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Bulkier Better?
Balancing bulkiness in gold(I) phosphino-triazole catalysis

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Abstract

The synthesis of a series of 1-phenyl-5-phosphino 1,2,3-triazoles are disclosed, within which, the phosphorus atom (at the 5-position of a triazole) is appended by one, two or three triazole motifs, and the valency of the phosphorous(III) atom is completed by two, one or zero ancillary (phenyl or cyclohexyl) groups respectively. This series of phosphines was compared to tricyclohexylphosphine and triphenylphosphine to study the effect of increasing the number of triazoles appended to the central phosphorus atom from zero to three triazoles. Gold(I) chloride complexes of the synthesised ligands were prepared and analysed by techniques including single crystal X-ray diffraction structure determination. Gold(I) complexes were also prepared from 1-(2,6-dimethoxy)-phenyl-5-dicyclohexyl-phosphino 1,2,3-triazole and 1-(2,6-dimethoxy)-phenyl-5-diphenyl-phosphino 1,2,3-triazole ligands. The crystal structures thus obtained were examined using the SambVca (2.0) web tool and percentage buried volumes determined. The effectiveness of these gold(I) chloride complexes to serve as precatalysts for alkyne hydration were assessed. Furthermore, the regioselectivity of hydration of but-1-yne-1,4-diyldibenzene was probed.

Introduction

Bulky phosphines offer significant and well-documented advantages as ligands in metal-catalysed reactions. The landmark contributions of Buchwald and co-workers have led to deeper understanding of the synthetic chemistry enabled by such bulky ligands, and ligands such as S-Phos and X-Phos are an often-required component of the tool...
There is emerging interest in the importance of categorising and evaluating steric and electronic parameters of these types of bulky phosphines in order to correlate and ultimately predict their suitability for use in metal-mediated catalysis. The Tolman cone angle has been used to describe the bulkiness of ligands, this descriptor has been complemented by Nolan describing bulkiness in terms of a percentage buried volume (%$V_{\text{bur}}$). The %$V_{\text{bur}}$ described by a ligand can be calculated by using Cavallo and co-workers’ web tool SambVca (2.0).

Some authors of this report previously detailed the synthesis, and application to palladium-catalysed Suzuki-Miyaura cross-coupling reactions, of 1,2,3-triazole-containing phosphines including analogues of the aforementioned Buchwald-type ligands, such as 1a (Figure 1). Analysis of the steric parameters (buried volume) using the SambVca (2.0) web tool confirmed that the bulkier ligands of those tested were the most effective in said catalysis.

Figure 1. Selected examples of a previously reported 1-aryl-5-phosphino triazoles (left) (1a–b) and single crystal X-ray diffraction structure of 1a (right), as reported elsewhere, H-atoms omitted for clarity.

The 1-aryl-5-phosphino-triazole ligands, such as 1a, present their 1-aryl fragment in the same orientation as the phosphorous lone pair (of the free ligand) or in the direction of the metal (of a phosphorous-metal complex thereof), thus significantly impacting the determined buried volume. Noting that ortho-aryl tris-phenylene phosphines (first reported, and somewhat overlooked, in 1940) can impart favourable properties as ligands in catalysis, it struck us that a bulky, and thus possibly superior, version of the triazole phosphine ligand is possible if the phosphorous atom were to be flanked by up to three, rather than one, triazole. A series of ligands ranging from zero to three triazoles, for comparison of the manifested bulk about the phosphorous centre by 1,5-disubstituted-triazole motif(s), was proposed. As such, a series of phosphines comprising of triphenylphosphine (2a) and tricyclohexylphosphine (2b) along with mono-triazole-appended phosphines 3a and 3b (available from a previous study), and the previously unprepared bis-triazoles 4a and 4b and 1-phenyl-5-phosphino-tris-triazole, 5 (Figure 2), was conceived.
Results and Discussion

The substituents attached to phosphorus and the triazole nitrogen, could in principle be varied significantly. To provide a benchmark in this initial investigation cyclohexyl (a) and phenyl (b) groups attached to phosphorus were selected and the substituent attached at the 1-N-position of the triazole was restricted to phenyl in the first instance (Figure 2). As such two series of aryl- and alkyl-substituted phosphines were planned.

Phosphine Synthesis

Dicyclohexylphosphino- and 5-diphenylphosphino- 1-phenyl triazoles, 3a and 3b respectively, were available from an earlier study. Their synthesis required 6 (Scheme 1 (i)) to be deprotonated with n-butyllithium\(^{12}\) and reacted with dicyclohexyl- or diphenyl- phosphorous chloride, Scheme 1 (ii) (see the earlier report for full details).\(^8\)
The synthesis of triazole 6. Deprotonation of 6 and reaction with: (ii) dicyclohexyl- or diphenyl-phosphorous chloride depicting the previously reported synthesis of 3a and 3b; (iii) cyclohexyl- or phenyl-phosphorous dichloride for the synthesis of 4a and 4b by respectively; (iv) phosphorous trichloride for the synthesis of tristriazole phosphine 5.

The same protocol for selective deprotonation of 6 at the 5-position\(^\text{[12]}\) was followed by addition of cyclohexyl- or phenyl-phosphorous dichloride leading to the formation and subsequent isolation of 4a and 4b in 71% and 54% yield respectively (Scheme 1 (iii)). When one third of an equivalent of phosphorous trichloride was added to deprotonated 6, the expected tris-1-phenyl 5-phosphino triazole 5, resulted and was subsequently isolated in 77% yield (Scheme 1 (iv)). The proton and carbon NMR spectrums of 5 (in d-chloroform at ambient temperature) displayed a single set of well-defined resonances, corresponding to the three equivalent triazole arms of the 5, suggesting a high degree of symmetry in solution on the NMR timescale.

Both 4a and 4b provided single crystals suitable for structural analysis by XRD (Figure 3 (a) and (b) respectively, and supplementary material). In both cases the 1-phenyl substituents of the triazole components point broadly in the same general direction as the phosphorous lone pair, thus boding well for a systematic study of the effect of modulating the steric crowding or bulkiness about a coordinated metal in a catalytically relevant complex. For compound 5, a single crystal XRD structure was obtained (Figure 4), the solid-state conformation contains two unique molecules in the unit.
cell, both of which show the aryl arms of the triazole are directed along the same orientation as the phosphorous lone pair, creating a bowl-shaped ligand.

Figure 3. (a) A molecule of 4a determined by single crystal X-ray diffraction structure analysis. Ortep representation, ellipsoid probability 50% (rendered in PovRay, H-atoms omitted for clarity) (lower) and a chemical drawing of 4a (upper); (b) A molecule of 4b determined by single crystal X-ray diffraction structure analysis. Ortep representation, ellipsoid probability 50% (rendered in PovRay, H-atoms omitted for clarity) (lower) and a chemical drawing of 4b (upper).

Figure 4. A molecule of 5 determined by single crystal X-ray diffraction structure analysis. Ortep representation, ellipsoid probability 50% (rendered in PovRay, H-atoms omitted for clarity) (lower) and a chemical drawing of 5 in approximately the same orientation (upper).

Gold(I) chloride complex synthesis and structural analysis

Complemented by commercially sourced tricyclohexylphosphine 2a and triphenylphosphine 2b, two ligand sets corresponding to Figure 2 (R = Cy or Ph) were therefore available for comparison in complexation of a chosen metal. Owing to the importance of gold(I) phosphines in catalysis, and that X-ray crystal structures of gold(I) chloride
complexes 2a and 2b have been previously reported by others,[14] the gold(I) chloride complexes of the ligands in the series presented in Figure 2 were compared. Ligation of the triazole-phosphines (3-5) to gold(I), through phosphorous, was achieved by performing dimethylsulfide-phosphine exchange reactions on chloro(dimethylsulfide)gold(I) (Scheme 2). Isolated yields of the corresponding gold(I) chloride complexes ranged from 58 to 91%. Triphenylphosphine and tricyclohexylphosphine gold(I) chloride complexes (7a and 7b) were purchased from commercial suppliers.

Scheme 2. Synthesis of gold(I) chloride complexes (i) 8a-b; (ii) 9a-b; and (iii) 10.

The single crystal X-ray structures of gold(I) chloride complexes 7a and 7b (gold(I) chloride complexes of tricyclohexylphosphine and triphenylphosphine) have been previously reported in the literature.[14] The deposited PDB files were used to render images (Ortep III for Windows and PovRay, Figure 5(a) and Figure 5(b), (i) and (ii) respectively) and determine the percentage buried volume using SambVca (2.0) (alternative representations of the XRD structure and a steric map thus resulting are shown in part (iii) of the corresponding figures). Tricyclohexylphosphine gold(I) chloride 7a has a 33.9% $V_{bur}$ whereas the triphenylphosphine gold(I) chloride complex 7b has a 30.8% $V_{bur}$. The single crystal X-ray diffraction structures of 8a (Figure 6(a)), 8b (Figure 6(b), 9a (Figure 7(a)), 9b (Figure 7(b)) and 10 (Figure 8) were obtained from the complexes synthesised herein, and similarly analysed to determine the corresponding buried volumes described by the ligands in their complexes with gold(I) chloride. The crystal structures of the gold-phosphorous bond lengths used in the buried volume determinations were those obtained crystallographically.
Figure 5. (a) Single crystal X-ray diffraction structure of arising from literature deposited CIF file of 7a: (i) Ortep representation, ellipsoid probability 50% (rendered in PovRay, H-atoms omitted for clarity); (ii) Space-filling representation; (iii) Percentage buried volume determined from the crystal structure of 7a (33.9%) steric map of ligand depicted (right). [14a] (b) Single crystal X-ray diffraction structure of 7b arising from literature deposited CIF file: (i) Ortep representation, ellipsoid probability 50% (rendered in PovRay, H-atoms omitted for clarity); (ii) Space-filling representation; (iii) Percentage buried volume determined from the crystal structure of 7b (30.8%) steric map of ligand depicted (right). [14b]

Figure 6. (a) Single crystal X-ray diffraction structure of 8a: (i) Ortep representation, ellipsoid probability 50% (rendered in PovRay, H-atoms omitted for clarity); (ii) Space-filling representation; (iii) Percentage buried volume determined from the crystal structure of 8a (44.3%) steric map of ligand depicted (right). (b) Single crystal X-ray diffraction structure of 8b: (i) Ortep representation, ellipsoid probability 50% (rendered in PovRay, H-atoms omitted for clarity); (ii) Space filling representation; (iii) Percentage buried volume determined from the crystal structure of 8b (40.3%) steric map of ligand depicted (right).
Figure 7. (a) Single crystal X-ray diffraction structure of 9a: (i) Ortep representation, ellipsoid probability 50\% (rendered in PovRay, H-atoms omitted for clarity); (ii) Space-filling representation; (iii) Percentage buried volume determined from the crystal structure of 9a (54.5\%) steric map of ligand depicted (right); (b) Single crystal X-ray diffraction structure of 9b: (i) Ortep representation, ellipsoid probability 50\% (rendered in PovRay, H-atoms omitted for clarity); (ii) Space-filling representation; (iii) Percentage buried volume determined from the crystal structure of 9b (45.1\%) steric map of ligand depicted (right).

Figure 8. Single crystal X-ray diffraction structure of 10: (i) Ortep representation ellipsoid probability 50\% (rendered in PovRay, H-atoms omitted for clarity); (ii) Space-filling representation; (iii) Percentage buried volume determined from the crystal structure of 10 (60.8\%) steric map of ligand depicted (right). The unit cell contains two molecules of the complex wherein the phenyl ring centroid to gold distances are on average 3.58 Å (3.456 Å, 3.581 Å and 3.634 Å in the one molecule and 3.351 Å, 3.692 Å and 3.759 Å in the other). Between the two molecules of the unit cell a head to tail arrangement is present and the closest intermolecular Au…Cl intermolecular distances are 7.365 Å (see supplementary material for depictions).
Plotting the %$V_{\text{bur}}$ across the phosphine series (Chart 1) shows that cyclohexyl substituents confer greater bulkiness about the coordination sphere of than the corresponding phenyl-substituted congeners. With both series terminating in the bulkiest of the complexes, 10, it can be concluded that the number of triazole motifs increases the bulkiness.

Since previously prepared mono-triazole-containing phosphines 1a and 1b were readily available to this programme of study, and as 1a was shown previously to have been among the superior ligands of the mono-triazole set in earlier palladium-mediated Suzuki-Miyaura catalysis, the synthesis of gold(I) chloride complexes thereof was also attempted. The gold(I) chloride complex of 1a (11) was prepared by the aforementioned dimethyl sulfide ligand exchange reaction, in good yield (95%, 0.25 mmol scale). A single crystal XRD structure of 11 was obtained (Figure 9 (a)), and closely matched (by visual inspection) the structure of 9a, with a 46.0%$V_{\text{bur}}$. Attempts to prepare a 1:1 complex of 1b and gold(I) chloride under the same conditions were inconclusive. However, a trigonal 2:1 ligand:gold(I) chloride complex 12 was identified by single crystal X-ray diffraction crystal structure determination (Figure 9 (b)) from a mixture of otherwise unidentified products. A 76.6%$V_{\text{bur}}$ (Figure 9 (b)) was determined from the obtained crystal structure. Attempts to prepare 12 by employing two equivalents of ligand 1b gave inconclusive results. It is noteworthy that this 2:1 trigonal gold(I) structure is similar to crystal structures reported for [(Ph$_3$P)$_2$Au$^{1+}$Cl]$_{15}$ and [(Ph$_3$P)$_2$Au$^{1+}$SCN].$^{16}$ Furthermore a linear cationic gold(I) chloride complex [(Ph$_3$P)$_2$Au$^{1+}$][Cl] bearing two triphenyl phosphine ligands with a fully dissociated chloride counter ion also been reported.$^{14b}$ Therefore, the crystal structure of 12 is included for
completeness. Attempts to prepare two and three 2,6-dimethoxy phenyl triazole-containing variants of 4(a or b) and 5 failed to deliver any desired products.[17]

Figure 9. (a) Single crystal X-ray diffraction structure of 11: (i) Ortep representation, ellipsoid probability 50% (rendered in PovRay, H-atoms omitted for clarity); (ii) Space-filling representation; (iii) Percentage buried volume determined from the crystal structure of 11 (46.0%) steric map of ligand depicted (right); Compound 11. (b) Single crystal X-ray diffraction structure of 12: Molecular drawing and Ortep representation, ellipsoid probability 50% (rendered in PovRay, H-atoms omitted for clarity) upper; space-filling representation and steric map (SambVca (2.0)) from which a 76.6% buried volume was determined.

Catalysis

With the set of gold chloride complexes of Figure 2 (7a-b, 8a-b, 9a-b and 10) along with complex 11 in hand, their effectiveness as precatalysts for gold-catalysed alkyne hydration was probed (Table 1).[18] Catalytically active cationic gold(I) species may be generated by silver-mediated halide abstraction, and choice of appropriate counter-anion has been shown to modulate catalytic effects.[19] In this case, triflate was selected as a counter-anion across all cationic gold(I) catalytic systems studied. Initially the gold-catalysed hydration of dec-1-yne (13a) was performed by in situ preactivation of 0.5 mol% of the corresponding gold complex through silver triflate-mediated halide abstraction, using an excess of silver triflate in methanol (or as explained below, dichloromethane in the case of 10), alkyne 13a was stirred in methanol to which the preactivated catalyst solution was added. Since complex 10 was not well solubilised in methanol a protocol of activation in dichloromethane and dilution in methanol was deployed. To facilitate comparison in the subsequent reactions with lower catalyst loadings (0.25 and 0.05 mol% of gold complex), the dichloromethane activation and methanol dilution protocol was used in those cases. Following addition of water (2 equiv.) all reactions were heated at 80 °C in a sealed tube for two hours and conversions to ketone 14a were determined by gas chromatography.
Table 1. Screening of ligands for gold-catalysed hydration of dec-1-yne (13a) to 2-decanone (14a).

| Entry | L-AuCl | R¹ | R² | Triazole No. (n) | Conversion (%) (m mol%) |
|-------|--------|----|----|-----------------|-------------------------|
|       |        |    |    |                 | 0.50¹ (a) 0.25² (b) 0.05³ (c) |
| 1     | 7a     | Cy | -  | 0               | >99 86 10               |
| 2     | 8a     | Cy | Ph | 1               | >99 >99 9               |
| 3     | 9a     | Cy | Ph | 2               | >99 46 3               |
| 4     | 10     | Cy | Ph | 3               | 32⁴ 11 4               |
| 5     | 9b     | Ph | Ph | 2               | >99 26 2               |
| 6     | 8b     | Ph | Ph | 1               | >99 57 4               |
| 7     | 7b     | Ph | -  | 0               | >99 52 3               |
| 8     | 11     | Cy | 2,6-DMP⁵ | 1 | >99 >99 10 |

¹ Methanol used as solvent, unless otherwise started; ² Catalyst precursor initially solubilised in dichloromethane and dispersed in methanol, such that the resulting solvent composition was 10% CH₂Cl₂ and 90% MeOH; ³ 2,6-DMP = 2,6-dimethoxyphenyl.

At the highest catalyst loading of 0.5 mol% only the bulkiest complex (10) failed to give complete conversion to product 14a (Table 1, entry 10 versus other entries in same table). When lower catalyst loadings were probed 0.05 mol% of gold(I) complexes proved to be too low to achieve satisfactory conversion within two hours (the maximum conversion observed across the set was 10% under these conditions). Good gradation across the test series was seen at a 0.25 mol% catalyst loading (Table 1) and confirmed the superior ligands, for this gold-catalysed transformation, to be those with one triazole substituent. The dicyclohexylphosphine-containing complex 8a afforded quantitative conversion to 14a (Table 1, entry 2). The corresponding mono-triazole-diphenylphosphine-containing complex 8b gave the best conversion to 14a among the phenyl-appended phosphine series of 57% (Table 1, entry 6). The three triazole congener (10) (Table 1, entry 4) gave only 11% conversion under the same conditions. Pleasingly, however, catalysts derived by halide abstraction in the same manner from complex 11 gave quantitative conversion of 13a to 14a (Table 1, entry 8).

Synthetic modification of phosphorous-containing ligands can result in significant differences in the outcomes of reactions catalysed by their corresponding cationic gold(I) complexes.⁴ The regioselectivity of hydration of unsymmetrical internal alkynes has been previously probed by Nolan and co-workers who identified anti-Markovnikov-selective gold(I)-carbene complex-catalysed hydration.²¹ As such, a model reaction, namely the hydration of unsymmetrical internal alkyne 15 was selected to probe selectivity that might arise from the structural modifications across the series of gold(I) complexes of phosphino-triazoles prepared in this study (Table 2). Reaction of water at the benzylic position (15-a) represents the generally expected (Markovnikov) outcome, with selective reaction at the alternate alkyne position (15-b, anti-Markovnikov) being more challenging.
Table 2. Selectivity of the hydration of unsymmetrical alkyne 15 to give ketones 16a and/or 16b.

| Entry | L-AuCl | R¹ | R² | Triazole No. (n) | Conv. (%) | Ratio (16a: 16b) |
|-------|--------|----|----|-----------------|-----------|-------------------|
| 1     | 7a     | Cy | -  | 0               | >99       | 3.5:1             |
| 2     | 8a     | Cy | Ph | 1               | >99       | 3.2:1             |
| 3     | 9a     | Cy | Ph | 2               | >99       | 4.3:1             |
| 4     | 10     | -  | Ph | 3               | 64        | 3.8:1             |
| 5     | 9b     | Ph | Ph | 2               | >99       | 3.3:1             |
| 6     | 8b     | Ph | Ph | 1               | >99       | 4.2:1             |
| 7     | 7b     | Ph | -  | 0               | >99       | 4.0:1             |
| 8     | 11     | Cy | 2,6-DMP | 1 | 95<sup>a</sup> | 2.3:1             |

<sup>a</sup> Ratio determined by GC analysis of reaction mixture; <sup>b</sup> Ratio determined by analysis of the proton NMR spectrums of mixtures of 16a and 16b obtained from the reactions; <sup>c</sup> Complete consumption of 16 was observed, the product mixture contained 5% of a dimethyl acetal adduct as determined by GC/GC-MS; <sup>d</sup> 2,6-DMP = 2,6-dimethoxyphenyl.

Compound 15 was added to a mixture of catalyst precursor (1 mol%) which had undergone silver triflate (2 mol%)-mediated in situ halide abstraction in a degassed methanol/water mixture. Consumption of 15 and the ratio of products 16a:16b was determined by ¹H NMR spectroscopy or gas chromatography. That quantitative conversion was observed in all-but-one case (tris-triazole complex 10, Table 2 entry 4),<sup>18a</sup> is in keeping with the results from the hydration of dec-1-yne 13a (Table 1). All complexes showed preference for Markovnikov addition at the benzylic position of the alkyne (position [a]). Whilst all cases gave product 16a in preference to 16b (ranging from 4.2:1 to 2.3:1 ratios of products 16a:16b), it is noteworthy that use of complexes 8a and 11 as catalyst precursors (Table 2, entries 2 and 8 respectively) afforded a greater proportion of the challenging anti-Markovnikov product 16b.

Having established that, for gold(I)-mediated hydration of alkynes, cationic gold(I) complexes bearing dicyclohexyl monotriazole ligands 1a and 3a (complexes 11 and 8a respectively) were superior in terms of activity (Table 1); and the 1a derived catalyst gave regioselectivity of <3:1 for 16a:16b (Table 2); complex 11 was deployed in a brief substrate scope survey (Table 3).
Table 3. Substrate scope survey for triazole-appended phosphine ligate gold(I) catalysed alkyne hydration.

| Entry | R<sup>1</sup> | Product | Isolated Yield (%) |
|-------|--------------|---------|-------------------|
| 1     | n-C<sub>8</sub>H<sub>17</sub> | 14a     | 79                |
| 2     | Cy           | 14b     | 64                |
| 3     |              | 14c     | 69                |
| 4     | Ph           | 14d     | 58                |
| 5     |              | 14e     | 80                |
| 6     | PhCH<sub>2</sub>CH<sub>2</sub>- | 14f | 89          |
| 7     | p-MeO-phenyl | 14g | 88             |
| 8     |              | 14h     | 81                |
| 9     |              | 14i     | 61                |
| 10    |              | 14j     | 27<sup>(a)</sup> |
| 11    |              | 14k     | 85<sup>(b)</sup> |
| 12    |              | 14l     | 30 (61% 14j)<sup>(b,c)</sup> |
| 13    |              | 14m'    | 94<sup>(c)</sup> |
| 14    |              | 14n-t   | No reaction      |

<sup>(a)</sup> 1 mol% L-AuCl and 2 mol% AgOTf; <sup>(b)</sup> Significant Boc-deprotection observed, isolated yield of 14j given in parenthesis.

Linear alkyl-alkynes 13a and 13f (Table 3, entries 1 and 6) gave slightly higher yields than the cyclic alkane ethynylcyclohexane 13b (Table 3, entry 2), 79 and 89% versus 64% respectively. 1-Ethynylcyclohex-1-ene 13c (Table
entry 3) gave a similar yield (69%) to 13b. Phenylacetylene 13d (Table 3, entry 4) gave 58% yield, with the yield for the methynaphthyl derivative 13e being somewhat better (80% yield, Table 3, entry 5). The yield for use of parame-thoxy phenyl acetylene 13g was better than for phenylacetylene (88 versus 58% yield, Table 3, entries 7 & 4 respectively). Pleasingly an aryl boronic ester 13g was accommodated under the reaction conditions employed (81% yield, Table 3, entry 8), as was thiophene derivative 13i, albeit in a slightly lower isolated yield (61% yield, Table 3, entry 9). Quaternary oxindoles containing alkynes have been of interest to co-authors of this report and their availability to this programme allowed 13j-l to be probed as substrates for gold(I) catalysed hydration (Table 3, entries 10 to 12). To obtain appreciable conversion to isolable oxindole-containing products catalyst loading had to be increased to 1 mol%. The N-H bearing substrate 13j was converted to product 14j in relatively low conversions (27%, Table 3, entry 10). The N-benzyl analogue 13k fared better giving 85% isolated yield (Table 3, entry 11). A major side product arose from in situ removal of the Boc-group upon reaction of 13l (Table 3, entry 12) giving rise to a mixture of desired product 14l (in 30% isolated yield) and deprotected product 14j (61% isolated yield). Reaction of 14m gave the dimethyl acetal of overall reaction at the alkyne terminus in 94% isolated yield (14m', Table 3, entry 13). Nitroarene 13n, aryl ester 13o, aryl bromides 13p and 13q, pyridyl substrates 13r and 13s and tertiary butyl 13t appended alkynes all failed to give any detectable hydration products under the conditions employed (Table 3, combined entry 14).

Conclusions

1,2,3-Triazoles bearing 1-aryl and 5-phosphino functionalities were prepared, wherein the phosphorous atom was appended to one, two or three such triazole motifs. In addition, the corresponding gold(I) chloride coordination complexes bearing phosphino triazoles (with ancillary cyclohexyl or phenyl groups on phosphorous to complete the valence requirement of phosphorous(III) where required)) were also prepared and their relative bulkiness determined using the online tool SambVca (2.0). Two more gold(I) chloride complexes were prepared from ligands containing a phosphorous atom appended by one triazole of the same general formula, where the 1-aryl substituent on the triazole was 2,6-dimethoxy phenyl. These complexes, along with complexes of tricyclohexyl phosphine and triphenyl phosphine were in situ converted to their corresponding cationic gold(I) triflate phosphine ligated congeners and compared as alkyne hydration catalysts. Increasing the ‘triazole number’ about the phosphorous atom confirmed that, among the triazole appended phosphines investigated, the monotriazole-containing phosphines were the most effective ligands for cationic gold(I)-catalysed hydration of alkynes.

In summary, the data derived from the above experimentation show triazole-phosphine ligand 1a to be the most promising of the ligands reported. The ease of synthesis and modification of the triazole ligand framework should prove useful in future ligand design, screening and optimisation campaigns.
Supplementary information

General and experimental procedures are available as a supplementary pdf file, which also includes a summary of the crystallographic data collection and analysis, and further analysis of structural features of the crystal structures of the complexes discussed. All crystal structures disclosed in this report have had the corresponding data deposited at the CCDC with deposition numbers 1922101-1922111. Experimental procedures, including the synthesis of non-commercially available alkynes, characterisation data and spectroscopic information are available as a supplementary file as are selected, preliminary palladium-catalysis findings. Citations therein refer to methods, data and software used.[24]

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Author Contributions

All authors contributed in varying degrees to planning the experiments, evaluating results and writing of the manuscript, specific contributions in addition to this are listed for each co-author in alphabetical order: BRB helped direct aspects of the research and gave input and critical assessment throughout the progress of the project; PWD suggested experiments, supervised and provided critical assessment for aspects of the work; JSF led and co-conceived the project, providing critical assessment of data, day-to-day project management and oversight, directed most aspects throughout, supervised most of the experimental work and wrote the majority of the manuscript; FM and TJS synthesised some of the alkynes used in Table 3; HvN contributed to preliminary studies detailed in the supplementary material and some aspects of mass spectrometry of complexes; MGW advised on the preparation of gold complexes and conducted experiments of Table 2; YZ co-conceived aspects of the project, conducted all ligand synthesis and most of the reactions, drafted a proportion of the ESI, offered critical suggestions and conducted the XRD data collection and analysis herein.
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Supplementary Information: Balancing bulkiness in gold(I) phosphino-triazole catalysis

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General Experimental

Unless otherwise stated, commercially available solvents and reagents were used as obtained, without further purification. At the University of Birmingham, $^1$H NMR spectrums were recorded on Bruker AVIII300/400/500 NMR spectrometers at 300, 400 and 500 MHz respectively. Proton decoupled $^{19}$F NMR spectrums were recorded on a Bruker AVIII300 NMR spectrometer at 282 MHz. Both proton-coupled and proton-decoupled $^{31}$P NMR spectrums were recorded on a Bruker AVIII300 NMR spectrometer at 131 MHz. The $^{31}$P chemical shifts are reported, unless otherwise stated, as obtained from the proton decoupled spectrum, where used for additional structural corroboration both proton-coupled and proton-decoupled spectral data are reported, and where both were obtained both processed spectra are included. Proton decoupled $^{13}$C NMR spectrums were recorded at room temperature on Bruker AVIII300/400/500 NMR spectrometers at 75, 101 and 126 MHz respectively.[1] The proton decoupled $^{13}$C NMR signal quality was superior when using the UDEFT pulse sequence, as such $^{13}$C NMR signals are typically reported as obtained by use of the UDEFT technique.[2] Furthermore, assignments of $^{13}$C NMR spectroscopy signals in some cases was facilitated by obtaining spectrums using the J-MOD pulse sequence, the sign relating to proton substitution is deployed as follows: Positive $\text{CH}$ and $\text{CH}_3$ (denoted [+] ); and negative $\text{C}_{\text{quat}}$ and $\text{CH}_2$ (denoted [-] ), relative in this case to solvent CDCl$_3$ [-].[3] The UDEFT pulse sequence was also used to enhance intensity of $^{13}$C signals in some cases, where a signal was observed utilising UDEFT but not observed with J-MOD the signal is give designation [u]. At Loughborough University, $^1$H proton and $^{13}$C (proton decoupled) carbon NMR spectra were measured at 400 and 100 MHz respectively, using either a Bruker Avance 400 or Jeol ECS 400 spectrometer (13j1 and S4). In all cases relevant coupling constants ($J$) are expressed in Hertz (Hz).[4] Multiplicities are reported as singlet (s), doublet (d), triplet (t), quartet (q), septet (sept), multiplet (m) and broad (br), the designation app is used to describe the apparent appearance of a signal believed to consist of overlapping signals or displaying other phenomena to reveal an apparent signal inconsistent with expected multiplicity.[5] NMR spectroscopic data was processed using Mestrenova v10.02.-15465 and/or Topspin v3.5. The chemical shifts for each signal in the proton NMR spectrums are reported as chemical $\delta$ (ppm) relative to either tetramethylsilane (TMS) where $\delta_{(TMS)} = 0.00$ or a residual solvent peak.[6] The chemical shifts for each signal in the $^{13}$C NMR spectrums are reported relative to signals of the solvent employed.[6] Mass spectrometry was conducted using a Waters LCT Time of Flight Mass Spectrometer (electrospray), a Waters GCT Premier Time of Flight Mass Spectrometer (EI GC/MS) or using Bruker microTOF-QII (ESI+) by direct injection from LC ultimate 3000. Infrared spectra were recorded at room temperature on either a PerkinElmer 100FT-IR spectrometer or a Varian 660-IR spectrometer with ATR attachments; a corresponding thin film was obtained by evaporation of dichloromethane solvent from a given sample. Melting points are uncorrected and were carried out in triplicate using a Stuart SMP10 melting point apparatus and average values reported as a range. Column (flash) chromatography was carried out using an Isco CombiFlash EZ Prep or Interchim PuriFlash XS 420 automated chromatography apparatus. Mobile and stationary phases are described in the general methods or the experimental procedures. Chromatographic traces were recorded at two wavelengths (254 nm and 288nm). Neighbouring tubes identified as pure were double-
checked by separate TLC analysis, prior to being combined into single fractions and evaporated to dryness in vacuo. Compounds synthesised that have been previously reported gave satisfactory correlation with spectroscopic observations given in the literature and cited herein. Compounds 1a, 3a, 3b and 6, were derived from the same batch as that prepared for and reported in a previous publication.[7]

Synthetic Procedures and Protocols

General Procedures

Phosphine Preparation Method (PPM)

Under anhydrous conditions and protected from air, a solution of the corresponding triazole (1 equiv.) in tetrahydrofuran (0.04 M) was stirred at -78 °C. To which n-butyl lithium (1.2 equiv., 2.0 M in tetrahydrofuran) was added dropwise.[8] The reaction mixture was stirred for two hours at this temperature and then the phenyl- or cyclohexyl- phosphine dichloride (0.5 equiv.) was carefully added. After addition was complete, the reaction mixture was allowed to slowly warm to room temperature. After stirring at room temperature for a further ten hours, the volatiles were removed in vacuo to afford a crude residue. The residue thus obtained, was purified by flash chromatography (Isco CombiFlash, silica 50-60 μm, or Interchim XS 420, 20 μm, 4 or 12 g column, gradient elution; hexane (100%) to hexane (20%): ethyl acetate (80%), detection absorption at 254 and 288 nm) to afford the corresponding products.

Preparation of Phosphine Gold(I) Chloride Complexes (PGC)

Dimethylsulfide gold(I)chloride S1 and corresponding phosphine (1 equiv.) were added to a dried flask. Dichloromethane was added and the solution thus obtained (to achieve a concentration of 0.1 M), which was stirred at room temperature, under argon, for two hours. After this time an at least equal volume amount of hexane was added resulting formation a white precipitate. The precipitate was collected via filtration and washed with a little hexane to yield the desired complexes.

Synthetic Protocols and Experimental Details

Synthesis of dimethylsulfide gold(I)chloride (S1)

Under anhydrous conditions and protected from air, a solution of the potassium tetrachloroaurate (377 mg, 1.0 mmol 1 equiv.) in methanol (1 mL) was added to a solution of dimethyl sulfide (0.22 mL, 3.0 mmol 3 equiv.) in methanol (4 mL). The resulting mixture was stirred at room temperature, protected from light, for two hours. The resulting white solid was collected by filtration and washed with cold methanol (~2 mL) to deliver the desired product as a white solid (248 mg, 84%).

Synthesis of 5,5’-(cyclohexylphosphanediyl)bis(1-phenyl-1H-1,2,3-triazole) (4a)

Following PPM General Procedure on a 1.47 mmol scale (triazole 6 used in synthesis): White solid (143 mg, 71%); m.p. 169-171 °C; 1H NMR (400 MHz, CDCl3) δ 7.78 (d, J 0.7, 2H, TrzH), 7.53-7.48 (m, 2H), 7.44 (t, J 7.4, 4H), 7.21-7.18 (m, 4H), 2.40-2.30 (m, 1H), 1.73-1.59 (m,
5H), 1.28-1.03 (m, 6H); $^{31}$P NMR (121 MHz, CDCl$_3$) δ 65.94; $^{13}$C NMR (101 MHz, CDCl$_3$) δ 139.04, 136.38, 132.79 (d, $^1$J$_{CP}$ 19.2), 129.96, 129.29, 125.87 (d, $^4$J$_{CP}$ 4.0), 37.82 (d, $^1$J$_{CP}$ 4.4), 29.42 (d, $^J_{CP}$ 16.1), 26.10 (d, $^J_{CP}$ 12.5), 25.74; IR ν (cm$^{-1}$) 3112, 3062, 2927, 2852, 1596, 1498, 1450; TOF MS ES+ m/z: 403.2 [M+H]$^+$, 375.2 [M+H-2N]$^+$; HR-MS calc. [C$_{22}$H$_{24}$N$_6$P]$^+$ 403.1795 obs. 403.1799. Structure corroborated by single crystal X-ray diffraction determination.

Synthesis of 5,5’-(penylphosphanediyl)bis(1-phenyl-1H-1,2,3-triazole) (4b)

Following PPM General Procedure on a 1.0 mmol scale (triazole 6 used in synthesis): White solid (104 mg, 54%); m.p. 165-167 °C; $^1$H NMR (400 MHz, CDCl$_3$) δ 7.47-7.38 (m, 12H, ArH), 7.28-7.24 (m, 5H, ArH); $^{31}$P NMR (121 MHz, CDCl$_3$) δ 64.31; $^{13}$C NMR (126 MHz, CDCl$_3$) δ 140.64, 136.32, 133.69 (d, $^1$J$_{CP}$ 23.0), 132.63 (d, $^J_{CP}$ 12.2), 131.27, 129.95, 129.60, 129.53, 129.42, 125.00 (d, $^J_{CP}$ 4.3); IR ν (cm$^{-1}$) 3107, 3058, 1596, 1498, 1436, 1286, 1229; TOF MS ES+ m/z: 397.1 [M+H]$^+$, 419.1 [M+Na]$^+$; HR-MS calc. [C$_{22}$H$_{18}$N$_6$P]$^+$ 397.1325 obs. 397.1330. Structure corroborated by single crystal X-ray diffraction determination.

Synthesis of tris(1-phenyl-1H-1,2,3-triazol-5-yl)phosphane (5)

Under anhydrous conditions and protected from air, a solution triazole 6 (145 mg, 1.0 mmol) in tetrahydrofuran (0.04 M) was stirred at -78 °C. To which n-butyl lithium (1.2 equiv., 2.0 M in tetrahydrofuran) was added dropwise. The reaction mixture was stirred for two hours at this temperature and then phosphorus trichloride (0.33 equiv.) was carefully added. After addition was complete, the reaction mixture was allowed to slowly warm to room temperature. After stirring at room temperature for a further ten hours, the volatiles were removed in vacuo to afford a crude residue. The residue thus obtained, was purified by flash chromatography (Isco CombiFlash, silica 50-60 μm, gradient elution hexane (100%) to hexane (0%): ethyl acetate (100%), detection 254 and 288 nm absorption) to afford the corresponding product. White solid (108 mg, 77%); mp. 186-188 °C; $^1$H NMR (400 MHz, CDCl$_3$) δ 7.63 (d, $^3$J$_{CP}$ 0.9, 3H, TrzH), 7.49 (tt, $^J$ 7.4, 1.2, 3H), 7.42 (t, $^J$ 7.9, 6H), 7.17-7.14 (m, 6H); $^{31}$P NMR (121 MHz, CDCl$_3$) δ -93.52; $^{13}$C NMR (101 MHz, CDCl$_3$) δ 141.07, 135.72, 130.45, 129.72, 129.43 (d, $^J_{CP}$ 4.2), 124.90 (d, $^J_{CP}$ 4.3); IR ν (cm$^{-1}$) 3105, 3058, 1595, 1497; TOF MS ES+ m/z: 464.2 [M+H]$^+$, 486.1 [M+Na]$^+$, 949.3 [2M+Na]$^+$; HR-MS calc. [C$_{24}$H$_{18}$N$_9$PNa]$^+$ 486.1315, obs. 486.1323. Structure corroborated by single crystal X-ray diffraction determination.

Synthesis of chloro[5-(dicyclohexylphosphanyl)-1-phenyl-1H-1,2,3-triazole] gold(I) (8a)

Following PGC General Procedure on a 0.1 mmol scale. White solid (48 mg, 83%); m.p. >250 °C; $^1$H NMR (400 MHz, CDCl$_3$) δ 7.99 (s, 1H, TrzH), 7.73 (t, $^J$ 7.51, 1H), 7.63 (t, $^J$ 7.8, 2H), 7.35 (d, $^J$ 7.6, 2H), 2.21-2.07 (m, 2H), 2.01-1.92 (m, 2H), 1.92-1.80 (m, 4H), 1.79-1.64 (m, 4H), 1.43-1.10 (m, 10H); $^{31}$P NMR (121 MHz, CDCl$_3$) δ 22.14; $^{13}$C NMR (101 MHz, CDCl$_3$) δ 139.18 (d, $^J_{CP}$ 7.2), 135.78, 131.65, 130.15, 127.54, 126.17 (d, $^J_{CP}$ 52.8), 35.63 (d, $^J_{CP}$ 35.8), 29.78 (d, $^J_{CP}$ 3.5), 28.58, 26.28 (d, $^J_{CP}$ 5.0), 26.13, 25.41; IR ν (cm$^{-1}$) 2927, 2852, 1595, 1497, 1448, 1287;
TOF MS ES$^+$ m/z: 574.10 [M+H]$^+$; HR-MS calc. [C$_{20}$H$_{29}$AuClN$_3$P]$^+$ 574.1448 obs. 574.1445. Structure corroborated by single crystal X-ray diffraction determination.

Synthesis of chloro[5-(diphenylphosphanyl)-1-phenyl-1H-1,2,3-triazole] gold(I) (8b)

Following PGC General Procedure on a 0.1 mmol scale. White solid (43 mg, 86%); m.p. 230 °C (decomp); $^1$H NMR (400 MHz, CDCl$_3$) δ 7.68-7.51 (m, 12H), 7.44 (t, $J$ 7.9, 2H), 7.19 (d, $J$ 7.4, 2H); $^{31}$P NMR (121 MHz, CDCl$_3$) δ 8.61; $^{13}$C NMR (101 MHz. CDCl$_3$) δ 141.53 (d, $J_{CP}$ 10.6), 135.55, 133.97 (d, $J_{CP}$ 15.2), 133.15 (d, $J_{CP}$ 2.5), 131.23, 129.86, 129.82, 129.73, 126.33, 126.55 (d, $J_{CP}$ 67.3); IR (cm$^{-1}$) 3056, 2923, 1595, 1498, 137, 1287, 1102; TOF MS ES$^+$ m/z: 562.06 [M+H]$^+$; HR-MS calc. [C$_{20}$H$_{17}$AuClN$_3$P]$^+$ 562.0509 obs. 562.0499. Structure corroborated by single crystal X-ray diffraction determination.

Synthesis of chloro [5,5'-(cyclohexylphosphanediyl)bis(1-phenyl-1H-1,2,3-triazole)] gold(I) (9a)

Following PGC General Procedure on a 0.1 mmol scale. White solid (51 mg, 80%); m.p. 235-237 °C; $^1$H NMR (400 MHz, CDCl$_3$) δ 7.84 (s, 2H, Trz$^\text{H}$), 7.69 (t, $J$ 7.6, 2H), 7.55 (t, $J$ 7.9, 4H), 7.08 (d, $J$ 7.3), 2.50-2.39 (m, 1H), 1.97-1.86 (m, 2H), 1.82-1.73 (m, 3H), 1.49-1.24 (m, 5H); $^{31}$P NMR (121 MHz, CDCl$_3$) δ -11.87; $^{13}$C NMR (101 MHz. CDCl$_3$) δ 140.42 (d, $J_{CP}$ 13.3), 135.01, 131.88, 130.16, 126.97, 125.74 (d, $J_{CP}$ 67.1), 38.15 (d, $J_{CP}$ 41.0), 29.40 (d, $J_{CP}$ 4.6), 25.79 (d, $J_{CP}$ 16.7), 25.03; IR ν (cm$^{-1}$) 3110, 3063, 2932, 2854, 1594, 1496, 1452; TOF MS ES$^+$ m/z: 635.07 [M+H]$^+$; HR-MS calc. [C$_{22}$H$_{24}$AuClN$_6$P]$^+$ 635.1149 obs. 635.1143. Structure corroborated by single crystal X-ray diffraction determination.

Synthesis of chloro [5,5'-(phenylphosphanediyl)bis(1-phenyl-1H-1,2,3-triazole)] gold(I) (9b)

Following PGC General Procedure on a 0.1 mmol scale. White solid (37 mg, 58%); m.p. 176-178 °C; $^1$H NMR (400 MHz, CDCl$_3$) δ 7.91-7.44 (m, 13H, Ar$^\text{H}$), 7.19-7.02 (m, 4H, Ar$^\text{H}$); $^{31}$P NMR (121 MHz, CDCl$_3$) δ -16.87; $^{13}$C NMR (101 MHz. CDCl$_3$) δ 141.43 (d, $J_{CP}$ 10.8), 135.04, 134.40, 133.99 (d, $J_{CP}$ 17.3), 131.70, 131.40 (d, $J_{CP}$ 13.6), 130.10, 127.09, 126.49, 126.28; IR ν (cm$^{-1}$) 3111, 3059, 1594, 1467, 1438, 1289; TOF MS ES$^+$ m/z: 397.10 [M-AuCl$^+$+H]$^+$, 629.01 [M+H]$^+$; HR-MS calc. [C$_{22}$H$_{18}$AuClN$_6$P]$^+$ 629.0679 obs. 629.0688; elemental analysis calc. C$_{22}$H$_{18}$AuClN$_6$P: C 42.02, H 2.73, N 13.37%, found C 42.25, H 2.69, N 13.52%. Structure corroborated by single crystal X-ray diffraction determination.
Synthesis of chloro[tris(1-phenyl-1H,1,2,3-triazol-5-yl)phosphane] gold(I) (10)

Following PGC General Procedure on a 0.1 mmol scale. White solid (63 mg, 91%); m.p. 230 (deco); \(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta\) 7.91 (s, 3H, Trz\(\text{H}\)), 7.61 (t, \(J\,7.6\), 3H), 7.47 (t, \(J\,7.94\), 6H), 7.62 (d, \(J\,7.6\), 6H); \(^3\)P NMR (121 MHz, CDCl\(_3\)) \(\delta\) -44.19; \(^{13}\)C NMR (101 MHz, CDCl\(_3\)) 141.75 (d, \(J\,CP\,12.0\)), 134.45, 132.16, 130.34, 126.22, 124.87 (d, \(J\,CP\,89.32\)); IR (cm\(^{-1}\)) 2923, 2853, 1759, 1496; TOF MS ES\(^+\) m/z: 464.11 [M-Au-Cl+H\(^+\)], 696.03 [M+H\(^+\)]; HR-MS calc. \([C_{24}H_{19}AuClN_9P]^+\) 696.0850 obs. 696.0866. Structure corroborated by single crystal X-ray diffraction determination.

Synthesis of chloro[5-(dicyclohexylphosphanyl)-1-(2,6-dimethoxyphenyl)-1H-1,2,3-triazole] gold(I) (11)

Following PGC General Procedure on a 0.1 mmol scale. White solid (48 mg, 86%); m.p. 260); \(^1\)H NMR (500 MHz, CDCl\(_3\)) \(\delta\) 7.97 (s, 1H), 7.60 (t, \(J\,8.6\), 1H), 6.72 (d, \(J\,8.6\), 3H, 2.15-2.07 (m, 2H), 1.94-1.68 (m, 10H), 1.37-1.17 (m, 10H); \(^3\)P NMR (121 MHz, CDCl\(_3\)) 22.03; \(^{13}\)C NMR (126 MHz, CDCl\(_3\)) 156.17, 138.23 (d, \(J\,7.2\)), 133.07, 127.11 (d, \(J\,58.6\)), 113.41, 104.78, 55.72, 35.53 (d, \(J\,36.4\)), 29.34 (d, \(J\,3.5\)), 28.53, 26.44 (d, \(J\,3.9\), 26.33, 25.52 (d, \(J\,1.5\)); IR v (cm\(^{-1}\)) 2928, 2852, 1600, 1483, 1447, 1262; TOF MS ES\(^+\) m/z: 634.11 [M+H\(^+\)]; HR-MS calc. \([C_{22}H_{33}AuClN_3O_2P]^+\) 634.1659 obs. 634.1657. Structure corroborated by single crystal X-ray diffraction determination.

Materials prepared for substrate screening

Synthesis of 2-methyl-1-naphthaldehyde (S2)

To an oven-dried, two-necked, round bottom flask, 1-bromo-2-methylnaphthalene (4 mL, 26.0 mmol) was dissolved in tetrahydrofuran (50 mL). The mixture was cooled to -78 °C, and n-BuLi (2.5 M in hexane, 15.5 mL, 31.0 mmol) was added dropwise. After stirring at that temperature for one hour, N,N-dimethylformamide (3 mL, 39.0 mmol) was added dropwise and the reaction mixture was allowed to warm to room temperature. Saturated ammonium chloride (30 mL, aqueous) was added and the mixture extracted with dichloromethane (3 × 15 mL). The combined organic fractions were dried over anhydrous magnesium sulphate, filtered, and concentrated \(in\,\text{vacuo}\) to afford a residue that was purified by flash chromatography (CombiFlash Rf, gradient elution hexane:ethyl acetate 1:0 to 0:1). Yellow solid, 3.53 g (80% yield); IR (neat) \(\nu_{\text{max}}\) (cm\(^{-1}\)) 3332, 3107, 2880, 2777, 1671, 1593; \(^1\)H NMR (300 MHz, CDCl\(_3\)) \(\delta\) 10.96 (s, 1H), 8.97 (dd, \(J\,8.7\,\&\,0.6\), 1H), 7.94 (d, \(J\,8.4\), 1H), 7.83 (d, \(J\,8.6\), 1H), 7.62 (ddd, \(J\,8.6, 6.9\,\&\,1.5\), 1H), 7.50 (ddd, \(J\,8.0, 6.9\,\&\,1.1\), 1H), 7.34 (d, \(J\,8.4\), 1H), 2.81 (s, 3H). \(^{13}\)C NMR (101 MHz, CDCl\(_3\)) \(\delta\) 193.3, 142.6, 134.3, 132.5, 131.5, 129.8, 128.8, 128.44, 128.41 126.0, 124.4, 20.1. TOF MS EI\(^+\) m/z 141 [M-CO\(^+\)], 170 [M\(^+\)]. Data are consistent with those described in the literature.[9]
Synthesis of dimethyl-1-diazo-2-oxopropylphosphonate (S3)

Following a reported procedure,[10] to a cooled solution of dimethyl (2-oxopropyl)phosphonate (970 μL, 5.81 mmol) in anhydrous acetonitrile (6 mL) potassium carbonate (1.044 g, 7.55 mmol) was added, followed by tosyl azide (30% v/v in hexane, 1.26 g, 6.39 mmol) at 0 °C protect from the atmosphere (argon). The reaction mixture was stirred at 0 °C until consumption of the starting material was judged complete (TLC analysis). Diethyl ether (30 mL) was added and the reaction mixture was filtered through a pad of celite and concentrated *in vacuo* to afford a residue that was purified by flash chromatography (CombiFlash Rf, gradient elution hexane:ethyl acetate 1:0 to 0:1). Pale yellow oil, 937 mg (84% yield); IR (neat) ν<sub>max</sub> (cm<sup>-1</sup>) 2120, 1655, 1260; 1H NMR (400 MHz, CDCl<sub>3</sub>) δ 3.85 (d, J<sub>11.9</sub>, 6H), 2.28 (s, 3H); 13C NMR (101 MHz, CDCl<sub>3</sub>) δ 189.9 (d, J<sub>13.2</sub>), 128.0 (d, J<sub>325.8</sub>), 53.6 (d, J<sub>5.5</sub>), 27.1 (d, J<sub>1.3</sub>); 31P NMR (162 MHz, CDCl<sub>3</sub>) δ 14.3 (sept, J<sub>11.9</sub>). TOF MS ES<sup>+</sup> m/z 165 [M-2N]<sup>+</sup>. Data are consistent with those described in the literature.[11]

Synthesis of 1-ethynyl-2-methylnaphthalene (13e)

To an oven-dried two-necked flask, 2-methyl-1-naphthaldehyde S2 (4.30 mmol) and anhydrous methanol (25 mL, anhydrous) were added, under an argon flow. To this solution potassium carbonate (10.75 mmol) was added, followed by dimethyl-1-diazo-2-oxopropylphosphonate S3 (5.16 mmol). The reaction was stirred at room temperature for ten hours. Diethyl ether (30 mL) was added and the reaction mixture was washed sodium hydrogen carbonate solution (0.1 M, aqueous, 1 x 15 mL) and brine (1 x 15mL). The organic fraction was dried over anhydrous magnesium sulphate, filtered, and concentrated *in vacuo* to afford a residue that was purified by flash chromatography (CombiFlash Rf, gradient elution hexane:ethyl acetate 1:0 to 0:1). Data are consistent with those described in the literature.[12] Pale pink oil, 520 mg (72% yield); IR (neat) ν<sub>max</sub> (cm<sup>-1</sup>) 3291, 3054, 2919, 2098, 1508. 1H NMR (300 MHz, CDCl<sub>3</sub>) δ 8.35 (d, J<sub>8.4</sub>, 1H), 7.80 (d, J<sub>8.1</sub>, 1H), 7.75 (d, J<sub>8.3</sub>, 1H), 7.6-7.49 (m, 1H), 7.51-7.36 (m, 1H), 7.34 (d, J<sub>8.4</sub>, 1H), 3.71 (s, 1H), 2.66 (s, 3H). 13C NMR (101 MHz, CDCl<sub>3</sub>) δ 140.2, 133.91, 131.5, 128.6, 128.1, 128.0, 127.0, 125.8, 125.6, 118.3, 86.4, 80.6, 21.4. TOF MS EI<sup>+</sup> m/z 165 [M-H]<sup>+</sup>, 166 [M]<sup>+</sup>.

Synthesis of 3-methyl-3-(prop-2-yn-1-yl)indolin-2-one (13j)[13]

n-Butyl lithium in hexanes (9.0 mL, 18.0 mmol, 2.0 M) was transferred into a nitrogen flushed flask. Anhydrous tetrahydrofuran (20 mL) was added and the solution cooled to -78 °C. A solution of 3-methyl-2-oxindole (2.02 g, 13.8 mmol) dissolved in tetrahydrofuran (20 mL) was added dropwise over 10 min to the stirred solution. The reaction mixture was stirred for a further 10 min before propargyl bromide (1.40 mL, 15.7 mmol) was added. The solution was allowed to warm to room temperature and stirred under a nitrogen atmosphere for 24 h. Methanol (20 mL) was added to quench any residual organometallic reagent. The solution was concentrated *in vacuo* and the residual oil was resuspended in ethyl acetate (50 mL) and washed with water (2 × 100 mL), brine (2 × 100 mL), dried over anhydrous magnesium sulphate, filtered and evaporated to dryness. The crude residue was purified by flash column chromatography (silica, petroleum
ether: ethyl acetate / 4:1) to afford the desired title compound 3-methyl-3-(prop-2-yn-1-yl)indolin-2-one (0.85 g, 33%, 13j) as a cream powdery solid. Compound 13j was synthesised multiple times during the course of this study in similar yields. The major product was however the doubly alkynylated 3-methyl-1,3-di(prop-2-yn-1-yl)indolin-2-one (1.33 g, S4) as a dark yellow-brown viscous oil, this material was retained for use in another study, and preliminary analysis given below. TLC Rf = 0.60 (silica, petroleum ether: ethyl acetate / 1:1); 1H NMR (400 MHz, CDCl3): \( \delta \) 9.14 (1H, brs, NH), 7.42 (1H, d, \( J \) 8.0, C\( _{Ar} \)H), 7.24 (1H, app td, \( J \) 8.0 & 1.2, C\( _{Ar} \)H), 7.06 (1H, app td, \( J \) 7.6 & 0.8, C\( _{Ar} \)H), 6.97 (1H, d, \( J \) 8.0, C\( _{Ar} \)H), 2.71 (1H, dd, \( J \) 16.4 & 2.8, CH\( H\)CCH), 2.56 (1H, dd, \( J \) 16.4 & 2.4, CHH\( H\)CCH), 1.98 (1H, t, \( J \) 2.4, C\( H\)CH), 1.49 (3H, s, CH\( _{3} \)). 13C NMR (100 MHz, CDCl3): 182.1, 140.2, 133.4, 128.2, 123.5, 122.5, 110.0, 79.5, 70.8, 47.2, 27.5, 21.9. Data are consistent with those described in the literature.[13]

Analysis of 3-methyl-1,3-di(prop-2-yn-1-yl)indolin-2-one (S4) obtained as described above [13] Dark yellow-brown viscous oil; TLC Rf = 0.88 (silica, petroleum ether: ethyl acetate / 1:1); 1H NMR (400 MHz, CDCl3): \( \delta \), 7.47 (1H, dt, \( J \) 7.4 & 0.7, C\( _{Ar} \)H), 7.34 (1H, app td, \( J \) 7.8 & 1.3, C\( _{Ar} \)H), 7.13 (1H, app td, \( J \) 7.6 & 1.0, C\( _{Ar} \)H), 7.10 (1H, d, \( J \) 7.8, C\( _{Ar} \)H), 4.53 (2H, d, \( J \) 2.5, CH\( H\)CCH), 2.71 (1H, dd, \( J \) 16.6 & 2.7, CH\( H\)CCH), 2.53 (1H, dd, \( J \) 16.5 & 2.6, CHH\( H\)CCH), 2.25 (1H, t, \( J \) 2.5, C\( H\)C\( H\)), 1.98 (1H, t, \( J \) 2.6, C\( H\)C\( H\)), 1.48 (3H, s, CH\( _{3} \)); 13C NMR (100 MHz, CDCl3): 178.4, 141.1, 132.8, 128.3, 123.3, 123.0, 109.1, 79.4, 77.0, 72.4, 71.0, 46.6, 29.3, 27.7, 21.8. Data are consistent with those described in the literature.[13]

Synthesis of 1-benzyl-3-methyl-3-(prop-2-yn-1-yl)indolin-2-one (13k)[13]

Sodium hydride (60% dispersion) (275 mg, 11.4 mmol) was stirred in anhydrous tetrahydrofuran (50 mL) under a nitrogen atmosphere. The reaction mixture was cooled to 0 °C (ice slush-bath) and stirred vigorously while a solution of 13j (752 mg, 4.06 mmol) in tetrahydrofuran (10 mL) was added dropwise. The reaction mixture was allowed to warm to room temperature and left to stir for two hours. Water (10 mL) was added dropwise to decompose any remaining sodium hydride and the resulting solution was extracted with ethyl acetate (3 × 50 mL). The combined organic phase was washed with brine (3 × 50 mL), dried over anhydrous magnesium sulphate, filtered and concentrated in vacuo. The residue thus obtained was purified by flash column chromatography (silica, petroleum ether: ethyl acetate / 4:1) and recrystallised from petroleum ether and ethyl acetate to afford the title compound as a pale yellow crystalline solid (799 mg, 71%). TLC Rf = 0.50 (silica, petroleum ether: ethyl acetate / 4:1); 1H NMR (400 MHz, CDCl3): \( \delta \) 7.37 (1H, d, \( J \) 7.6, C\( _{Ar} \)H), 7.20-7.26 (5H, m, C\( _{Ar} \)H), 7.13 (1H, app td, \( J \) 7.6 & 1.2, C\( _{Ar} \)H), 7.00 (1H, app td, \( J \) 7.6 & 0.8, C\( _{Ar} \)H), 6.68 (1H, d, \( J \) 7.6, C\( _{Ar} \)H), 5.01 (d, 1H, \( J \) 15.6 CH\( H\)Ph), 4.83 (d, 1H, \( J \) 15.6 CH\( H\)Ph), 2.75 dd, 1H, \( J \) 16.4 & 2.8, CH\( H\)C\( H\)), 2.60 (dd, 1H, \( J \) 16.4 & 2.8, CH\( H\)C\( H\)), 1.87 (1H, t, \( J \) 2.4, C\( H\)), 1.46 (3H, s, CH\( _{3} \)); 13C NMR (100 MHz, CDCl3): \( \delta \) 179.4, 142.1, 135.8, 132.9, 128.7, 128.1, 127.6, 127.3, 123.2, 122.6, 109.1, 79.7, 70.7, 46.7, 43.7, 27.7, 22.3. Data are consistent with those described in the literature.[13]
Synthesis of tert-butyl 3-methyl-2-oxo-3-(prop-2-yn-1-yl)indoline-1-carboxylate (13l)[13]

To a stirred solution of 13j (1.02 g, 5.53 mmol) in anhydrous tetrahydrofuran (50 mL) anhydrous sodium carbonate (4.75 g, 44.8 mmol) and di-tert-butyl dicarbonate (3.01 g, 13.8 mmol) were added, under a nitrogen atmosphere. The reaction mixture was heated at reflux starting material was consumed (as just by TLC analysis). The resulting mixture was allowed to cool to room temperature and concentrated in vacuo. The residue thus obtained was suspended in water (50 mL) and extracted with ethyl acetate (3 × 50 mL). The combined organic extracts were washed with brine (2 × 50 mL), dried over anhydrous magnesium sulphate, filtered and solvent remove in vacuo. The residue obtained was purified by flash column chromatography (silica, petroleum ether:ethylacetate / 5:1) to the title compound as a pale yellow viscous oil (2.28 g, quant.) TLC $R_f = 0.51$ (silica, petroleum ether:ethylacetate / 6:1); $^1$H NMR (400 MHz, CDCl$_3$): δ 7.86 (1H, d, $J$ 8.0, C$_{Ar}$H), 7.44 (1H, dt, $J$ 7.6 & 0.8, C$_{Ar}$H), 7.32 (1H, app td, $J$ 7.6 & 1.2, C$_{Ar}$H), 7.18 (1H, app td, $J$ 7.6 & 1.2, ArH), 2.70 (1H, dd, $J$ 16.4 & 2.8, CHHCCH), 2.57 (1H, dd, $J$ 16.8 & 2.8, CHHCCH), 1.99 (1H, t, $J$ 2.8, CCH), 1.64 (9H, s, t-Bu), 1.49 (3H, s, CH$_3$); $^{13}$C NMR (100 MHz, CDCl$_3$): δ 177.9, 149.2, 138.8, 131.7, 128.4, 124.4, 123.0, 114.9, 84.4, 79.0, 71.3, 47.0, 28.4, 28.0, 22.8. Data are consistent with those described in the literature.[13]

Analysis of materials resulting from substrate screening in catalysis

Analysis of decan-2-one (14a)[14]

Colourless oil; $^1$H NMR (400 MHz, CDCl$_3$) δ 2.41 (t, $J$ 7.5, 2H), 2.13 (s, 3H), 1.62-1.52 (m, 2H), 1.28 (brs, 10H), 0.88 (t, $J$ 6.9, 3H); $^{13}$C NMR (101 MHz, CDCl$_3$) δ 209.43[-], 43.84[-], 31.82[-], 29.86[+], 29.37[-], 29.20[-], 29.14[-], 23.89[-], 22.65[-], 14.10[+]; IR (cm$^{-1}$) 2924, 2854, 1716, 1464, 1358, 1162; TOF MS EI+ m/z: 156.2 [M]+. Data are consistent with those described in the literature.[14]

Analysis of 1-cyclohexylethan-1-one (14b)

Colourless oil; $^1$H NMR (400 MHz, CDCl$_3$) δ 2.37-2.28 (m, 1H), 2.13 (s, 3H, CH$_3$), 1.93-1.58 (m, 5H), 1.40-1.13 (m,5H); $^{13}$C NMR (101 MHz, CDCl$_3$) δ 212.15[-], 51.38[+], 28.39[-], 27.80[+], 25.82[-], 25.59[-]; IR v (cm$^{-1}$) 2927, 285, 1705, 1448, 1351, 1166; TOF MS EI+ m/z: 126.1 [M]+.

Analysis of 1-(cyclohex-1-en-1-yl)ethan-1-one (14c)

Yellowish oil; $^1$H NMR (400 MHz, CDCl$_3$) δ 6.95-6.86 (m, 1H), 2.30-2.18 (m, 7H), 1.68-1.57 (m, 4H); $^{13}$C NMR (101 MHz, CDCl$_3$) δ 199.30[-], 140.89[+], 139.63[-], 26.07[-], 25.12[+], 22.92[-], 21.89[-], 21.50[-]; IR v (cm$^{-1}$) 2932, 2860, 1662, 1432, 1224; TOF MS EI+ m/z: 124.1 [M]+.

Me
\[O\]
\[\text{Cy}\]
Me
\[O\]
\[\text{Me}\]
14a

Me
\[O\]
\[\text{Me}\]
14b

Me
\[O\]
\[\text{Me}\]
14c

Me
\[O\]
\[\text{Boc}\]
13l
Analysis of acetophenone (14d)\(^{[14]}\)

Pale yellow oil; \(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta\) 7.99 (dd, \(J\) 8.4, 1.3, 2H, ArH), 7.56 (t, \(J\) 7.3, 1.3, 1H, ArH), 7.45 (t, \(J\) 7.3, 2H, ArH), 2.59 (s, 3H, CH\(_3\)); \(^{13}\)C NMR (101 MHz, CDCl\(_3\)) \(\delta\) 198.12[\(-\)], 137.13[\(-\)], 133.10[\(+\)], 128.57[\(+\)], 128.30[\(+\)], 26.60[\(+\)]; IR (cm\(^{-1}\)) 1680, 1598, 1448, 1358, 1263; TOF MS EI\(^+\) m/z: 120.1 [M]\(^+\). Data are consistent with those described in the literature.\(^{[14]}\)

Analysis of 1-(2-methylnaphthalen-1-yl)ethan-1-one (14e)

Colourless oil; \(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta\) 7.82 (d, \(J\) 7.5, 1H), 7.76 (d, \(J\) 8.5, 1H), 7.50-7.42 (m, 2H), 2.62 (s, 3H), 2.43 (s, 3H); \(^{13}\)C NMR (101 MHz, CDCl\(_3\)) 208.25[\(-\)], 138.78[\(-\)], 131.76[\(-\)], 129.94[\(-\)], 128.90[\(-\)], 128.77[\(+\)], 126.91[\(+\)], 125.48[\(+\)], 123.91[\(+\)], 32.93[\(+\)], 19.39[\(+\)]; IR (cm\(^{-1}\)) 1697, 1714, 1496, 1357, 1161; TOF MS EI\(^+\) m/z: 184.1 [M]\(^+\), 169.1 [M-CH\(_3\)]\(^+\).

Analysis of 4-phenylbutan-2-one (14f)\(^{[15]}\)

Colourless oil; \(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta\) 7.32-7.25 (m, 2H) 7.23-7.16 (m, 3H), 2.90 (t, \(J\) 7.7, 2H), 2.76 (t, \(J\) 7.5, 2H), 2.14 (s, 3H, CH\(_3\)); \(^{13}\)C NMR (101 MHz, CDCl\(_3\)) 207.9[\(-\)], 141.0[\(-\)], 128.5[\(+\)], 128.3[\(+\)], 126.1[\(+\)], 45.2[\(-\)], 30.1[\(+\)], 29.8[\(-\)]; IR (cm\(^{-1}\)) 2924, 1714, 1496, 1357, 1161; TOF MS EI\(^+\) m/z: 148.1 [M]\(^+\).

Analysis of 1-(4-methoxyphenyl)ethan-1-one (14g)\(^{[14]}\)

Yellow solid (literature reported as yellow oil); \(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta\) 7.92 (d, \(J\) 9.0, 2H, ArH), 6.91 (d, \(J\) 8.9, 2H, ArH), 3.84 (s, 3H, OCH\(_3\)), 2.53 (s, 3H, CH\(_3\)); \(^{13}\)C NMR (101 MHz, CDCl\(_3\)) \(\delta\) 196.7[\(-\)], 163.4[\(-\)], 130.5[\(+\)], 130.2[\(-\)], 113.6[\(+\)], 55.4[\(+\)], 26.3[\(+\)]; IR (cm\(^{-1}\)) 1671, 1597, 1509, 1459, 1417, 1356, 1247, 1169; TOF MS EI\(^+\) m/z: 150.1 [M]\(^+\).

Analysis of 1-(4-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)phenyl)ethan-1-one (14h)

White solid; \(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta\) 7.93 (d, \(J\) 8.4, ArH), 7.89 (d, \(J\) 8.4, ArH), 2.61 (s, 3H, CH\(_3\)), 1.36 (s, 12H, C(CH\(_3\))\(_2\)), \(^{13}\)C NMR (101 MHz, CDCl\(_3\)) \(\delta\) 198.5[\(-\)], 139.0[\(-\)], 134.9[\(+\)], 127.3[\(+\)], 84.2[\(-\)], 26.8[\(+\)], 24.9[\(+\)]; IR (cm\(^{-1}\)) 2979, 1686, 1507, 1397, 1356, 1265; TOF MS EI\(^+\) m/z: 246.2 [M]\(^+\).

Analysis of 1-(thiophen-3-yl)ethan-1-one (14i)

White solid; \(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta\) 8.31 (dd, \(J\) 2.9, 1.3, 1H), 7.54 (dd, \(J\) 5.1, 1.3, 1H), 7.31 (dd, \(J\) 5.1, 2.9), 2.53 (s, 3H, CH\(_3\)); \(^{13}\)C NMR (101 MHz, CDCl\(_3\)) \(\delta\) 192.3[\(-\)], 142.6[\(-\)], 132.4[\(+\)], 132.4[\(+\)], 127.0[\(+\)], 126.4[\(+\)], 27.6[\(+\)]; IR (cm\(^{-1}\)) 3103, 1667, 1510, 1410, 1352, 1254; TOF MS ES\(^+\) m/z: 126.0 [M]\(^+\).
Analysis of 3-methyl-3-(2-oxopropyl)indolin-2-one (14j)

White solid; m.p. 150-152 °C; 1H NMR (400 MHz, CDCl 3) δ 7.96 (brs, 1H, NH), 7.18 (td, J 7.7, 1.3, 1H, ArH), 7.12 (dt, J 7.4, 0.6, 1H, ArH), 6.99 (td, J 7.5, 1.0, 1H, ArH), 6.90 (d, J 7.7, 1H, ArH), 3.12 (ABq, J 17.8, 2H, CH 2), 2.02 (s, 3H, COCH 3), 1.35 (s, 3H, CH 3); 13C NMR (101 MHz, CDCl 3) δ 204.7, 182.1, 140.7, 133.9, 127.9, 122.3, 122.2, 109.9, 50.4, 45.6, 30.0; IR ν (cm −1) 1709, 1620, 1472, 1196; TOF MS EI+ m/z: 203.1 [M]+; HRMS calc. [C 12H 13NO 2]+ 203.0940, obs. 203.0945.

Analysis of 1-benzyl-3-methyl-3-(2-oxopropyl)indolin-2-one (14k)

White solid; m.p. 115-117 °C; 1H NMR (400 MHz, CDCl 3) δ 7.39 (d, J 7.6, 2H), 7.33 (t, J 7.3, 2H), 7.24 (t, J 7.1, 1H), 7.15-7.08 (m, 2H), 6.96 (td, J 7.5, 1.0, 1H), 6.69 (d, J 7.8, 1H), 4.97 (ABq, J 15.9, 2H, PhCH 2), 3.16 (ABq, J 17.8, 2H, CH 2CO), 2.01 (s, 3H, COCH 3), 1.39 (s, 3H, CH 3); 13C NMR (101 MHz, CDCl 3) δ 204.5, 180.4, 142.8, 136.2, 133.5, 128.7, 127.8, 127.4, 127.3, 122.3, 119.4, 50.4, 45.3, 44.0, 30.0; IR ν (cm −1) 1704, 1611, 1489, 1355, 1176; TOF MS EI+ m/z: 293.2 [M]+; HRMS calc. [C 19H 19NO 2]+ 293.1410, obs. 293.1417.

Analysis of tert-butyl 3-methyl-2-oxo-3-(2-oxopropyl)indoline-1-carboxylate (14l)

White solid; m.p. 120-121 °C; 1H NMR (400 MHz, CDCl 3) δ 7.88 (d, J 8.2, 1H), 7.30-7.24 (m, 1H), 7.13-7.08 (m, 2H), 3.17 (ABq, J 17.8, 2H), 2.00 (s, 3H, COCH 3), 1.66 (s, 9H, C(CH 3) 3), 1.36 (s, 3H, CH 3); 13C NMR (101 MHz, CDCl 3) δ 204.2, 178.9, 149.5, 139.7, 132.4, 128.1, 124.2, 121.3, 115.4, 84.1, 51.6, 45.5, 28.2, 25.6; IR ν (cm −1) 1764, 1717, 1601, 1480, 1297, 1148. TOF MS ES+ m/z: 326.1 [M+Na]+; HRMS calc. [C 17H 21NO 4Na]+ 326.1363, obs. 326.1368.

Analysis of 3,3-dimethoxy-1-phenylpropan-1-one (14m')

Light yellow oil; 1H NMR (400 MHz, CDCl 3) δ 7.95 (d, J 8.5, 2H), 7.59 (tt, J 7.3, 1.3, 1H), 7.46 (t, J 7.6, 2H), 5.01 (t, J 5.5, 1H, CH 2CH), 3.41 (s, 6H, OCH 3), 3.28 (d, J 5.5, 2H, CH 2CH); 13C NMR (101 MHz, CDCl 3) δ 196.9, 137.1, 133.3, 128.6, 128.3, 102.2, 54.2, 42.6; IR ν (cm −1) 2935, 1683, 1597, 1448, 1186, 1118; TOF MS EI+ m/z: 194.1 [M]+, 179.1 [M-CH 3].

Materials synthesised for or arising from regioselectivity study

Synthesis of but-1-yne-1,4-diyldibenzene (15)

A dry flask was charged with bis(triphenylphosphine)palladium(II) dichloride (84.0 mg, 0.02 mmol), copper(I) iodide (45.0 mg, 0.24 mmol), tetrahydrofuran (30 mL, degassed), iodobenzene (0.67 mL, 6.01 mmol) triethylamine (5.8 mL, 41.6 mmol, degassed) and 4-phenyl-1-butene (0.93 mL,
6.61 mmol) sequentially and stirred at room temperature for 20 h. The solvent was removed in vacuo and the resulting slurry was filtered through a pad of silica (3 cm) eluting with diethyl ether. The eluted filtrate was concentrated in vacuo and purified by flash chromatography (silica, hexane) to give alkyne 15 as a colourless oil (1.23 g, 99%); IR (cm\(^{-1}\)) 3027, 2927, 1599, 1490; \(^1\)H NMR (400 MHz, CDCl\(_3\)): δ 7.39-7.19 (m, 10H), 2.92 (t, \(J = 7.5, 2\)H), 2.69 (t, \(J = 7.5, 2\)H); \(^1\)C NMR (101 MHz, CDCl\(_3\)): δ 140.9[-], 131.7[+], 128.7[+], 128.5[+], 128.3[+], 127.8[+], 126.5[+], 124.0[+], 89.6[-], 81.5[-], 35.3[-], 21.8[-]. Spectroscopic data are consistent with those reported.\(^{[16]}\)

Procedure resulting in mixtures of 16a and 16b
Following a method adapted from a literature procedure,\(^{[17]}\) an 8 mL vial equipped with a screw cap and magnetic stirrer bar was charged with alkyne 15 (103 mg, 0.50 mmol) and purged with argon for 2 minutes. Gold(I) chloride complex (1 mol %), silver(I) triflate (2 mol %), methanol (0.5 mL, degassed) and water (18 µL, 1.0 mmol, degassed) were sequentially added and the sealed reaction vessel heated at 80 °C for 14 h. After allowing to cool to room temperature, the reaction mixture was filtered through a pad of Celite (2 cm eluted with dichloromethane) and concentrated in vacuo. The conversion of 15 into products 16a and 16b was analysed and the ratio thereof determined. For proton NMR spectroscopic analysis methyl 3,5-dinitrobenzoate was added as an internal standard (4.09 ppm, CDCl\(_3\)), integration of 16a measured from quintet resonance at 2.09 ppm and integration of 16b measured from benzylic methylene at 3.69 ppm. In some cases overlapping signals in the proton NMR spectrum prevented accurate determination of the proportion of the minor regioisomer (see Supplementary Figure S 68, Supplementary Figure S 69 (corresponding to Table 2, Entry 1, main text) and Supplementary Figure S 70 (corresponding to Table 2, Entry 2, main text)) and gas chromatography was used to confirm conversion to and ratios of 16a and 16b in those cases. Furthermore, isolated yields (flash chromatography) were used to determine yield and selectivity for use of 8a and 9a as precatalysts.

Analysis of 1,4-diphenylbutan-1-one (16a)
![16a](image)

White solid; IR ν (cm\(^{-1}\)) 3062, 3027, 2936, 1683, 1598 1448; \(^1\)H NMR (300 MHz, CDCl\(_3\)): δ 7.97-7.89 (m, 2H), 7.59-7.52 (m, 1H), 7.49-7.41 (m, 2H), 7.34-7.26 (m, 2H), 7.25-7.17 (m, 3H), 2.99 (t, \(J = 7.3, 2\)H), 2.73 (t, \(J = 7.5, 2\)H), 2.09 (app. quint, \(J = 7.4, 2\)H); \(^1\)C NMR (101 MHz, CDCl\(_3\)): δ 200.3, 141.8, 137.1, 133.1, 128.7, 128.7, 128.5, 128.2, 126.1, 37.8, 35.3, 25.8. Data are consistent with those described in the literature.\(^{[18]}\)

Analysis of 1,4-diphenylbutan-2-one (16b)
![16b](image)

Pale yellow oil; IR ν (cm\(^{-1}\)) 6063, 3028, 2926, 1710, 1496, 1454; \(^1\)H NMR (300 MHz, CDCl\(_3\)): δ 7.37-7.22 (m, 5H), 7.22-7.08 (m, 5H), 3.67 (s, 2H), 2.87 (m, 2H), 2.77 (m, 2H); \(^1\)C NMR (101 MHz, CDCl\(_3\)): δ 207.6, 141.0, 134.2, 129.5, 128.9, 128.6, 128.5, 127.2, 126.2, 50.5, 43.6, 29.9. Data are consistent with those described in the literature.\(^{[19]}\)
**Preliminary palladium-catalysed cross-coupling findings**

Replicating a procedure previously employed by some of the co-authors of this report in an early disclosure of mono-triazole-containing phosphine ligands (and in which ligand 1a, 3a and 3b were reported)\[7, 20\], the range of multi-triazole phosphines of this study were compared (alongside the three aforementioned ligands) in the S7-forming Suzuki-Miyaura cross-coupling reaction shown in Supplementary Figure S 1.

Disappointingly, the ‘bulkiest’ of the ligands tested (5) failed to convert any of the starting material to product S7, indeed decreasing the triazole number (as witnessed for the gold(I)-catalysed hydration of the main text) led to increased levels of product formation (1a and 3a giving quantitative conversion to product S7 within six hours). In the preliminary survey it may be concluded that mono-triazole-phosphines (of the probed series) are the most effective ligand constructs for palladium-catalysed Suzuki-Miyaura reactions of sterically encumbered aryl-bromides.

At the same time as probing the above reactions (Supplementary Figure S 1) it was deemed of interest to also investigate C-N cross coupling with the same ligand set. In a first test (details not shown) with the same ligand set, it was ligand 1a that showed the most promise for palladium-catalysed C-N cross-coupling (of p-chloro-toluene with N-methyl-aniline). Since palladium-catalysed C-N cross-coupling with triazole containing ligands (of type 1) had not previously been deployed as ligands in such reactions a short survey of preliminary activity (of 1a as a ligand) was embarked upon, details are shown in Supplementary Figure S 2. Four different C-N cross-coupled products were synthesised but yields were not overwhelmingly promising. Further optimisation will be needed to translate the effectiveness of the 1-type
ligands from C-C cross-coupling to C-N coupling and is beyond the scope of the current study. Experimental details of the four cross-coupled products (S8a-d) are given below and in later sections.

**Supplementary Figure S 2.** Palladium-catalysed C-N cross-coupling facilitated by triazole-containing ligand 1a.

**General procedure for palladium-catalysed C-N cross-coupling**

To a 16 mL Kimble tube sodium tertiary butoxide (1.2 equiv.), p-chloro-toluene (1.0 equiv.), Pd2(dba)3 (0.25 mol%), and ligand 1a (1 mol%) were added. The mixture was dissolved in toluene (3 mL) and the flask flushed with argon. The reaction vessel was placed into an ADS19 OCTO reaction station and heated at 110 °C for 20 hours. After which the vessel was cooled to room temperature and the mixture diluted with ethyl acetate (10 mL) and was washed with brine (6 mL). The aqueous layer was extracted further with ethyl acetate (2 × 10 mL). The combine organic fractions were dried with sodium sulphate and solvent evaporated in vacuo. The residues thus obtained were purified by flash chromatography (Isco CombiFlash, silica 50-60 μm, 4 or 12 g column, hexane (100%) to hexane (80%): ethyl acetate (20%) gradient elution, detection 254 and 288 nm absorption) to afford the corresponding products.

**Synthesis of N,N,N',4-dimethyl-N-phenylaniline S8a**

Pale Yellow liquid, >99% isolated yield; 1H NMR (300 MHz, CDCl3) δ 7.28-7.17 (m, 2H), 7.16-7.07 (m, 2H), 7.04-6.95 (m, 2H), 6.96-6.82 (m, 3H), 3.28 (s, 3H), 2.32 (s, 3H).

13C NMR (101 MHz, CDCl3) δ 149.37, 146.60, 132.07, 129.93, 129.03, 122.59, 118.17, 118.17, 40.34, 20.77. TOF MS ES+ m/z: 198.12 [M+H]+. Data are consistent with those described in the literature.[21]
Synthesis of $N,N$-dibenzyl-4-methylaniline S8b

Colourless liquid, 33% isolated yield; $^1$H NMR (300 MHz, CDCl$_3$) $\delta$ 7.38-7.18 (m, 10H), 6.98 (d, $J$ 8.2, 2H), 6.65 (d, $J$ 8.7, 2H), 4.62 (s, 4H), 2.22 (s, 3H). $^{13}$C NMR (101 MHz, CDCl$_3$) $\delta$ 147.05, 138.87, 129.74, 128.60, 126.81, 126.70, 125.85, 112.63, 54.38, 20.22. TOF MS ES+ m/z: 288.17 [M+H]$^+$. Data are consistent with those described in the literature.[21]

Synthesis of $N$-butyl-4-methylaniline S8c

Colourless liquid, 29% isolated yield; $^1$H NMR (300 MHz, CDCl$_3$) $\delta$ 7.02-6.93 (m, 2H), 6.58-6.47 (m, 2H), 3.43 (s, 1H), 3.08 (t, $J$ 7.1, 2H), 2.23 (s, 3H), 1.65-1.52 (m, 2H), 1.49-1.31 (m, 2H), 0.95 (t, $J$ 7.3, 3H). $^{13}$C NMR (101 MHz, CDCl$_3$) $\delta$ 146.36, 129.74, 126.30, 120.85, 112.93, 44.09, 31.77, 20.36, 13.98. TOF MS ES+ m/z: 164.13 [M+H]$^+$. Data are consistent with those described in the literature.[21]

Synthesis of 4-($p$-tolyl)morpholine S8d

White crystalline solid, 15% isolated yield; $^1$H NMR (300 MHz, CDCl$_3$) $\delta$ 7.09 (d, $J$ 8.1, 2H), 6.83 (d, $J$ 8.6, 2H), 3.88-3.83 (m, 4H), 3.19-2.95 (m, 4H), 2.27 (s, 3H). $^{13}$C NMR (101 MHz, CDCl$_3$) $\delta$ 149.23, 129.74, 129.59, 116.06, 67.01, 49.95, 20.46. TOF MS ES+ m/z: 178.12 [M+H]$^+$. Data are consistent with those described in the literature.[21]
NMR Spectra

**Supplementary Figure S 3.** $^1$H NMR spectrum of 4a.

**Supplementary Figure S 4.** $^{13}$C NMR spectrum of 4a.
Supplementary Figure S 5. $^{31}$P NMR spectrum of 4a.
**Supplementary Figure S 6.** $^1$H NMR spectrum of 4b.

**Supplementary Figure S 7.** $^{13}$C NMR spectrum of 4b.
Supplementary Figure S 8. $^{31}$P NMR spectrum of 4b.
Supplementary Figure S 9. $^1$H NMR spectrum of 5a.

Supplementary Figure S 10. $^{13}$C NMR spectrum of 5a.
Supplementary Figure S11. $^{31}$P NMR spectrum of 5a.
**Supplementary Figure S 12.** $^1$H NMR spectrum of 8a.

**Supplementary Figure S 13.** $^{13}$C NMR spectrum of 8a.
Supplementary Figure S 14. 31P NMR spectrum of 8a.
Supplementary Figure S 15. $^1$H NMR spectrum of 8b.

Supplementary Figure S 16. $^{13}$C NMR spectrum of 8b.
Supplementary Figure S 17. $^{31}$P NMR spectrum of 8b.
**Supplementary Figure S 18.** $^1$H NMR spectrum of 9a.

**Supplementary Figure S 19.** $^{13}$C NMR spectrum of 9a.
Supplementary Figure S 20. $^3$P NMR spectrum of 9a.
**Supplementary Figure S 21.** $^1$H NMR spectrum of 9b.

**Supplementary Figure S 22.** $^{13}$C NMR spectrum of 9b.
Supplementary Figure S 23. $^3$P NMR spectrum of 9b.
Supplementary Figure S 24. $^1$H NMR spectrum of 10.

Supplementary Figure S 25. $^{13}$C NMR spectrum of 10.
**Supplementary Figure S 26**  
$^3$P NMR spectrum of 10.
**Supplementary Figure S 27.** $^1$H NMR spectrum of 11.

**Supplementary Figure S 28.** $^{13}$C NMR spectrum of 11.
Supplementary Figure S 29. $^{31}$P NMR spectrum of 11.
Supplementary Figure S 30. $^1$H NMR spectrum of 13j.

Supplementary Figure S 31. $^{13}$C NMR spectrum of 13j.
Supplementary Figure S 32. $^1$H NMR spectrum of 13k.

Supplementary Figure S 33. $^{13}$C NMR spectrum of 13k.
Supplementary Figure S 34. $^1$H NMR spectrum of 13I.

Supplementary Figure S 35. $^{13}$C NMR spectrum of 13I.
Supplementary Figure S 36. $^1$H NMR spectrum of 13e.

Supplementary Figure S 37. $^{13}$C NMR spectrum of 13e.
**Supplementary Figure S 38**. ¹H NMR spectrum of 14a.

**Supplementary Figure S 39**. ¹³C NMR spectrum of 14a.
Supplementary Figure S 40. $^1$H NMR spectrum of 14b.

Supplementary Figure S 41. $^{13}$C NMR spectrum of 14b.
Supplementary Figure S 42. $^1$H NMR spectrum of 14c.

Supplementary Figure S 43. $^{13}$C NMR spectrum of 14c.
Supplementary Figure S 44. $^1$H NMR spectrum of 14d.

Supplementary Figure S 45. $^{13}$C NMR spectrum of 14d.
Supplementary Figure S 46. $^1$H NMR spectrum of 14e.

Supplementary Figure S 47. $^{13}$C NMR spectrum of 14e.
Supplementary Figure S 48. $^1$H NMR spectrum of 14f.
**Supplementary Figure S 50.** $^1$H NMR spectrum of 14g.

**Supplementary Figure S 51.** $^{13}$C NMR spectrum of 14g.
Supplementary Figure S 52. $^1$H NMR spectrum of 14h.

Supplementary Figure S 53. $^{13}$C NMR spectrum of 14h.
**Supplementary Figure S 54.** $^1$H NMR spectrum of 14i.

**Supplementary Figure S 55.** $^{13}$C NMR spectrum of 14i.
Supplementary Figure S 56. $^1$H NMR spectrum of 14j.

Supplementary Figure S 57. $^{13}$C NMR spectrum of 14j.
Supplementary Figure S 58. $^1$H NMR spectrum of 14k.

Supplementary Figure S 59. $^{13}$C NMR spectrum of 14k.
Supplementary Figure S 60. $^1$H NMR spectrum of 14l.

Supplementary Figure S 61. $^{13}$C NMR spectrum of 14l.
**Supplementary Figure S 62.** $^1$H NMR spectrum of 14m'.

**Supplementary Figure S 63.** $^{13}$C NMR spectrum of 14m'.
Supplementary Figure S 64. $^1$H NMR spectrum of 15.

Supplementary Figure S 65. $^{13}$C (J-MOD) NMR spectrum of 15.
Supplementary Figure S 66: $^1$H NMR spectrum of 16a.

Supplementary Figure S 67: $^1$H NMR spectrum of 16b.
Supplementary Figure S 68. Representative $^1$H NMR spectrum of a mixture of 16a and 16b resulting obtained directly from a catalysed reaction, includes internal standard (methyl 3,5-dinitrobenzoate), corresponding to Table 2, entry 1, main text.

Supplementary Figure S 69. Overlapping resonance that prevents accurate determination of the proportion of minor regioisomer from NMR spectroscopic analysis (Table 2, entry 1, main text). Signal at 4.08 ppm internal standard 3,5-dinitrobenzoate. Signal at 3.69 benzylic methylene of 16b.
Supplementary Figure S 70. Representative $^1$H NMR spectrum of a mixture of 16a and 16b resulting obtained directly from a catalysed reaction, includes internal standard (methyl 3,5-dinitrobenzoate), corresponding to Table 2, entry 2, main text.
**Supplementary Figure S 71.** $^1$H NMR spectrum of S2.

**Supplementary Figure S 72.** $^{13}$C NMR spectrum of S2.
Supplementary Figure S 73. $^1$H NMR spectrum of S3.

Supplementary Figure S 74. $^{13}$C NMR spectrum of S3.
Supplementary Figure S 75. $^{31}$P NMR spectrum of S3.
Supplementary Figure S 78. $^1$H NMR spectrum of S8a.

Supplementary Figure S 79. $^{13}$C NMR spectrum of S8a.
Supplementary Figure S 80. $^1$H NMR spectrum of S8b.

Supplementary Figure S 81. $^{13}$C NMR spectrum of S8b.
Supplementary Figure S 82. $^1$H NMR spectrum of S8c.

Supplementary Figure S 83. $^{13}$C NMR spectrum of S8c.
Supplementary Figure S 84. $^1$H NMR spectrum of Std.

Supplementary Figure S 85. $^{13}$C NMR spectrum of Std.
X-Ray Crystallographic Information

The datasets were measured on an Agilent SuperNova diffractometer using an Atlas detector. The data collections were driven and processed and absorption corrections were applied using CrystAlisPro. All structure were solved using ShelXT. All structures were refined by a full-matrix least-squares procedure on F^2 in ShelXL. All non-hydrogen atoms were refined with anisotropic displacement parameters. All hydrogen atoms were added at calculated positions and refined by use of a riding model with isotropic displacement parameters based on the equivalent isotropic displacement parameter (Ueq) of the parent atom. Reports were produced using OLEX2.

The CIFs for 4a, 4b, 5, 8a, 8b, 9a, 9b, 10, 11, 12 and S5 have been deposited with the CCDC and have been given the deposition numbers 1922101-1922111 respectively. These numbers contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

Compound 4a
C_{22}H_{23}N_{6}P (M = 402.43 g/mol): monoclinic, space group P2_1/n (no. 14), a = 8.5878(6) Å, b = 30.5588(18) Å, c = 8.7236(7) Å, β = 115.922(9)°, V = 2059.0(3) Å^3, Z = 4, T = 100.01(10) K, μ(CuKα) = 1.343 mm^{-1}, Dcalc = 1.298 g/cm^3, 7580 reflections measured (11.584° ≤ θ ≤ 143.892°), 3925 unique (Rint = 0.0346, Rsigma = 0.0518) which were used in all calculations. The final R1 was 0.0467 (I > 2σ(I)) and wR2 was 0.1327 (all data).

Compound 4b
C_{22}H_{17}N_{6}P (M = 396.38 g/mol): triclinic, space group P-1 (no. 2), a = 8.8796(11) Å, b = 10.1744(12) Å, c = 11.6292(13) Å, α = 74.241(10)°, β = 75.180(10)°, γ = 87.296(10)°, V = 977.2(2) Å^3, Z = 2, T = 100.00(10) K, μ(MoKα) = 0.162 mm^{-1}, Dcalc = 1.347 g/cm^3, 7802 reflections measured (6.762° ≤ θ ≤ 52.742°), 3983 unique (Rint = 0.0301, Rsigma = 0.0495) which were used in all calculations. The final R1 was 0.0481 (I > 2σ(I)) and wR2 was 0.1300 (all data).

Compound 5
C_{24}H_{18}N_{9}P, (CH_{3}COCH_{3}) (M = 521.52 g/mol): triclinic, space group P-1 (no. 2), a = 10.2901(4) Å, b = 10.5099(5) Å, c = 13.7597(7) Å, α = 101.908(4)°, β = 110.581(4)°, γ = 93.969(4)°, V = 1346.71(11) Å^3, Z = 2, T = 100.01(10) K, μ(MoKα) = 0.140 mm^{-1}, Dcalc = 1.286 g/cm^3, 10967 reflections measured (5.394° ≤ θ ≤ 59.17°), 6298 unique (Rint = 0.0248, Rsigma = 0.0448) which were used in all calculations. The final R1 was 0.0454 (I > 2σ(I)) and wR2 was 0.1080 (all data).
Compound 8a

C₂₀H₂₈N₃PClAu (M = 573.84 g/mol): triclinic, space group P-1 (no. 2), a = 9.3253(3) Å, b = 10.7200(5) Å, c = 11.7307(7) Å, α = 108.817(5)°, β = 98.520(4)°, γ = 103.935(4)°, V = 1044.28(9) Å³, Z = 2, T = 100.01(10) K, μ(MoKα) = 7.257 mm⁻¹, Dcalc = 1.825 g/cm³, 9349 reflections measured (6.726° ≤ 2θ ≤ 58.854°), 4915 unique (Rint = 0.0334, Rsigma = 0.0513) which were used in all calculations. The final R₁ was 0.0277 (I > 2σ(I)) and wR₂ was 0.0538 (all data).

Supplementary Figure S 86. Phenyl centroid metal distances in 8a 3.502 Å. Shortest intermolecular Au…Cl distance 5.550 Å

Compound 8b

C₂₀H₁₆AuClN₃P (M = 561.74 g/mol): triclinic, space group P-1 (no. 2), a = 9.1495(3) Å, b = 13.5665(5) Å, c = 15.9837(6) Å, α = 77.761(3)°, β = 82.352(3)°, γ = 79.954(3)°, V = 1899.64(12) Å³, Z = 4, T = 100.01(10) K, μ(MoKα) = 7.978 mm⁻¹, Dcalc = 1.964 g/cm³, 19415 reflections measured (5.242° ≤ 2θ ≤ 58.738°), 9018 unique (Rint = 0.0251, Rsigma = 0.0395) which were used in all calculations. The final R₁ was 0.0342 (I > 2σ(I)) and wR₂ was 0.0621 (all data).

Supplementary Figure S 87. Centroid metal distances of the two molecules 8b within the unit cell 3.664 Å and 3.365 Å. Shortest intermolecular Au…Cl distance 3.649 Å.
Compound 9a

\( \text{C}_{22}\text{H}_{23}\text{AuClN}_{6}\text{P} \) (\( M = 634.85 \) g/mol): monoclinic, space group \( \text{P}_2_1/\text{n} \) (no. 14), \( a = 15.1740(13) \) Å, \( b = 9.0970(5) \) Å, \( c = 17.9495(17) \) Å, \( \beta = 114.837(11)^\circ \), \( V = 2248.5(4) \) Å\(^3\), \( Z = 4 \), \( T = 100.01(10) \) K, \( \mu(\text{CuK}\alpha) = 14.241 \) mm\(^{-1}\), \( \text{D}_{\text{calc}} = 1.875 \) g/cm\(^3\), 25510 reflections measured (10.002° ≤ 2\( \theta \) ≤ 136.466°), 4116 unique (\( R_{\text{int}} = 0.0965 \), \( R_{\text{sigma}} = 0.0400 \)) which were used in all calculations. The final \( R_1 \) was 0.0366 (I > 2\( \sigma(I) \)) and \( wR_2 \) was 0.1032 (all data).

**Supplementary Figure S 88.** Phenyl centroid metal distances in 9a 3.513 Å and 3.517 Å. Shortest intermolecular Au...Cl distance 6.585 Å.

Compound 9b

\( \text{C}_{22}\text{H}_{17}\text{N}_{6}\text{PClAu} \) (\( M = 628.80 \) g/mol): monoclinic, space group \( \text{P}_2_1/\text{c} \) (no. 14), \( a = 8.2902(2) \) Å, \( b = 14.1064(4) \) Å, \( c = 19.1489(6) \) Å, \( \beta = 99.717(3)^\circ \), \( V = 2207.24(11) \) Å\(^3\), \( Z = 4 \), \( T = 100.01(10) \) K, \( \mu(\text{CuK}\alpha) = 14.506 \) mm\(^{-1}\), \( \text{D}_{\text{calc}} = 1.892 \) g/cm\(^3\), 8034 reflections measured (7.824° ≤ 2\( \theta \) ≤ 143.504°), 4217 unique (\( R_{\text{int}} = 0.0314 \), \( R_{\text{sigma}} = 0.0405 \)) which were used in all calculations. The final \( R_1 \) was 0.0277 (I > 2\( \sigma(I) \)) and \( wR_2 \) was 0.0719 (all data).

**Supplementary Figure S 89.** Phenyl centroid metal distances in 9b 3.662 Å and 4.675 Å. Shortest intermolecular Au...Cl distance 3.377 Å.

Compound 10

\( \text{C}_{24}\text{H}_{18}\text{AuClN}_{9}\text{P}[\text{CH}_2\text{Cl}_2] \) (\( M = 780.79 \) g/mol): triclinic, space group \( \text{P}-\text{1} \) (no. 2), \( a = 10.2434(4) \) Å, \( b = 14.6032(6) \) Å, \( c = 19.0803(7) \) Å, \( \alpha = 92.986(3)^\circ \), \( \beta = 93.407(3)^\circ \), \( \gamma = 100.172(3)^\circ \), \( V = 2798.63(19) \) Å\(^3\), \( Z = 4 \), \( T = 100.00(10) \) K,
$\mu$(MoK$\alpha$) = 5.634 mm$^{-1}$, $D_{calc} = 1.853$ g/cm$^3$, 28543 reflections measured ($4.508^\circ \leq 2\Theta \leq 59.02^\circ$), 13281 unique ($R_{int} = 0.0252$, $R_{sigma} = 0.0392$) which were used in all calculations. The final $R_1$ was 0.0253 ($I > 2\sigma(I)$) and $wR_2$ was 0.0544 (all data).

**Supplementary Figure S 90.** Centroid metal distances of the two molecules 10 within the unit cell: (3.456 Å, 3.581 Å and 3.634 Å) and (3.351 Å, 3.692 Å and 3.759 Å). Shortest intermolecular Au...Cl distance 7.365 Å.

Compound 11

C$_{22}$H$_{32}$AuCl$_{3}$N$_{3}$O$_{2}$P[CHCl$_{3}$] ($M$ = 753.26 g/mol): monoclinic, space group P2$_1$/c (no. 14), $a = 16.3596(7)$ Å, $b = 19.1615(7)$ Å, $c = 9.1916(4)$ Å, $\beta = 94.769(4)^\circ$, $V = 2871.4(2)$ Å$^3$, $Z = 4$, $T = 100.01(10)$ K, $\mu$(CuK$\alpha$) = 13.785 mm$^{-1}$, $D_{calc} = 1.742$ g/cm$^3$, 10995 reflections measured ($7.12^\circ \leq 2\Theta \leq 140.136^\circ$), 5404 unique ($R_{int} = 0.0587$, $R_{sigma} = 0.0713$) which were used in all calculations. The final $R_1$ was 0.0527 ($I > 2\sigma(I)$) and $wR_2$ was 0.1441 (all data).

**Supplementary Figure S 91.** Phenyl centroid metal distance in 11 3.708 Å. Shortest intermolecular Au...Cl distance 6.983 Å.
Compound 12

C_{44}H_{40}AuClN_{6}O_{4}P_{2}, 3(CH_{2}Cl_{2}) (M = 1265.95 g/mol): monoclinic, space group P2_{1}/c (no. 14), a = 11.7669(5) Å, b = 41.4044(10) Å, c = 11.5627(4) Å, β = 115.166(5)°, V = 5098.6(4) Å³, Z = 4, T = 100.01(10) K, µ(MoKα) = 3.364 mm⁻¹, \(D_{calc} = 1.649 \text{ g/cm}^3\), 28129 reflections measured (4.362° ≤ 2θ ≤ 52.742°), 10437 unique \((R_{int} = 0.0360, R_{sigma} = 0.0493)\) which were used in all calculations. The final \(R_1\) was 0.0320 (I > 2σ(I)) and \(wR_2\) was 0.0575 (all data).

**Supplementary Figure S 92.** Centroid metal distances of the two molecules of 12 within the unit cell, 3.770 Å and 3.604 Å.
Compound **S5** (S-Phos Gold(I) chloride complex)

C_{52}H_{70}Au_2Cl_2O_4P_2 , (CH_2Cl_2) \((M = 1370.77 \text{ g/mol})\): triclinic, space group P-1 (no. 2), \(a = 10.0987(3) \text{ Å}, b = 12.4469(4) \text{ Å}, c = 22.7136(7) \text{ Å}, \alpha = 96.723(3)^\circ, \beta = 99.291(2)^\circ, \gamma = 107.669(2)^\circ, V = 2642.47(15) \text{ Å}^3, Z = 2, \ T = 100.01(10) \text{ K}, \mu(\text{MoK}) = 5.852 \text{ mm}^{-1}, \text{Dcalc} = 1.723 \text{ g/cm}^3, 27290 \text{ reflections measured (5.044}^\circ \leq \Theta \leq 52.744^\circ), 10815 \text{ unique (Rint = 0.0259, } R_{\sigma} = 0.0358) \text{ which were used in all calculations. The final } R_1 \text{ was 0.0224 (I > 2}\sigma(I)) \text{ and } wR_2 \text{ was 0.0418 (all data). This structure has been reported previously by Rabaa et al. from a twinned dataset measured at 200 K.}^{[26]} \text{ The structure presented here is refined from a dataset measured at 100 K from a single crystal.}

**Supplementary Figure S 93.**

**Supplementary Figure S 94.** Centroid metal distances of the two molecules of S5 within the unit cell, 3.365 Å and 3.429. Shortest intermolecular Au…Cl distance 6.445 Å.
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