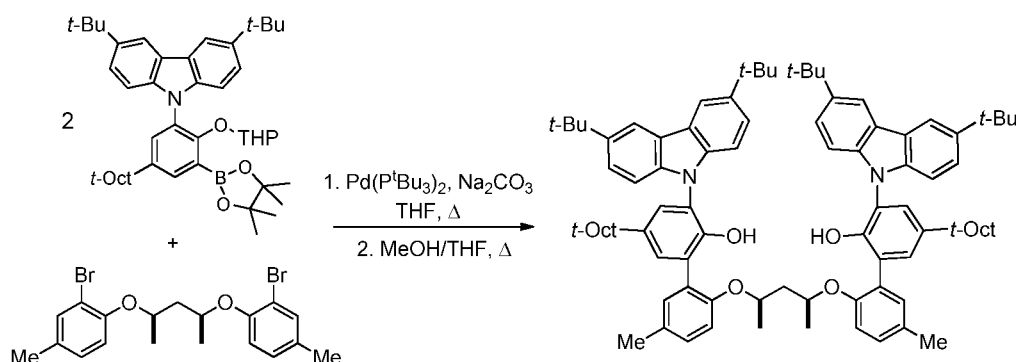
An oven, dried three-neck, round-bottomed flask, under nitrogen atmosphere, is charged with MCl_4 (approximately 1.0 equivalents) and cold toluene or hexane (approximately 10 mL per mmol of ligand, at -40 to -20°C). XMgBr (approximately 4.0 equivalents) is then added to the cold suspension, and the resulting mixture is stirred for 2-15 minutes. The ligand (approximately 0.95 equivalents) is then added, and the reaction mixture is allowed to warm to ambient temperature, and stirred for approximately 4 hours, and then dried under vacuum. The resulting residue is extracted with hexane and/or toluene, filtered, and dried under vacuum. This crude material can be further purified by recrystallization from a suitable solvent (e.g. hexane, toluene).

EXPERIMENTAL

The following examples illustrate the present invention but are not intended to limit the scope of the invention.

Specific embodiments for synthesis of inventive catalyst

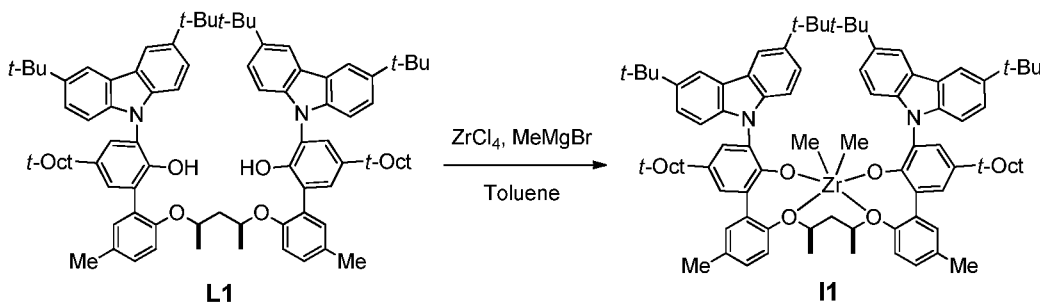
Example 1. 1a. Preparation of Ligand 1 (L1).



A round bottom flask was charged with 3,6-di-tert-butyl-9-(2-((tetrahydro-2H-pyran-2-yl)oxy)-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-5-(2,4,4-trimethylpentan-2-yl)phenyl)-9H-carbazole (7.285 g, 11.91 mmol) and *meso*-4,4'-pentane-2,4-diylbis(oxy))bis(3-bromo-1-methylbenzene) (2.194 g, 4.96 mmol), and 60 mL of THF. Na₂CO₃ (3.156 g, 29.78 mmol) was dissolved in 30 mL of water, and added to the THF solution, forming a biphasic solution, which was then sparged with N₂ for 15 minutes. Pd(P(t-Bu)₃)₂ (0.076 g, 0.15 mmol) was dissolved in 20 mL degassed THF, in a nitrogen-filled glovebox, then added to the reaction mixture, which was heated under reflux, under nitrogen for 24 hours. The reaction mixture was allowed to cool to ambient temperature, and then the aqueous phase was separated and discarded. THF was removed from the organic phase on a rotary evaporator, and dichloromethane (120 mL) was added to the residue, and the solution was washed with 120 mL of water. Brine (30 mL) was added to aid phase separation.

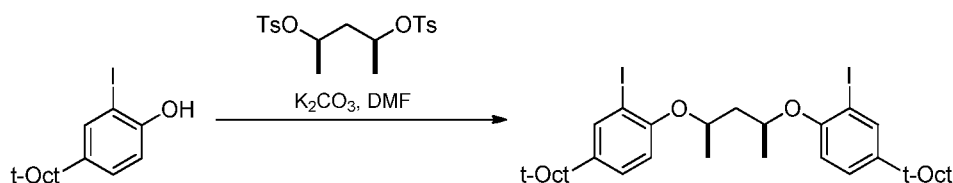
The organic phase was collected and evaporated to dryness under vacuum. The residue was dissolved in 50 mL of diethyl ether, filtered through a plug of silica gel and evaporated to dryness under reduced pressure. MeOH (100 mL), THF (40 mL) and concentrated HCl (4 drops) were added to the residue, and the solution was refluxed for two hours. The reaction mixture was allowed cool to room temperature, but no precipitation occurred. Therefore, the solution was concentrated to approximately half its original volume on a rotary evaporator, causing orange-colored solids to form. The solids were filtered, washed with methanol and dried under vacuum (1.83 g). The mother liquor was evaporated to dryness, then the residue was dissolved in diethyl ether (approximately 15 mL), and poured into approximately 200 mL of methanol, causing a small amount of precipitate to form. The volume was decreased by half on under vacuum, causing more solids to crash out. The pale orange solids were filtered, washed with methanol and dried under vacuum, to give pure product (1.90 g). A third crop of product (0.26 g) was recovered from the mother liquor. Overall isolated yield: 3.99 g, 64%. ¹H NMR (400 MHz, CDCl₃) δ 8.16 (t, *J* = 2.1 Hz, 4H), 7.40 (m, 8H), 7.17 (d, *J* = 2.2 Hz, 2H), 7.11 (t, *J* = 8.1 Hz, 4H), 6.88 (dd, *J* = 8.4, 2.2 Hz, 2H), 6.64 (d, *J* = 8.3 Hz, 2H), 6.22 (s, 2H), 4.43 (m, 2H), 2.31 (s, 6H), 2.09 (dt, *J* = 13.8, 6.8 Hz, 1H), 1.75 (s, 4H), 1.64 (dt, *J* = 16.1, 5.9 Hz, 1H), 1.47 (s, 18H), 1.45 (s, 18H), 1.39 (s, 12H), 1.08 (d, *J* = 6.0 Hz, 6H), and 0.82 (s, 18H).

1b. Preparation of Pro-Catalyst 1 (II).



The ligand (0.500 g, 0.40 mmol) was dissolved in 10 mL of hexane, under a dry nitrogen atmosphere, and the solution was added to a stirred suspension of ZrCl_4 (0.093 g, 0.40 mmol) in 5 mL of hexane. MeMgBr (0.63 mL, 1.64 mmol; 2.6 M in Et_2O) was added dropwise, via syringe, at ambient temperature. The mixture was stirred for 14 hours. The color of the reaction mixture slowly turned black. The suspension was filtered, and the filtrate evaporated to dryness under vacuum. Hexane (10 mL) was added to the residue, the light suspension was filtered, and the filtrate evaporated to dryness under vacuum. The treatment with hexane was repeated, and the product was thoroughly dried under vacuum, to afford **I1** in good purity as a tan solid (0.193 g, 35%). ^1H NMR (400 MHz, C_6D_6): δ 8.69 (t, $J = 2.0$ Hz, 2H), 8.45 (d, $J = 1.7$ Hz, 1H), 8.40 (d, $J = 1.7$ Hz, 1H), 7.38-7.85 (m, 16H), 7.13 (d, $J = 2.2$ Hz, 1H), 7.08 (d, $J = 2.3$ Hz, 1H), 6.65 (dd, $J = 8.4, 2.1$ Hz, 1H), 6.62 (dd, $J = 8.3, 2.1$ Hz, 1H), 5.02 (d, $J = 6.5$ Hz, 1H), 4.85 (d, $J = 6.8$ Hz, 1H), 4.33 (dt, $J = 13.2, 6.8$ Hz, 1H), 3.86 (m, 1H), 1.88 (s, 3H), 1.87 (s, 3H), 0.79-1.71 (m, 70H), 0.73 (d, $J = 6.7$ Hz, 3H), 0.54 (d, $J = 6.7$ Hz, 3H), -0.70 (s, 3H), and -0.86 (s, 3H). $^{13}\text{C}\{^1\text{H}\}$ NMR (101 MHz, CDCl_3) δ 151.4, 147.9, 142.5, 142.2, 139.8, 139.7, 132.7, 131.7, 129.9, 129.0, 128.8, 127.8, 126.6, 125.0, 123.4, 123.2, 116.2, 115.5, 109.5, 73.4, 57.1, 42.4, 38.2, 34.7, 32.4, 32.1, 32.1, 31.9, 31.7, 31.6, 20.6, and 19.7.

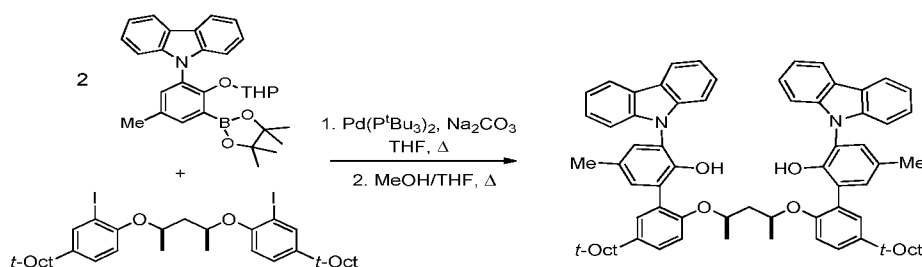
Example 2. 2a. Preparation of meso-4,4'-pentane-2,4-diylbis(oxy)bis(1-(tert-butyl)-3-iodobenzene).



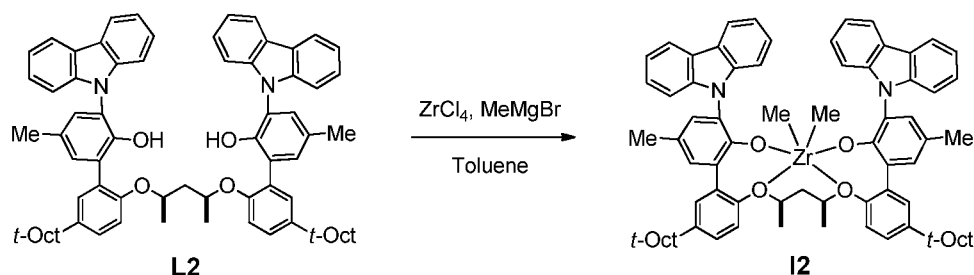
A round-bottom flask was charged with meso-ditosylate (3.1 g, 7.5 mmol), 2-iodo-4-*t*-octylphenol (5.0 g, 15.1 mmol), and DMF (100 mL). K_2CO_3 (4.2 g, 30.1 mmol) was added, and the reaction was heated under reflux for one day. The volatiles were then removed by bulb to bulb distillation, yielding a brown solid. The solid was taken up in Et_2O (250 mL), rinsed with 3M NaOH solution (2×100 mL), brine (100 mL), and then dried over MgSO_4 . The reaction mixture was filtered, and concentrated on a rotary evaporator, to yield the crude product, and was

further purified by column chromatography (SiO₂, hexanes/EtOAc 95:5) to afford the desired product (1.6 g, 29% theoretical 5.5 g). ¹H NMR (400 MHz, CDCl₃) δ 7.74 (d, *J* = 2.3 Hz, 2H), 7.28 (dd, *J* = 8.7, 2.3 Hz, 1H), 6.87 (d, *J* = 8.7 Hz, 2H), 4.77 – 4.61 (m, 2H), 2.42 (dt, *J* = 13.8, 6.8 Hz, 1H), 1.84 (dt, *J* = 14.0, 5.9 Hz, 1H), 1.68 (s, 4H), 1.36 (d, *J* = 6.1 Hz, 6H), 1.33 (s, 12H), 0.74 (s, 18H).

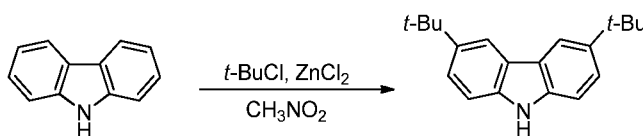
2d. Preparation of Ligand 2 (L2).



A round bottom flask was charged with *meso*-4,4'-pentane-2,4-diylbis(oxy))bis(1-(*tert*-octyl)-3-iodobenzene)) (0.790 g, 1.08 mmol) and 9-(5-methyl-2-((tetrahydro-2H-pyran-2-yl)oxy)-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)phenyl)-9H-carbazole (1.052 g, 2.37 mmol), and 40 mL of THF. Na₂CO₃ (0.686 g, 6.47 mmol) was dissolved in 20 mL of water, and added to the THF solution, forming a biphasic solution, which was then sparged with N₂ for 15 minutes. Pd(P(*t*-Bu)₃)₂ (0.017 g, 0.03 mmol) was dissolved in 6 mL degassed THF in the drybox, and then added to the reaction mixture, which was heated under reflux, under nitrogen for three days. After allowing the reaction mixture to cool to ambient temperature, the aqueous phase was discarded, and THF was removed from the organic phase using a rotary evaporator. Dichloromethane (80 mL) was added, and the solution was washed with 80 mL of water mixed with 20 mL of brine. The organic phase was evaporated to dryness, under vacuum, and the residue was dissolved in 50 mL diethyl ether, filtered through a plug of silica gel, and evaporated to dryness under vacuum. Methanol (80 mL), THF (15 mL) and conc. HCl (6 drops) were added, and the solution was refluxed overnight, and then the solvent was removed, under vacuum, and the residue was triturated with a small amount of methanol, and again dried under vacuum. The resulting material was purified via column chromatography on silica gel, gradient eluting with 1% EtOAc in hexane → 5% EtOAc in hexane, furnishing the pure ligand **L2** (0.820 g, 74%). ¹H NMR (400 MHz, CDCl₃): δ 8.15 (dd, *J* = 7.5, 1.2 Hz, 4H), 7.40 (d, *J* = 2.5 Hz, 2H), 7.33 (m, 10H), 7.23 (m, 6H), 7.16 (dd, *J* = 8.5, 2.3 Hz, 2H), 6.66 (d, *J* = 8.7 Hz, 2H), 6.23 (s, 2H), 4.52 (m, 2H), 2.47 (s, 6H), 2.22 (m, 1H), 1.74 (s, 4H), 1.71 (m, 1H), 1.38 (d, *J* = 6.1 Hz, 12H), 1.18 (d, *J* = 6.0 Hz, 6H), and 0.75 (s, 18H). ¹³C{¹H} NMR (101 MHz, CDCl₃) δ 151.1, 148.3, 144.0, 141.3, 141.2, 131.7, 130.3, 130.3, 129.2, 129.1, 127.19, 126.8, 125.6, 125.6, 125.2, 123.3, 123.2, 120.2, 120.6, 119.5, 113.8, 110.3, 110.2, 72.7, 57.0, 42.7, 38.1, 32.4, 31.8, 31.5, 20.7, and 19.8.

2d. Preparation of Pro-Catalyst 2 (I2).

The ligand **L4** (0.500 g, 0.49 mmol) was dissolved in 10 mL of toluene, under a dry nitrogen atmosphere, and the solution was added to a stirred suspension of ZrCl_4 (0.114 g, 0.490 mmol) in 5 mL of toluene. MeMgBr (0.77 mL, 2.00 mmol; 2.6 M in Et_2O) was added dropwise via syringe at ambient temperature. The mixture was stirred for two hours. The color of the reaction mixture slowly turned black. Hexane (5 mL) was added to the suspension, which was then filtered, and the filtrate evaporated to dryness under vacuum. Toluene (15 mL) and hexane (5 mL) were added to the residue, the light suspension was filtered, and the filtrate evaporated to dryness under vacuum, furnishing **I4** in high purity (292 mg, 52%). ^1H NMR (400 MHz, C_6D_6) δ 8.35 (m, 2H), 8.10 (m, 2H), 7.67 (m, 1H), 7.57 – 7.32 (m, 12H), 7.23 – 7.08 (m, 5H), 6.84 (ddd, J = 10.8, 8.5, 2.5 Hz, 2H), 5.04 (d, J = 8.5 Hz, 1H), 4.87 (d, J = 8.6 Hz, 1H), 4.04 (m, 1H), 3.68 (m, 1H), 2.22 (s, 6H), 1.76 – 1.60 (m, 4H), 1.24 (s, 3H), 1.22 (s, 3H), 1.21 (s, 3H), 1.19 (s, 3H), 0.76 (s, 9H), 0.75 (s, 9H), 0.50 (d, J = 6.2 Hz, 3H), 0.32 (d, J = 6.5 Hz, 3H), -0.77 (s, 3H), and -0.91 (s, 3H).

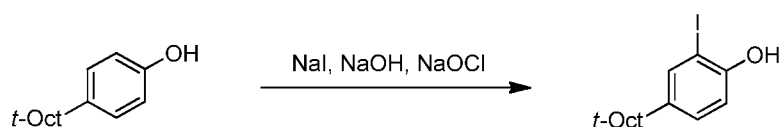
Example 3 3a. Preparation of 3,6-bis(1,1-dimethylethyl)-9H-carbazole.

A 500 mL, three-neck, round bottom flask, equipped with an overhead stirrer, nitrogen gas bubbler, and an addition funnel, was charged with 20.02g (120.8 mmol) of carbazole, 49.82g (365.5 mmol) of ZnCl_2 , and 300 mL of nitromethane at room temperature. To the resulting dark brown slurry, was added, 49.82g (365.5 mmol) of 2-chloro-2-methylpropane (also known as tertiary-butyl chloride), dropwise from the addition funnel, over the period of 2.5 hours. After completing the addition, the resulting slurry was stirred for an additional 18 hours, and the reaction mixture was poured into 800 mL of ice cold water, and extracted with methylene chloride (3 x 500 mL). The combined extracts were dried with anhydrous magnesium sulfate, filtered, and concentrated, first by rotary evaporation, and then by evaporation under high vacuum to remove nitromethane. The resulting residue was dissolved in hot methylene chloride

(70 mL), followed by hot hexanes (50 mL), and the resulting solution was cooled to room temperature, and then placed it in a refrigerator overnight. The resulting solids which formed were isolated, washed with cold hexanes, and then dried under high vacuum to yield 10.80g (32.0%) of the desired product as off-white crystals.

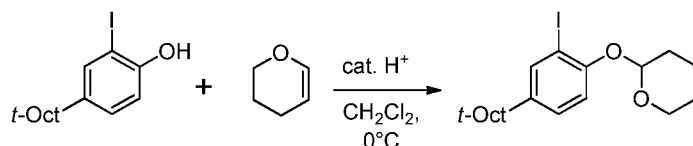
^1H NMR (400 MHz, CDCl_3) δ 8.11 (d, $J = 1.6$ Hz, 2H), 7.75 (s, 1H), 7.48 (dd, $J = 8.5, 1.9$ Hz, 2H), 7.31 (d, $J = 8.5$ Hz, 2H), 1.48 (s, 18H). $^{13}\text{C}\{^1\text{H}\}$ NMR (101 MHz, CDCl_3) δ 142.17 (s), 137.96 (s), 123.45 (s), 123.28 (s), 116.11 (s), 109.97 (s), 34.73 (s), 32.09 (s).

3b. Preparation of 2-iodo-4-(2,4,4-trimethylpentan-2-yl)phenol



To a stirred solution of 10.30 g (50.00 mmol) of 4-(2,4,4-trimethylpentan-2-yl)phenol, in 125 mL of methanol at 0°C , was added 7.48 g (50.00 mmol) of NaI and 2.00 g (50.0 mmol) of NaOH. To the resulting mixture, was added, 86 mL of 5% aqueous NaOCl solution (commercial bleach) over a one hour period. The resulting slurry was stirred for one more hour at 0°C , then 30 mL of aqueous 10% $\text{Na}_2\text{S}_2\text{O}_3$ solution was added, and the resulting reaction mixture was acidified with the addition of dilute hydrochloric acid. The resulting mixture was extracted with methylene chloride, and the resulting organic layer was washed with brine, and then dried over anhydrous magnesium sulfate. The volatiles were removed under vacuum, and the resulting residue was purified by flash chromatography on silica gel, eluting with 5 volume percent (vol%) ethyl acetate in hexanes to yield 11.00 g (66%) of the desired product as a viscous oil. ^1H NMR (CDCl_3) δ 7.60 (d, $J = 2.5$ Hz, 1H), 7.25 (dd, $J = 8.5$ and 2.2 Hz, 1H), 6.90 (d, $J = 8.5$ Hz, 1H), 5.13 (s, 1H), 1.69 (s, 2H), 1.32 (s, 6H) and 0.74 (s, 9H). $^{13}\text{C}\{^1\text{H}\}$ NMR (CDCl_3) δ 152.21, 144.52, 135.56, 128.03, 114.17, 85.36, 56.92, 38.01, 32.43, 31.90 and 31.64. GC/MS (m/e): 332 (M^+).

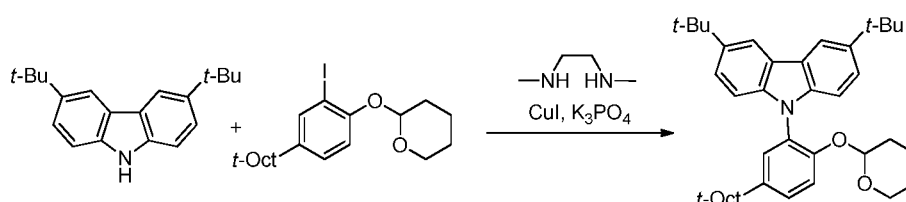
3c. Preparation of 2-(2-iodo-4-(2,4,4-trimethylpentan-2-yl)phenoxy)tetrahydro-2H-pyran.



To a stirred solution of 4.91 g (14.8 mmol) of 4-(2,4,4-trimethylpentan-2-yl)phenol and 1.50 g (17.8 mmol) of 3,4-dihydropyran, in 5 mL of methylene chloride, at 0°C , was added, 0.039g (0.205 mmol) of *para*-toluenesulfonic acid monohydrate. The resulting solution was allowed to warm to room temperature, and stirred thereat for approximately 10 minutes. Then triethylamine (0.018 g, 0.178 mmol) was added, and the resulting mixture was diluted with 50

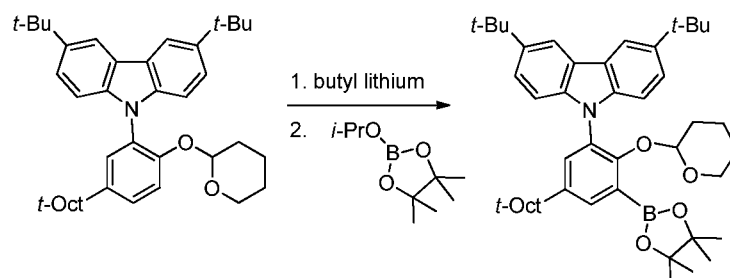
mL of methylene chloride, and successively washed with 50 mL each of 1M NaOH, water, and brine. The organic phase was dried with anhydrous magnesium sulfate, filtered, and concentrated, to give a crude material, which was purified by flash chromatography on silica gel, using 5 vol% ethyl acetate in hexanes, to yield 5.18 g (93.12%) of the desired product as a golden oil. ^1H NMR (CDCl_3) δ 7.74 (d, $J = 2.3$ Hz, 1H), 7.27 (dd, $J = 2.3$ and 8.6 Hz, 1H), 6.99 (d, $J = 8.6$ Hz, 1H), 5.49 (m, 1H), 3.91 (m, 1H), 3.61 (m, 1H), 2.20-1.60 (m, 6H), 1.69 (s, 2H), 1.34 (s, 6H) and 0.75 (s, 9H). $^{13}\text{C}\{^1\text{H}\}$ NMR (CDCl_3) δ 153.27, 145.49, 136.98, 127.08, 114.44, 96.72, 87.09, 61.69, 56.91, 37.95, 32.33, 31.81, 31.52, 31.44, 30.26, 25.27, 18.36.

3d. Preparation of 3,6-di-tert-butyl-9-(2-(tetrahydro-2H-pyran-2-yloxy)-5-(2,4,4-trimethylpentan-2-yl)phenyl)-9H-carbazole.



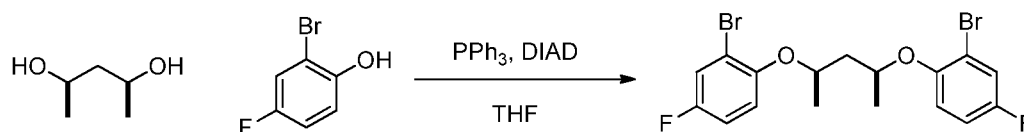
To a 50 mL, three necked, round bottom flask, equipped with a stir bar and condenser, under N₂ atmosphere, was added the following: 20 mL of dry toluene, 5.00 g (12.01 mmol) of 2-(2-iodo-4-(2,4,4-trimethylpentan-2-yl)phenoxy)tetrahydro-2H-pyran; 3.56 g (12.01 mmol) of 3,6-di-tert-butyl carbazole, 0.488g (2.56 mmol) of CuI, 7.71g (36.2 mmol) of K₃PO₄, and 0.338 g (3.84 mmol) of N,N'-dimethylethylenediamine. The resulting reaction mixture was heated, under reflux, for 48 hours, cooled, and filtered through a bed of silica gel. The silica gel was rinsed with tetrahydrofuran (THF), and the resulting solution was concentrated to give a crude residue. Purification was accomplished by recrystallization from acetonitrile, to yield 4.57 g (67.0%) of the desired product as a white solid. ^1H NMR (CDCl_3) δ 8.13 (t, $J = 1.71$ Hz, 1H), 7.48 (d, $J = 2.4$ Hz, 1H), 7.40 (m, 3H), 7.31 (d, $J = 8.68$ Hz, 1H), 7.14 (d, $J = 8.68$ Hz, 1H), 7.08 (d, $J = 8.56$ Hz, 1H), 5.22 (t, $J = 2.81$ Hz, 1H), 3.72 (td, $J = 11.12$ and 2.8 Hz, 1H), 3.47 (dt, $J = 11.12$ and 3.47 Hz, 1H), 1.75 (s, 2H), 1.474 (s, 9H), 1.472 (s, 9H), 1.394 (s, 3H), 1.391 (s, 3H), 1.37-1.12 (m, 6H), 0.82 (s, 9H). $^{13}\text{C}\{^1\text{H}\}$ NMR (CDCl_3) δ 150.96, 144.22, 142.07, 140.02, 127.49, 126.60, 126.56, 123.14, 123.12, 122.96, 116.37, 115.88, 115.72, 110.18, 109.52, 97.02, 61.56, 57.03, 38.23, 34.69, 32.41, 32.07, 31.86, 31.72, 31.50, 29.98, 25.06, 17.61.

3e. Preparation of 3,6-di-tert-butyl-9-(2-((tetrahydro-2H-pyran-2-yl)oxy)-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-5-(2,4,4-trimethylpentan-2-yl)phenyl)-9H-carbazole.



To a stirred solution of 2.5 g (4.4 mmol) of carbazole derivative, in 40 mL of THF, at 0°C, under nitrogen atmosphere, 2.8 mL (7.0 mmol) of *n*-butyl lithium (2.5 M solution in hexanes) was added, over a period of five minutes. The solution was stirred at 0°C for three more hours. 2-Isopropoxy-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (1.44 mL, 7.0 mmol) was added to this, and the stirring continued at 0°C for one more hour. The reaction mixture was slowly warmed to room temperature, and stirred for 18 hrs. The reaction mixture was concentrated to dryness and by rotary evaporation, and 100 mL of ice cold water was added. The mixture was extracted with methylene chloride. The organic layer was washed with brine, and dried over anhydrous magnesium sulfate. Removal of the solvent, followed by recrystallization from acetonitrile, gave 2.4 g (78.6%) of titled product as white solid. ^1H NMR (CDCl_3) δ 8.30-7.96 (m, 2H), 7.81(d, J = 2.5 Hz, 1H), 7.58-7.32 (m, 3H), 7.14 (d, J = 8.6 Hz, 2H), 4.85 (d, J = 2.8 Hz, 1H), 2.76 (td, J = 11.0, 2.7 Hz, 1H), 2.59 (dd, J = 7.9, 3.5 Hz, 1H), 1.73 (s, 2H), 1.67-0.87 (m, 6H), 1.46 (s, 9H), 1.45 (s, 9H), 1.38 (s, 9H), 1.37 (s, 9H), 0.78 (s, 9H); $^{13}\text{C}\{^1\text{H}\}$ NMR (CDCl_3) δ 156.25, 145.86, 142.05, 142.01, 139.79, 139.78, 133.82, 130.61, 129.72, 123.39, 123.37, 123.05, 115.59, 115.55, 110.20, 110.11, 101.41, 83.64, 61.20, 56.95, 38.37, 34.68, 32.42, 32.08, 31.90, 31.45, 29.97, 25.06, 25.04, 24.79, 18.16. MS m/e 716.38 ($\text{M}+\text{Na}$).

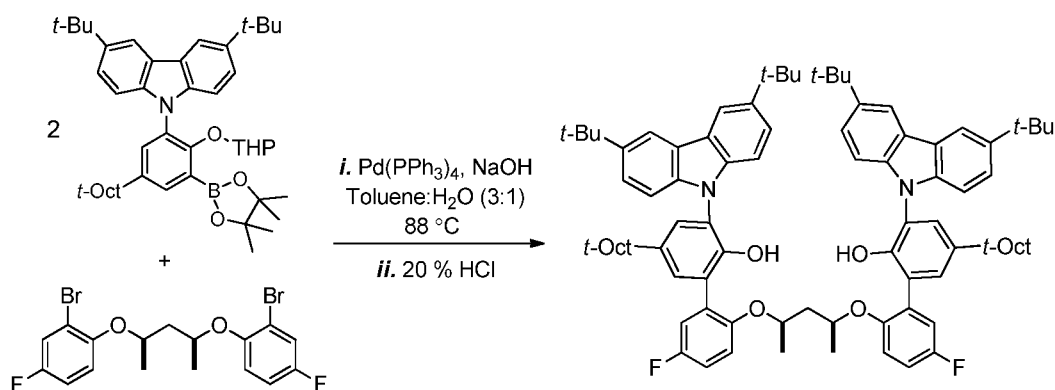
3f. Preparation of meso-4,4'-pentane-2,4-diylbis(oxy))bis(3-bromo-1-fluorobenzene).



A 2-L, three-neck, round bottom flask, equipped with a thermometer, a magnetic stirrer, an addition funnel, and a nitrogen pad, was charged with 2,4-pentanediol (30.46 g, 292.5 mmol, 1 equiv), 2-bromo-4-fluorophenol (114.39 g, 598.9 mmol, 2.04 equiv), triphenylphosphine (157.12 g, 599.0 mmol, 2.04 equiv), and THF (600 mL), and the contents cooled to 2°C in an ice-water bath. A solution of DIAD (121.11 g, 598.9 mmol, 2.04 equiv) in THF (130 mL), in the addition funnel, was added, at such a rate, to maintain the reaction below 5°C (the addition took approximately 4 hours). The resulting mixture was stirred at 2- °C for an additional one hour, and a sample was taken for GC-MS analysis, which indicated the reaction was near to completion. After stirring overnight, at ambient temperature, volatiles were removed under

reduced pressure. Cyclohexane (700 mL) was added to the residue and the slurry was stirred at room temperature for 30 minutes. The insoluble solid was filtered, rinsed with cyclohexane (100 mL x 3). The cyclohexane solution was washed with 1N NaOH (200 mL), water (200 mL), 1N HCl (200 mL), water (500 mL x2), and then concentrated, under reduced pressure, to give an oil residue. The oil residue was dissolved in hexane (100 mL), and then passed through a pad of silica gel (315 g), eluting with hexane (300 mL), and hexane-EtOAc (20:1 in volume, hexane 2 L + EtOAc 100 mL), concentrated, and dried, to give the desired bottom group (123.8 grams, 94% yield). ^1H NMR (400 MHz, C_6D_6) δ 7.14 (dd, $J = 8.4, 3.9$ Hz, 2H), 6.64 (dt, $J = 9.1, 3.9$ Hz, 2H), 6.48 (dd, $J = 9.0, 3.7$ Hz, 2H), 4.22 (m, 2H), 2.17 (dt, $J = 13.6, 6.5$ Hz, 1H), 1.45 (dt, $J = 13.6, 5.6$ Hz, 1H), and 0.98 (d, $J = 6.1$ Hz, 6H). ^{13}C NMR (101 MHz, CDCl_3) δ 156.9 (d, $J = 235.8$ Hz), 150.9 (d, $J = 2.8$ Hz), 120.9 (d, $J = 25.8$ Hz), 115.62 (d, $J = 7.7$ Hz), 114.9 (d, $J = 21.5$ Hz), 113.7 (d, $J = 10.1$ Hz), 72.8, 42.7, and 19.6. ^{19}F NMR (376 MHz, C_6D_6) δ -121.33.

3g. Preparation of Ligand 3 (L3).



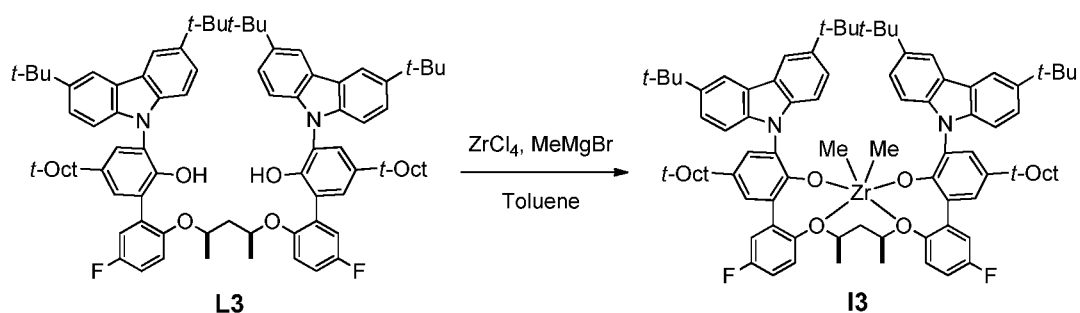
Method 1: To a 2 L reactor vessel, was added, *meso*-4,4'-pentane-2,4-diylbis(oxy))bis(3-bromo-1-fluorobenzene) (80 g, 177.7 mmol) and 3,6-di-tert-butyl-9-(2-(((tetrahydro-2H-pyran-2-yl)oxy)-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-5-(2,4,4-trimethylpentan-2-yl)phenyl)-9H-carbazole (271.3 g, 391.0 mmol), dissolved in 800 mL of toluene, under a nitrogen atmosphere, with stirring. To this, was added, NaOH (42.7g dissolved in 100 mL of water, 1.0 mol), followed by quick addition of Pd(PPh₃)₄ (8.21 g, 7.11 mmol), and the reaction heated to 88°C. The course of the reaction was monitored via LC, until deemed complete at the five hour mark. At this point, the reaction vessel was cooled to rt (room temperature), the caustic layer removed, and 200 mL of a 20% HCl solution was added, and the reaction heated once more to 88°C for five hours. The reactor was cooled to ambient temperature, the aqueous layer removed, and the organic layer washed with brine, and dried over MgSO₄. Filtration to remove the MgSO₄, followed by concentration via rotary evaporation, gave an off-white solid, which was washed with acetonitrile, and the remaining solid dried under vacuum to provide pure DOC-6163 ligand (199.5 grams, 89 % yield).

Method 2 (two step procedure)

Ph₃P (1.05 g, 4 mmol), *meso*-4,4'-pentane-2,4-diylbis(oxy))bis(3-bromo-1-fluorobenzene) (45.01 g, 100.0 mmol), aliquot 336 (0.326 g) and toluene (500 mL) were added into a 2L, three-neck, round bottom flask, equipped with cold water condenser, magnetic stirrer, a thermometer, and a nitrogen pad in an oil bath. The mixture was sparged with nitrogen for 30 minutes. Pd(OAc)₂ (449.02 mg, 2.0 mmol, 0.02 equiv) was added, and the mixture was stirred for 5-10 minutes, until solid Pd(OAc)₂ dissolved, while sparging with nitrogen. Then 2N NaOH (300 mL, pre-sparged with nitrogen) was added, under nitrogen, and the mixture was sparged with nitrogen for five minutes. The reaction mixture was heated to 75-78°C, and a solution of 3,6-di-tert-butyl-9-(2-(((tetrahydro-2H-pyran-2-yl)oxy)-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-5-(2,4,4-trimethylpentan-2-yl)phenyl)-9H-carbazole (156.64 g, 220 mmol) in 400 mL of toluene (sparged with nitrogen for 30 min) was added, over three hours, via a syringe pump. The reaction mixture

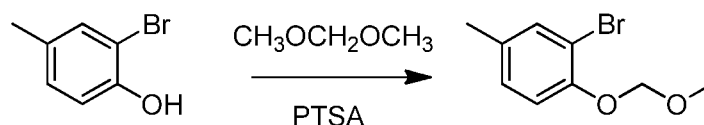
was heated at 80-86°C overnight (the reaction was complete over 4-6 hours, as monitored by LC), under nitrogen atmosphere, in a 105°C oil bath, which resulted in a dark mixture. After being cooled to 50°C, air was bubbled into the reaction mixture for one hour to destroy the catalyst. The reaction mixture was then settled for phase-cut. The bottom aqueous layer was removed, and extracted with toluene (100 mL). The toluene phase was washed with water (500 mL x 2). 2N HCl (300 mL, prepared from 100 mL 6N HCl + 200 mL H₂O) was added to the toluene solution. The resulting mixture was stirred 80-86°C, in a 105-108°C oil bath, under nitrogen overnight. LC analysis of the reaction mixture indicated that the deprotection of the THP group was complete. The reaction mixture was allowed to cool to ambient temperature. The bottom aqueous layer was removed, which was subsequently extracted with toluene (100 mL). The yellow to brown toluene phase was washed with water (500 mL x 2). The toluene solution was filtered through a pad of silica gel (60-100 g). The silica gel wet cake was rinsed with toluene (100 mL). The slightly yellow toluene solution was concentrated, under reduced pressure, by rotovap, which gave a thick residue (~185.5 g). Acetonitrile (500 mL) was added to the residue, and the mixture was spun on roto-vap at 60°C. The thick residue was gradually dissolved, forming a clear, slightly yellow solution. White solid precipitated out from the solution after a while. After cooling to ambient temperature overnight, the solid was collected by filtration, washed/rinsed with acetonitrile (200 mL x 2), suck-dried, and dried in vacuum oven, to give the desired product (115.5 grams, 92.0% yield). ¹H NMR (400 MHz, C₆D₆) δ 8.45 (t, *J* = 2.4 Hz, 4H), 7.50-7.56 (m, 6H), 7.41 (d, *J* = 8.8 Hz, 2H), 7.16 (obscured by CD₅H), 6.32 (s, 2H), 6.30 (dd, *J* = 9.3, 4.7 Hz, 2H), 6.23 (s, 2H), 4.16 (m, 2H), 2.01 (dt, *J* = 14.3, 6.9 Hz, 1H), 1.55 (s, 4H), 1.37 (dt, *J* = 14.2, 5.0 Hz, 1H), 1.44 (s, 18H), 1.43 (s, 18H), 1.20 (s, 12H), 0.83 (d, *J* = 6.0 Hz, 6H), and 0.80 (s, 18H). ¹³C{¹H} NMR (101 MHz, C₆D₆) δ 158.2 (d, *J* = 241.2 Hz), 149.8 (d, *J* = 1.7 Hz), 148.9, 143.2, 143.0, 143.0, 140.7 (d, *J* = 5.5 Hz), 131.1 (d, *J* = 7.5 Hz), 129.4, 127.2, 126.1, 124.2 (d, *J* = 2.7 Hz), 118.9 (d, *J* = 23.4 Hz), 117.3 (d, *J* = 9.2 Hz), 116.8, 115.8 (d, *J* = 22.8 Hz), 110.2 (d, *J* = 10.0 Hz), 73.7, 57.1, 42.66, 38.3, 34.9, 32.5, 32.2, 32.1, 31.7, 31.6, and 19.5. ¹⁹F NMR (376 MHz, C₆D₆) δ -120.95.

3g. Preparation of Pro-Catalyst 3 (I3).



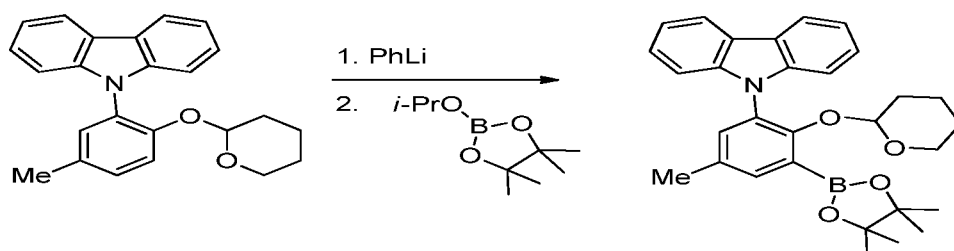
A 5 L reactor was charged with 4.5 L of toluene, and cooled to -30°C . To this, was added, ZrCl_4 (38.8 g, 166.8 mmol), followed by MeMgBr (211.8 mL of a 3M solution, 635.5 mmol). The resulting mixture was allowed to stir for five minutes, after which, the ligand **L3** (199.5 g, 158.9 mmol) was added. The suspension was allowed to gradually warm to room temperature, and was stirred for an additional three hours, and then filtered. The toluene was then removed, under vacuum, to provide **I3** as an off white solid in good purity (quantitative, 234 grams). ^1H NMR (400 MHz, C_6D_6) δ 8.53 (m, 2H), 8.41 (dd, $J = 2.0, 12.0$ Hz, 2H), 7.72 (m, 2H), 7.67 (d, $J = 3.0$ Hz, 1H), 7.57-7.61 (m, 6H), 7.44 (ddd, $J = 2.9, 8.1, 9.4$ Hz, 2H), 7.24 (dd, $J = 2.0, 14$ Hz, 2H), 7.01 (dd, $J = 3.7, 8.9$ Hz, 2H), 6.95 (dd, 4.0, 7.3 Hz, 1H), 6.60 (m, 2H), 4.95 (dd, $J = 4.4, 8.2$ Hz, 2H), 4.82 (dd, $J = 4.4, 8.2$ Hz, 2H), 4.21 (m, 2H), 3.78 (m, 2H), 1.64 (s, 3H), 1.58 (s, 3H), 1.48 (s, 9H), 1.46 (s, 9H), 1.32 (s, 9H), 1.30 (s, 9H), 0.77-0.90 (m, 8H), 1.20-1.28 (m, 8H), 0.60 (d, $J = 7.3$ Hz, 3H), 0.41 (d, $J = 7.3$ Hz, 3H), -0.72 (s, 3H), and -0.88 (s, 3H). ^{19}F NMR (376 MHz, C_6D_6) δ -114.83.

Example 4. 4a. Preparation of 2-bromo-1-(methoxymethoxy)-4-methylbenzene.



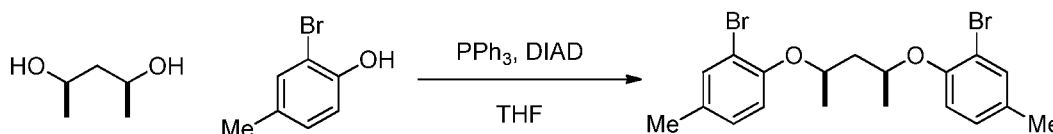
2-Bromo-4-methylphenol (13.1 g, 70.0 mmol), dimethoxymethane (35 mL), *p*-toluenesulfonic acid (100 mg) and methylene chloride (300 mL) were heated, under reflux, in a nitrogen atmosphere for three days, using a Soxhlet condenser containing activated 3 Å molecular sieves. The molecular sieves were exchanged for newly activated ones after every 24 hours. The reaction mixture was cooled, and the volatiles were removed by rotary evaporation. The residue was taken up in 100 mL of ether, and washed successively with 100 mL of 2M sodium hydroxide solution, 100 mL of water and 100 mL of brine. The organic layer was dried over anhydrous magnesium sulfate and passed through a small bed of silica gel. Removal of the solvent gave 14.5 g (92%) of pure **2**, as a pale yellow oil, which was used as such for the next step. ^1H NMR (CDCl_3) δ 7.40 (m, 1H), 7.07 (m, 2H), 5.25 (s, 2H), 3.55 (s, 3H) and 2.31 (s, 3H).

4c. Preparation of 9-(5-methyl-2-((tetrahydro-2H-pyran-2-yl)oxy)-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)phenyl)-9H-carbazole



The 9-(5-methyl-2-((tetrahydro-2H-pyran-2-yl)oxy)phenyl)-9H-carbazole (40 g, 0.11 mol) was dissolved in 300 mL of THF, in a nitrogen-filled glovebox, and deprotonated by the slow addition of PhLi (74.6 mL, 0.13 mol; 1.8 M in *n*-Bu₂O). The reaction mixture was stirred for one hour. 2-Isopropoxy-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (25.1 mL, 0.12 mol) was added slowly, and the reaction mixture was stirred for another hour. Solvent removal, under vacuum, gave an oily residue, which was dissolved in 450 mL of chloroform, and washed with water (2 x 450 mL). The organic layer was dried over MgSO₄, filtered, and the filtrate concentrated, under vacuum, to afford a dark oil, which was then mixed with 600 mL hexane, and concentrated to approximately 250 mL, causing a large amount of light brown solids to form. The solids were filtered and dried under vacuum (42 g, 78%). ¹H NMR (400 MHz, CDCl₃) δ 7.99 (m, 2H), 7.59 (d, *J* = 2.3 Hz, 1H), 7.28 (ddd, *J* = 15.4, 8.2, 1.1 Hz, 2H), 7.14 (m, 5H), 4.78 (t, *J* = 3.0 Hz, 1H), 2.44 (m, 2H), 2.25 (s, 3H), 1.59 (m, 1H), 1.28 (s, 6H), 1.27 (s, 6H), 1.09 (m, 4H), 0.82 (m, 1H).

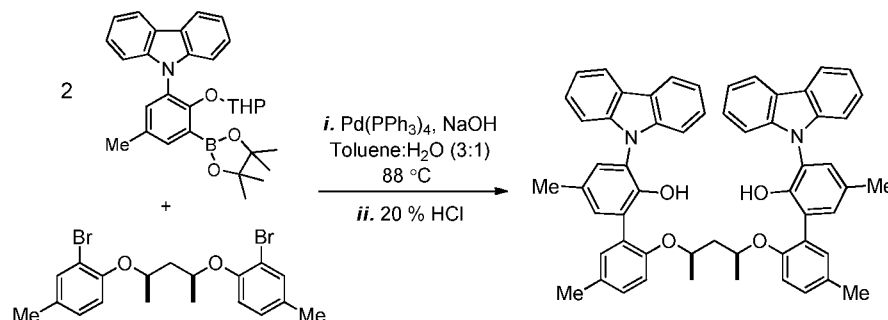
4d. Preparation of *meso*-4,4'-pentane-2,4-diylbis(oxy))bis(3-bromo-1-methylbenzene).



A 2-L, three-neck, round bottom flask, equipped with a thermometer, a magnetic stirrer, and an addition funnel, was charged with *meso*-2,4-pentanediol, (30.50 g, 293 mmol), 2-bromo-4-methylphenol (112.03 g, 599 mmol), triphenylphosphine (157.12 g, 599 mmol), and THF (600 mL). The reaction vessel was then placed under a nitrogen atmosphere, and the addition funnel was charged with diisopropyl azodicarboxylate (DIAD, 121.11 g, 599 mmol) and THF (250 mL). The contents in the flask were cooled to 2°C in an ice-water bath, the DIAD solution, in the addition funnel, was added, at such a rate, to maintain the reaction temperature at 2-5°C (the addition took approximately 3.5 hours). The resulting mixture was stirred at 2-5°C for an additional one hour (a sample was taken for GC-MS analysis, which showed the reaction was near to completion), and then allowed to warm up to ambient temperature overnight. The volatiles were removed, under reduced pressure, to give a solid residue (~ 424 g). The residue was extracted with cyclohexane (1000 mL), at 35°C, by spinning on a rotary-evaporator for 30 minutes, without pulling vacuum. This process was repeated for additional three times with cyclohexane (350 mL x 3) at 35°C. The combined cyclohexane solution was washed with 1N NaOH (350 mL x 2), water (500 mL), 1N HCl (350 mL), and water (500 mL x 2). The washed cyclohexane solution was concentrated to approximately 300 mL, passed through a pad of silica gel (350 g), and eluted with hexane/ EtOAc (20:1 in volume), concentrated, and dried, to give the

desired bottom group (119.0 grams, 91.5%). ^1H NMR (400 MHz, CDCl_3) δ 7.26 (d, $J = 2.3$ Hz, 2H), 7.04 (dd, $J = 8.5, 2.3$ Hz, 2H), 6.94 (d, $J = 8.5$ Hz, 2H), 4.63 (m, 2H), 2.39 (dt, $J = 13.8, 6.7$ Hz, 1H), 2.26 (s, 6H), 1.82 (dt, $J = 14.1, 5.9$ Hz, 1H), and 1.37 (d, $J = 6.1$ Hz, 6H). $^{13}\text{C}\{^1\text{H}\}$ NMR (101 MHz, CDCl_3) δ 152.1, 133.9, 131.8, 115.2, 114.77, 112.9, 72.5, 42.9, 20.3, and 20.0.

4e. Preparation of Ligand 4 (L4).



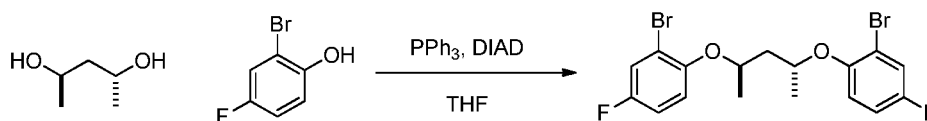
To a 2-L reactor vessel, was added, *meso*-4,4'-pentane-2,4-diylbis(oxy))bis(3-bromo-1-methyl-benzene) (40.0 g, 90.5 mmol) and 9-(5-methyl-2-((tetrahydro-2H-pyran-2-yl)oxy)-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)phenyl)-9H-carbazole (96.2 g, 199.0 mmol, 2.2 equiv), dissolved in 300 mL of toluene, under a nitrogen atmosphere, with stirring. To this, was added, NaOH (21.7 g dissolved in 100 mL of water, 0.5 mol, 6 equiv), followed by quick addition of $\text{Pd}(\text{PPh}_3)_4$ (4.18 g, 3.61 mmol, 0.04 equiv). The reaction was then heated to 88°C , until complete. The course of the reaction was monitored via LC, until deemed complete at the seven hour mark. At this point, the reaction vessel was cooled to ambient temperature, the caustic layer removed, 200 mL of a 20% HCl solution was added, and the reaction heated under reflux for five hours. The reactor was cooled to ambient temperature, the stirring was halted, and the aqueous layer removed. The organic layer washed with brine, dried over MgSO_4 , then filtered, and concentrated via rotary evaporation, to give an off-white solid. The crude residue was washed with acetonitrile and dried under vacuum to provide pure **L2** ligand (44.2 grams, 60 % yield). ^1H NMR (400 MHz, CDCl_3) δ 8.13 (d, $J = 7.6$ Hz, 4H), 7.25 (m, 18H), 6.91 (dd, $J = 8.3, 2.0$ Hz, 2H), 6.64 (d, $J = 8.3$ Hz, 2H), 6.30 (s, 2H), 4.45 (m, 2H), 2.41 (s, 6H), 2.32 (s, 6H), 2.16 (m, 1H), 1.68 (m, 1H), and 1.14 (d, $J = 6.1$ Hz, 6H). $^{13}\text{C}\{^1\text{H}\}$ NMR (101 MHz, CDCl_3) δ 151.4, 148.4, 141.4, 141.3, 133.1, 131.9, 130.6, 130.1, 129.3, 128.8, 128.0, 125.8, 125.4, 123.4, 123.4, 120.3, 119.6, 114.9, 110.4, 110.3, 73.3, 42.7, 20.8, 20.7, and 19.9.

4f. Preparation of Pro-Catalyst 4 (I4).



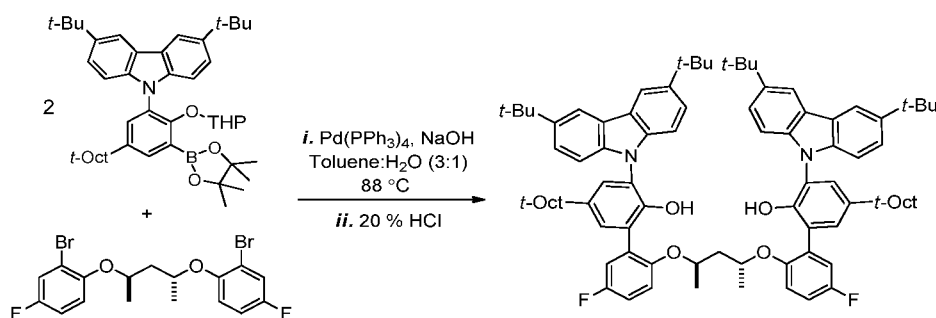
A 5 L reactor vessel was charged with 3 L of toluene, and cooled to -30°C . To this, was added, ZrCl_4 (29.6 g, 127 mmol), followed by MeMgBr (161 mL of a 3M solution, 484 mmol). The resulting mixture was allowed to stir for five minutes, after which, the ligand (100 g, 121 mmol) was added. The suspension was allowed to gradually warm to room temperature, stirred for an additional three hours, and then filtered. The filtrate was concentrated, and analyzed via ^1H NMR spectroscopy, which showed the presence of **14**, but with low purity. The filter cake was then extracted with methylene chloride (1.5 L), and concentrated, to provide **14** in high purity (66 grams, 58 % yield). ^1H NMR (400 MHz, CDCl_3) δ 8.30 (dd, $J = 8.5, 12.1$ Hz, 2H), 8.12 (dd, $J = 7.4, 10.3$ Hz, 2H), 7.57 (d, $J = 8.25$ Hz, 1H), 7.26-7.0 (m, 21 H), 6.40 (dd, $J = 2.2, 8.5$ Hz, 1H), 6.30 (dd, $J = 2.5, 7.15$ Hz, 1H), 4.44 (d, $J = 8.1$ Hz, 1H), 4.30 (d, $J = 7.9$ Hz, 1H), 4.05 (m, 1H), 3.70 (m, 1H), 2.38 (s, 3H), 2.37 (s, 3H), 2.23 (s, 6H), 1.35 (m, 1H), 0.59 (d, $J = 6.8$ Hz, 3H), 0.43 (d, $J = 7.2$ Hz, 3H), -1.51 (s, 3H), and -1.68 (s, 3H).

Example 5. 5a. Preparation of *rac*-4,4'-pentane-2,4-diylbis(oxy))bis(3-bromo-1-fluorobenzene).



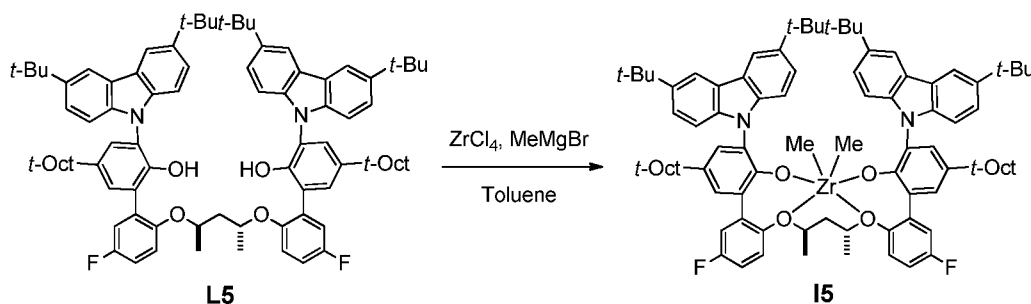
A 2-L, round bottomed flask, equipped with a magnetic stir, was charged with *rac*-2,4-pentanediol (16.9 g, 162.3 mmol), 2-bromo-4-fluorophenol (65.09 g, 340.8 mmol), triphenylphosphine (89.38 g, 340.76 mmol), and THF (600 mL), and was cooled to 0°C , in an ice-water bath. A solution of DIAD (67.09 g, 340.76 mmol), in THF (130 mL), was slowly added to the flask, via the addition funnel. The resulting mixture was stirred overnight, at ambient temperature, and the following day, the volatiles were removed under reduced pressure. Pentane (700 mL) was added to the residue, and the slurry was stirred at room temperature for 30 minutes. The insoluble solid was filtered, rinsed with pentane (100 mL x 3), and then concentrated, under reduced pressure, to give an oil residue. The oil residue was dissolved in hexane (100 mL), and then passed through a pad of silica gel, eluting first with hexane (300 mL), followed by hexane-EtOAc (4:1 in volume), furnishing the desired product in high purity (42.1 grams, 48% yield). ^1H NMR (400 MHz, CDCl_3): δ 7.20 (dd, $J = 7.8, 3.0$ Hz, 2H), 6.83 (ddd, $J = 9.1, 7.7, 3.0$ Hz, 2H), 6.74 (dd, $J = 9.1, 4.9$ Hz, 2H), 4.68 (sextet, $J = 6.1$ Hz, 2H), 2.05 (dd, $J = 7.3, 5.5$ Hz, 2H), and 1.35 (d, $J = 6.2$ Hz, 6H). $^{13}\text{C}\{^1\text{H}\}$ NMR (101 MHz, CDCl_3): δ 156.5 (d, $J = 243.2$ Hz), 151.1 (d, $J = 2.8$ Hz), 120.1 (d, $J = 25.8$ Hz), 116.0 (d, $J = 8.4$ Hz), 114.8 (d, $J = 22.7$ Hz), 113.3 (d, $J = 10.1$ Hz), 73.4, 44.8, and 20.2. ^{19}F NMR (376 MHz, C_6D_6) δ -121.22.

5e. Preparation of Ligand 5 (L5).



To a vial, was added, the *rac*-4,4'-pentane-2,4-diylbis(oxy))bis(3-bromo-1-fluorobenzene) (0.602 g, 1.34 mmol) and the top group (2.04 g, 2.94 mmol) dissolved in 5 mL of toluene, under a nitrogen atmosphere, with stirring. To this, was added, NaOH (0.321 g dissolved in 1 mL of water, 8.02 mmol), followed by quick addition of $\text{Pd(PPh}_3)_4$ (0.060 g, 0.054 mmol), and the reaction heated to 88°C. The course of the reaction was monitored via LC, until deemed complete at the five hour mark. At this point, the reaction vessel was cooled to rt, the caustic layer removed, 2 mL of a 20% HCl solution was added, and the reaction heated once more to reflux for five hours. The reactor was cooled to rt, the aqueous layer removed, and the organic layer washed with brine, and dried over MgSO_4 . Filtration to remove the MgSO_4 , followed by concentration via rotary evaporation, gave an off-white solid, which was washed with acetonitrile, and the remaining solid dried under vacuum to provide pure **L5** (1.41 grams, 84 % yield). ^1H NMR (400 MHz, CDCl_3): δ 8.19 (dt, $J = 3.3, 1.5$ Hz, 4H), 7.44 (m, 6H), 7.32 (t, $J = 1.8$ Hz, 2H), 7.07 (m, 6H), 6.66 (td, $J = 8.3, 3.1$ Hz, 2H), 6.41 (dd, $J = 9.2, 4.6$ Hz, 2H), 5.91 (s, 2H), 4.36 (m, 2H), 1.74 (s, 4H), 1.71 (m, 2H), 1.49 (s, 18H), 1.47 (s, 18H), 1.39 (s, 12H), 0.92 (d, $J = 5.8$ Hz, 6H), and 0.80 (s, 18H). ^{13}C NMR (101 MHz, CDCl_3): δ 157.5 (d, $J = 241.3$ Hz), 150.0 (d, $J = 1.8$ Hz), 147.9, 142.8, 142.6 (d, $J = 8.4$ Hz), 139.8 (d, $J = 10.9$ Hz), 130.2 (d, $J = 7.8$ Hz), 129.0, 127.2, 126.56, 124.8, 123.6 (d, $J = 13.3$ Hz), 123.3, 123.1, 118.2 (d, $J = 23.4$ Hz), 116.4, 116.3, 115.4 (d, $J = 22.8$ Hz), 109.2 (d, $J = 31.6$ Hz), 73.1, 57.0, 44.7, 38.2, 34.7 (d, $J = 1.6$ Hz), 32.4, 32.0, 31.9, 31.7, 31.6, and 19.7. ^{19}F NMR (376 MHz, C_6D_6) δ -121.96.

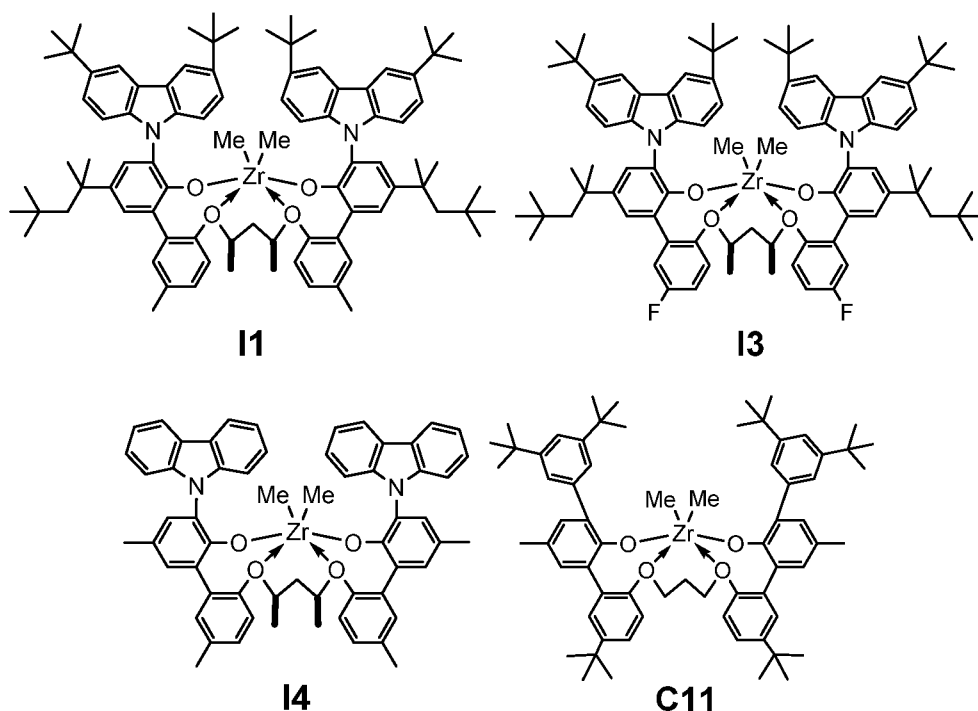
5e. Preparation of Pro-Catalyst 5 (I5).



A flask was charged with 30 mL of cold toluene (-30 °C) and ZrCl_4 (0.340 grams, 1.50 mmol). To the resulting cold suspension, was added, MeMgBr (1.90 mL of a 3M solution in

Et₂O, 5.70 mmol). The resulting mixture was allowed to stir for 2-3 minutes, at which point, the ligand **L5** (1.79 grams, 1.43 mmol) was added. The suspension was allowed to warm to room temperature naturally, and was stirred for two hours. The solvent was then removed under vacuum, and the dark brown suspension was extracted with hexanes (100 mL) and filtered. The filtrate was collected, and dried under vacuum, providing **I5** as an off white solid in good purity (1.46 grams, 75% yield). ¹H NMR (400 MHz, C₆D₆) δ 8.59 (m, 2H), 8.40 (m, 2H), 7.79 – 7.52 (m, 8H), 7.43 (dd, *J* = 8.4, 1.9 Hz, 2H), 7.23 (dd, *J* = 12.7, 2.5 Hz, 2H), 6.98 (dt, *J* = 9.0, 3.2 Hz, 2H), 6.66 (ddd, *J* = 8.9, 7.4, 3.2 Hz, 1H), 6.59 (ddd, *J* = 8.9, 7.4, 3.1 Hz, 1H), 5.04 (dd, *J* = 8.9, 5.0 Hz, 1H), 4.88 (dd, *J* = 8.9, 4.9 Hz, 1H), 4.16 (m, 1H), 3.74 (m, 1H), 1.80 (m, 1H), 1.67 – 1.57 (m, 5H), 1.48 (s, 9H), 1.47 (s, 9H), 1.31 (s, 9H), 1.30 (s, 9H), 1.28 – 1.20 (m, 12H), 0.86 (s, 9H), 0.85 (s, 9H), 0.59 (d, *J* = 6.4 Hz, 3H), 0.40 (d, *J* = 6.6 Hz, 3H), -0.82 (s, 3H), -0.82 (s, 3H). ¹⁹F NMR (376 MHz, C₆D₆) δ -114.59, and -114.68.

Procatalysts used in this study are shown below (Inventive Examples I1, I3 and I4; Comparative Example C11).



Continuous Reactor Ethylene/Octene Copolymerizations

Raw materials (ethylene, 1-octene) and the process solvent (a narrow boiling range high-purity isoparaffinic solvent trademarked SBP 100/140, commercially available from SHELL) are purified with molecular sieves, before introduction into the reaction environment. Hydrogen is supplied at 1160 psig (80 bar), and reduced to about 580 psig (40 bar); and is supplied as a high purity grade, and is not further purified. The reactor monomer feed (ethylene) stream is

pressurized, via mechanical compressor, to above reaction pressure at 525 psig. The solvent and comonomer (1-octene) feed is pressurized, via mechanical positive displacement pump, to above reaction pressure at 525 psig. Modified methylaluminoxane (MMAO), commercially available from AkzoNobel, is used as an impurity scavenger. The individual catalyst components (procatalyst, cocatalyst) are manually batch diluted, to specified component concentrations, with purified solvent (ISOPAR E), and pressurized to 525 psig. The cocatalyst is $[\text{HNMe}(\text{C}_{18}\text{H}_{37})_2][\text{B}(\text{C}_6\text{F}_5)_4]$, commercially available from Boulder Scientific, and is used at a 1.2 molar ratio relative to the procatalyst. All reaction feed flows are measured with mass flow meters, and independently controlled with computer automated valve control systems.

The continuous solution polymerizations are carried out in a 5L, continuously stirred-tank reactor (CSTR). The reactor has independent control of all fresh solvent, monomer, comonomer, hydrogen, and catalyst component feeds. The combined solvent, monomer, comonomer and hydrogen feed, to the reactor is temperature, controlled, to anywhere from 5°C to 50°C, and typically 25°C. The fresh comonomer feed to the polymerization reactor is fed in with the solvent feed. The cocatalyst is fed, based on a calculated specified molar ratio (1.2 molar equivalents) to the procatalyst component. Immediately, following each fresh injection location, the feed streams are mixed, with the circulating polymerization reactor contents, with static mixing elements. The effluent from the polymerization reactor (containing solvent, monomer, comonomer, hydrogen, catalyst components, and molten polymer) exits the first reactor loop, and passes through a control valve (responsible for maintaining the pressure of the first reactor at a specified target). As the stream exits the reactor, it is contacted with water to stop the reaction. In addition, various additives such as anti-oxidants, can be added at this point. The stream then goes through another set of static mixing elements, to evenly disperse the catalyst kill and additives.

Following additive addition, the effluent (containing solvent, monomer, comonomer, hydrogen, catalyst components, and molten polymer) passes through a heat exchanger, to raise the stream temperature, in preparation for separation of the polymer from the other lower boiling reaction components. The stream then enters a two stage separation and devolatilization system, where the polymer is removed from the solvent, hydrogen, and unreacted monomer and comonomer. The separated and devolatilized polymer melt is pumped through a die, specially designed for underwater pelletization, cut into uniform solid pellets, dried, and transferred into a box for storage.

Table 1: Continuous process single reactor polymerization data for 0.3 g/10 min (I_2), 0.894-0.896 g/cm³ density resins produced at 150°C

Ex.	Cat Eff	H ₂	Density	I ₂	I ₁₀ /I ₂	C2 feed	C8 feed	C2 Conv
	(MM g polymer / g Metal)	(mol %)	(g/cm ³)	(g/10 min)		(kg/h)	(kg/h)	(%)
Inv 1 (I1)	1.30	0.16	0.895	0.30	6.1	3.50	3.75	78.6
Inv 2 (I3)	1.70	0.14	0.895	0.33	6.2	3.50	3.10	78.0
Inv 3 (I3)	1.80	0.15	0.895	0.34	5.9	3.45	3.45	79.4
Inv 4 (I4)	1.55	0.13	0.894	0.24	6.1	3.50	4.25	78.8
Comp 1 (C11)	3.80	0.23	0.896	0.30	7.1	3.50	3.65	78.2

Table 2: Continuous process single reactor resin data for 0.2-0.3g/10 min (I_2), 0.894-0.896 g/cm³ density resins produced at 150°C

Ex.	Mw	MWD	Tan delta (0.1 rad/s; 190°C)	η_0	ZSVR	CEF: peak width at 25% peak height
	(g/mole)			(Pa•s)		Degrees C (°C)
Inv 1 (I1)	140,100	2.0	11.2	25,889	1.86	9.1
Inv 2 (I3)	135,800	1.9	8.9	25,513	2.05	11.0
Inv 3 (I3)	146,200	1.8	11.5	23,441	1.44	11.0
Inv 4 (I4)	142,300	2.0	12.2	31,491	2.14	8.4
Comp 1 (C11)	124,600	2.5	4.0	36,212	3.98	8.8

Table 3: Continuous process single reactor polymerization data for 0.5g/10 min (I_2) and 0.911-0.914 g/cm³ density resins produced at 150°C

Ex.	Cat Eff	H ₂	Density	I ₂	I ₁₀ /I ₂	C2 feed	C8 feed	C2 Conv
	(MM g polymer / g Metal)	(mol %)	(g/cm ³)	(g/10 min)		(kg/h)	(kg/h)	(%)
Inv 5 (I1)	1.40	0.39	0.912	0.48	5.8	3.91	1.88	79.0
Inv 6 (I3)	2.70	0.35	0.914	0.51	5.6	3.92	1.35	78.6
Inv 7 (I4)	2.90	0.35	0.911	0.49	5.6	3.91	1.88	78.5
Comp 2- (C11)	3.10	0.41	0.913	0.53	6.6	3.91	1.86	78.4

Table 4: Continuous process single reactor resin data for 0.5g/10 min (I_2) and 0.911-0.914 g/cm³ density resins produced at 150°C

Ex.	Mw	MWD	Tan delta (0.1 rad/s; 190°C)	η_0	ZSVR	CEF: peak width at 25% peak height
	(g/mole)			(Pa•s.)		Degrees C (°C)
Inv 5 (I1)	127,000	1.9	16.0	15,313	1.57	7.3
Inv 6 (I3)	119,500	2.1	15.4	15,325	1.97	7.4

Inv 7 (I4)	125,000	1.9	21.0	15,015	1.64	6.0
Comp 2 (C11)	114,300	2.0	5.9	19,493	2.94	6.2

Table 5: Continuous process single reactor polymerization data for 1g/10 min (I_2), and 0.912-0.914 g/cm³ density resins produced at 150°C

Example	Cat Eff	H ₂	Density	I ₂	I ₁₀ /I ₂	C2 feed	C8 feed	C2 Conv
	(MM g poly/g M)	(mol %)	(g/cm ³)	(g/10 min)		(kg/h)	(kg/h)	(%)
Inv 8 (I1)	1.30	0.49	0.912	0.93	5.7	3.91	1.91	78.7
Inv 9 (I3)	2.10	0.45	0.913	1.02	5.5	4.39	1.79	78.9
Inv 10 (I4)	3.00	0.41	0.914	1.05	5.5	3.91	2.00	78.6
Comp 3 (C11)	3.60	0.51	0.912	1.08	6.2	3.91	2.10	78.4

Table 6: Continuous process single reactor resin data for 1g/10 min (I_2), and 0.912-0.914 g/cm³ density resins produced at 150°C

Ex.	Mw	MWD	Tan delta (0.1 rad/s; 190°C)	η_0	ZSVR	CEF: peak width at 25% peak height
	(g/mole)			(Pa•s)		(°C)
Inv 8 (I1)	107,600	2.0	36.1	7,923	1.49	7.9
Inv 9 (I3)	108,500	1.9	30.1	7,361	1.34	8.9
Inv 10 (I4)	99,900	1.9	44.2	6,821	1.68	6.8
Comp 3 (C11)	96,100	2.1	13.0	8,045	2.29	7.2
Comp 4*	113,632	2.3	54.2	6,949	1.07	35.7

*Comp 4 is EXCEED 1012 available from ExxonMobil.

As seen in Tables 1-6, the inventive ethylene-based polymers have a unique combination of structural properties, characterized by low levels of long chain branching, low zero shear viscosity ratio, optimal tan delta, narrow comonomer distribution (CEF profile; each inventive polymer had a single peak, in the CEF-Comonomer Distribution, at a temperature from 60°C to 100°C (see Tables 2, 4 and 6 for the “peak width at 25% peak height”), and narrow molecular weight distribution. The inventive polymers would be useful for the fabrication of molded articles with improved properties (for example, optical properties, dart drop impact resistance, puncture resistance, crack resistance, etc.).

Test Methods

Density

Samples that are measured for density are prepared according to ASTM D-1928. Measurements are made within one hour of sample pressing using ASTM D- 792, Method B.

Melt Index

Melt index (I_2) is measured in accordance with ASTM-D 1238, Condition 190°C/2.16 kg, and is reported in grams eluted per 10 minutes. Melt flow rate (I_{10}) is measured in accordance with ASTM-D 1238, Condition 190°C/10 kg, and is reported in grams eluted per 10 minutes.

Conventional Gel Permeation Chromatography (conv. GPC)

A GPC-IR high temperature chromatographic system from, PolymerChAR (Valencia, Spain), was equipped with a Precision Detectors (Amherst, MA), 2-angle laser light scattering detector Model 2040, an IR5 infra-red detector and a 4-capillary viscometer, both from PolymerChAR. Data collection was performed using PolymerChAR InstrumentControl software and data collection interface. The system was equipped with an on-line, solvent degas device and pumping system from Agilent Technologies (Santa Clara, CA).

Injection temperature was controlled at 150 degrees Celsius. The columns used were three 10-micron "Mixed-B" columns from Polymer Laboratories (Shropshire, UK). The solvent used was 1,2,4-trichlorobenzene. The samples were prepared at a concentration of "0.1 grams of polymer in 50 milliliters of solvent." The chromatographic solvent and the sample preparation solvent each contained "200 ppm of butylated hydroxytoluene (BHT)." Both solvent sources were nitrogen sparged. Ethylene-based polymer samples were stirred gently at 160 degrees Celsius for three hours. The injection volume was 200 microliters, and the flow rate was 1 milliliters/minute. The GPC column set was calibrated by running 21 "narrow molecular weight distribution" polystyrene standards. The molecular weight (MW) of the standards ranged from 580 to 8,400,000 g/mole, and the standards were contained in six "cocktail" mixtures. Each standard mixture had at least a decade of separation between individual molecular weights. The standard mixtures were purchased from Polymer Laboratories. The polystyrene standards were prepared at "0.025 g in 50 mL of solvent" for molecular weights equal to, or greater than, 1,000,000 g/mole, and at "0.050 g in 50 mL of solvent" for molecular weights less than 1,000,000 g/mole.

The polystyrene standards were dissolved at 80°C, with gentle agitation, for 30 minutes. The narrow standards mixtures were run first, and in order of decreasing "highest molecular weight component," to minimize degradation. The polystyrene standard peak molecular weights were converted to polyethylene molecular weight using Equation 1 (as described in Williams and Ward, *J. Polym. Sci., Polym. Letters*, 6, 621 (1968)):

$$M_{\text{polyethylene}} = A \times (M_{\text{polystyrene}})^B \quad (\text{Eqn. 1}),$$

where M is the molecular weight, A is equal to 0.4316 and B is equal to 1.0.

Number-average molecular weight (Mn(conv gpc)), weight average molecular weight (Mw(conv gpc)), and z-average molecular weight (Mz(conv gpc)) were calculated according to Equations 2-4 below:

$$Mn(\text{conv gpc}) = \frac{\sum_{i=RV_{\text{integration start}}}^{i=RV_{\text{integration end}}} (IR_{\text{measurement channel}_i})}{\sum_{i=RV_{\text{integration start}}}^{i=RV_{\text{integration end}}} \left(IR_{\text{measurement channel}_i} / M_{PE_i} \right)} \quad (\text{Eqn. 2}),$$

$$Mw(\text{conv gpc}) = \frac{\sum_{i=RV_{\text{integration start}}}^{i=RV_{\text{integration end}}} (M_{PE_i} IR_{\text{measurement channel}_i})}{\sum_{i=RV_{\text{integration start}}}^{i=RV_{\text{integration end}}} (IR_{\text{measurement channel}_i})} \quad (\text{Eqn. 3}),$$

$$Mz(\text{conv gpc}) = \frac{\sum_{i=RV_{\text{integration start}}}^{i=RV_{\text{integration end}}} (M_{PE_i}^2 IR_{\text{measurement channel}_i})}{\sum_{i=RV_{\text{integration start}}}^{i=RV_{\text{integration end}}} (M_{PE_i} IR_{\text{measurement channel}_i})} \quad (\text{Eqn. 4}).$$

In Equations 2-4, the RV is column retention volume (linearly-spaced), collected at “1 point per second,” the IR is the baseline-subtracted IR detector signal, in Volts, from the IR5 measurement channel of the GPC instrument, and M_{PE} is the polyethylene-equivalent MW determined from Equation 1. Data calculations were performed using “GPC One software (version 2.013H)” from PolymerChAR.

Creep Zero Shear Viscosity Measurement Method

Zero-shear viscosities were obtained via creep tests, which were conducted on an AR-G2 stress controlled rheometer (TA Instruments; New Castle, Del), using “25-mm-diameter” parallel plates, at 190°C. The rheometer oven was set to test temperature for at least 30 minutes, prior to zeroing the fixtures. At the testing temperature, a compression molded sample disk was inserted between the plates, and allowed to come to equilibrium for five minutes. The upper plate was then lowered down to 50 μm (instrument setting) above the desired testing gap (1.5 mm). Any superfluous material was trimmed off, and the upper plate was lowered to the desired gap. Measurements were done under nitrogen purging at a flow rate of 5 L/min. The default creep time was set for two hours.

Each sample was compression-molded into “2 mm thick x 25 mm diameter” circular plaque, at 177°C, for five minutes, under 10 MPa pressure, in air. The sample was then taken out of the press and placed on a counter top to cool.

A constant low shear stress of 20 Pa was applied for all of the samples, to ensure that the steady state shear rate was low enough to be in the Newtonian region. The resulting steady state

shear rates were in the range from 10^{-3} to 10^{-4} s^{-1} for the samples in this study. Steady state was determined by taking a linear regression for all the data, in the last 10% time window of the plot of “log (J(t)) vs. log(t),” where J(t) was creep compliance and t was creep time. If the slope of the linear regression was greater than 0.97, steady state was considered to be reached, then the creep test was stopped. In all cases in this study, the slope meets the criterion within two hours. The steady state shear rate was determined from the slope of the linear regression of all of the data points, in the last 10% time window of the plot of “ ϵ vs. t,” where ϵ was strain. The zero-shear viscosity was determined from the ratio of the applied stress to the steady state shear rate.

In order to determine if the sample was degraded during the creep test, a small amplitude oscillatory shear test was conducted before, and after, the creep test, on the same specimen from 0.1 to 100 rad/s. The complex viscosity values of the two tests were compared. If the difference of the viscosity values, at 0.1 rad/s, was greater than 5%, the sample was considered to have degraded during the creep test, and the result was discarded.

Zero-Shear Viscosity Ratio (ZSVR) is defined as the ratio of the zero-shear viscosity (ZSV) of the branched polyethylene material to the ZSV of a linear polyethylene material (see ANTEC proceeding below) at the equivalent weight average molecular weight ($M_w(\text{conv gpc})$), according to the following Equation 5:

$$\text{ZSVR} = \frac{\eta_{0B}}{\eta_{0L}} = \frac{\eta_{0B}}{2.29^{-15} M_{w(\text{conv.gpc})}^{3.65}} \quad (\text{Eqn. 5}).$$

The ZSV value was obtained from creep test, at 190°C , via the method described above. The $M_w(\text{conv gpc})$ value was determined by the conventional GPC method (Equation 3), as discussed above. The correlation between ZSV of linear polyethylene and its $M_w(\text{conv gpc})$ was established, based on a series of linear polyethylene reference materials. A description for the ZSV- M_w relationship can be found in the ANTEC proceeding: Karjala et al., *Detection of Low Levels of Long-chain Branching in Polyolefins*, Annual Technical Conference - Society of Plastics Engineers (2008), 66th 887-891.

CEF Method

Comonomer distribution analysis was performed with Crystallization Elution Fractionation (CEF) (PolymerChAR in Spain (see also B Monrabal et al, Macromol. Symp. , 257, 71-79, 2007). Ortho-dichlorobenzene (ODCB) with “600 ppm antioxidant butylated hydroxytoluene (BHT)” was used as solvent. Sample preparation was done with auto sampler at 160°C , for two hours, under shaking at 4 mg/ml (unless otherwise specified). The injection volume was 300 μl . The temperature profile of CEF was as follows: crystallization at $3^\circ\text{C}/\text{min}$ from 110°C to 30°C ; thermal equilibrium at 30°C for five minutes; elution at $3^\circ\text{C}/\text{min}$ from 30°C

to 140°C. The flow rate during crystallization was at 0.052 ml/min. The flow rate during elution was at 0.50 ml/min. The data was collected at one data point/second.

CEF column was packed with glass beads at $125\ \mu\text{m} \pm 6\%$ (MO-SCI Specialty Products) using 1/8 inch stainless tubing. Glass beads were acid washed by MO-SCI Specialty. The column volume was 2.06 ml. The column temperature calibration was performed using a mixture of NIST Standard Reference Material Linear polyethylene 1475a (1.0mg/ml), and Eicosane (2mg/ml) in ODCB. The temperature was calibrated by adjusting elution heating rate, so that the NIST linear polyethylene 1475a had a peak temperature at 101.0°C, and Eicosane had a peak temperature of 30.0°C. The CEF column resolution was calculated with a mixture of the NIST linear polyethylene 1475a (1.0mg/ml) and hexacontane (Fluka, purum, $\geq 97.0\%$, 1mg/ml). A baseline separation of hexacontane and NIST polyethylene 1475a was achieved. The area of hexacontane (from 35.0 to 67.0°C) to the area of NIST 1475a (from 67.0 to 110.0°C) was “50 to 50,” the amount of soluble fraction below 35.0°C was less than ($<$) 1.8 wt%. The CEF column resolution was defined in Equation 1A, where the column resolution was 6.0.

$$\text{Resolution} = \frac{\text{Peak temperature of NIST 1475a} - \text{Peak Temperature of Hexacontane}}{\text{Half - height Width of NIST 1475a} + \text{Half - height Width of Hexacontane}} \quad (\text{Eqn. 1A}).$$

Determination of Peak Width at 25 Percent Height of the CEF Elution Profile

The CEF instrument was calibrated according to the CEF Method described herein, and a plot of the relative IR detector signal was made as a function of temperature. A single baseline was subtracted from the IR measurement signal, in order create a relative mass-elution profile plot, starting, and ending, at zero relative mass at its lowest and highest elution temperatures (typically between 25°C and 110°C). In the relative mass-elution profile plot, the peak that represents an area of at least 50% of the total integrated signal between 35°C and 95°C degrees was assigned. If the peak did not return to the baseline by at least 10% of the relative mass-elution height (connected by more than 10% height at their lowest point), it was defined as part of the single peak (no deconvolution or similar numerical methods are used to mathematically separate convoluted peaks). The peak was then measured for width in, °C, at 25% of the maximum height of the peak in the mass-elution profile plot.

Dynamic Shear Rheology

Each sample was compression-molded into “3 mm thick x 25 mm diameter” circular plaque, at 177°C, for five minutes, under 10 MPa pressure, in air. The sample was then taken out of the press, and placed on a counter top to cool. Constant temperature, frequency sweep measurements were performed on an ARES strain controlled rheometer (TA Instruments), equipped with “25 mm” parallel plates, under a nitrogen purge. For each measurement, the

rheometer was thermally equilibrated for at least 30 minutes, prior to zeroing the gap. The sample disk was placed on the plate, and allowed to melt for five minutes at 190°C. The plates were then closed to 2 mm, the sample trimmed, and then the test was started. The method had an additional five minute delay built in, to allow for temperature equilibrium. The experiments were performed at 190°C, over a frequency range from 0.1 to 100 rad/s, at five points per decade interval. The strain amplitude was constant at 10%. The stress response was analyzed in terms of amplitude and phase, from which the storage modulus (G'), loss modulus (G''), complex modulus (G^*), dynamic viscosity (η^* or Eta^*), and $\tan \delta$ (or $\tan \delta$) were calculated.

The present invention may be embodied in other forms, without departing from the spirit and the essential attributes thereof, and, accordingly, reference should be made to the appended claims, rather than to the foregoing specification, as indicating the scope of the invention.

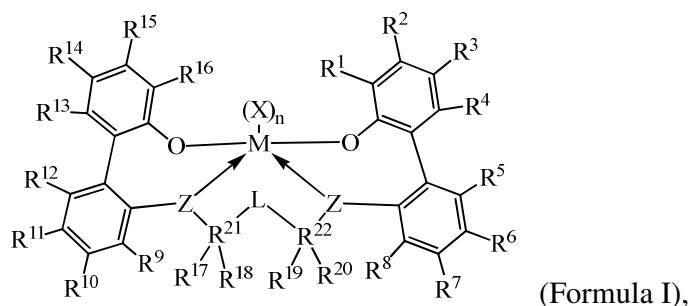
CLAIMS:

1. An ethylene-based polymer comprising the following properties:
 - a) a zero-shear viscosity ratio (ZSVR) value from 1.2 to 2.6,
 - b) a molecular weight distribution (MWD or M_w/M_n) from 1.5 to 2.8,
 - c) a tan delta (0.1 rad/s; 190°C) from 5.0 to 50, and
 - d) a melt index (I2) from 0.93 to 1.05 g/10 min.
2. The ethylene-based polymer of claim 1, wherein the ethylene-based polymer has a tan delta (0.1 rad/s; 190°C) from greater than 5.0 to 50.
3. The ethylene-based polymer of claim 1, wherein the ethylene-based polymer has the following properties: a tan delta (0.1 rad/s; 190°C) from greater than 15 to 50; and a ZSVR value from 1.3 to 2.6.
4. The ethylene-based polymer of claim 1 or 2, wherein the ethylene-based polymer is an ethylene/ α -olefin interpolymer.
5. The ethylene-based polymer of any one of the previous claims, wherein the polymer has a density from 0.885 to 0.940 g/cc.
6. The ethylene-based polymer of any one of the previous claims, wherein the polymer has a single peak in the Crystallization Elution Fractionation (CEF)-Comonomer Distribution, at a temperature from 60°C to 100°C.
7. The ethylene-based polymer of any one of the previous claims, wherein the polymer has a single peak in the CEF-Comonomer Distribution, at a temperature from 60 to 100°C, and wherein the peak width at 25% peak height is less than 30°C.
8. The ethylene-based polymer of any one of the previous claims, wherein the polymer has an I_{10}/I_2 ratio from 5.0 to 10.
9. The ethylene-based polymer of any one of the previous claims, wherein the polymer has a MWD from 1.7 to 2.5.
10. The ethylene-based polymer of any one of the previous claims, wherein the polymer has a MWD from 1.7 to 2.2.

11. A process for producing the ethylene-based polymer as defined in any one of the previous claims comprising polymerizing at least ethylene, in the presence of at least one catalyst system comprising the reaction product of the following:

A) at least one cocatalyst; and

B) a procatalyst comprising a metal-ligand complex of Formula (I):



wherein:

M is titanium, zirconium, or hafnium, each independently being in a formal oxidation state of +2, +3, or +4; and n is an integer from 0 to 3, and wherein when n is 0, X is absent; and

Each X, independently, is a (C₁-C₄₀)hydrocarbyl, a (C₁-C₄₀)heterohydrocarbyl, or a halide, and wherein each X, independently, is a monodentate ligand that is neutral, monoanionic, or dianionic; or

wherein two Xs are taken together to form a bidentate ligand that is neutral, monoanionic, or dianionic; and

wherein X and n are chosen, in such a way, that the metal-ligand complex of Formula (I) is, overall, neutral; and

Each Z, independently, is an oxygen atom, a sulfur atom, -N[(C₁-C₄₀)hydrocarbyl]-, or -P[(C₁-C₄₀)hydrocarbyl]-; and

L is a substituted or unsubstituted (C₁-C₄₀)hydrocarbylene, or a substituted or unsubstituted (C₁-C₄₀)heterohydrocarbylene, and

wherein, for L, the (C₁-C₄₀)hydrocarbylene has a portion that comprises a 1-carbon atom to 10-carbon atom linker backbone linking R²¹ and R²² in Formula (I) (to which L is bonded), or

wherein, for L, the (C₁-C₄₀)heterohydrocarbylene has a portion that comprises a 1-atom to 10-atom linker backbone linking R²¹ and R²² in Formula (I), wherein each of the 1 to 10 atoms of the 1-atom to 10-atom linker backbone of the (C₁-C₄₀)heterohydrocarbylene, independently, is one of the following: i) a carbon atom, ii) a heteroatom, wherein each heteroatom independently is -O- or -S-, or iii) a substituent selected from -S(O)-, -S(O)₂-, -Si(R^C)₂-,

-Ge(R^C)₂-, -P(R^C)-, or -N(R^C)-, and wherein each R^C is, independently, a substituted or unsubstituted (C₁-C₃₀)hydrocarbyl, or a substituted or unsubstituted (C₁-C₃₀) hetero-hydrocarbyl; and

R²¹ and R²² are each, independently, C or Si; and

R^1 through R^{20} are each, independently, selected from the group consisting of the following: a substituted or unsubstituted (C_1 - C_{40})hydrocarbyl, a substituted or unsubstituted (C_1 - C_{40})hetero-hydrocarbyl, $-\text{Si}(R^C)_3$, $-\text{Ge}(R^C)_3$, $-\text{P}(R^C)_2$, $-\text{N}(R^C)_2$, $-\text{OR}^C$, $-\text{SR}^C$, $-\text{NO}_2$, $-\text{CN}$, $-\text{CF}_3$, $-\text{S}(\text{O})\text{R}^C$, $-\text{S}(\text{O})_2\text{R}^C$, $-\text{N}=\text{C}(\text{R}^C)_2$, $-\text{OC}(\text{O})\text{R}^C$, $-\text{C}(\text{O})\text{OR}^C$, $-\text{N}(\text{R})\text{C}(\text{O})\text{R}^C$, $-\text{C}(\text{O})\text{N}(\text{R}^C)_2$, a halogen atom, and a hydrogen atom; and wherein each R^C is independently a substituted or unsubstituted (C_1 - C_{30})hydrocarbyl, or a substituted or unsubstituted (C_1 - C_{30}) heterohydrocarbyl; and

wherein, when R^{17} is a hydrogen atom, then R^{18} is a substituted or unsubstituted (C_1 - C_{40})hydrocarbyl, a substituted or unsubstituted (C_1 - C_{40})heterohydrocarbyl, $-\text{Si}(R^C)_3$, $-\text{Ge}(R^C)_3$, $-\text{P}(R^C)_2$, $-\text{N}(R^C)_2$, $-\text{OR}^C$, $-\text{SR}^C$, $-\text{NO}_2$, $-\text{CN}$, $-\text{CF}_3$, $-\text{S}(\text{O})\text{R}^C$, $-\text{S}(\text{O})_2\text{R}^C$, $-\text{N}=\text{C}(\text{R}^C)_2$, $-\text{OC}(\text{O})\text{R}^C$, $-\text{C}(\text{O})\text{OR}^C$, $-\text{N}(\text{R})\text{C}(\text{O})\text{R}^C$, $-\text{C}(\text{O})\text{N}(\text{R}^C)_2$, a halogen atom, or a hydrogen atom; and wherein each R^C is independently a substituted or unsubstituted (C_1 - C_{30})hydrocarbyl, or a substituted or unsubstituted (C_1 - C_{30}) heterohydrocarbyl; or

wherein, when R^{18} is a hydrogen atom, then R^{17} is a substituted or unsubstituted (C_1 - C_{40})hydrocarbyl, a substituted or unsubstituted (C_1 - C_{40})heterohydrocarbyl, $-\text{Si}(R^C)_3$, $-\text{Ge}(R^C)_3$, $-\text{P}(R^C)_2$, $-\text{N}(R^C)_2$, $-\text{OR}^C$, $-\text{SR}^C$, $-\text{NO}_2$, $-\text{CN}$, $-\text{CF}_3$, $-\text{S}(\text{O})\text{R}^C$, $-\text{S}(\text{O})_2\text{R}^C$, $-\text{N}=\text{C}(\text{R}^C)_2$, $-\text{OC}(\text{O})\text{R}^C$, $-\text{C}(\text{O})\text{OR}^C$, $-\text{N}(\text{R})\text{C}(\text{O})\text{R}^C$, $-\text{C}(\text{O})\text{N}(\text{R}^C)_2$, a halogen atom, or a hydrogen atom; and wherein each R^C is independently a substituted or unsubstituted (C_1 - C_{30})hydrocarbyl, or a substituted or unsubstituted (C_1 - C_{30}) heterohydrocarbyl; and/or

wherein, when R^{19} is a hydrogen atom, then R^{20} is a substituted or unsubstituted (C_1 - C_{40})hydrocarbyl, a substituted or unsubstituted (C_1 - C_{40})heterohydrocarbyl, $-\text{Si}(R^C)_3$, $-\text{Ge}(R^C)_3$, $-\text{P}(R^C)_2$, $-\text{N}(R^C)_2$, $-\text{OR}^C$, $-\text{SR}^C$, $-\text{NO}_2$, $-\text{CN}$, $-\text{CF}_3$, $-\text{S}(\text{O})\text{R}^C$, $-\text{S}(\text{O})_2\text{R}^C$, $-\text{N}=\text{C}(\text{R}^C)_2$, $-\text{OC}(\text{O})\text{R}^C$, $-\text{C}(\text{O})\text{OR}^C$, $-\text{N}(\text{R})\text{C}(\text{O})\text{R}^C$, $-\text{C}(\text{O})\text{N}(\text{R}^C)_2$, a halogen atom, or a hydrogen atom; and wherein each R^C is independently a substituted or unsubstituted (C_1 - C_{30})hydrocarbyl, or a substituted or unsubstituted (C_1 - C_{30}) heterohydrocarbyl; or

wherein, when R^{20} is a hydrogen atom, then R^{19} is a substituted or unsubstituted (C_1 - C_{40})hydrocarbyl, a substituted or unsubstituted (C_1 - C_{40})heterohydrocarbyl, $-\text{Si}(R^C)_3$, $-\text{Ge}(R^C)_3$, $-\text{P}(R^C)_2$, $-\text{N}(R^C)_2$, $-\text{OR}^C$, $-\text{SR}^C$, $-\text{NO}_2$, $-\text{CN}$, $-\text{CF}_3$, $-\text{S}(\text{O})\text{R}^C$, $-\text{S}(\text{O})_2\text{R}^C$, $-\text{N}=\text{C}(\text{R}^C)_2$, $-\text{OC}(\text{O})\text{R}^C$, $-\text{C}(\text{O})\text{OR}^C$, $-\text{N}(\text{R})\text{C}(\text{O})\text{R}^C$, $-\text{C}(\text{O})\text{N}(\text{R}^C)_2$, a halogen atom, or a hydrogen atom; and wherein each R^C is independently a substituted or unsubstituted (C_1 - C_{30})hydrocarbyl,

or a substituted or unsubstituted (C₁-C₃₀) heterohydrocarbyl; and

wherein, for Formula I, two or more of R¹ through R²², optionally, may form one or more ring structures, and wherein each ring structure has from 3 to 50 atoms in the ring, excluding any hydrogen atoms; and

wherein, for Formula I, one or more hydrogen atoms may optionally be substituted with one or more deuterium atoms.

12. The process of claim 11, wherein, for Formula I, wherein when R¹⁷ is a hydrogen atom, then R¹⁸ is a substituted or unsubstituted (C₁-C₄₀)hydrocarbyl, a substituted or unsubstituted

(C₁-C₄₀)heterohydrocarbyl, -Si(R^C)₃, -Ge(R^C)₃, -P(R^C)₂, -N(R^C)₂, -OR^C, -SR^C, -NO₂, -CN, -CF₃, -S(O)R^C, -S(O)₂R^C, -N=C(R^C)₂, -OC(O)R^C, -C(O)OR^C, -N(R)C(O)R^C, -C(O)N(R^C)₂, or a halogen atom; and wherein each R^C is independently a substituted or unsubstituted (C₁-C₃₀)hydrocarbyl, or a substituted or unsubstituted (C₁-C₃₀) heterohydrocarbyl; or

wherein, when R¹⁸ is a hydrogen atom, then R¹⁷ is a substituted or unsubstituted (C₁-C₄₀)hydrocarbyl, a substituted or unsubstituted (C₁-C₄₀)heterohydrocarbyl, -Si(R^C)₃, -Ge(R^C)₃, -P(R^C)₂, -N(R^C)₂, -OR^C, -SR^C, -NO₂, -CN, -CF₃, -S(O)R^C, -S(O)₂R^C, -N=C(R^C)₂, -OC(O)R^C, -C(O)OR^C, -N(R)C(O)R^C, -C(O)N(R^C)₂, or a halogen atom; and wherein each R^C is independently a substituted or unsubstituted (C₁-C₃₀)hydrocarbyl, or a substituted or unsubstituted (C₁-C₃₀) heterohydrocarbyl; and/or

wherein, when R¹⁹ is a hydrogen atom, then R²⁰ is a substituted or unsubstituted (C₁-C₄₀)hydrocarbyl, a substituted or unsubstituted (C₁-C₄₀)heterohydrocarbyl, -Si(R^C)₃, -Ge(R^C)₃, -P(R^C)₂, -N(R^C)₂, -OR^C, -SR^C, -NO₂, -CN, -CF₃, -S(O)R^C, -S(O)₂R^C, -N=C(R^C)₂, -OC(O)R^C, -C(O)OR^C, -N(R)C(O)R^C, -C(O)N(R^C)₂, or a halogen atom; and wherein each R^C is independently a substituted or unsubstituted (C₁-C₃₀)hydrocarbyl, or a substituted or unsubstituted (C₁-C₃₀) heterohydrocarbyl; or

wherein, when R²⁰ is a hydrogen atom, then R¹⁹ is a substituted or unsubstituted (C₁-C₄₀)hydrocarbyl, a substituted or unsubstituted (C₁-C₄₀)heterohydrocarbyl, -Si(R^C)₃, -Ge(R^C)₃, -P(R^C)₂, -N(R^C)₂, -OR^C, -SR^C, -NO₂, -CN, -CF₃, -S(O)R^C, -S(O)₂R^C,

$-\text{N}=\text{C}(\text{R}^{\text{C}})_2$, $-\text{OC}(\text{O})\text{R}^{\text{C}}$, $-\text{C}(\text{O})\text{OR}^{\text{C}}$, $-\text{N}(\text{R})\text{C}(\text{O})\text{R}^{\text{C}}$, $-\text{C}(\text{O})\text{N}(\text{R}^{\text{C}})_2$, or a halogen atom; and wherein each R^{C} is independently a substituted or unsubstituted (C_1 - C_{30})hydrocarbyl, or a substituted or unsubstituted (C_1 - C_{30}) heterohydrocarbyl.

13. A composition comprising the ethylene-based polymer of any one of claims 1-10.
14. An article comprising at least one component formed from the composition of claim 13.