

Title: Mathematica - Lecture 3b

Date: Dec 10, 2012 10:30 AM

URL: <http://www.pirsa.org/12120021>

Abstract:

X_{Times}
 $\{\}$ vs 1

```
wick[X_Times] :=
Block[{list = List @@ X},
  Length[list]
  Sum[<list[[1]], list[[j]]> wick[Times @@ Drop[Drop[list, {j}], 1]],
    {j, 2}
]
wick[phi[a_] phi[b_]] := <phi[a], phi[b]>
```

Example:

In[185]:=

```
wick[phi[k1] phi[k2] phi[k3] phi[k4] + phi[k1] phi[k2]]
```

Out[185]=

```
wick[phi[k1] phi[k2] + phi[k1] phi[k2] phi[k3] phi[k4]]
```

In[181]:=

```
ClearAll[tograph]
tograph[term_] :=
tograph[term] = List @@ term /. <phi[k[a_]], phi[k[b_]]> => Rule[a[[0]], b[[0]] //
  GraphPlot[#, VertexLabeling -> True, ImageSize -> 200] /.
  Text[Framed[c___], b___] /; ! NumericQ[{c}][1] => Text[""] &
```


■ Function and Notation

X_Times
{} vs 1

```
wick[X_Times] :=
Block[{list = List @@ X},
Length[list]
Sum[<list[[1]], list[[j]]> wick[Times @@ Drop[Drop[list, {j}], 1]],
j=2]
wick[φ[a_] φ[b_]] := <φ[a], φ[b]>
```

Example:

In[185]:=

```
wick[φ[k1] φ[k2] φ[k3] φ[k4] + φ[k1] φ[k2]]
```

Out[185]=

```
wick[φ[k1] φ[k2] + φ[k1] φ[k2] φ[k3] φ[k4]]
```

In[181]:=

```
ClearAll[tograph]
tograph[term_] :=
```

$\{\}$ vs 1

```
wick[X_Times] :=  
Block[{list = List @@ X},  
  Length[list]  
  Sum[<list[[1]], list[[j]]> wick[Times @@ Drop[Drop[list, {j}], 1]],  
  {j, 2}]]  
wick[φ[a_] φ[b_]] := <φ[a], φ[b]>
```

Example:

In[191]:=

```
wick[φ[k1] φ[k2] φ[k3] φ[k4]]
```

Out[191]=

$$\langle \phi[k_1], \phi[k_4] \rangle \langle \phi[k_2], \phi[k_3] \rangle + \langle \phi[k_1], \phi[k_3] \rangle \langle \phi[k_2], \phi[k_4] \rangle + \langle \phi[k_1], \phi[k_2] \rangle \langle \phi[k_3], \phi[k_4] \rangle$$

In[181]:=

```
ClearAll[tograph]  
tograph[term_] :=  
  tograph[term] = List @@ term /. <φ[k[a_]], φ[k[b_]]> => Rule[a[[0]], b[[0]]] //  
  GraphPlot[#, VertexLabeling -> True, ImageSize -> 200] /.  
    Text[Framed[c___], b___] /; ! NumericQ[{c}[[1]]] => Text[""] &
```


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$\sum_{j=2}$

```
wick[ $\phi[a_]$   $\phi[b_]$ ] :=  $\langle \phi[a], \phi[b] \rangle$ 
```

Example:

In[191]:=

```
wick[ $\phi[k_1]$   $\phi[k_2]$   $\phi[k_3]$   $\phi[k_4]$ ]
```

Out[191]=

$$\langle \phi[k_1], \phi[k_4] \rangle \langle \phi[k_2], \phi[k_3] \rangle + \langle \phi[k_1], \phi[k_3] \rangle \langle \phi[k_2], \phi[k_4] \rangle + \langle \phi[k_1], \phi[k_2] \rangle \langle \phi[k_3], \phi[k_4] \rangle$$

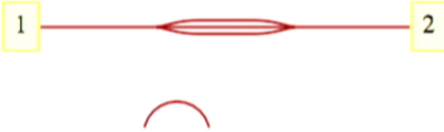
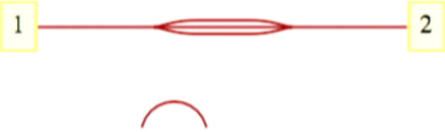
In[192]:=

```
ClearAll[tograph]
tograph[term_] :=
  tograph[term] = List @@ term /.  $\langle \phi[k[a_]], \phi[k[b_]] \rangle$  => Rule[a[[0]], b[[0]]] //
  GraphPlot[#, VertexLabeling -> True, ImageSize -> 200] /.
  Text[Framed[c___], b___] /; ! NumericQ[{c}[[1]]] => Text[""] &
```

In[184]:=

```
tograph /@ wickcontracted
```

Out[184]=

96  + 96  +

200%

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$\sum_{j=2}$

`wick[ $\phi[a_]$   $\phi[b_]$ ] :=  $\langle \phi[a], \phi[b] \rangle$`

Example:

In[191]:=

`wick[ $\phi[k_1]$   $\phi[k_2]$   $\phi[k_3]$   $\phi[k_4]$ ]`

Out[191]=

$\langle \phi[k_1], \phi[k_4] \rangle \langle \phi[k_2], \phi[k_3] \rangle + \langle \phi[k_1], \phi[k_3] \rangle \langle \phi[k_2], \phi[k_4] \rangle + \langle \phi[k_1], \phi[k_2] \rangle \langle \phi[k_3], \phi[k_4] \rangle$

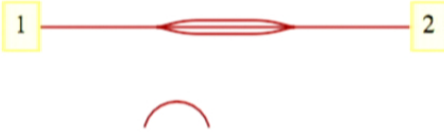
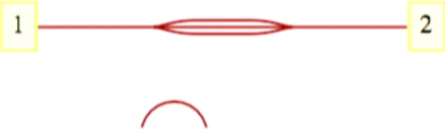
In[192]:=

`ClearAll[tograph]
tograph[term_] :=
 tograph[term] = List @@ term /. $\langle \phi[k[a_]], \phi[k[b_]] \rangle \rightarrow$ Rule[a[[0]], b[[0]]] //
 GraphPlot[#, VertexLabeling -> True, ImageSize -> 200] /.
 Text[Framed[c___], b___] /; ! NumericQ[{c}][[1]] -> Text[""] &`

In[184]:=

`tograph /@ wickcontracted`

Out[184]=

96  + 96  +

200%

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$\sum_{j=2}$

`wick[ $\phi[a_]$   $\phi[b_]$ ] :=  $\langle \phi[a], \phi[b] \rangle$`

Example:

In[191]:=

`wick[ $\phi[k_1]$   $\phi[k_2]$   $\phi[k_3]$   $\phi[k_4]$ ]`

Out[191]=

$\langle \phi[k_1], \phi[k_4] \rangle \langle \phi[k_2], \phi[k_3] \rangle + \langle \phi[k_1], \phi[k_3] \rangle \langle \phi[k_2], \phi[k_4] \rangle + \langle \phi[k_1], \phi[k_2] \rangle \langle \phi[k_3], \phi[k_4] \rangle$

`List @@ wickcontra /.  $\langle \phi[k[a_]], \phi[k[b_]] \rangle \rightarrow$  Rule[a[[0]], b[[0]]]`

In[192]:=

`ClearAll[tograph]
tograph[term_] :=
tograph[term] = List @@ term /. $\langle \phi[k[a_]], \phi[k[b_]] \rangle \rightarrow$ Rule[a[[0]], b[[0]]] //
GraphPlot[#, VertexLabeling -> True, ImageSize -> 200] /.
Text[Framed[c___], b___] /; ! NumericQ[{c}][[1]] -> Text[""] &`

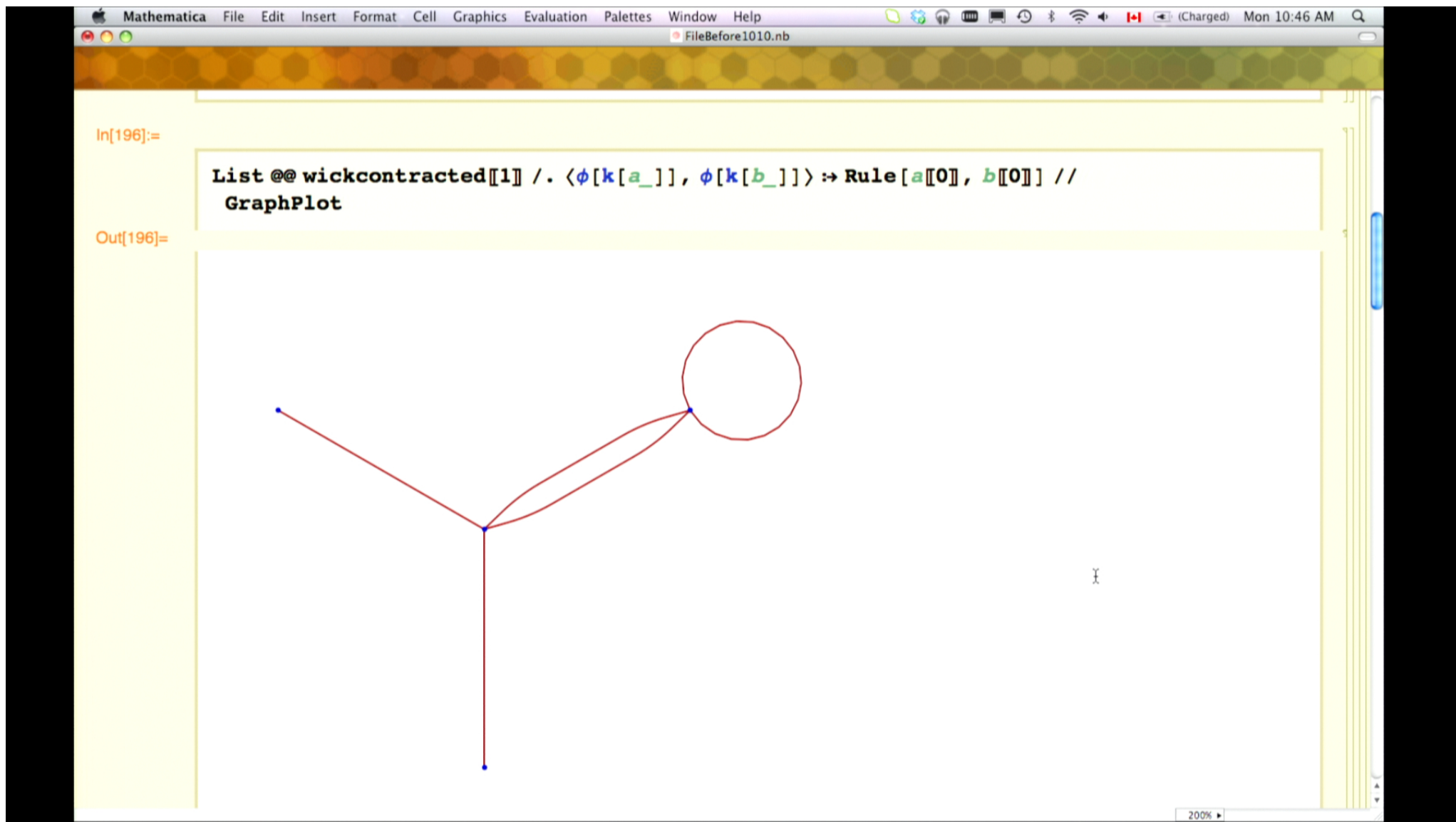
In[184]:=

`tograph /@ wickcontracted`

Out[184]=

q_6 1 --- 2 $\perp$ q_6 1 --- 2 $\perp$

200%



```
List @@ wickcontracted[1] /. <math display="block">\phi[k[a\_]], \phi[k[b\_]]> \Rightarrow \text{Rule}[a[0], b[0]] //
```

GraphPlot

In[192]:=

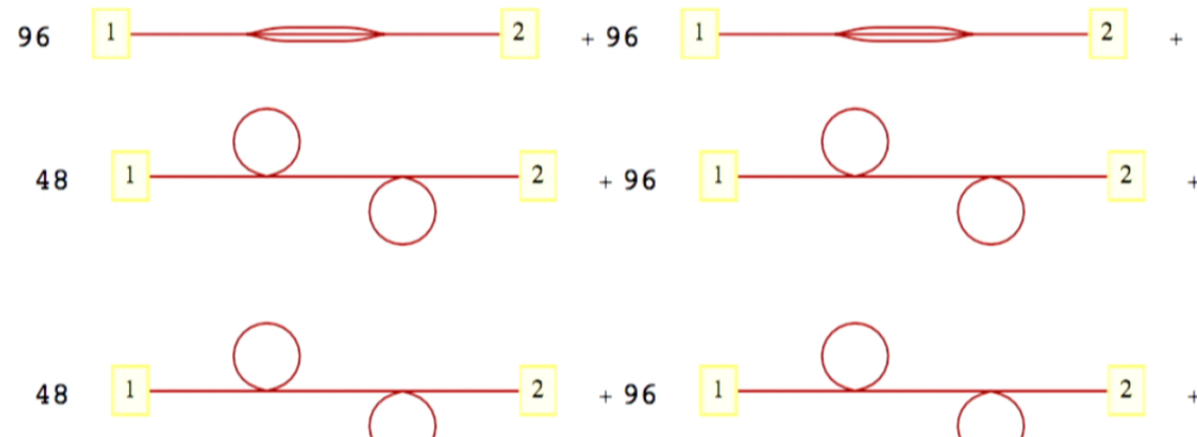
```
ClearAll[tograph]
tograph[term_] :=
  tograph[term] = List @@ term /. <math display="block">\phi[k[a\_]], \phi[k[b\_]]> \Rightarrow \text{Rule}[a[0], b[0]] //
```

GraphPlot[#, VertexLabeling → True, ImageSize → 200] /.
Text[Framed[c___], b___] /; ! NumericQ[{c}[1]] => Text[""] &

In[184]:=

tograph /@ wickcontracted

Out[184]=



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```
tograph[term] = List @@ term /. <math>\phi[k[a\_]], \phi[k[b\_]]> \Rightarrow \text{Rule}[a[[0]], b[[0]]] //
```

```
GraphPlot[#, VertexLabeling -> True, ImageSize -> 200] /.  
Text[Framed[c___], b___] /; ! NumericQ[{c}][1] => Text[""] &
```

In[201]:=

```
? tograph
```

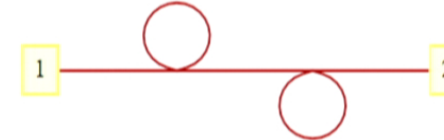
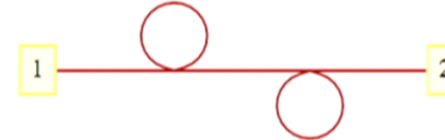
Global` tograph

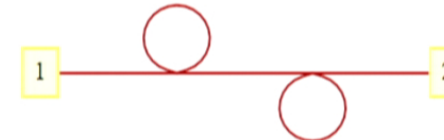
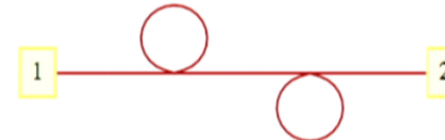
In[200]:=

```
tograph /@ wickcontracted
```

Out[200]=

96  + 96  +

48  + 96  +

48  + 96  +

200%

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```
tograph[term] = List @@ term /. <math display="block">\phi[k[a]], \phi[k[b]]> \Rightarrow \text{Rule}[a[[0]], b[[0]]] //
```

```
GraphPlot[#, VertexLabeling -> True, ImageSize -> 200] /.
Text[Framed[c___], b___] /; ! NumericQ[{c}[1]] => Text[""] &
```

In[201]:=

? tograph

Global` tograph

```
tograph[<math display="block">\phi[k_1[]], \phi[k_{\alpha\$805[4]}]> <math display="block">\phi[k_2[]], \phi[k_{\alpha\$805[3]}]>
```

```
<math display="block">\phi[k_{\alpha\$804[1]}], \phi[k_{\alpha\$805[2]}]> <math display="block">\phi[k_{\alpha\$804[2]}], \phi[k_{\alpha\$805[1]}]> <math display="block">\phi[k_{\alpha\$804[3]}], \phi[k_{\alpha\$804[4]}]>] =
```

```
Graphics[Annotation[GraphicsComplex[{{0., 1.5}, {0.866025, 1.}, {0.866025, 0.},
```

```
{1.73205, 1.5}, {1.65574, 1.42621}, {1.63496, 1.40681}, {1.61351, 1.38815},
```

```
{1.59143, 1.37025}, {1.56873, 1.35314}, {1.54545, 1.33683}, {1.52161, 1.32134},
```

```
{1.49724, 1.3067}, {1.15083, 1.1067}, {1.12597, 1.09292}, {1.10064, 1.08002},
```

```
{1.07487, 1.06801}, {1.0487, 1.05691}, {1.02216, 1.04673}, {0.995277, 1.03749},
```

```
{0.968087, 1.0292}, {1.62999, 1.4708}, {1.6028, 1.46251}, {1.57592, 1.45327},
```

```
{1.54937, 1.44309}, {1.5232, 1.43199}, {1.49744, 1.41998}, {1.47211, 1.40708},
```

```
{1.44724, 1.3933}, {1.10083, 1.1933}, {1.07647, 1.17866}, {1.05263, 1.16317},
```

```
{1.02935, 1.14686}, {1.00665, 1.12975}, {0.984564, 1.11185}, {0.963119, 1.09319},
```

```
{0.94234, 1.07379}, {1.73014, 1.50343}, {1.70482, 1.56955}, {1.69904, 1.64011},
```

```
{1.71328, 1.70946}, {1.7464, 1.77204}, {1.79573, 1.82283}, {1.85732, 1.85774},
```

```
{1.92623, 1.87399}, {1.99693, 1.87027}, {2.06375, 1.84687}, {2.12134, 1.80568},
```

```
{2.16506, 1.75}, {2.19142, 1.68429}, {2.1983, 1.61383}, {2.18515, 1.54426},
```

```
{2.15303, 1.48117}, {2.1045, 1.42961}, {2.04347, 1.39373}, {1.97482, 1.37641},
```

```
{1.90407, 1.37902}, {1.83689, 1.40136}, {1.77866, 1.44164}, {1.73407, 1.49663}],
```

200%

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```

60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 4}, {4, 74, 75, 76, 77,
78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 4}}]],
{Text[Framed[1, {Background → RGBColor[1, 1, 0.8], FrameStyle →
  RGBColor[0.94, 0.85, 0.36], FrameMargins → Automatic}], 1],
Text[Framed[2, {Background → RGBColor[1, 1, 0.8], FrameStyle → RGBColor[
  0.94, 0.85, 0.36], FrameMargins → Automatic}], 2], Text[], Text[]], {}],
VertexCoordinateRules → {{2.62503, -0.208343}, {1.62503, -0.208343},
{0.708343, -0.708343}, {0.708343, -2.12503}}],
FrameTicks → None, PlotRange → All, PlotRangePadding → Scaled[0.1],
AspectRatio → Automatic,
ImageSize → 200]

tograph[term_] :=
tograph[term] = (GraphPlot[#, VertexLabeling → True, ImageSize → 200] /.
Text[Framed[c___], b___] /; ! NumericQ[{c}][[1]] => Text[] &) [
List @@ term /. {φ[ka], φ[kb]} => a[[0] → b[[0]]]

```

In[200]:=

tograph /@ wickcontracted

Out[200]=

96  + 96  +

 a  b

200%

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```
tograph[term] = List @@ term /. <math display="block">\phi[k[a\_]], \phi[k[b\_]]> \Rightarrow \text{Rule}[a[[0]], b[[0]]] //
```

```
GraphPlot[#, VertexLabeling -> True, ImageSize -> 200] /.  
Text[Framed[c___], b___] /; ! NumericQ[{c}][1] -> Text[""] &
```

In[202]:=

Out[202]=

tograph /@ wickcontracted

96 + 96 +

48 + 96 +

48 + 96 +

200%

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144

72

+ 72

+ 24

200%

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144

1

2

+ 72

1

2

+

72

1

2

+ 24

2

1

+

200%

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144

1

2

+ 72

1

2

+

72

1

2

+ 24

2

1

+

200%

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In[196]:=

```
List @@ wickcontracted[[1]] /. <math>\phi[k[a\_]], \phi[k[b\_]]> \Rightarrow \text{Rule}[a[[0]], b[[0]]] // \text{GraphPlot}
```

In[197]:=

```
ClearAll[tograph]
tograph[term_] :=
  tograph[term] = List @@ term /. <math>\phi[k[a\_]], \phi[k[b\_]]> \Rightarrow \text{Rule}[a[[0]], b[[0]]] //
    GraphPlot[#, VertexLabeling \rightarrow \text{True}, ImageSize \rightarrow 200] /.
      Text[Framed[c___], b___] /; ! NumericQ[{c}[[1]]] \Rightarrow \text{Text}[""] &

tograph /@ wickcontracted;
```

■ Computing the Wick contractions

In[7]:=

```
<< Notation`
```

In[9]:=

```
Notation[ ki  $\Leftrightarrow$  k[i_] ]
```

```
(* vertex[n_, α_] :=  $\prod_{j=1}^n \phi[k_{\alpha[j]}]$ ; *)
```

```
vertex[n_] := Block[{letter = Unique[α]},  $\prod_1^n \phi[k_{\text{letter}[j]}]$ ]
```

200%

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In[196]:=

```
List @@ wickcontracted[l] /. <math display="block">\phi[k[a\_]], \phi[k[b\_]]> \Rightarrow \text{Rule}[a[[0]], b[[0]]] // \text{GraphPlot}
```

dummy =

In[197]:=

```
ClearAll[tograph]
tograph[term_] :=
  tograph[term] = List @@ term /. <math display="block">\phi[k[a\_]], \phi[k[b\_]]> \Rightarrow \text{Rule}[a[[0]], b[[0]]] //
  \text{GraphPlot}[\#, \text{VertexLabeling} \rightarrow \text{True}, \text{ImageSize} \rightarrow 200] /.
  \text{Text}[\text{Framed}[c\_\_\_], b\_\_\_] /; ! \text{NumericQ}[\{c\}[[1]]] \Rightarrow \text{Text}[""] \&
```

tograph /@ wickcontracted;

■ Computing the Wick contractions

In[7]:=

```
<< Notation`
```

In[9]:=

```
Notation[ ki  $\Leftrightarrow$  k[i_] ]
```

(* vertex[n, α] := $\prod_{i=1}^n \phi[k_{\alpha[i+1]}]$; *)

200%

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In[196]:=

```
List @@ wickcontracted[[1]] /. <math display="block">\phi[k[a\_]], \phi[k[b\_]]> \Rightarrow \text{Rule}[a[[0]], b[[0]]] // \text{GraphPlot}
```

In[205]:=

```
dummy = Union@Cases[wickcontracted, ka[b_] => a /; ! NumericQ[a], ∞]
Permutations[dummy]
```

Out[205]=

```
{α$804, α$805}
```

Out[206]=

```
{{α$804, α$805}, {α$805, α$804}}
```

In[197]:=

```
ClearAll[tograph]
tograph[term_] :=
  tograph[term] = List @@ term /. <math display="block">\phi[k[a\_]], \phi[k[b\_]]> \Rightarrow \text{Rule}[a[[0]], b[[0]]] //
    \text{GraphPlot}[\#, \text{VertexLabeling} \rightarrow \text{True}, \text{ImageSize} \rightarrow 200] /.
      \text{Text}[\text{Framed}[c\_\_\_], b\_\_\_] /; ! \text{NumericQ}[\{c\}[[1]]] \Rightarrow \text{Text}[""] \&

tograph /@ wickcontracted;
```

■ Computing the Wick contractions

200%

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In[196]:=

```
List @@ wickcontracted[[1]] /. <math display="block">\phi[k[a\_]], \phi[k[b\_]]> \Rightarrow \text{Rule}[a[[0]], b[[0]]] // \text{GraphPlot}
```

In[205]:=

```
dummy = Union@Cases[wickcontracted, ka[b_] => a /; ! NumericQ[a], ∞]
Permutations[dummy]
```

Out[205]=

```
{α$804, α$805}
```

Out[206]=

```
{{α$804, α$805}, {α$805, α$804}}
```

In[197]:=

```
ClearAll[tograph]
tograph[term_] :=
  tograph[term] = List @@ term /. <math display="block">\phi[k[a\_]], \phi[k[b\_]]> \Rightarrow \text{Rule}[a[[0]], b[[0]]] //
    \text{GraphPlot}[\#, \text{VertexLabeling} \rightarrow \text{True}, \text{ImageSize} \rightarrow 200] /.
      \text{Text}[\text{Framed}[c\_\_\_], b\_\_\_] /; ! \text{NumericQ}[\{c\}[[1]]] \Rightarrow \text{Text}[""] \&

tograph /@ wickcontracted;
```

■ Computing the Wick contractions

200%

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In[196]:=

```
List @@ wickcontracted[[1]] /. <math display="block">\phi[k[a\_]], \phi[k[b\_]]> \Rightarrow \text{Rule}[a[[0]], b[[0]]] // \text{GraphPlot}
```

In[215]:=

```
listdummy := Block[{dummy, permutations},
  dummy = Union@Cases[wickcontracted, ka[b_]  $\Rightarrow$  a /; ! NumericQ[a],  $\infty$ ];
  permutations = Permutations[dummy];
  relabelings = Table[dummy[[j]]  $\rightarrow$  permutations[[k, j]], {k, Length[permutations]},
    {j, Length[dummy]}];
]
```

In[216]:=

```
listdummy
```

In[218]:=

```
relabelings
```

Out[218]=

```
{ { $\alpha_{804} \rightarrow \alpha_{804}$ ,  $\alpha_{805} \rightarrow \alpha_{805}$ }, { $\alpha_{804} \rightarrow \alpha_{805}$ ,  $\alpha_{805} \rightarrow \alpha_{804}$ } }
```

In[197]:=

```
ClearAll[tograph]
tograph[term] :=
```

200%

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In[196]:=

```
List @@ wickcontracted[[1]] /. <math display="block">\phi[k[a]], \phi[k[b]]> \Rightarrow \text{Rule}[a[[0]], b[[0]]] // \text{GraphPlot}
```

In[215]:=

```
listdummy := Block[{dummy, permutations},
  dummy = Union@Cases[wickcontracted, ka[b]  $\Rightarrow$  a /; ! NumericQ[a],  $\infty$ ];
  permutations = Permutations[dummy];
  relabelings = Table[dummy[[j]]  $\rightarrow$  permutations[[k, j]], {k, Length[permutations]},
    {j, Length[dummy]}];
]
```

In[216]:=

```
listdummy
```

In[218]:=

```
relabelings
```

Out[218]=

```
{ { $\alpha_{804} \rightarrow \alpha_{804}$ ,  $\alpha_{805} \rightarrow \alpha_{805}$ }, { $\alpha_{804} \rightarrow \alpha_{805}$ ,  $\alpha_{805} \rightarrow \alpha_{804}$ } }
```

In[197]:=

```
ClearAll[tograph]
tograph[term] :=
```

200%

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In[196]:=

```
List @@ wickcontracted[l] /. <math display="block">\phi[k[a\_]], \phi[k[b\_]] \rangle \Rightarrow \text{Rule}[a[[0]], b[[0]]] // \text{GraphPlot}
```

In[220]:=

```
listdummy := Block[{dummy, permutations},
  dummy = Union@Cases[wickcontracted, ka[b_]  $\Rightarrow$  a /; ! NumericQ[a],  $\infty$ ];
  permutations = Permutations[dummy];
  relabelings = Table[dummy[[j]]  $\rightarrow$  permutations[[k, j]], {k, Length[permutations]},
    {j, Length[dummy]}];
]
```

In[216]:=

```
listdummy
```

In[218]:=

```
relabelings
```

Out[218]=

```
{ { $\alpha_{804} \rightarrow \alpha_{804}$ ,  $\alpha_{805} \rightarrow \alpha_{805}$ }, { $\alpha_{804} \rightarrow \alpha_{805}$ ,  $\alpha_{805} \rightarrow \alpha_{804}$ } }
```

In[197]:=

```
ClearAll[tograph]
tograph[term] :=
```

200%

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```

relabelings = Table[dummy[[j]] → permutations[[k, j]], {k, Length[permutations]},
                    {j, Length[dummy]}};
]

```

In[197]:=

```

ClearAll[tograph]
tograph[term_] :=
  tograph[term] = List @@ term /. <math>\langle \phi[k[a\_]], \phi[k[b\_]] \rangle \Rightarrow \text{Rule}[a[[0]], b[[0]] \text{ // }
    GraphPlot[#, VertexLabeling \rightarrow \text{True}, ImageSize \rightarrow 200] /.
    Text[Framed[c\_], b\_] /; ! NumericQ[{c}][1] \Rightarrow \text{Text}[""] \&

```

tograph /@ wickcontracted;

■ Computing the Wick contractions

In[7]:=

```

<< Notation`

```

In[9]:=

```

Notation[ k_i_ \Leftrightarrow k[i_] ]

(* vertex[n_, \alpha_] := \prod_{j=1}^n \phi[k_{\alpha[j]}]; *)
vertex[n_] := Block[{letter = Unique[\alpha]}, \prod_{j=1}^n \phi[k_{letter[j]}]]

```

200%

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```

relabelings = Table[dummy[[j]] → permutations[[k, j]], {k, Length[permutations]},
  {j, Length[dummy]}};
]

```

In[223]:=

```
listdummy;
```

In[225]:=

↓

```
List @@ wickcontracted[[1]] /. <φ[k[a_]], φ[k[b_]]> ⇒ Rule[a[[0]], b[[0]]]
```

Out[225]=

```
{1 → α$805, 2 → α$805, α$804 → α$805, α$804 → α$805, α$804 → α$804}
```

In[197]:=

```

ClearAll[tograph]
tograph[term_] :=
  tograph[term] = List @@ term /. <φ[k[a_]], φ[k[b_]]> ⇒ Rule[a[[0]], b[[0]] //
    GraphPlot[#, VertexLabeling → True, ImageSize → 200] /.
      Text[Framed[c___], b___] /; ! NumericQ[{c}[[1]]] ⇒ Text[""] &

tograph /@ wickcontracted;

```

■ Computing the Wick contractions

In[7] :=

200%

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```

relabelings = Table[dummy[[j]] → permutations[[k, j]], {k, Length[permutations]},
  {j, Length[dummy]}};
]

```

In[223]:=

```
listdummy;
```

In[226]:=

```
object = List @@ wickcontracted[1] /. <math display="block">\phi[k[a]], \phi[k[b]]> \Rightarrow \text{Rule}[a[[0]], b[[0]]
```

Out[226]=

```
{1 →  $\alpha$ $805, 2 →  $\alpha$ $805,  $\alpha$ $804 →  $\alpha$ $805,  $\alpha$ $804 →  $\alpha$ $805,  $\alpha$ $804 →  $\alpha$ $804}
```

In[197]:=

```

ClearAll[tograph]
tograph[term_] :=
  tograph[term] = List @@ term /. <math display="block">\phi[k[a]], \phi[k[b]]> \Rightarrow \text{Rule}[a[[0]], b[[0]] //
  GraphPlot[#, VertexLabeling → True, ImageSize → 200] /.
    Text[Framed[c___], b___] /; ! NumericQ[{c}][[1]] => Text[""] &

tograph /@ wickcontracted;

```

■ Computing the Wick contractions

In[71]:=

200%

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```

Sort@Rule[1, 3]
Rule[3, 1]
Sort@Rule[3, 1]

```

Out[233]=

$$1 \rightarrow 3$$

Out[234]=

$$3 \rightarrow 1$$

Out[235]=

$$1 \rightarrow 3$$

Out[228]=

```

Table[object /. relabelings[[2]] /. R_Rule -> Sort@R, {j, Length[relabelings]}]

```

$$\{1 \rightarrow \alpha\$804, 2 \rightarrow \alpha\$804, \alpha\$805 \rightarrow \alpha\$804, \alpha\$805 \rightarrow \alpha\$804, \alpha\$805 \rightarrow \alpha\$805\}$$

In[197]:=

```

ClearAll[tograph]
tograph[term_] :=
  tograph[term] = List @@ term /. <math>\phi[k[a\_]], \phi[k[b\_]]> \Rightarrow \text{Rule}[a[[0]], b[[0]]]> //
    GraphPlot[#, VertexLabeling -> True, ImageSize -> 200] /.
      Text[Framed[c___], b___] /; ! NumericQ[{c}[[1]]] -> Text[""] &

```

200%

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1 → 3

In[242]:=

```
CanOrder[object_] :=
  First@Sort@Table[object /. relabelings[[j]] /. R_Rule -> Sort@R,
    {j, Length[relabelings]}]
```

In[250]:=

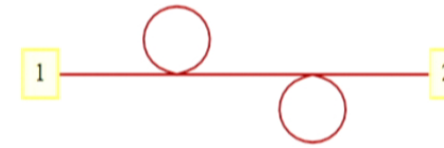
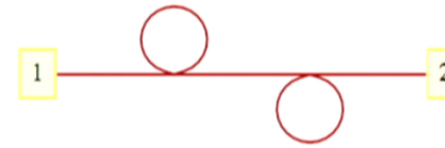
```
ClearAll[tograph]
tograph[term_] :=
  tograph[term] = List @@ term /. <math>\phi[k[a\_]], \phi[k[b\_]]> \rightarrow \text{Rule}[a[[0]], b[[0]]] //
    GraphPlot[# // CanOrder, VertexLabeling -> True, ImageSize -> 200] /.
      Text[Framed[c___], b___] /; ! NumericQ[{c}[[1]]] -> Text[""] &
```

In[252]:=

```
tograph /@ wickcontracted
```

Out[252]=

96  + 96  +

48  + 96  +

200%

$$\langle \phi[k_1], \phi[k_4] \rangle \langle \phi[k_2], \phi[k_3] \rangle + \langle \phi[k_1], \phi[k_3] \rangle \langle \phi[k_2], \phi[k_4] \rangle + \langle \phi[k_1], \phi[k_2] \rangle \langle \phi[k_3], \phi[k_4] \rangle$$

In[220]:=

```
listdummy := Block[{dummy, permutations},
  dummy = Union@Cases[wickcontracted, k_a[b_] :=> a /; ! NumericQ[a], ∞];
  permutations = Permutations[dummy];
  relabelings = Table[dummy[[j]] -> permutations[[k, j]], {k, Length[permutations]},
    {j, Length[dummy]};
]
```

In[242]:=

```
CanOrder[object_] :=
  First@Sort@Table[object /. relabelings[[j]] /. R_Rule :=> Sort@R,
    {j, Length[relabelings]}]
```

In[250]:=

```
ClearAll[tograph]
tograph[term_] :=
  tograph[term] = List @@ term /. <phi[k[a_]], phi[k[b_]]> :=> Rule[a[[0]], b[[0]] //
    GraphPlot[# // CanOrder, VertexLabeling -> True, ImageSize -> 200] /.
    Text[Framed[c___], b___] /; ! NumericQ[{c}[[1]]] :=> Text[""] &
```

■ Computing the Wick contractions

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192 $\boxed{1} \text{---} \text{---} \boxed{2} +$

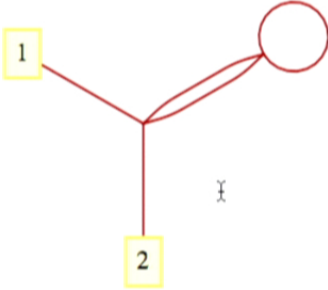
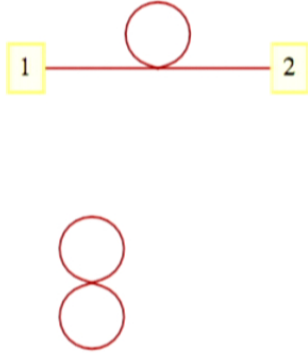
192 $\boxed{1} \text{---} \text{---} \boxed{2} + 96 \boxed{1} \text{---} \text{---} \boxed{2} +$

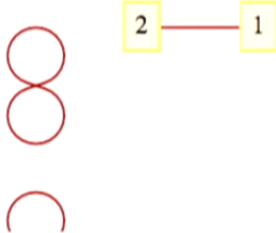
288 $\boxed{1} \text{---} \text{---} \boxed{2} + 24 \boxed{2} \text{---} \text{---} \boxed{1} +$

200%

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192  + 192  + 96  +

288  + 24  + 72  +

36  + 36  + 9 

200%

```
First@Sort@Table[object /. relabelings[[j]] /. R_Rule -> Sort@R,
  {j, Length[relabelings]}]
```

```
ClearAll[tograph]
tograph[term_] :=
  tograph[term] = List @@ term /. <phi[k[a_]], phi[k[b_]]> -> Rule[a[[0]], b[[0]] //
    F[# // CanOrder,
      GraphPlot[# // CanOrder, VertexLabeling -> True, ImageSize -> 150] /.
        Text[Framed[c_], b_] /; ! NumericQ[{c}][1] -> Text[""] &
```

■ Computing the Wick contractions

In[261]:=

```
(* vertex[n_, alpha_] := Product[j=1 to n] phi[k_alpha[j]]; *)

vertex[n_] := Block[{letter = Unique[alpha]}, Product[j=1 to n] phi[k_letter[j]]]
```

In[266]:=

```
towick = phi[k_1[]] phi[k_2[]] vertex[4] vertex[4];
EvenQ@Count[towick, phi[_]]
```

Out[267]=

True

tograph /@ wickcontracted

Out[278]=

192

$F[\{ 1 \rightarrow \alpha\$39788, 2 \rightarrow \alpha\$39789, \alpha\$39788 \rightarrow \alpha\$39789, \alpha\$39788 \rightarrow \alpha\$39789, \alpha\$39788 \rightarrow \alpha\$39789 \}]$



$F[\{ 1 \rightarrow \alpha\$39788, 2 \rightarrow \alpha\$39789, \alpha\$39788 \rightarrow \alpha\$39789, \alpha\$39788 \rightarrow \alpha\$39788, \alpha\$39789 \rightarrow \alpha\$39789 \}]$



$F[\{ 1 \rightarrow \alpha\$39788, 2 \rightarrow \alpha\$39789, \alpha\$39788 \rightarrow \alpha\$39789, \alpha\$39789 \rightarrow \alpha\$39789, \alpha\$39788 \rightarrow \alpha\$39788 \}]$



$F[\{ 1 \rightarrow \alpha\$39788, 2 \rightarrow \alpha\$39789, \alpha\$39789 \rightarrow \alpha\$39789, \alpha\$39788 \rightarrow \alpha\$39789, \alpha\$39788 \rightarrow \alpha\$39788 \}]$



$F[\{ 1 \rightarrow \alpha\$39788, 2 \rightarrow \alpha\$39789, \alpha\$39788 \rightarrow \alpha\$39788, \alpha\$39788 \rightarrow \alpha\$39789, \alpha\$39789 \rightarrow \alpha\$39789 \}]$



tograph /@ wickcontracted

Out[278]=

192

$F[\{ 1 \rightarrow \alpha\$39788, 2 \rightarrow \alpha\$39789, \alpha\$39788 \rightarrow \alpha\$39789, \alpha\$39788 \rightarrow \alpha\$39789, \alpha\$39788 \rightarrow \alpha\$39789 \}]$



$F[\{ 1 \rightarrow \alpha\$39788, 2 \rightarrow \alpha\$39789, \alpha\$39788 \rightarrow \alpha\$39789, \alpha\$39788 \rightarrow \alpha\$39788, \alpha\$39789 \rightarrow \alpha\$39789 \}]$



$F[\{ 1 \rightarrow \alpha\$39788, 2 \rightarrow \alpha\$39789, \alpha\$39788 \rightarrow \alpha\$39789, \alpha\$39789 \rightarrow \alpha\$39789, \alpha\$39788 \rightarrow \alpha\$39788 \}]$



$F[\{ 1 \rightarrow \alpha\$39788, 2 \rightarrow \alpha\$39789, \alpha\$39789 \rightarrow \alpha\$39789, \alpha\$39788 \rightarrow \alpha\$39789, \alpha\$39788 \rightarrow \alpha\$39788 \}]$



$F[\{ 1 \rightarrow \alpha\$39788, 2 \rightarrow \alpha\$39789, \alpha\$39788 \rightarrow \alpha\$39788, \alpha\$39788 \rightarrow \alpha\$39789, \alpha\$39789 \rightarrow \alpha\$39789 \}]$



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Example.

In[256]:=

```
wick[ $\phi[k_1]$   $\phi[k_2]$   $\phi[k_3]$   $\phi[k_4]$ ]
```

Out[256]=

$$\langle \phi[k_1], \phi[k_4] \rangle \langle \phi[k_2], \phi[k_3] \rangle + \langle \phi[k_1], \phi[k_3] \rangle \langle \phi[k_2], \phi[k_4] \rangle + \langle \phi[k_1], \phi[k_2] \rangle \langle \phi[k_3], \phi[k_4] \rangle$$

In[257]:=

```
listdummy := Block[{dummy, permutations},
  dummy = Union@Cases[wickcontracted,  $k_{a_{[b_]}}$   $\Rightarrow$   $a$  /; ! NumericQ[ $a$ ],  $\infty$ ];
  permutations = Permutations[dummy];
  relabelings = Table[dummy[[j]]  $\rightarrow$  permutations[[k, j]], {k, Length[permutations]},
    {j, Length[dummy]}];
]
```

In[258]:=

```
CanOrder[object_] :=
  First@Sort@Table[object /. relabelings[[j]] /. R_Rule  $\Rightarrow$  Sort@R,
    {j, Length[relabelings]}]
```

In[274]:=

```
ClearAll[tograph]
tograph[term_] :=
  tograph[term] = List @@ term /.  $\langle \phi[k_{a_{[ ]}}], \phi[k_{b_{[ ]}}] \rangle \Rightarrow$  Rule[a[[0]], b[[0]] //
```

200%

```

tograph[term_] :=
  tograph[term] = List @@ term /. <math>\phi[k[a\_]], \phi[k[b\_]]> \Rightarrow \text{Rule}[a[[0]], b[[0]]] //
    F[# // CanOrder] GraphPlot[# // CanOrder, VertexLabeling -> True, ImageSize -> 150] /.
      Text[Framed[c___], b___] /; ! NumericQ[{c}][1] => Text[""] &

```

■ Computing the Wick contractions

In[261]:=

```

(* vertex[n_, α_] :=  $\prod_{j=1}^n \phi[k_{\alpha[j]}]$ ; *)

vertex[n_] := Block[{letter = Unique[α]},  $\prod_{j=1}^n \phi[k_{\text{letter}[j]}]$ ]

```

In[266]:=

```

towick =  $\phi[k_1[]] \phi[k_2[]]$  vertex[4] vertex[4];
EvenQ@Count[towick,  $\phi[_]$ ]

```

Out[267]=

True

In[268]:=

```

wickcontracted = Expand@wick@towick;
listdummy;

```

In[278]--

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```
listdummy := Block[{dummy, permutations},
  dummy = Union@Cases[wickcontracted, ka[b_] => a /; ! NumericQ[a], ∞];
  permutations = Permutations[dummy];
  relabelings = Table[dummy[[j]] -> permutations[[k, j]], {k, Length[permutations]},
    {j, Length[dummy]}];
]
```

In[279]:=

relabelings

Out[279]=

```
{ {α$39788 -> α$39788, α$39789 -> α$39789}, {α$39788 -> α$39789, α$39789 -> α$39788} }
```

In[258]:=

```
CanOrder[object_] :=
  First@Sort@Table[object /. relabelings[[j]] /. R_Rule -> Sort@R,
    {j, Length[relabelings]}]
```

In[274]:=

```
ClearAll[tograph]
tograph[term_] :=
  tograph[term] = List @@ term /. <φ[k[a_]], φ[k[b_]]> -> Rule[a[[0]], b[[0]] //
    F[# // CanOrder] GraphPlot[# // CanOrder, VertexLabeling -> True, ImageSize -> 150] /.
    Text[Framed[c, b] /; ! NumericQ[{c}]] -> Text[""] &
```

200%

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```
listdummy := Block[{dummy, permutations},
  dummy = Union@Cases[wickcontracted, ka[b_] :=> a ;; ! NumericQ[a], ∞];
  permutations = Permutations[dummy];
  relabelings = Table[dummy[[j]] -> permutations[[k, j]], {k, Length[permutations]},
    {j, Length[dummy]}];
]
```

In[279]:=

relabelings

Out[279]=

```
{ {α$39788 -> α$39788, α$39789 -> α$39789}, {α$39788 -> α$39789, α$39789 -> α$39788} }
```

```
CanOrder[object_] :=
  First@Sort@Table[object /. relabelings[[j]] /. R_Rule :=> Sort@R // Sort|,
    {j, Length[relabelings]}]
```

In[274]:=

```
ClearAll[tograph]
tograph[term_] :=
  tograph[term] = List @@ term /. <φ[k[a_]], φ[k[b_]]> :=> Rule[a[[0]], b[[0]] //
    F[# // CanOrder] GraphPlot[# // CanOrder, VertexLabeling -> True, ImageSize -> 150] /.
    Text[Framed[c___], b___] ;; ! NumericQ[{c}[[1]]] :=> Text[""] &
```

200%

■ Computing the Wick contractions

In[261]:=

```
vertex[n_] := Block[{letter = Unique[α]},  $\prod_{j=1}^n \phi[k_{\text{letter}[j]}]$ 
(* vertex[n_, α_] :=  $\prod_{j=1}^n \phi[k_{\alpha[j]}]$ ; *)
```

In[266]:=

```
vertex[n_] := Block[{letter = Unique[α]},  $\prod_{j=1}^n \phi[k_{\text{letter}[j]}]$ 
towick =  $\phi[k_1[]] \phi[k_2[]]$  vertex[4] vertex[4];
EvenQ@Count[towick, φ[_]]
```

In[266]:=

Out[267]:=

```
towick =  $\phi[k_1[]] \phi[k_2[]]$  vertex[4] vertex[4];
True
EvenQ@Count[towick, φ[_]]
```

Out[267]:=

In[268]:=

```
True
wickcontracted = Expand@wick@towick;
listdummy;
```

In[268]:=

In[278]:=

```
wickcontracted = Expand@wick@towick;
loggraph /@ wickcontracted
```

Out[278]:=

In[278]:=

```
192
loggraph /@ wickcontracted
F[{1 → α$39788, 2 → α$39789, α$39788 → α$39789, α$39788 → α$39789, α$39788 → α$39789}]
1
2 + 48
192
F[{1 → α$39788, 2 → α$39789, α$39788 → α$39789, α$39788 → α$39789, α$39788 → α$39789}]
```

Out[278]:=

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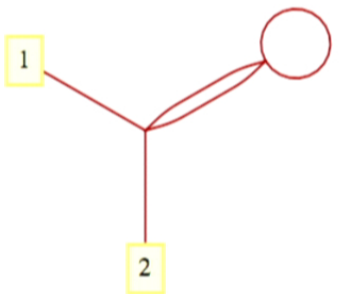
$\langle \phi[k_{\alpha 39788}[2]], \phi[k_{\alpha 39789}[1]] \rangle \langle \phi[k_{\alpha 39788}[3]], \phi[k_{\alpha 39788}[4]] \rangle$

In[295]:=

tograph /@ wickcontracted

Out[295]=

192  + 288  +

288  + 24  +

200%

■ Function and Notation

■ Computing the Wick contractions

In[261]:=

```
(* vertex[n_,α_] :=  $\prod_{j=1}^n \phi[k_{\alpha[j]}]$ ; *)  
  
vertex[n_] := Block[{letter = Unique[α]},  $\prod_{j=1}^n \phi[k_{\text{letter}[j]}]$ ]
```

In[266]:=

```
towick =  $\phi[k_1[]]$   $\phi[k_2[]]$  vertex[4] vertex[4];  
EvenQ@Count[towick,  $\phi[[]]$ ]
```

Out[267]=

True

In[268]:=

```
wickcontracted = Expand@wick@towick;  
listdummy;
```

■ Plotting the Graphs

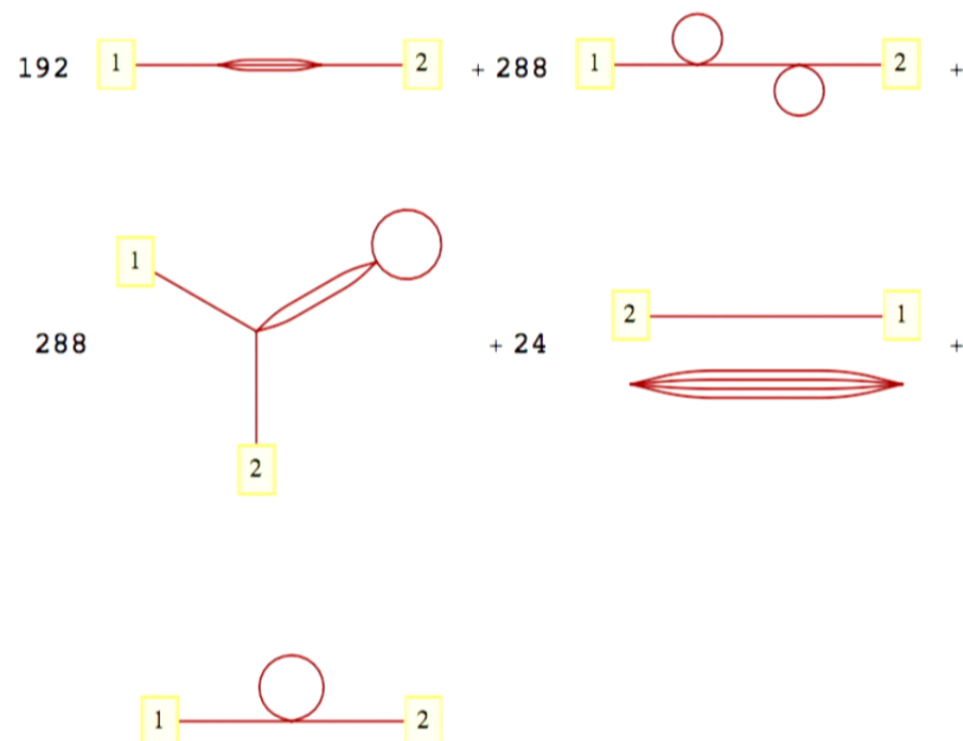
In[269]:=

■ Plotting the Graphs

In[301]:=

```
tograph /@ wickcontracted
```

Out[301]=



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FileBefore1010.nb

```
{ {α$39788 → α$39788, α$39789 → α$39789}, {α$39788 → α$39789, α$39789 → α$39788} }
```

In[289]:=

```
CanOrder[object_] :=  
  First@Sort@Table[object /. relabelings[[j]] /. R_Rule -> Sort@R // Sort,  
    {j, Length[relabelings]}]
```

In[293]:=

```
ClearAll[tograph]  
tograph[term_] :=  
  tograph[term] = List @@ term /. <φ[k[a_]], φ[k[b_]]> -> Rule[a[[0]], b[[0]] //  
    GraphPlot[# // CanOrder, VertexLabeling -> True, ImageSize -> 150] /.  
    Text[Framed[c___], b___] /; ! NumericQ[{c}][1] -> Text[""] &
```

```
{a -> b, b -> c, d -> e} // GraphDistan
```

In[303]:=

```
{a -> b, b -> c, d -> e} // Graph
```

Out[303]=



200%

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In[293]:=

```
ClearAll[tograph]
tograph[term_] :=
  tograph[term] = List @@ term /. <math>\phi[k[a\_]], \phi[k[b\_]]> \Rightarrow \text{Rule}[a[[0]], b[[0]]] //
    GraphPlot[# // CanOrder, VertexLabeling \rightarrow \text{True}, ImageSize \rightarrow 150] /.
      Text[Framed[c___], b___] /; ! NumericQ[{c}][[1]] \Rightarrow \text{Text}[""] \&
```

In[306]:=

```
{a \rightarrow b, b \rightarrow c, d \rightarrow e} // Graph // GraphDistanceMatrix // MatrixForm
```

Out[306]//MatrixForm=

$$\begin{pmatrix} 0 & 1 & 2 & \infty & \infty \\ \infty & 0 & 1 & \infty & \infty \\ \infty & \infty & 0 & \infty & \infty \\ \infty & \infty & \infty & 0 & 1 \\ \infty & \infty & \infty & \infty & 0 \end{pmatrix}$$

In[303]:=

```
{a \rightarrow b, b \rightarrow c, d \rightarrow e} // Graph
```

Out[303]=



200%

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FileBefore1010.nb

In[293]:=

```
ClearAll[tograph]
tograph[term_] :=
  tograph[term] = List @@ term /. <math>\langle \phi[k[a\_]], \phi[k[b\_]] \rangle \Rightarrow \text{Rule}[a[[0]], b[[0]]]</math> //
    GraphPlot[# // CanOrder, VertexLabeling -> True, ImageSize -> 150] /.
      Text[Framed[c___], b___] /; ! NumericQ[{c}][[1]] => Text[""] &
```

In[313]:=

```
{a -> b, b -> c} /. Rule[a_, b_] => Sequence[Rule[a, b], Rule[b, a]]
```

Out[313]=

```
{a -> b, b -> a, b -> c, c -> b}
```

In[317]:=

```
<< GraphUtilities`
```

```
{a -> b, b -> c, b -> c, d -> e} /. Rule[a_, b_] => Sequence[Rule[a, b], Rule[b, a]] //
  GraphDistanceMatrix
```

Graph::supp : Mixed graphs and multigraphs are not supported. >>

GraphDistanceMatrix::graph : A graph object is expected at position 1
in GraphDistanceMatrix[Graph[{a -> b, b -> a, b -> c, c -> b, b -> c, c -> b, d -> e, e -> d}]]. >>

Out[316]=

```
GraphDistanceMatrix[Graph[{a -> b, b -> a, b -> c, c -> b, b -> c, c -> b, d -> e, e -> d}]]
```

200%

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```
{j, Length[relabelings]]]
```

In[293]:=

```
ClearAll[tograph]
tograph[term_] :=
  tograph[term] = List @@ term /. <math>\phi[k[a\_]], \phi[k[b\_]]> \Rightarrow \text{Rule}[a[[0]], b[[0]]]> //
    GraphPlot[# // CanOrder, VertexLabeling \rightarrow \text{True}, ImageSize \rightarrow 150] /.
      Text[Framed[c\_], b\_]; ! NumericQ[{c}][1]] \Rightarrow \text{Text}[""] &
```

In[313]:=

```
{a \rightarrow b, b \rightarrow c} /. Rule[a_, b_] \Rightarrow Sequence[Rule[a, b], Rule[b, a]]
```

Out[313]=

```
{a \rightarrow b, b \rightarrow a, b \rightarrow c, c \rightarrow b}
```

In[317]:=

```
<< GraphUtilities`
```

In[320]:=

```
{a \rightarrow b, b \rightarrow c, b \rightarrow c, d \rightarrow e} /. Rule[a_, b_] \Rightarrow Sequence[Rule[a, b], Rule[b, a]] //
  GraphDistanceMatrix
```

Out[320]=

```
{{0, 1, 3, \infty, \infty}, {1, 0, 2, \infty, \infty}, {3, 2, 0, \infty, \infty}, {\infty, \infty, \infty, 0, 1}, {\infty, \infty, \infty, 1, 0}}
```

200%

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```
{j, Length[relabelings]]]
```

In[293]:=

```
ClearAll[tograph]
tograph[term_] :=
  tograph[term] = List @@ term /. <math>\phi[k[a\_]], \phi[k[b\_]]> \Rightarrow \text{Rule}[a[[0]], b[[0]]]> //
    GraphPlot[# // CanOrder, VertexLabeling \rightarrow \text{True}, ImageSize \rightarrow 150] /.
      Text[Framed[c\_], b\_]; ! NumericQ[{c}][1]] \Rightarrow \text{Text}[""] &
```

In[321]:=

```
wickcontracted[[1]]
```

Out[321]=

```
<math>\phi[k_1[]], \phi[k_{\alpha\$39789[4]}]> <math>\phi[k_2[]], \phi[k_{\alpha\$39789[3]}]> <math>\phi[k_{\alpha\$39788[1]}], \phi[k_{\alpha\$39789[2]}]>
<math>\phi[k_{\alpha\$39788[2]}], \phi[k_{\alpha\$39789[1]}]> <math>\phi[k_{\alpha\$39788[3]}], \phi[k_{\alpha\$39788[4]}]>
```

disconnectedQ[x_] := disconnected[Q]

In[313]:=

```
{a \rightarrow b, b \rightarrow c} /. Rule[a_, b_] \Rightarrow Sequence[Rule[a, b], Rule[b, a]]
```

Out[313]=

```
{a \rightarrow b, b \rightarrow a, b \rightarrow c, c \rightarrow b}
```

In[317]:=

200%

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FileBefore1010.nb

```
{j, Length[relabelings]]]
```

In[293]:=

```
ClearAll[tograph]
tograph[term_] :=
  tograph[term] = List @@ term /. <math>\phi[k[a\_]], \phi[k[b\_]]> \Rightarrow \text{Rule}[a[[0]], b[[0]]]> //
    GraphPlot[#, CanOrder, VertexLabeling \rightarrow \text{True}, ImageSize \rightarrow 150] /.
      Text[Framed[c___], b___] /; ! NumericQ[{c}][1] \Rightarrow \text{Text}[""] \&
```

In[323]:=

```
wickcontracted[1] // disconnectedQ
```

GraphDistance::argrx : GraphDistance called with 1 arguments; 3 arguments are expected. >>
GraphDistance::argtu : GraphDistance called with 1 argument; 2 or 3 arguments are expected. >>

Out[323]=

```
True
```

In[322]:=

```
disconnectedQ[X_] :=
  disconnectedQ[X] =
    (List @@ X) /. <math>\phi[k[a\_]], \phi[k[b\_]]> \Rightarrow \text{Sequence}[\text{Rule}[a[[0]], b[[0]]], \text{Rule}[b[[0]], a[[0]]]] //
      GraphDistance // FreeQ[#, \infty] \&
```

In[313]:=

```
{a, b, b, a} /. Rule[a, b] \Rightarrow \text{Sequence}[\text{Rule}[a, b], \text{Rule}[b, a]]
```

200%

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```

ClearAll[tograph]
tograph[term_] :=
  tograph[term] = List @@ term /. <math>\phi[k[a\_]], \phi[k[b\_]]> \Rightarrow \text{Rule}[a[[0]], b[[0]]] //
    GraphPlot[# // CanOrder, VertexLabeling \rightarrow \text{True}, ImageSize \rightarrow 150] /.
      Text[Framed[c___], b___] /; ! NumericQ[{c}][1] \Rightarrow \text{Text}[""] \&

```

In[323]:=

```

wickcontracted[[1]] // disconnectedQ

```

GraphDistance::argrx : GraphDistance called with 1 arguments; 3 arguments are expected. >>
GraphDistance::argtu : GraphDistance called with 1 argument; 2 or 3 arguments are expected. >>

Out[323]=

```

True

```

In[324]:=

```

(List @@ wickcontracted[[1]]) /.
  <math>\phi[k[a\_]], \phi[k[b\_]]> \Rightarrow \text{Sequence}[\text{Rule}[a[[0]], b[[0]]], \text{Rule}[b[[0]], a[[0]]]]

```

Out[324]=

```

{1 \rightarrow \alpha\$39789, \alpha\$39789 \rightarrow 1, 2 \rightarrow \alpha\$39789, \alpha\$39789 \rightarrow 2, \alpha\$39788 \rightarrow \alpha\$39789, \alpha\$39789 \rightarrow \alpha\$39788,
  \alpha\$39788 \rightarrow \alpha\$39789, \alpha\$39789 \rightarrow \alpha\$39788, \alpha\$39788 \rightarrow \alpha\$39788, \alpha\$39788 \rightarrow \alpha\$39788}

```

In[322]:=

```

disconnectedQ[x_] :=
  disconnectedQ[x] =

```

200%

GraphDistance::argrx : GraphDistance called with 1 arguments; 3 arguments are expected. >>
 GraphDistance::argtu : GraphDistance called with 1 argument; 2 or 3 arguments are expected. >>

Out[323]=

True

In[329]:=

```
connectedQ[X_] :=  
  connectedQ[X] =  
    (List @@ X) /. <φ[k[a_]], φ[k[b_]]> => Sequence[Rule[a[[0]], b[[0]], Rule[b[[0]], a[[0]]] //  
      GraphDistanceMatrix // FreeQ[#, ∞] &
```

In[339]:=

connectedQ[**wickcontracted**[[450]]]

Out[339]=

False

In[340]:=

wickcontracted[[450]]

Out[340]=

$$\langle \phi[k_1[]], \phi[k_2[]] \rangle \langle \phi[k_{\alpha 39788[1]}], \phi[k_{\alpha 39788[2]}] \rangle \langle \phi[k_{\alpha 39788[3]}], \phi[k_{\alpha 39789[3]}] \rangle$$

$$\langle \phi[k_{\alpha 39788[4]}], \phi[k_{\alpha 39789[4]}] \rangle \langle \phi[k_{\alpha 39789[1]}], \phi[k_{\alpha 39789[2]}] \rangle$$

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FileBefore1010.nb

```

relabelings = Table[dummy[[j]] -> permutations[[k, j]], {k, Length[permutations]},
  {j, Length[dummy]}};
]

In[289]:=
CanOrder[object_] :=
  First@Sort@Table[object /. relabelings[[j]] /. R_Rule -> Sort@R // Sort,
    {j, Length[relabelings]}}]

In[293]:=
ClearAll[tograph]
tograph[term_] :=
  tograph[term] = List @@ term /. <phi[k[a_]], phi[k[b_]]> -> Rule[a[[0]], b[[0]] //
    GraphPlot[# // CanOrder, VertexLabeling -> True, ImageSize -> 150] /.
      Text[Framed[c___], b___] /; ! NumericQ[{c}][1] -> Text[""] &

connectedQ[X_] :=
  connectedQ[X] =
    (List @@ X) /. <phi[k[a_]], phi[k[b_]]> -> Sequence[Rule[a[[0]], b[[0]], Rule[b[[0]], a[[0]]] //
      GraphDistanceMatrix // FreeQ[#, infinity] &

■ Computing the Wick contractions

In[261]:=
(* vertex[n_, alpha_] := Product_{i=1}^n phi[k_{alpha[i]}]; *)

```

200%

Out[267]=

True

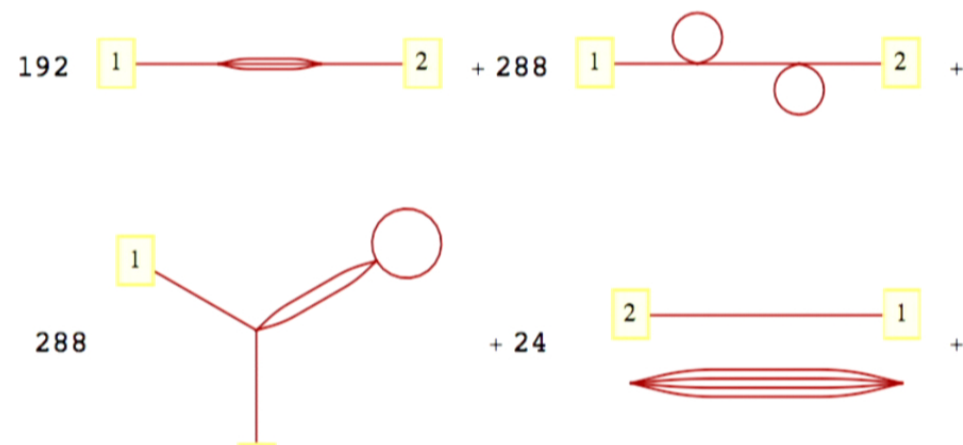
In[268]:=

```
wickcontracted = Expand@wick@towick;  
listdummy;
```

■ Plotting the (connected) Graphs

```
Sum[wickcontracted[[L]]  
  , {L, Length[wickcontracted]}]
```

Out[301]=



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Out[267]=
True

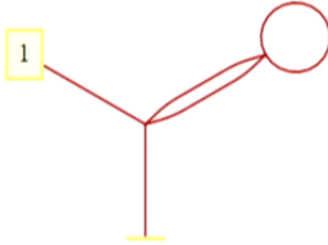
In[268]:=
wickcontracted = Expand@wick@towick;
listdummy;

■ Plotting the (connected) Graphs

Monitor[Sum[If[connectedQ@wickcontracted[[L]], tograph@wickcontracted[[L]], 0], {L, Length[wickcontracted]}], {

Out[301]=

192  2 + 288  +

288  + 24  +

200%

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Out[267]=
True

In[268]:=
wickcontracted = Expand@wick@towick;
listdummy;

■ Plotting the (connected) Graphs

In[344]:=
Monitor[Sum[If[connectedQ@wickcontracted[[L]], tograph@wickcontracted[[L], 0]
, {L, Length[wickcontracted]}],
{ProgressIndicator[L, {1, Length[wickcontracted]}], L, Length[wickcontracted]}]

Out[344]=

192 1 2 + 288 1 2 + 288

200%

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Out[267]=

True

In[268]:=

```
wickcontracted = Expand@wick@towick;
listdummy;
```

■ Plotting the (connected) Graphs

In[347]:=

```
Monitor[Sum[If[connectedQ@wickcontracted[[L]], tograph@wickcontracted[[L], 0]
, {L, Length[wickcontracted]}],
{ProgressIndicator[L, {1, Length[wickcontracted]}], L, Length[wickcontracted]}]
```

Out[347]=

192 1 2 + 288 1 2 + 288

200%

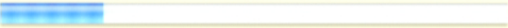
Mathematica File Edit Insert Format Cell Graphics Evaluation Palettes Window Help
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In[350]:=

```
wickcontracted = Expand@wick@towick;  
listdummy;
```

■ Plotting the (connected) Graphs

In[352]:=

```
Monitor[Sum[If[connectedQ@wickcontracted[[L]], tograph@wickcontracted[[L]], 0]  
  , {L, Length[wickcontracted]}],  
  {ProgressIndicator[L, {1, Length[wickcontracted]}], L, Length[wickcontracted]}]  
{, 2119, 10 395}
```

200%

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1296

+ 648

648

+ 648

648

+ 648

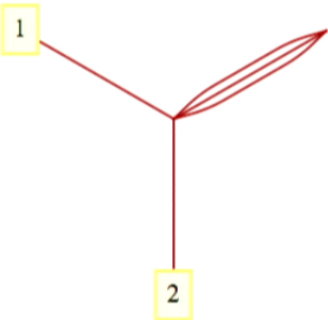
+ 648

200%

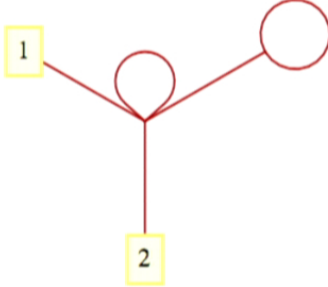
Mathematica File Edit Insert Format Cell Graphics Evaluation Palettes Window Help
FileBefore1010.nb

Out[359]=

120

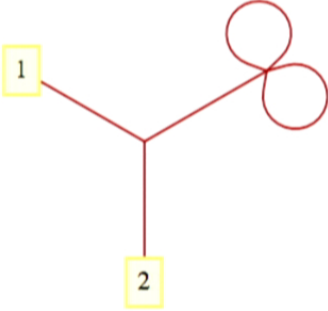


+ 180



+

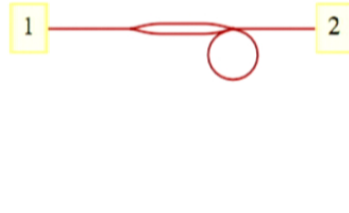
90



+ 180



+ 180



`graphs /. a_. G_Graphics :>`

200%

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graphs /. a_. G_Graphics :> |

200%

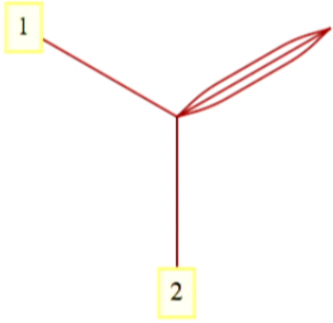
Mathematica File Edit Insert Format Cell Graphics Evaluation Palettes Window Help
FileBefore1010.nb

2

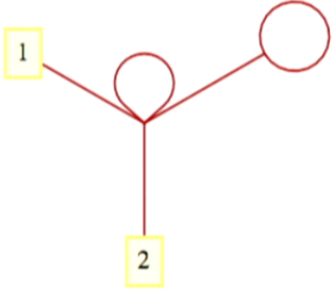
`Labeled[graphs /. a_. G_Graphics -> Labeled[G,  $\frac{a}{3! 5!}$ , Left], "Connect|`

Out[365]=

$\frac{1}{6}$

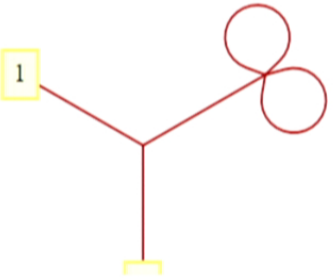


$+$ $\frac{1}{4}$



$+$

$\frac{1}{8}$



$+$ $\frac{1}{4}$



$+$ $\frac{1}{4}$



200%

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FileBefore1010.nb

2 2

$\frac{1}{8}$

1 2

$+$ $\frac{1}{4}$

1 2

$+$ $\frac{1}{4}$

1 2

In[369]:=

NotebookDirectory []

Out[369]=

/Users/pvieira/Desktop/Dropbox/Physics/Courses/PSI Mathematica/2013/December 10/

Export [(**NotebookDirectory** [] <> "nicegraphs.p

200%

```
<< GraphUtilities`
<< Notation`
```

```
In[9]:= Notation[ k_i_ ==> k[i_] ]
```

```
In[254]:= wick[X_Times] := Block[{list = List @@ X, Sum[Length[list], {j, 2}]}
  <list[[1]], list[[j]]> wick[Times @@ Drop[Drop[list, {j}], 1]]]
  wick[phi[a_] phi[b_]] := <phi[a], phi[b]>
```

Example:

```
In[256]:= wick[phi[k1] phi[k2] phi[k3] phi[k4]]
```

```
Out[256]:= <phi[k1], phi[k4]> <phi[k2], phi[k3]> + <phi[k1], phi[k3]> <phi[k2], phi[k4]> + <phi[k1], phi[k2]> <phi[k3], phi[k4]>
```

```
In[257]:= listdummy := Block[{dummy, permutations},
  dummy = Union@Cases[wickcontracted, k_a[b_] ==> a /; ! NumericQ[a], infinity];
  permutations = Permutations[dummy];
  relabelings = Table[dummy[[j]] ==> permutations[[k, j]], {k, Length[permutations]}, {j, Length[dummy]}];
]
```

```
In[289]:= CanOrder[object_] := First@Sort@Table[object /. relabelings[[j]] /. R_Rule ==> Sort@R // Sort, {j, Length[relabelings]}]
```

```
In[293]:= ClearAll[tograph]
tograph[term_] :=
  tograph[term] = List @@ term /. <phi[k[a_]], phi[k[b_]]> ==> Rule[a[[0]], b[[0]] //
  GraphPlot[# // CanOrder, VertexLabeling -> True, ImageSize -> 150] /.
  Text[Framed[a -> b /; ! NumericQ[a]]] ==> Text[""] &
```

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In[256]:= `wick[ $\phi[k_1] \phi[k_2] \phi[k_3] \phi[k_4]$ ]`

Out[256]= $\langle \phi[k_1], \phi[k_4] \rangle \langle \phi[k_2], \phi[k_3] \rangle + \langle \phi[k_1], \phi[k_3] \rangle \langle \phi[k_2], \phi[k_4] \rangle + \langle \phi[k_1], \phi[k_2] \rangle \langle \phi[k_3], \phi[k_4] \rangle$

In[257]:= `listdummy := Block[{dummy, permutations},
 dummy = Union@Cases[wickcontracted, $k_{a_{[b]}}$ $\Rightarrow$ a /; ! NumericQ[a], ∞];
 permutations = Permutations[dummy];
 relabelings = Table[dummy[[j]] $\rightarrow$ permutations[[k, j]], {k, Length[permutations]}, {j, Length[dummy]}];
]`

In[289]:= `CanOrder[object_] := First@Sort@Table[object /. relabelings[[j]] /. R_Rule  $\Rightarrow$  Sort@R // Sort, {j, Length[relabelings]}]`

In[293]:= `ClearAll[tograph]
tograph[term_] :=
 tograph[term] = List @@ term /. $\langle \phi[k_{a_{[]}}], \phi[k_{b_{[]}}] \rangle \Rightarrow$ Rule[a[[0], b[[0]]] //
 GraphPlot[# // CanOrder, VertexLabeling $\rightarrow$ True, ImageSize $\rightarrow$ 150] /.
 Text[Framed[c___], b___] /; ! NumericQ[{c}[[1]]] $\Rightarrow$ Text[""] &`

`ClearAll[connectedQ]
connectedQ[X_] :=
 connectedQ[X] =
 (List @@ X) /. $\langle \phi[k_{a_{[]}}], \phi[k_{b_{[]}}] \rangle \Rightarrow$ Sequence[Rule[a[[0], b[[0]]], Rule[b[[0], a[[0]]]] // GraphDistanceMatrix //
 FreeQ[#, ∞] &`

■ Computing the Wick contractions

In[261]:= `(* vertex[n_, α] := $\prod_{j=1}^n \phi[k_{\alpha[j]}]$; *)
vertex[n_] := Block[{letter = Unique[α]}, $\prod_{j=1}^n \phi[k_{\text{letter}[j]}]$]`

150%

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```
Text[Framed[c___], b___] /; ! NumericQ[{c}][[1]] => Text[""] &
```

```
ClearAll[connectedQ]
connectedQ[X_] :=
connectedQ[X] =
(List@@X) /. <phi[k[a_]], phi[k[b_]]> => Sequence[Rule[a[[0]], b[[0]], Rule[b[[0]], a[[0]]] // GraphDistanceMatrix //
FreeQ[#, infinity] &
```

■ Computing the Wick contractions

```
In[261]:= (* vertex[n_, alpha_] := Product[j=1 to n, phi[k_alpha[j]]]; *)
vertex[n_] := Block[{letter = Unique[alpha]}, Product[j=1 to n, phi[k_letter[j]]]
```

```
In[266]:= towick = phi[k_1[]] phi[k_2[]] vertex[4] vertex[4];
EvenQ@Count[towick, phi[_]]
```

```
Out[267]:= True
```

```
towick = phi[k_1[]] phi[k_2[]] phi[k_3[]] vertex[3] vertex[3] vertex[3];
EvenQ@Count[towick, phi[_]]
```

```
In[355]:= towick = phi[k_1[]] phi[k_2[]] vertex[3] vertex[5];
EvenQ@Count[towick, phi[_]]
```

```
Out[356]:= True
```

```
In[357]:= wickcontracted = Expand@wick@towick;
listdummy;
```

150%

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FreeQ[#, ∞] &

■ Computing the Wick contractions

In[261]:=

```
(* vertex[n_, α_] :=  $\prod_{j=1}^n \phi[k_{\alpha(j)}]$ ; *)
```

```
vertex[n_] := Block[{letter = Unique[α]},  $\prod_{j=1}^n \phi[k_{\text{letter}[j]}]$ ]
```

In[266]:=

```
towick =  $\phi[k_{1[]}] \phi[k_{2[]}]$  vertex[4] vertex[4];
```

```
EvenQ@Count[towick,  $\phi[_]$ ]
```

Out[267]=

```
True
```

```
towick =  $\phi[k_{1[]}] \phi[k_{2[]}] \phi[k_{3[]}]$  vertex[3] vertex[3] vertex[3];
```

```
EvenQ@Count[towick,  $\phi[_]$ ]
```

In[355]:=

```
towick =  $\phi[k_{1[]}] \phi[k_{2[]}]$  vertex[3] vertex[5];
```

```
EvenQ@Count[towick,  $\phi[_]$ ]
```

Out[356]=

```
True
```

```
towick =  $\phi[k_{1[]}] \phi[k_{2[]}] \phi[k_{3[]}] \phi[k_{4[]}]$  vertex[3] vertex[3] vertex[4];
```

In[357]:=

```
wickcontracted = Expand@wick@towick;
```

```
listdummy;
```

■ Plotting the (connected) Graphs

150%


```
vertex[n_] := Block[{letter = Unique[α]}, Table[φ[kletter[j]], {j, 1, n}]]
```

```
In[266]:= towick = φ[k1[1]] φ[k2[1]] vertex[4] vertex[4];
EvenQ@Count[towick, φ[_]]
```

```
Out[267]:= True
```

```
towick = φ[k1[1]] φ[k2[1]] φ[k3[1]] vertex[3] vertex[3] vertex[3];
EvenQ@Count[towick, φ[_]]
```

```
In[355]:= towick = φ[k1[1]] φ[k2[1]] vertex[3] vertex[5];
EvenQ@Count[towick, φ[_]]
```

```
Out[356]:= True
```

```
In[373]:= towick = φ[k1[1]] φ[k2[1]] φ[k3[1]] φ[k4[1]] vertex[3] vertex[3] vertex[4];
EvenQ@Count[towick, φ[_]]
```

```
In[376]:= wickcontracted = Expand@wick@towick;
listdummy;
```

■ Plotting the (connected) Graphs

```
In[378]:= graphs = Monitor[Sum[If[connectedQ@wickcontracted[[L]], tograph@wickcontracted[[L]], 0]
, {L, Length[wickcontracted]}], {ProgressIndicator[L, {1, Length[wickcontracted]}], L, Length[wickcontracted]}];
{ProgressIndicator[L, {1, 135 135}], L, 135 135}
```

```
In[368]:= nicegraphs = Labeled[graphs /. a_. G_Graphics -> Labeled[G,  $\frac{a}{3! 5!}$ , Left],
```



```
vertex[n_] := Block[{letter = Unique[α]}, Table[φ[k[letter[j]]], {j, 1, n}]]
```

In[266]:=

```
towick = φ[k1[1]] φ[k2[1]] vertex[4] vertex[4];
EvenQ@Count[towick, φ[_]]
```

Out[267]:=

True

```
towick = φ[k1[1]] φ[k2[1]] φ[k3[1]] vertex[3] vertex[3] vertex[3];
EvenQ@Count[towick, φ[_]]
```

In[355]:=

```
towick = φ[k1[1]] φ[k2[1]] vertex[3] vertex[5];
EvenQ@Count[towick, φ[_]]
```

Out[356]:=

True

In[373]:=

```
towick = φ[k1[1]] φ[k2[1]] φ[k3[1]] φ[k4[1]] vertex[3] vertex[3] vertex[4];
EvenQ@Count[towick, φ[_]];
```

In[376]:=

```
wickcontracted = Expand@wick@towick;
listdummy;
```

■ Plotting the (connected) Graphs

In[378]:=

```
graphs = Monitor[Sum[If[connectedQ@wickcontracted[[L]], tograph@wickcontracted[[L]], 0],
  {L, Length[wickcontracted]}], {ProgressIndicator[L, {1, Length[wickcontracted]}], L, Length[wickcontracted]}];
{ , 10 139, 135 135 }
```

In[368]:=

```
nicegraphs = Labeled[graphs /. a_ . G_Graphics -> Labeled[G,  $\frac{a}{2, \epsilon, \text{Left}}$ ],
```

150%

```
EvenQ@Count[towick,  $\phi$ [_]]
```

Out[356]= True

```
In[373]:= towick =  $\phi$ [k1[_]]  $\phi$ [k2[_]]  $\phi$ [k3[_]]  $\phi$ [k4[_]] vertex[3] vertex[3] vertex[4];
EvenQ@Count[towick,  $\phi$ [_]];
```

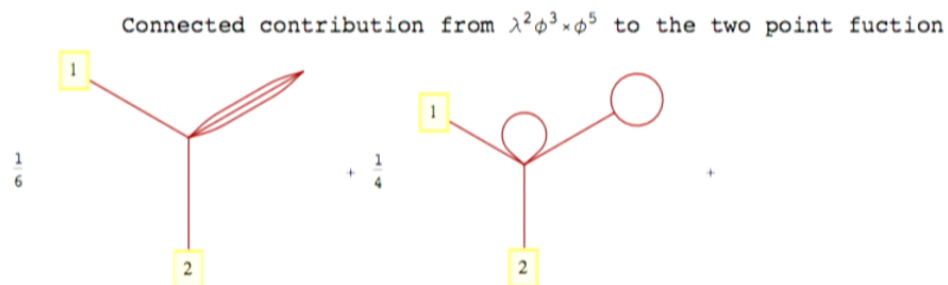
```
In[376]:= wickcontracted = Expand@wick@towick;
listdummy;
```

■ Plotting the (connected) Graphs

```
In[378]:= graphs = Monitor[Sum[If[connectedQ@wickcontracted[[ $\ell$ ]], tograph@wickcontracted[[ $\ell$ ], 0]
, { $\ell$ , Length[wickcontracted]}], {ProgressIndicator[ $\ell$ , {1, Length[wickcontracted]}],  $\ell$ , Length[wickcontracted]}];
{ , 19 530, 135 135 }
```

```
In[368]:= nicegraphs = Labeled[graphs /. a_. G_Graphics -> Labeled[G,  $\frac{a}{3! 5!}$ , Left],
"Connected contribution from  $\lambda^2 \phi^3 \times \phi^5$  to the two point fuction", Top]
```

Out[368]=



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In[368]:=

```
nicegraphs = Labeled[graphs /. a_ . G_Graphics -> Labeled[G,  $\frac{a}{3! 5!}$ , Left],  
  "Connected contribution from  $\lambda^2 \phi^3 \times \phi^5$  to the two point fuction", Top]
```

Out[368]=

Connected contribution from $\lambda^2 \phi^3 \times \phi^5$ to the two point fuction

In[370]:=

```
Export[(NotebookDirectory[] <> "nicegraphs.pdf"), nicegraphs]
```

Out[370]=

```
/Users/pvieira/Desktop/Dropbox/Physics/Courses/PSI Mathematica/2013/December 10/nicegraphs.pdf
```

150%

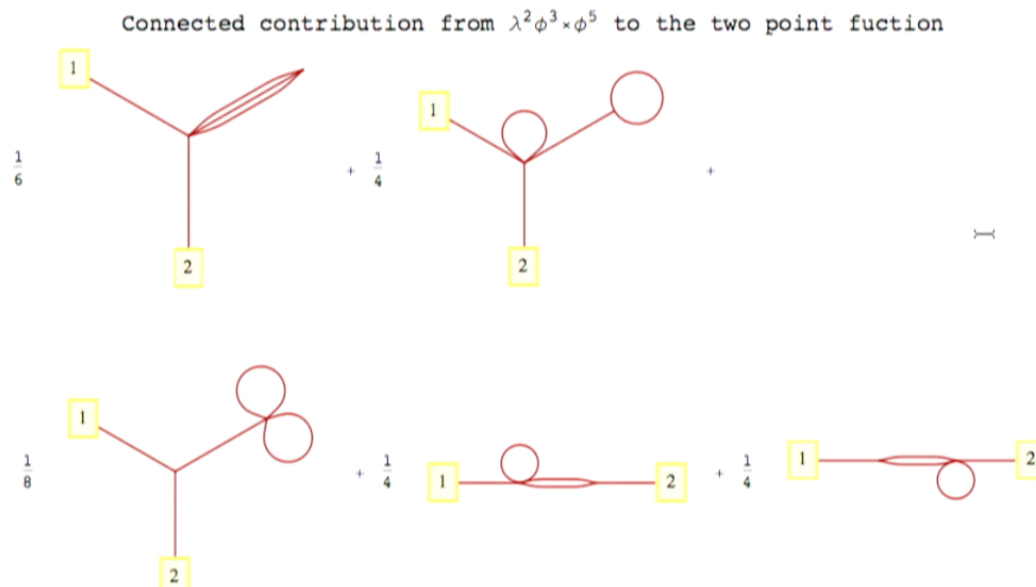

```
wickcontracted = Expand@wick@lowick;
listdummy;
```

■ Plotting the (connected) Graphs

```
In[378]:= graphs = Monitor[Sum[If[connectedQ@wickcontracted[[L]], tograph@wickcontracted[[L], 0]
, {L, Length[wickcontracted]}], {ProgressIndicator[L, {1, Length[wickcontracted]}], L, Length[wickcontracted]}];
{ , 46 633, 135 135 }
```

```
In[368]:= nicegraphs = Labeled[graphs /. a_ . G_Graphics -> Labeled[G,  $\frac{a}{3! 5!}$ , Left],
"Connected contribution from  $\lambda^2 \phi^3 \times \phi^5$  to the two point fuction", Top]
```

Out[368]=



Mathematica File Edit Insert Format Cell Graphics Evaluation Palettes Window Help
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Plotting the (connected) Graphs

In[378]:=

```
graphs = Monitor[Sum[If[connectedQ@wickcontracted[[L]], tograph@wickcontracted[[L], 0], {L, Length[wickcontracted]}], {ProgressIndicator[L, {1, Length[wickcontracted]}], L, Length[wickcontracted]}];
```

{ , 61288, 135135 }

In[368]:=

```
nicegraphs = Labeled[graphs /. a_. G_Graphics -> Labeled[G,  $\frac{a}{3!5!}$ , Left], "Connected contribution from  $\lambda^2\phi^3\times\phi^5$  to the two point fuction", Top]
```

Connected contribution from $\lambda^2\phi^3\times\phi^5$ to the two point fuction

Out[368]=

$\frac{1}{6}$ $+$ $\frac{1}{4}$ $+$ $\frac{1}{8}$ $+$ $\frac{1}{4}$

In[370]=

150%

Mathematica File Edit Insert Format Cell Graphics Evaluation Palettes Window Help
Running...FileBefore1010.nb

Plotting the (connected) Graphs

In[378]:=

```
graphs = Monitor[Sum[If[connectedQ@wickcontracted[l], tograph@wickcontracted[l], 0], {l, Length[wickcontracted]}], {ProgressIndicator[l, {1, Length[wickcontracted]}], l, Length[wickcontracted]}];
```

{ , 74 253, 135 135 }

In[368]:=

```
nicegraphs = Labeled[graphs /. a_. G_Graphics -> Labeled[G,  $\frac{a}{3! 5!}$ , Left], "Connected contribution from  $\lambda^2 \phi^3 \times \phi^5$  to the two point fuction", Top]
```

Connected contribution from $\lambda^2 \phi^3 \times \phi^5$ to the two point fuction

Out[368]=

$\frac{1}{6}$ $+$ $\frac{1}{4}$ $+$ $\frac{1}{8}$ $+$ $\frac{1}{4}$

In[370]:=

150%

Mathematica File Edit Insert Format Cell Graphics Evaluation Palettes Window Help
Running...FileBefore1010.nb

Plotting the (connected) Graphs

In[378]:=

```
graphs = Monitor[Sum[If[connectedQ@wickcontracted[[L]], tograph@wickcontracted[[L], 0]
, {L, Length[wickcontracted]}], {ProgressIndicator[L, {1, Length[wickcontracted]}], L, Length[wickcontracted]}];
```

{ , 80 293, 135 135 }

In[368]:=

```
nicegraphs = Labeled[graphs /. a_. G_Graphics -> Labeled[G,  $\frac{a}{3! 5!}$ , Left],
"Connected contribution from  $\lambda^2 \phi^3 \times \phi^5$  to the two point fuction", Top]
```

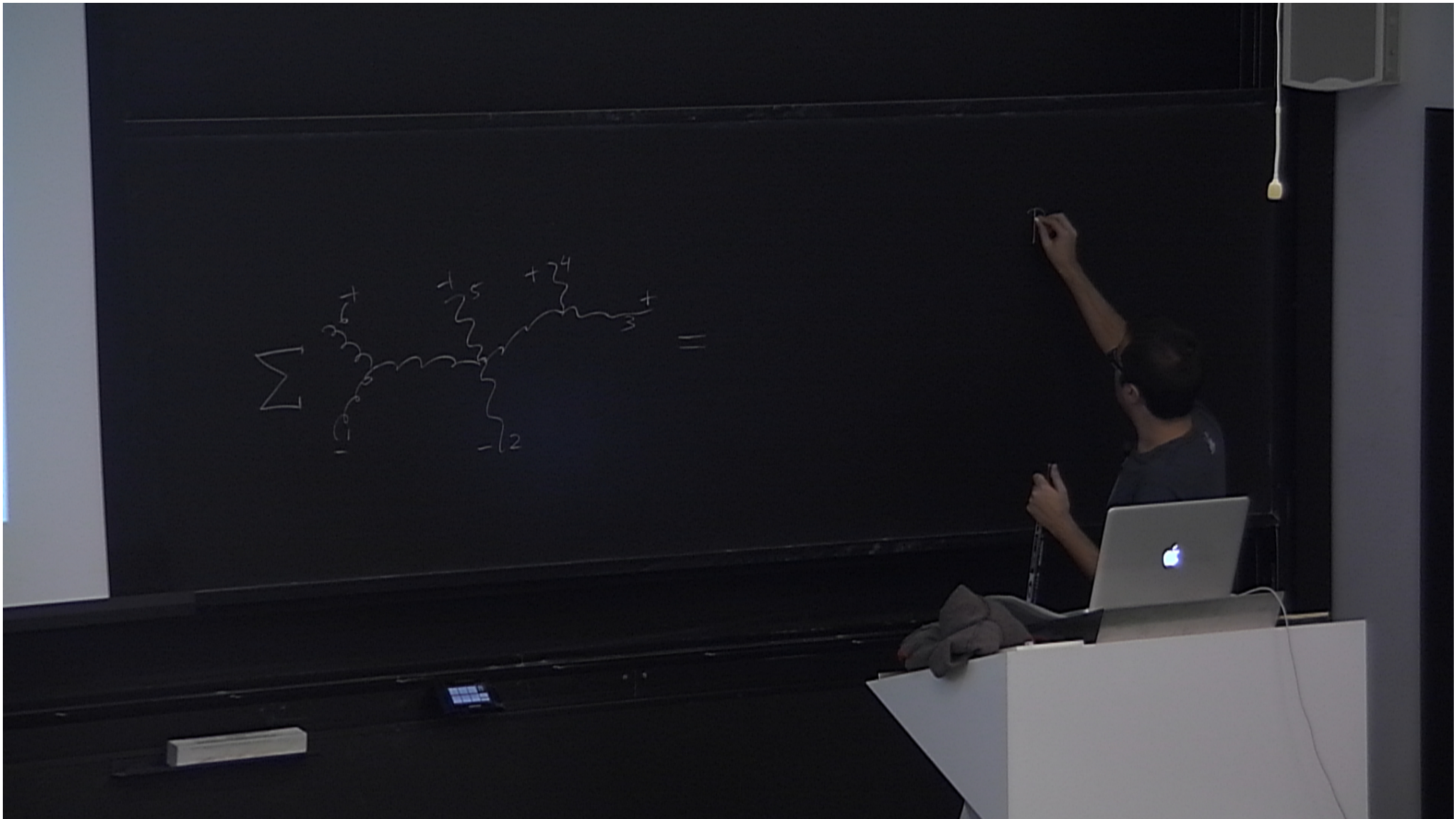
Connected contribution from $\lambda^2 \phi^3 \times \phi^5$ to the two point fuction

Out[368]=

$\frac{1}{6}$ $+$ $\frac{1}{4}$ $+$ $\frac{1}{8}$ $+$ $\frac{1}{4}$

In[370]=

150%



$$\sum \text{diagram} = \frac{\langle 12 \rangle^4}{\langle 12 \rangle \langle 23 \rangle \langle 31 \rangle}$$

The diagram on the left is a Feynman diagram with four external legs labeled 1, 2, 3, and 4. It consists of a loop with two internal vertices. The external legs are connected to the vertices as follows: leg 1 is a wavy line to the bottom-left vertex, leg 2 is a wavy line to the bottom-right vertex, leg 3 is a wavy line to the top-right vertex, and leg 4 is a wavy line to the top-left vertex. The internal lines are also wavy. The diagram is summed over all possible internal line configurations.

$$\begin{pmatrix} p_1^{(a)} + p_2^{(a)} & p_3^{(a)} + i p_4^{(a)} \\ \dots & \dots \end{pmatrix}_{ab} = \lambda_a^{(a)} \tilde{\lambda}_b^{(a)}$$

$$\langle ij \rangle \equiv \lambda_a^{(i)} \lambda_b^{(j)} \epsilon^{ab}$$

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FileBefore1010.nb

```
, {L, Length[wickcontracted]}], {ProgressIndicator[L, {1, Length[wickcontracted]}], L, Length[wickcontracted]}}];
```

In[379]:=

```
nicegraphs = Labeled[graphs /. a_. G_Graphics -> Labeled[G,  $\frac{a}{3! 5!}$ , Left],  
"Connected contribution from  $\lambda^2 \phi^3 \times \phi^5$  to the two point fuction", Top]
```

Connected contribution from $\lambda^2 \phi^3 \times \phi^5$ to the two point fuction

Out[379]=

150%

```
EvenQ@Count[towick,  $\phi$ [_]];
```

In[376]:=

```
wickcontracted = Expand@wick@towick;  
listdummy;
```

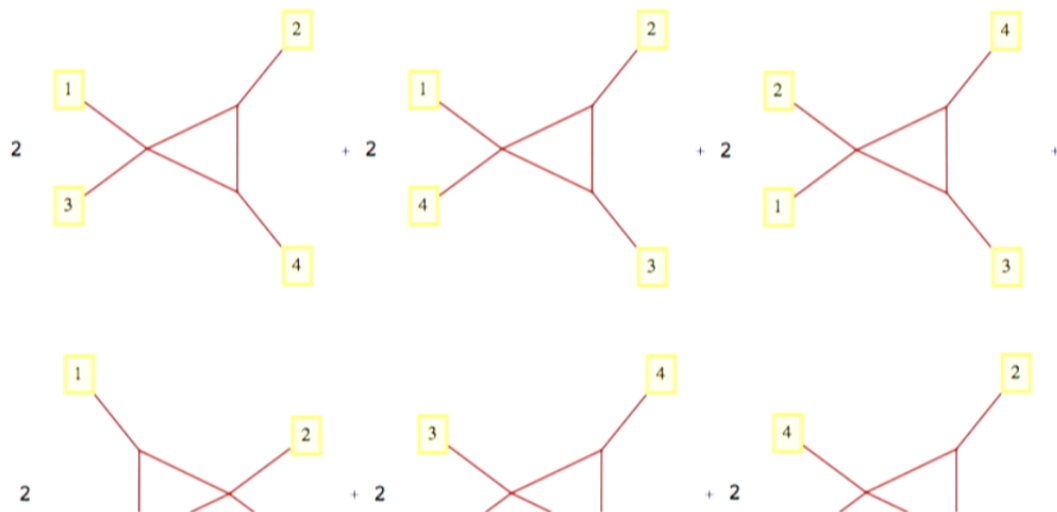
- Plotting the (connected) Graphs

```
graphs = Monitor[Pare[If[connectedQ@wickcontracted[[L]], tograph@wickcontracted[[L]], 0], {L, Length[wickcontracted]}], {ProgressIndicator[L, {1, Length[wickcontracted]}], L, Length[wickcontracted]}];
```

In[380]:=

```
nicegraphs = Labeled[graphs /. a_. G_Graphics  $\rightarrow$  Labeled[G,  $\frac{a}{3! \ 3! \ 4!}$ , Left],
  "Connected contribution from  $\lambda^2 \phi^3 \times \phi^5$  to the two point fuction", Top]
```

Connected contribution from $\lambda^2 \phi^3 \times \phi^5$ to the two point function



```
EvenQ@Count[towick,  $\phi$ [_]]];
```

In[376]:=

```
wickcontracted = Expand@wick@towick;
listdummy;
```

■ Plotting the (connected) Graphs

In[382]:=

```
graphs = Monitor[Sum[If[connectedQ@wickcontracted[[ $\ell$ ]], tograph@wickcontracted[[ $\ell$ ], 0]
, { $\ell$ , Length[wickcontracted]}], {ProgressIndicator[ $\ell$ , {1, Length[wickcontracted]}],  $\ell$ , Length[wickcontracted]}];
{ProgressIndicator[ $\ell$ , {1, 135 135}],  $\ell$ , 135 135}
```

In[380]:=

```
nicegraphs = Labeled[graphs /. a_. G_Graphics  $\rightarrow$  Labeled[G,  $\frac{a}{3! 3! 4!}$ , Left],
"Connected contribution from  $\lambda^2 \phi^3 \times \phi^5$  to the two point fuction", Top]
```

Out[380]:=

