

Pensieve header: A unified verification notebook for the \$sl\_2\$-portfolio project, Uxi version. Continues pensieve://Projects/PPSA/nb/Verification.pdf.

Continues pensieve://2017-06/ and pensieve://2017-08/.

## Prolog

```
wdir = SetDirectory["C:\\drorbn\\AcademicPensieve\\Projects\\SL2Portfolio"];
NotebookOpen[wdir <> "\\MakeSnips.nb"];
```

```
In[*]:= HL[ε_] := Style[ε, Background → Yellow];
```

## DocileQ

DocileQ

```
In[*]:= DQ[ε_] := (Exponent[Normal@ε /.
  {a → a / ε, a_i → a_i / ε, (u : x | y) ⇒ ε-1/2 u, (u : x | y)_i ⇒ ε-1/2 u_i}, ε, Min] ≥ 0);
```

```
In[*]:= DQ /@ {ε2 x y a2, ε2 x2 y3}
```

```
Out[*]:= {True, False}
```

## Initialization / Utilities

It is verification-risky to work with low \$E\$!

TD

```
In[*]:= $p = 2; $k = 1; $E := {$k, $p};
$trim := {hp /; p > $p → 0, ek /; k > $k → 0};
SetAttributes[{SS, SST}, HoldAll];
TRule = {T_i → eh t_i, T → eh t}; q_h = ey ε h;
SS[ε_, op_] := Collect[
  Normal@Series[If[$p > 0, ε, ε /. TRule], {h, 0, $p}],
  h, op];
SS[ε_] := SS[ε, Together];
SST[ε_, op___] := SS[ε /. TRule, op];
Simp[ε_, op_] := Collect[ε, _CU | _QU, op];
Simp[ε_] := Simp[ε, SS[#, Expand] &];
SimpT[ε_] := Collect[ε, _CU | _QU, SST[#, Expand] &];
```

Differential polynomials (DP):

Utils

```
In[*]:= DPα→Dx, β→Dy[P_] [λ_] :=
  Total[CoefficientRules[Normal@P, {α, β}] /. ({m_, n_} → c_) ⇒ c ∂{x,m},{y,n} λ]
```

```
HL[DPx→Dε, y→Dη[x2 y3] [eδ ε η] == 6 eδ η ε δ3 ε + 6 eδ η ε δ4 η ε2 + eδ η ε δ5 η2 ε3]
```

**True**

CF

```
In[ ]:= CF[ $\mathcal{E}$ _] := ExpandDenominator@
ExpandNumerator@Together[Expand[ $\mathcal{E}$ ] /. ex- ey-  $\Rightarrow$  ex+y /. ex-  $\Rightarrow$  eCF[x]];
```

SeriesData

```
In[ ]:= Unprotect[SeriesData];
SeriesData /: CF[sd_SeriesData] := MapAt[CF, sd, 3];
SeriesData /: Expand[sd_SeriesData] := MapAt[Expand, sd, 3];
SeriesData /: Simplify[sd_SeriesData] := MapAt[Simplify, sd, 3];
SeriesData /: Together[sd_SeriesData] := MapAt[Together, sd, 3];
SeriesData /: Collect[sd_SeriesData, specs__] := MapAt[Collect[#, specs] &, sd, 3];
Protect[SeriesData];
```

Self-Pair (SP):

SP

```
In[ ]:= SP[{}][P_] := P; SP[ $\{\xi \rightarrow x, ps\_ \}$ ][P_] := Expand[P // SP[ps]] /. f_ .  $\xi^{d_}$   $\Rightarrow$   $\partial_{\{x,d\}}$  f
```

$$\text{SP}_{\{\xi \rightarrow x\}}[(\xi^2 + \xi + 3)(x^5 e^x + 7x) + 99a]$$

$$7 + 99a + 21x + 20e^x x^3 + 15e^x x^4 + 5e^x x^5$$

$$\text{SP}_{\{\xi \rightarrow x, \eta \rightarrow y\}}[(\xi^2 + \xi + 3 + 2\xi\eta)(x^5 e^x + 7x) + 99a + e^{\delta xy} \xi \eta]$$

$$7 + 99a + 21x + 20e^x x^3 + 15e^x x^4 + 5e^x x^5 + e^{xy\delta} \delta + e^{xy\delta} xy \delta^2$$

## DeclareAlgebra

QLImplementation

```
In[ ]:= Unprotect[NonCommutativeMultiply]; Attributes[NonCommutativeMultiply] = {};
(NCM = NonCommutativeMultiply)[x_] := x;
NCM[x_, y_, z_] := (x ** y) ** z;
0 ** _ = _ ** 0 = 0;
(x_Plus) ** y_ := (# ** y) & /@ x; x_ ** (y_Plus) := (x ** #) & /@ y;
B[x_, x_] = 0; B[x_, y_] := x ** y - y ** x;
B[x_, y_, e_] := B[x, y, e] = B[x, y];
```

QLImplementation

In[ ]:=

```

DeclareAlgebra[U_Symbol, opts__Rule] := Module[{gp, sr, g, cp, M, CE, pow, k = 0,
  gs = Generators /. {opts},
  cs = Centrals /. {opts} /. Centrals -> {}},
  (#u = U@#) & /@gs;
  gp = Alternatives @@ gs; gp = gp | gp; (* gens *)
  sr = Flatten@Table[{g -> ++k, gi -> {i, k}}, {g, gs}]; (* sorting -> *)
  cp = Alternatives @@ cs; (* cents *)
  SetAttributes[M, HoldRest]; M[0, _] = 0; M[a_, x_] := a x;
  CE[_] := Collect[_U, Expand] /. $trim;
  Ui[_] := _ /. {t : cp -> ti, u_U -> (#i &) /@u};
  Ui[NCM[]] = pow[_] = U@{ } = 1_U = U[];
  B[U@(x_)i_, U@(y_)i_] := Ui@B[U@x, U@y];
  B[U@(x_)i_, U@(y_)j_] /; i != j := 0;
  B[U@y_, U@x_] := CE[-B[U@x, U@y]];
  x_ ** (c_. 1_U) := CE[c x]; (c_. 1_U) ** x_ := CE[c x];
  (a_. U[xx___, x_]) ** (b_. U[yy___]) := If[OrderedQ[{x, y} /. sr],
    CE@M[a b /. $trim, U[xx, x, y, yy]],
    U@xx ** CE@M[a b /. $trim, U@y ** U@x + B[U@x, U@y, $E]] ** U@yy];
  U@{c_. * (L : gp)^n_, r___} /; FreeQ[c, gp] := CE[c U@Table[L, {n}] ** U@{r}];
  U@{c_. * L : gp, r___} := CE[c U[L] ** U@{r}];
  U@{c_, r___} /; FreeQ[c, gp] := CE[c U@{r}];
  U@{L_Plus, r___} := CE[U@{#, r} & /@ L];
  U@{L_, r___} := U@{Expand[L], r};
  U[_NonCommutativeMultiply] := U /@ _;
  OU[specs___, poly_] := Module[{sp, null, vs, us},
    sp = Replace[{specs}, L_List -> L_null, {1}];
    vs = Join@@(First /@ sp);
    us = Join@@(sp /. L_s_ -> (L /. x_i_ -> x_s));
    CE[Total[
      CoefficientRules[poly, vs] /. (p_ -> c_) -> c U@(us^p)
    ] /; x_null -> x];
  pow[_] = pow[_] := pow[_ - 1] ** _;
  SU[_] := CE@Total[
    CoefficientRules[_] /.
      (p_ -> c_) -> c NCM@@MapThread[pow, {Last /@ {ss}, p}]];
  sigma_rs___[c_. * u_U] := (c /. (t : cp)j_ -> tj /. {rs}) U[List@@(u /. v_j_ -> vj /. {rs})];
  m_j_to_k[c_. * u_U] := CE[((c /. (t : cp)j_ -> tk) DeleteCases[u, _j|k]) **
    U@@Cases[u, w_j -> wk] ** U@@Cases[u, _k]];
  U /: c_. * u_U * v_U := CE[c u ** v];
  Si[c_. * u_U] := CE[((c /. Si[U, Centrals]) DeleteCases[u, _i]) **
    Ui[NCM@@Reverse@Cases[u, x_i -> S@U@x]];
  Delta_i_to_j_k[c_. * u_U] := CE[((c /. Delta_i_to_j_k[U, Centrals]) DeleteCases[u, _i]) **
    (NCM@@Cases[u, x_i -> sigma_1_to_j_2_to_k@Delta@U@x] /. NCM[] -> U[])];

```

## DeclareMorphism

QLImplementation

```
In[ ]:= DeclareMorphism[m_, U_ -> V_, ongs_List, oncs_List: {}] := (
  Replace[ongs,
    {(g_ -> img_) -> (m[U[g]] = img), (g_ -> img_) -> (m[U[g]] := img /. $trim)}, {1}];
  m[1_U] = 1_V;
  m[U[g_i_]] := V_i[m[U@g]];
  m[U[vs_]] := NCM@@(m/@U/@{vs});
  m[E_] := Simp[E /. oncs /. u_U -> m[u]] /. $trim;
```

## Meta-Operations

QLImplementation

```
In[ ]:= sigma_RS__[E_Plus] := sigma_RS /@ E;
  m_j -> j_ = Identity; m_j -> k_[0] = 0;
  m_j -> k_[E_Plus] := Simp[m_j -> k_ /@ E];
  m_i_s __, i_, j_ -> k_[E_] := m_j -> k_ @ m_i_s, i -> j @ E;
  S_i_[E_Plus] := Simp[S_i_ /@ E];
  Delta_i_s __[E_Plus] := Simp[Delta_i_s /@ E];
```

## Implementing $CU = \mathcal{U}(sl_2^{\mathbb{C}})$

Verify  $\sigma$  and  $\Delta$ ! Also Generalize  $\Delta$  to  $\Delta_{i,j_1,j_2,\dots}$ .

CU

```
In[ ]:= DeclareAlgebra[CU, Generators -> {y, a, x}, Centrals -> {t}];
  B[a_CU, y_CU] = -y y_CU; B[x_CU, a_CU] = -x x_CU;
  B[x_CU, y_CU] = 2 e a_CU - t 1_CU;
  (S@y_CU = -y_CU; S@a_CU = -a_CU; S@x_CU = -x_CU);
  S_i_[CU, Centrals] = {t_i -> -t_i};
  Delta@y_CU = CU@y_1 + CU@y_2; Delta@a_CU = CU@a_1 + CU@a_2; Delta@x_CU = CU@x_1 + CU@x_2;
  Delta_i -> j_, k_[CU, Centrals] = {t_i -> t_j + t_k};
```

Verifying associativity on triples of generators:

```
With[{bas = CU /@ {y, a, x}},
  Table[z1 ** (z2 ** z3) - (z1 ** z2) ** z3 // Simp // HL,
    {z1, bas}, {z2, bas}, {z3, bas} ] ]
{{{0, 0, 0}, {0, 0, 0}, {0, 0, 0}},
 {{0, 0, 0}, {0, 0, 0}, {0, 0, 0}}, {{0, 0, 0}, {0, 0, 0}, {0, 0, 0}}}
```

Verifying associativity on a “random” triple:

```
With[{z1 = CU[y, y, a, a, x, x], z2 = CU[y, a, x], z3 = CU[y, y, a, x]}, {
  (rhs = (z1 ** z2) ** z3 // Simp) // Short,
  z1 ** (z2 ** z3) - rhs // Simp // HL
}] // Timing
{1.32813,
{(28 t^2 γ^4 + 116 t γ^5 ε) CU[y, y, y, x, x] + <<21>> + CU[y, y, y, y, y, a, a, a, a, x, x, x, x], 0}}
```

## Implementing QU = $\mathcal{U}_q(\mathfrak{sl}_2^{\gamma\epsilon})$

Aside

```
Series[(1 - T e^{-2ε a ħ}) / ħ, {a, 0, 3}]
```

Aside

$$\frac{1 - T}{\hbar} + 2 T \epsilon a - 2 (T \epsilon^2 \hbar) a^2 + \frac{4}{3} T \epsilon^3 \hbar^2 a^3 + O[a]^4$$

```
In[*]:= HL /@ DQ /@ Series[{{(1 - T e^{-2ε a ħ}) / ħ, e^{ħ ε a}}, {ε, 0, 5}]
```

```
Out[*]:= {True, True}
```

QU

```
In[*]:= DeclareAlgebra[QU, Generators -> {y, a, x}, CentralS -> {t, T}];
B[aQU, yQU] = -γ yQU; B[xQU, aQU] = -γ QU@x;
B[xQU, yQU] := SS[qħ - 1] QU@{y, x} + OQU[{a}, SS[(1 - T e^{-2ε a ħ}) / ħ]];
(S@yQU := OQU[{a, y}, SS[-T^{-1} e^{ħ ε a} y]]; S@aQU = -aQU; S@xQU := OQU[{a, x}, SS[-e^{ħ ε a} x]];
Si[QU, CentralS] = {ti -> -ti}, Ti -> Ti^{-1}};
Δ@yQU := OQU[{y1, a1}1, {y2}2, SS[y1 + T1 e^{-ħ ε a1} y2]];
Δ@aQU = QU@a1 + QU@a2; Δ@xQU := OQU[{a1, x1}1, {x2}2, SS[x1 + e^{-ħ ε a1} x2]];
Δi -> j, k[QU, CentralS] = {ti -> tj + tk}, Ti -> Tj Tk}}
```

```
With[{bas = QU /@ {y, a, x}}, Table[{z1, z2} -> Simp[z1 ** z2 - z2 ** z1], {z1, bas}, {z2, bas}]]
{{{QU[y], QU[y]} -> 0, {QU[y], QU[a]} -> γ QU[y],
{QU[y], QU[x]} -> ((-1 + T) QU[] / ħ) - 2 T ε QU[a] - γ ε ħ QU[y, x]},
{{QU[a], QU[y]} -> -γ QU[y], {QU[a], QU[a]} -> 0, {QU[a], QU[x]} -> γ QU[x]},
{{QU[x], QU[y]} -> ((1 - T) QU[] / ħ) + 2 T ε QU[a] + γ ε ħ QU[y, x],
{QU[x], QU[a]} -> -γ QU[x], {QU[x], QU[x]} -> 0}}
```

Verifying associativity on triples of generators:

```
With[{bas = QU /@ {y, a, x}},
Table[HL[z1 ** (z2 ** z3) - (z1 ** z2) ** z3] // Simp,
{z1, bas}, {z2, bas}, {z3, bas}]]
{{{0, 0, 0}, {0, 0, 0}, {0, 0, 0}},
{{0, 0, 0}, {0, 0, 0}, {0, 0, 0}}, {{0, 0, 0}, {0, 0, 0}, {0, 0, 0}}}
```

Verifying associativity on a “random” triple (~34 secs @ \$p=5, \$k=2):

```
With[{z1 = QU[y, y, a, a, x, x], z2 = QU[y, a, x], z3 = QU[y, y, a, x]}, {
  (rhs = (z1 ** z2) ** z3 // Simp) // Short,
  HL[z1 ** (z2 ** z3) - rhs // Simp]
}] // Timing

{3.78125, {
  (

$$\frac{28 \gamma^4 - 56 T \gamma^4 + 28 T^2 \gamma^4}{\hbar^2} + \frac{82 \gamma^5 \epsilon - 280 T \ll 1 \gg \epsilon + 198 T^2 \gamma^5 \epsilon}{\hbar}$$

    ) QU[y, y, y, x, x] +
  <<18>> + (1 + 8 \gamma \epsilon \hbar) QU[y, <<11>>, x], 0}}

```

Verifying that  $\lim_{\hbar \rightarrow 0} QU = CU$  using a “random” product (~23 secs @ \$p=5, \$k=2):

```
With[{z1 = CU[y, y, a, a, x, x], z2 = CU[y, a, x], z3 = CU[y, y, a, x]}, {
  Short[lhs = z1 ** (z2 ** z3)],
  Short[rhs = (QU@@z1) ** ((QU@@z2) ** (QU@@z3))],
  Expand[Limit[rhs /. TRule[Union[{QU -> CU}, \hbar -> 0] - lhs] // HL] // Timing
}]

{10.125, {
  28 t^2 \gamma^4 CU[y, y, y, x, x] +
  116 t \gamma^5 \epsilon CU[y, y, y, x, x] + <<44>> + CU[y, y, y, y, a, a, a, a, x, x, x, x],
  2 (

$$\frac{\gamma^4}{\hbar^2} - \frac{2 T \gamma^4}{\hbar^2} + \frac{T^2 \gamma^4}{\hbar^2} + \frac{\gamma^5 \epsilon}{\hbar} - \frac{2 T \gamma^5 \epsilon}{\hbar} + \frac{T^2 \gamma^5 \epsilon}{\hbar}$$

    ) QU[y, y, y, x, x] +
  <<209>> + (1 + 8 \gamma \epsilon \hbar) QU[y, y, y, <<7>>, x, x, x], 0}}

```

## Verifying $\sigma, m, S,$ and $\Delta$ .

Verifying  $\sigma_{i \rightarrow j, k \rightarrow l}$ :

```
In[*]:= CU@x1 + CU@x2 // \sigma_{1 \to 3, 2 \to 4}
Out[*]:= CU[x3] + CU[x4]
```

Verifying relabeling using  $m$ :

```
In[*]:= t1 t3 CU[y1, a1, x2] + t1 t1 CU[y1, a2, x2] // m_{1 \to 3}
Out[*]:= CU[a2, x2, y3] t3^2 + CU[x2, y3, a3] t3^2
```

Verifying the meta-associativity of  $m$ :

```
In[*]:= Module[{z, u},
  Table[u = CU[z[[1]]1, z[[2]]2, z[[3]]3]; HL[m_{1,3 \to 3} @ m_{2,3 \to 3} @ u == m_{2,3 \to 3} @ m_{1,2 \to 2} @ u],
  {z, Tuples[{y, a, x}, 3]}, {U, {CU, QU}}]]
Out[*]:= {{True, True}, {True, True}, {True, True}, {True, True}, {True, True},
  {True, True}, {True, True}, {True, True}, {True, True}, {True, True},
  {True, True}, {True, True}, {True, True}, {True, True}, {True, True}, {True, True},
  {True, True}, {True, True}, {True, True}, {True, True}, {True, True},
  {True, True}, {True, True}, {True, True}, {True, True}, {True, True}}
```

Verifying the involutivity of  $S$  on  $CU$  on products of triples:

```
In[ ]:= With[{bas = CU /@ {y1, a1, x1}},
  Table[HL@Simp[z1 ** z2 ** z3 - S1@S1[z1 ** z2 ** z3]],
    {z1, bas}, {z2, bas}, {z3, bas} ] ]
Out[ ]:= {{{0, 0, 0}, {0, 0, 0}, {0, 0, 0}},
  {{0, 0, 0}, {0, 0, 0}, {0, 0, 0}}, {{0, 0, 0}, {0, 0, 0}, {0, 0, 0}}}
```

Verifying that S is an anti-homomorphism on CU/QU:

```
In[ ]:= With[{bas = U /@ {y1, a1, x1}},
  Table[HL@Simp[S1[z1 ** z2] - S1[z2] ** S1[z1]],
    {z1, bas}, {z2, bas}, {U, {CU, QU}} ] ]
Out[ ]:= {{{0, 0}, {0, 0}, {0, 0}}, {{0, 0}, {0, 0}, {0, 0}}, {{0, 0}, {0, 0}, {0, 0}}}
```

Verifying the co-associativity of  $\Delta$ :

```
In[ ]:= Block[{bas = U /@ {y1, a1, x1}},
  Table[(z1 ** z2 ** z3 //  $\Delta_{1 \rightarrow 1, 2}$  //  $\Delta_{2 \rightarrow 2, 3}$ ) - (z1 ** z2 ** z3 //  $\Delta_{1 \rightarrow 1, 3}$  //  $\Delta_{1 \rightarrow 1, 2}$ ) // Simp // HL,
    {z1, bas}, {z2, bas}, {z3, bas}, {U, {CU, QU}} ] ]
Out[ ]:= {{{{0, 0}, {0, 0}, {0, 0}}, {{0, 0}, {0, 0}, {0, 0}}, {{0, 0}, {0, 0}, {0, 0}}},
  {{{0, 0}, {0, 0}, {0, 0}}, {{0, 0}, {0, 0}, {0, 0}}, {{0, 0}, {0, 0}, {0, 0}}},
  {{{0, 0}, {0, 0}, {0, 0}}, {{0, 0}, {0, 0}, {0, 0}}, {{0, 0}, {0, 0}, {0, 0}}}}
```

Verifying S- $\Delta$  compatibility:

```
In[ ]:= Block[{bas = U /@ {y1, a1, x1}},
  Table[z1 ** z2 ** z3 //  $\Delta_{1 \rightarrow 1, 2}$  // Si //  $m_{1, 2 \rightarrow 1}$  // Simp // HL,
    {U, {CU, QU}}, {i, 2}, {z1, bas}, {z2, bas}, {z3, bas} ] ]
Out[ ]:= {{{{{0, 0, 0}, {0, 0, 0}, {0, 0, 0}}, {{0, 0, 0}, {0, 0, 0}, {0, 0, 0}},
  {{0, 0, 0}, {0, 0, 0}, {0, 0, 0}}, {{0, 0, 0}, {0, 0, 0}, {0, 0, 0}}},
  {{{0, 0, 0}, {0, 0, 0}, {0, 0, 0}}, {{0, 0, 0}, {0, 0, 0}, {0, 0, 0}},
  {{{0, 0, 0}, {0, 0, 0}, {0, 0, 0}}, {{0, 0, 0}, {0, 0, 0}, {0, 0, 0}},
  {{{0, 0, 0}, {0, 0, 0}, {0, 0, 0}}, {{0, 0, 0}, {0, 0, 0}, {0, 0, 0}}}}
```

Verifying S- $\Delta$  compatibility for opposite  $m$ , only for CU:

```
In[ ]:= Block[{bas = CU /@ {y1, a1, x1}},
  Table[z1 ** z2 ** z3 //  $\Delta_{1 \rightarrow 1, 2}$  // Si //  $m_{2, 1 \rightarrow 1}$  // Simp // HL,
    {i, 2}, {z1, bas}, {z2, bas}, {z3, bas} ] ]
Out[ ]:= {{{{0, 0, 0}, {0, 0, 0}, {0, 0, 0}}, {{0, 0, 0}, {0, 0, 0}, {0, 0, 0}},
  {{0, 0, 0}, {0, 0, 0}, {0, 0, 0}}, {{0, 0, 0}, {0, 0, 0}, {0, 0, 0}}},
  {{{0, 0, 0}, {0, 0, 0}, {0, 0, 0}}, {{0, 0, 0}, {0, 0, 0}, {0, 0, 0}},
  {{{0, 0, 0}, {0, 0, 0}, {0, 0, 0}}, {{0, 0, 0}, {0, 0, 0}, {0, 0, 0}}}}
```

Verifying  $m$ - $\Delta$  compatibility:

```
In[ ]:= Block[{bas1 = U /@ {y1, a1, x1}, bas2 = U /@ {y2, a2, x2}},
  Table[{z1 ** z2 ** z3 ** z4 // m1,2→1 // Δ1→1,2} -
    (z1 ** z2 ** z3 ** z4 // Δ1→3,4 // Δ2→5,6 // m3,5→1 // m4,6→2) // Simp // HL,
    {U, {CU, QU}}, {z1, bas1}, {z2, bas1}, {z3, bas2}, {z4, bas2} ] ]
```

```
Out[ ]:= {{{{0, 0, 0}, {0, 0, 0}, {0, 0, 0}},
  {{0, 0, 0}, {0, 0, 0}, {0, 0, 0}}, {{0, 0, 0}, {0, 0, 0}, {0, 0, 0}}},
  {{{0, 0, 0}, {0, 0, 0}, {0, 0, 0}}, {{0, 0, 0}, {0, 0, 0}, {0, 0, 0}},
  {{0, 0, 0}, {0, 0, 0}, {0, 0, 0}}, {{{0, 0, 0}, {0, 0, 0}, {0, 0, 0}},
  {{0, 0, 0}, {0, 0, 0}, {0, 0, 0}}, {{0, 0, 0}, {0, 0, 0}, {0, 0, 0}}},
  {{{{0, 0, 0}, {0, 0, 0}, {0, 0, 0}}, {{0, 0, 0}, {0, 0, 0}, {0, 0, 0}},
  {{0, 0, 0}, {0, 0, 0}, {0, 0, 0}}}, {{{0, 0, 0}, {0, 0, 0}, {0, 0, 0}},
  {{0, 0, 0}, {0, 0, 0}, {0, 0, 0}}, {{0, 0, 0}, {0, 0, 0}, {0, 0, 0}}},
  {{{0, 0, 0}, {0, 0, 0}, {0, 0, 0}}, {{0, 0, 0}, {0, 0, 0}, {0, 0, 0}},
  {{0, 0, 0}, {0, 0, 0}, {0, 0, 0}}}}}
```

## Implementing $\theta$

theta

```
In[ ]:= DeclareMorphism[Cθ, CU → CU, {y → -xCU, a → -aCU, x → -yCU}, {t → -t, T → T-1}] ;
DeclareMorphism[Qθ, QU → QU, {y := QQU[{a, x}, SS[-T-1/2 eħεa x]],
  a → -aQU, x := QQU[{a, y}, SS[-T-1/2 eħεa y]]}, {t → -t, T → T-1}]
```

Verifying involutivity on CU:

```
With[{bas = CU /@ {y, a, x}},
  Table[z → Cθ[z] → HL[Cθ[Cθ[z]]], {z, bas} ]
{CU[y] → -CU[x] → CU[y], CU[a] → -CU[a] → CU[a], CU[x] → -CU[y] → CU[x]}
```

Verifying that  $\theta$  is a multiplicative homomorphism on CU:

```
With[{bas = CU /@ {y, a, x}},
  Table[Cθ[z1 ** z2] - Cθ[z1] ** Cθ[z2] // HL, {z1, bas}, {z2, bas} ]
{{0, 0, 0}, {0, 0, 0}, {0, 0, 0}}
```

Verifying involutivity on QU:

```
With[{bas = QU /@ {y, a, x}},
  Table[z → Qθ[z] → HL[Simp[Qθ[Qθ[z]], PowerExpand]], {z, bas} ]
{QU[y] → - $\frac{QU[x]}{\sqrt{T}}$  -  $\frac{\epsilon \hbar QU[a, x]}{\sqrt{T}}$  → QU[y], QU[a] → -QU[a] → QU[a],
  QU[x] →  $\left(-\frac{1}{\sqrt{T}} + \frac{\gamma \epsilon \hbar}{\sqrt{T}}\right) QU[y] - \frac{\epsilon \hbar QU[y, a]}{\sqrt{T}}$  → QU[x]}
```

Verifying that  $\theta$  is a multiplicative homomorphism on QU:



```
With[{bas = QU /@ {y, a, x}},
  Table[{z1, z2} → HL[Simp[QΘ[z1 ** z2] - QΘ[z1] ** QΘ[z2]]], {z1, bas}, {z2, bas}] ]
{{{QU[y], QU[y]} → 0, {QU[y], QU[a]} → 0, {QU[y], QU[x]} → 0},
 {QU[a], QU[y]} → 0, {QU[a], QU[a]} → 0, {QU[a], QU[x]} → 0},
 {QU[x], QU[y]} → 0, {QU[x], QU[a]} → 0, {QU[x], QU[x]} → 0}}
```

## The Asymmetric Dequantizer

Following pensieve://People/VanDerVeen/Dequant1.pdf.

ADeq

$$AD\$f = \gamma \left( \left( \text{Cosh} \left[ \hbar \left( a \epsilon + \frac{\gamma \epsilon}{2} - \frac{t}{2} \right) \right] - \text{Cosh} \left[ \hbar \sqrt{\left( \frac{t - \gamma \epsilon}{2} \right)^2 + \epsilon \omega} \right] \right) / \right. \\ \left. \left( \hbar e^{\hbar ((a+\gamma) \epsilon - t/2)} \text{Sinh} \left[ \frac{\gamma \epsilon \hbar}{2} \right] (a^2 \epsilon + a \gamma \epsilon - a t - \omega) \right) \right);$$

Docility of AD\$:f:

```
In[ ]:= HL@DQ@Block[{$p = 4}, Collect[SS@AD$f /. ω → a1, ε]]
```

Out[ ]:= True

Scaling behaviour of AD\$:f:

```
HL@Simplify[AD$f == ((AD$f /. γ → 1) /. {ε → γ ε, a → γ-1 a, ω → γ-1 ω})]
```

True

```
HL@FullSimplify[
  AD$f == ((AD$f /. γ → 1) /. {ħ → γ2 ħ, ε → ε / γ, a → a / γ, t → γ-2 t, ω → γ-3 ω})]
```

True

ADeq

$$AD\$ω = \gamma \text{CU}[y, x] + \epsilon \text{CU}[a, a] - (t - \gamma \epsilon) \text{CU}[a];$$

ADeq

```
In[ ]:= DeclareMorphism[AD, QU → CU,
  {a → aCU, x → CU@x, y := SCU[SS[AD$f], a → aCU, ω → AD$ω] ** yCU}]
```

Verifying that the asymmetric dequantizer is a homomorphism:

```
With[{bas = QU /@ {y, a, x}},
  Table[{z1, z2} → HL[SimpT[AD[z1 ** z2] - AD[z1] ** AD[z2]]], {z1, bas}, {z2, bas}] ]
{{{QU[y], QU[y]} → 0, {QU[y], QU[a]} → 0, {QU[y], QU[x]} → 0},
 {QU[a], QU[y]} → 0, {QU[a], QU[a]} → 0, {QU[a], QU[x]} → 0},
 {QU[x], QU[y]} → 0, {QU[x], QU[a]} → 0, {QU[x], QU[x]} → 0}}
```

## The Symmetric Dequantizer

Following pensieve://People/VanDerVeen/Dequant1.pdf.

SDeq

$$\text{In[*]:= SD\$g = \sqrt{\left( \left( 2 \gamma \left( \text{Cosh} \left[ \frac{\hbar}{2} \sqrt{t^2 + \gamma^2 \epsilon^2 + 4 \epsilon \varpi} \right] - \text{Cosh} \left[ \frac{t - \epsilon \gamma - 2 \epsilon a}{2 / \hbar} \right] \right) \right) / \left( \text{Sinh} \left[ \frac{\gamma \epsilon \hbar}{2} \right] (t (2 a + \gamma) - 2 a (a + \gamma) \epsilon + 2 \varpi) \hbar \right) \right)};$$

SDeq

$$\text{In[*]:= SD\$f = Simplify} \left[ e^{\hbar (t/2 - \epsilon a)} (\text{SD\$g} /. \{a \rightarrow -a, t \rightarrow -t\}) \right];$$

Verify agreement with the formulas in pensieve://People/VanDerVeen/Dequant1.pdf:

$$\text{In[*]:= } \left\{ \text{SD\$P} = \frac{\text{Cosh} \left[ \hbar \left( \frac{\epsilon - t}{2} + \epsilon a \right) \right] - \text{Cosh} \left[ \hbar \sqrt{\frac{t^2 + \epsilon^2}{4} + \epsilon \varpi} \right]}{\hbar \text{Sinh} \left[ \frac{-\epsilon \hbar}{2} \right] (\varpi - \epsilon a^2 + (t - \epsilon) a + t/2)} \right.,$$

$$\text{Simplify} [\text{SD\$P} /. \{a \rightarrow -a - 1, t \rightarrow -t\}] // \text{HL},$$

$$\text{PowerExpand} @ \text{Simplify} \left[ (\text{SD\$P} /. \{\hbar \rightarrow \gamma^2 \hbar, \epsilon \rightarrow \epsilon / \gamma, a \rightarrow a / \gamma, t \rightarrow \gamma^{-2} t, \varpi \rightarrow \gamma^{-3} \varpi\}) == \right.$$

$$\text{SD\$g} (\text{SD\$g} /. \{a \rightarrow -a - \gamma, t \rightarrow -t\}) // \text{HL},$$

$$\text{SD\$Q} = \text{Simplify} [\text{SD\$P} /. \{a \rightarrow c - 1/2\}],$$

$$\text{Simplify} [\text{SD\$Q} == (\text{SD\$Q} /. \{c \rightarrow -c, t \rightarrow -t\})] // \text{HL},$$

$$\text{FullSimplify} [\text{SD\$g} == \text{FullSimplify} [$$

$$\sqrt{\text{SD\$Q}} /. c \rightarrow a + 1/2 /. \{\hbar \rightarrow \gamma^2 \hbar, \epsilon \rightarrow \epsilon / \gamma, a \rightarrow a / \gamma, t \rightarrow \gamma^{-2} t, \varpi \rightarrow \gamma^{-3} \varpi\}] // \text{HL},$$

$$\text{HL@DQ@Block} [\{\$p = 4\}, \text{Collect} [\text{SS@SD\$g} /. \omega \rightarrow a_1, \epsilon]],$$

$$\text{HL@DQ@Block} [\{\$p = 4\}, \text{Collect} [\text{SS@SD\$f} /. \omega \rightarrow a_1, \epsilon]]$$

$$\left. \right\}$$

$$\text{Out[*]:= } \left\{ - \left( \left( \left( \text{Cosh} \left[ \left( a \epsilon + \frac{1}{2} (-t + \epsilon) \right) \hbar \right] - \text{Cosh} \left[ \sqrt{\frac{1}{4} (t^2 + \epsilon^2) + \epsilon \varpi} \hbar \right] \right) \text{Csch} \left[ \frac{\epsilon \hbar}{2} \right] \right) / \right.$$

$$\left. \left( \left( \frac{t}{2} + a (t - \epsilon) - a^2 \epsilon + \varpi \right) \hbar \right) \right), \text{True, True},$$

$$- \left( \left( 4 \left( \text{Cosh} \left[ \frac{1}{2} (t - 2 c \epsilon) \hbar \right] - \text{Cosh} \left[ \frac{1}{2} \sqrt{t^2 + \epsilon^2 + 4 \epsilon \varpi} \hbar \right] \right) \text{Csch} \left[ \frac{\epsilon \hbar}{2} \right] \right) / \right.$$

$$\left. \left( (4 c t + \epsilon - 4 c^2 \epsilon + 4 \varpi) \hbar \right) \right), \text{True, True, True, True} \left. \right\}$$

SDeq

$$\text{In[*]:= SD\$w = \gamma CU} [y, x] + \epsilon \text{CU} [a, a] - (t - \gamma \epsilon) \text{CU} [a] - t \gamma \text{1cu} / 2;$$

SDeq

```
In[ ]:= DeclareMorphism[SID, QU -> CU, {a -> aCU,
  x := SCU[SS[SID$f], a -> aCU, w -> SID$w] ** xCU,
  y := SCU[SS[SID$g], a -> aCU, w -> SID$w] ** yCU }]
```

Verifying the  $\theta$ -symmetry:

```
Table[HL@SimpT[C@SID[z]] == SID[Q@z]], {z, QU /@ {y, a, x}}]
{True, True, True}
```

Verifying that the symmetric dequantizator is a homomorphism:

```
With[{bas = QU /@ {y, a, x}},
  Table[{z1, z2} -> HL@SimpT[SID[z1 ** z2] - SID[z1] ** SID[z2]], {z1, bas}, {z2, bas}]]
{{{QU[y], QU[y]} -> 0, {QU[y], QU[a]} -> 0, {QU[y], QU[x]} -> 0},
 {{QU[a], QU[y]} -> 0, {QU[a], QU[a]} -> 0, {QU[a], QU[x]} -> 0},
 {{QU[x], QU[y]} -> 0, {QU[x], QU[a]} -> 0, {QU[x], QU[x]} -> 0}}
```

## The representation $\rho$

rho

```
In[ ]:= rho@yCU = rho@yQU =  $\begin{pmatrix} 0 & 0 \\ \epsilon & 0 \end{pmatrix}$ ; rho@aCU = rho@aQU =  $\begin{pmatrix} \gamma & 0 \\ 0 & 0 \end{pmatrix}$ ;
rho@xCU =  $\begin{pmatrix} 0 & \gamma \\ 0 & 0 \end{pmatrix}$ ; rho@xQU =  $\begin{pmatrix} 0 & (1 - e^{-\gamma \epsilon \hbar}) / (\epsilon \hbar) \\ 0 & 0 \end{pmatrix}$ ;
rho[eε] := MatrixExp[rho[ε]];
rho[ε_] := (ε /. TRule /. t -> γ ε /. (U : CU | QU) [u___] := Fold[Dot,  $\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$ , rho /@ U /@ {u}])
```

Verifying that  $\rho$  represents CU and QU:

```
Table[HL[SS[rho[z1 ** z2]] == rho[z1].rho[z2]] /. ek. /; k > $k -> 0],
  {U, {CU, QU}}, {z1, U /@ {y, a, x}}, {z2, U /@ {y, a, x}}]
{{{True, True, True}, {True, True, True}, {True, True, True}},
 {{True, True, True}, {True, True, True}, {True, True, True}}}
```

Commuting  $e^{\alpha a}$  with  $e^{\xi x}$ :

```
Table[HL[rho[eε Uex].rho[eα Uea]] == rho[eα Uea].rho[ee-γ α ε Uex]], {U, {CU, QU}}]
{True, True}
```

## $\mathbb{C}$ and the logoi $\wedge$

Logoi from Pensieve://Talks/Toulouse-1705/DogmaDemo.nb and from Pensieve://Talks/Sydney-1708/ExtraDetails@@.nb.

MultiplyingOEs

```
In[ ]:= CU[s1_, Q1_, P1_] CU[s2_, Q2_, P2_] ^:= CU[s1, s2, Q1 + Q2, P1 P2];
```

CdsO

```
In[*]:= CU@CU[specs___, Q_, P_] := OCU[specs, SS[e^Q P]];
QU@QU[specs___, Q_, P_] := OQU[specs, SS[e^Q P]];
```

Logos

```
In[*]:= c_Integer k_Integer := c + O[ε]^{k+1};
ΛU,k_[{α_, β_}, {x_, x_}] := CU[{x}, (α + β) x, 1_k];
ΛU,k_[{ξ_, α_}, {x, a}] := CU[{a, x}, α a + e^{-α ξ} x, 1_k];
ΛU,k_[{α_, η_}, {a, y}] := CU[{y, a}, α a + e^{-α η} y, 1_k];
```

Table[

```
{ΛU,1[{α, β}, {u, u}],
  lhs = U@CU[{u1, u2}, ħ (α u1 + β u2), 1], HL[lhs == U@ΛU,1[ħ {α, β}, {u, u}]]},
{U, {CU, QU}}, {u, {y, a, x}}
{{CU[{y}, y (α + β), 1 + O[ε]^2],
  CU[] + (α ħ + β ħ) CU[y] + (α^2 ħ^2 / 2 + α β ħ^2 + β^2 ħ^2 / 2) CU[y, y], True},
{CU[{a}, a (α + β), 1 + O[ε]^2], CU[] + (α ħ + β ħ) CU[a] + (α^2 ħ^2 / 2 + α β ħ^2 + β^2 ħ^2 / 2) CU[a, a],
  True}, {CU[{x}, x (α + β), 1 + O[ε]^2],
  CU[] + (α ħ + β ħ) CU[x] + (α^2 ħ^2 / 2 + α β ħ^2 + β^2 ħ^2 / 2) CU[x, x], True}},
{QU[{y}, y (α + β), 1 + O[ε]^2], QU[] + (α ħ + β ħ) QU[y] + (α^2 ħ^2 / 2 + α β ħ^2 + β^2 ħ^2 / 2) QU[y, y],
  True}, {QU[{a}, a (α + β), 1 + O[ε]^2], QU[] + (α ħ + β ħ) QU[a] +
  (α^2 ħ^2 / 2 + α β ħ^2 + β^2 ħ^2 / 2) QU[a, a], True}, {QU[{x}, x (α + β), 1 + O[ε]^2],
  QU[] + (α ħ + β ħ) QU[x] + (α^2 ħ^2 / 2 + α β ħ^2 + β^2 ħ^2 / 2) QU[x, x], True}}}
```

```
{Λ#,1[{ξ, α}, {x, a}], lhs = #@CU#[{x, a}, ħ (ξ x + α a), 1],
```

```
HL[lhs == #@Λ#,1[ħ {ξ, α}, {x, a}]] & /@ {CU, QU}
```

```
{{CU[{a, x}, a α + e^{-α ξ} x, 1 + O[ε]^2],
  CU[] + α ħ CU[a] + (ξ ħ - α γ ξ ħ^2) CU[x] + 1/2 α^2 ħ^2 CU[a, a] + α ξ ħ^2 CU[a, x] + 1/2 ξ^2 ħ^2 CU[x, x],
  True}, {QU[{a, x}, a α + e^{-α ξ} x, 1 + O[ε]^2], QU[] + α ħ QU[a] +
  (ξ ħ - α γ ξ ħ^2) QU[x] + 1/2 α^2 ħ^2 QU[a, a] + α ξ ħ^2 QU[a, x] + 1/2 ξ^2 ħ^2 QU[x, x], True}}
```

```
{Λ_{#,2}[{α, η}, {a, y}], lhs = #@C_{#}[{a, y}, ħ (η y + α a), 1],
  HL[lhs = #@Λ_{#,2}[ħ {α, η}, {a, y}]] & /@ {CU, QU}
{{C_{CU}[{y, a}, a α + e^{-α y} y η, 1 + 0[ε]^3],
  CU[] + α ħ CU[a] + (η ħ - α γ η ħ^2) CU[y] + 1/2 α^2 ħ^2 CU[a, a] + α η ħ^2 CU[y, a] + 1/2 η^2 ħ^2 CU[y, y],
  True}, {C_{QU}[{y, a}, a α + e^{-α y} y η, 1 + 0[ε]^3], QU[] + α ħ QU[a] +
  (η ħ - α γ η ħ^2) QU[y] + 1/2 α^2 ħ^2 QU[a, a] + α η ħ^2 QU[y, a] + 1/2 η^2 ħ^2 QU[y, y], True}}
```

Goal. In either  $U$ , compute  $F = e^{-\eta y} e^{\xi x} e^{\eta y} e^{-\xi x}$ . First compute  $G = e^{\xi x} y e^{-\xi x}$ , a finite sum. Now  $F$  satisfies the ODE  $\partial_\eta F = \partial_\eta (e^{-\eta y} e^{\eta G}) = -yF + FG$  with initial conditions  $F(\eta = 0) = 1$ . So we set it up and solve:

```
If[$k > 0, With[{U = CU},
  Module[{G, F, fs, bs, e, b, es, sol},
    G = Echo@Simp[Table[ξ^k / k!, {k, 0, $k + 1}].NestList[Simp[B[x_U, #]] &, y_U, $k + 1]];
    fs = Echo@Flatten@Table[f_{1,i,j,k}[η], {1, 0, $k}, {i, 0, 1}, {j, 0, 1}, {k, 0, 1}];
    F = Echo[fs. (bs = fs /. f_{L_,i_,j_,k_}[η] => e^L U@{y^i, a^j, x^k})];
    es = Flatten[
      Table[Coefficient[e, b] == 0, {e, {F - 1_U /. η -> 0, F ** G - y_U ** F - ∂_η F}}, {b, bs}]];
    sol = Echo@First[F /. DSolve[es, fs, η]];
    Echo[sol /. {e -> 1, U -> Times}];
    Collect[sol /. {e -> 1, U -> Times}, ε, Simplify]
  ]]]
" -t ξ CU[] + 2 ε ξ CU[a] - γ ε ξ^2 CU[x] + CU[y]
" {f_{0,0,0,0}[η], f_{1,0,0,0}[η], f_{1,0,0,1}[η], f_{1,0,1,0}[η],
  f_{1,0,1,1}[η], f_{1,1,0,0}[η], f_{1,1,0,1}[η], f_{1,1,1,0}[η], f_{1,1,1,1}[η]}
" CU[] f_{0,0,0,0}[η] + ε CU[] f_{1,0,0,0}[η] + ε CU[x] f_{1,0,0,1}[η] + ε CU[a] f_{1,0,1,0}[η] + ε CU[a, x] f_{1,0,1,1}[η] +
  ε CU[y] f_{1,1,0,0}[η] + ε CU[y, x] f_{1,1,0,1}[η] + ε CU[y, a] f_{1,1,1,0}[η] + ε CU[y, a, x] f_{1,1,1,1}[η]
" e^{-t η ξ} CU[] + 1/2 e^{-t η ξ} t γ ε η^2 ξ^2 CU[] + 2 e^{-t η ξ} ε η ξ CU[a] - e^{-t η ξ} γ ε η ξ^2 CU[x] - e^{-t η ξ} γ ε η^2 ξ CU[y]
" 1 + 2 a ε η ξ - y γ ε η^2 ξ - x γ ε η ξ^2 + 1/2 t γ ε η^2 ξ^2
  1 + 1/2 ε η ξ (4 a + γ (-2 y η - 2 x ξ + t η ξ))
```

Logos

In[\*]:=

```

 $\Lambda_{U,kk}[\{\xi_1, \eta_1\}, \{x, y\}] := \Lambda_{U,kk}[\{\xi_1, \eta_1\}, \{x, y\}] =$ 
Block[{$k = kk, $p = kk}, Module[{ $\xi, \eta, G, F, fs, f, bs, e, b, es$ },
  G = Simp[Table[ $\xi^k/k!$ , {k, 0, $k+1}].NestList[Simp[B[xU, #]] &, yU, $k+1]];
  fs = Flatten@Table[f1,i,j,k[ $\eta$ ], {1, 0, $k}, {i, 0, 1}, {j, 0, 1}, {k, 0, 1}];
  F = fs.(bs = fs /. fL-,i-,j-,k-[ $\eta$ ]  $\rightarrow e^L U@{y^i, a^j, x^k}$ );
  es = Flatten[
    Table[Coefficient[e, b] == 0, {e, {F - 1U /.  $\eta \rightarrow 0$ , F ** G - yU ** F -  $\partial_\eta F$ }}, {b, bs}]];
  F = F /. DSolve[es, fs,  $\eta$ ] [[1]];
   $\mathbb{C}_U[\{y, a, x$ ,
     $\xi x + \eta y + (U /. \{CU \rightarrow -t \eta \xi, QU \rightarrow \eta \xi (1 - T) / \hbar\})$ ,
     $F + \theta_{\$k} /. \{e \rightarrow 1, U \rightarrow Times\}$ 
  ] /. { $\xi \rightarrow \xi_1, \eta \rightarrow \eta_1$ }]];

```

In[\*]:= Timing@ $\Lambda_{QU,2}[\{\xi, \eta\}, \{x, y\}]$

Out[\*]:=  $\{1.64063, \mathbb{C}_{QU}[\{y, a, x\}, y \eta + x \xi + \frac{(1-T) \eta \xi}{\hbar}, 1 + \frac{1}{4 \hbar}$

$$\eta \xi (\gamma \eta \xi - 4 T \gamma \eta \xi + 3 T^2 \gamma \eta \xi + 8 a T \hbar + 2 y \gamma \eta \hbar - 6 T y \gamma \eta \hbar + 2 x \gamma \xi \hbar - 6 T x \gamma \xi \hbar + 4 x y \gamma \hbar^2) \epsilon +$$

$$\left( -a T y \gamma \eta^2 \xi (-\eta \xi + 3 T \eta \xi - 3 \hbar) - a T x \gamma \eta \xi^2 (-\eta \xi + 3 T \eta \xi - 3 \hbar) + 2 a^2 T \eta \xi (T \eta \xi - \hbar) +$$

$$2 a T x y \gamma \eta^2 \xi^2 \hbar - \frac{1}{2} x y^2 \gamma^2 \eta^2 \xi (-\eta \xi + 3 T \eta \xi - \hbar) \hbar - \frac{1}{2} x^2 y \gamma^2 \eta \xi^2 (-\eta \xi + 3 T \eta \xi - \hbar) \hbar +$$

$$\frac{1}{2} x^2 y^2 \gamma^2 \eta^2 \xi^2 \hbar^2 + \frac{1}{24} y^2 \gamma^2 \eta^3 \xi (3 \eta \xi - 18 T \eta \xi + 27 T^2 \eta \xi + 4 \hbar - 28 T \hbar) + \frac{1}{24} x^2 \gamma^2 \eta \xi^3$$

$$(3 \eta \xi - 18 T \eta \xi + 27 T^2 \eta \xi + 4 \hbar - 28 T \hbar) + \frac{1}{2 \hbar} a T \gamma \eta^2 \xi^2 (\eta \xi - 4 T \eta \xi + 3 T^2 \eta \xi + 4 \hbar - 6 T \hbar) +$$

$$\frac{1}{4} x y \gamma^2 \eta \xi (2 \eta^2 \xi^2 - 10 T \eta^2 \xi^2 + 12 T^2 \eta^2 \xi^2 + 5 \eta \xi \hbar - 21 T \eta \xi \hbar + 2 \hbar^2) - \frac{1}{24 \hbar}$$

$$y \gamma^2 \eta^2 \xi (-3 \eta^2 \xi^2 + 21 T \eta^2 \xi^2 - 45 T^2 \eta^2 \xi^2 + 27 T^3 \eta^2 \xi^2 - 10 \eta \xi \hbar + 68 T \eta \xi \hbar - 82 T^2 \eta \xi \hbar -$$

$$6 \hbar^2 + 30 T \hbar^2) - \frac{1}{24 \hbar} x \gamma^2 \eta \xi^2 (-3 \eta^2 \xi^2 + 21 T \eta^2 \xi^2 - 45 T^2 \eta^2 \xi^2 + 27 T^3 \eta^2 \xi^2 - 10 \eta \xi \hbar +$$

$$68 T \eta \xi \hbar - 82 T^2 \eta \xi \hbar - 6 \hbar^2 + 30 T \hbar^2) + \frac{1}{288 \hbar^2} (-1 + T) \gamma^2 \eta^2 \xi^2 (-9 \eta^2 \xi^2 + 63 T \eta^2 \xi^2 -$$

$$135 T^2 \eta^2 \xi^2 + 81 T^3 \eta^2 \xi^2 - 40 \eta \xi \hbar + 272 T \eta \xi \hbar - 328 T^2 \eta \xi \hbar - 36 \hbar^2 + 180 T \hbar^2) \right) \epsilon^2 + O[\epsilon^3] \}$$

$\{\Lambda_{CU,1}[\{\xi, \eta\}, \{x, y\}], lhs = CU@C_{CU}[\{x, y\}, \hbar (\xi x + \eta y), 1],$   
 $HL[lhs = CU@Lambda_{CU,1}[\hbar \{\xi, \eta\}, \{x, y\}]]\}$

$\{C_{CU}[\{y, a, x\}, y \eta + x \xi - t \eta \xi, 1 + \frac{1}{2} \eta \xi (4 a - 2 y \gamma \eta - 2 x \gamma \xi + t \gamma \eta \xi) \epsilon + O[\epsilon^2],$

$$(1 - t \eta \xi \hbar^2) CU[] + 2 \epsilon \eta \xi \hbar^2 CU[a] + \xi \hbar CU[x] + \eta \hbar CU[y] +$$

$$\frac{1}{2} \xi^2 \hbar^2 CU[x, x] + \eta \xi \hbar^2 CU[y, x] + \frac{1}{2} \eta^2 \hbar^2 CU[y, y], True\}$$

```
In[*]:= {ΔQU,1[{ξ, η}, {x, y}], lhs = QU@CQU[{x, y}, ħ (ξ x + η y), 1],
  HL@SimpT[lhs == QU@ΔQU,1[ħ {ξ, η}, {x, y}]]}
```

```
Out[*]:= {CQU[{y, a, x}, y η + x ξ +  $\frac{(1-T) \eta \xi}{\hbar}$ , 1 +  $\frac{1}{4 \hbar}$ 
  η ξ (γ η ξ - 4 T γ η ξ + 3 T2 γ η ξ + 8 a T ħ + 2 y γ η ħ - 6 T y γ η ħ + 2 x γ ξ ħ - 6 T x γ ξ ħ + 4 x y γ ħ2) ε +
  O[ε]2], (1 + η ξ ħ - T η ξ ħ) QU[] + 2 T ε η ξ ħ2 QU[a] + ξ ħ QU[x] +
  η ħ QU[y] +  $\frac{1}{2}$  ξ2 ħ2 QU[x, x] + η ξ ħ2 QU[y, x] +  $\frac{1}{2}$  η2 ħ2 QU[y, y], True}
```

```
{tt = Last[ΔCU,2[{ξ, η}, {x, y}]], Log[tt],
  Exponent[Normal@Log[tt] /. {ξ → ħ ξ, η → ħ η, x → ħ x, y → ħ y}, ħ]} // Expand
```

```
{1 + (2 a η ξ - y γ η2 ξ - x γ η ξ2 +  $\frac{1}{2}$  t γ η2 ξ2) ε +
  (2 a2 η2 ξ2 - a γ η2 ξ2 - 2 a y γ η3 ξ2 + y γ2 η3 ξ2 +  $\frac{1}{2}$  y2 γ2 η4 ξ2 - 2 a x γ η2 ξ3 + x γ2 η2 ξ3 + a t γ η3 ξ3 -
   $\frac{1}{3}$  t γ2 η3 ξ3 + x y γ2 η3 ξ3 -  $\frac{1}{2}$  t y γ2 η4 ξ3 +  $\frac{1}{2}$  x2 γ2 η2 ξ4 -  $\frac{1}{2}$  t x γ2 η3 ξ4 +  $\frac{1}{8}$  t2 γ2 η4 ξ4) ε2 + O[ε]3,
  (2 a η ξ - y γ η2 ξ - x γ η ξ2 +  $\frac{1}{2}$  t γ η2 ξ2) ε + (-a γ η2 ξ2 + y γ2 η3 ξ2 + x γ2 η2 ξ3 -  $\frac{1}{3}$  t γ2 η3 ξ3) ε2 +
  O[ε]3, 6}
```

```
{tt = Last[ΔQU,2[{ξ, η}, {x, y}]], Log[tt],
  Exponent[Normal@Log[tt] /. {ξ → d ξ, η → d η, x → d x, y → d y}, d]} // Expand
```

$$\begin{aligned}
 & \left\{ 1 + \left( 2 a T \eta \xi + \frac{1}{2} y \gamma \eta^2 \xi - \frac{3}{2} T y \gamma \eta^2 \xi + \right. \right. \\
 & \quad \left. \frac{1}{2} x \gamma \eta \xi^2 - \frac{3}{2} T x \gamma \eta \xi^2 + \frac{\gamma \eta^2 \xi^2}{4 \hbar} - \frac{T \gamma \eta^2 \xi^2}{\hbar} + \frac{3 T^2 \gamma \eta^2 \xi^2}{4 \hbar} + x y \gamma \eta \xi \hbar \right) \epsilon + \\
 & \left( 2 a^2 T^2 \eta^2 \xi^2 + 2 a T \gamma \eta^2 \xi^2 - 3 a T^2 \gamma \eta^2 \xi^2 + \frac{1}{8} \gamma^2 \eta^2 \xi^2 - \frac{3}{4} T \gamma^2 \eta^2 \xi^2 + \frac{5}{8} T^2 \gamma^2 \eta^2 \xi^2 + \right. \\
 & \quad a T y \gamma \eta^3 \xi^2 - 3 a T^2 y \gamma \eta^3 \xi^2 + \frac{5}{12} y \gamma^2 \eta^3 \xi^2 - \frac{17}{6} T y \gamma^2 \eta^3 \xi^2 + \frac{41}{12} T^2 y \gamma^2 \eta^3 \xi^2 + \frac{1}{8} y^2 \gamma^2 \eta^4 \xi^2 - \\
 & \quad \frac{3}{4} T y^2 \gamma^2 \eta^4 \xi^2 + \frac{9}{8} T^2 y^2 \gamma^2 \eta^4 \xi^2 + a T x \gamma \eta^2 \xi^3 - 3 a T^2 x \gamma \eta^2 \xi^3 + \frac{5}{12} x \gamma^2 \eta^2 \xi^3 - \frac{17}{6} T x \gamma^2 \eta^2 \xi^3 + \\
 & \quad \frac{41}{12} T^2 x \gamma^2 \eta^2 \xi^3 + \frac{1}{2} x y \gamma^2 \eta^3 \xi^3 - \frac{5}{2} T x y \gamma^2 \eta^3 \xi^3 + 3 T^2 x y \gamma^2 \eta^3 \xi^3 + \frac{1}{8} x^2 \gamma^2 \eta^2 \xi^4 - \\
 & \quad \frac{3}{4} T x^2 \gamma^2 \eta^2 \xi^4 + \frac{9}{8} T^2 x^2 \gamma^2 \eta^2 \xi^4 + \frac{\gamma^2 \eta^4 \xi^4}{32 \hbar^2} - \frac{T \gamma^2 \eta^4 \xi^4}{4 \hbar^2} + \frac{11 T^2 \gamma^2 \eta^4 \xi^4}{16 \hbar^2} - \frac{3 T^3 \gamma^2 \eta^4 \xi^4}{4 \hbar^2} + \\
 & \quad \frac{9 T^4 \gamma^2 \eta^4 \xi^4}{32 \hbar^2} + \frac{a T \gamma \eta^3 \xi^3}{2 \hbar} - \frac{2 a T^2 \gamma \eta^3 \xi^3}{\hbar} + \frac{3 a T^3 \gamma \eta^3 \xi^3}{2 \hbar} + \frac{5 \gamma^2 \eta^3 \xi^3}{36 \hbar} - \frac{13 T \gamma^2 \eta^3 \xi^3}{12 \hbar} + \\
 & \quad \frac{25 T^2 \gamma^2 \eta^3 \xi^3}{12 \hbar} - \frac{41 T^3 \gamma^2 \eta^3 \xi^3}{36 \hbar} + \frac{y \gamma^2 \eta^4 \xi^3}{8 \hbar} - \frac{7 T y \gamma^2 \eta^4 \xi^3}{8 \hbar} + \frac{15 T^2 y \gamma^2 \eta^4 \xi^3}{8 \hbar} - \frac{9 T^3 y \gamma^2 \eta^4 \xi^3}{8 \hbar} + \\
 & \quad \frac{x \gamma^2 \eta^3 \xi^4}{8 \hbar} - \frac{7 T x \gamma^2 \eta^3 \xi^4}{8 \hbar} + \frac{15 T^2 x \gamma^2 \eta^3 \xi^4}{8 \hbar} - \frac{9 T^3 x \gamma^2 \eta^3 \xi^4}{8 \hbar} - 2 a^2 T \eta \xi \hbar + 3 a T y \gamma \eta^2 \xi \hbar + \\
 & \quad \frac{1}{4} y \gamma^2 \eta^2 \xi \hbar - \frac{5}{4} T y \gamma^2 \eta^2 \xi \hbar + \frac{1}{6} y^2 \gamma^2 \eta^3 \xi \hbar - \frac{7}{6} T y^2 \gamma^2 \eta^3 \xi \hbar + 3 a T x \gamma \eta \xi^2 \hbar + \frac{1}{4} x \gamma^2 \eta \xi^2 \hbar - \\
 & \quad \frac{5}{4} T x \gamma^2 \eta \xi^2 \hbar + 2 a T x y \gamma \eta^2 \xi^2 \hbar + \frac{5}{4} x y \gamma^2 \eta^2 \xi^2 \hbar - \frac{21}{4} T x y \gamma^2 \eta^2 \xi^2 \hbar + \frac{1}{2} x y^2 \gamma^2 \eta^3 \xi^2 \hbar - \\
 & \quad \frac{3}{2} T x y^2 \gamma^2 \eta^3 \xi^2 \hbar + \frac{1}{6} x^2 \gamma^2 \eta \xi^3 \hbar - \frac{7}{6} T x^2 \gamma^2 \eta \xi^3 \hbar + \frac{1}{2} x^2 y \gamma^2 \eta^2 \xi^3 \hbar - \frac{3}{2} T x^2 y \gamma^2 \eta^2 \xi^3 \hbar + \\
 & \quad \left. \frac{1}{2} x y \gamma^2 \eta \xi \hbar^2 + \frac{1}{2} x y^2 \gamma^2 \eta^2 \xi \hbar^2 + \frac{1}{2} x^2 y \gamma^2 \eta \xi^2 \hbar^2 + \frac{1}{2} x^2 y^2 \gamma^2 \eta^2 \xi^2 \hbar^2 \right) \epsilon^2 + 0[\epsilon]^3, \\
 & \left( 2 a T \eta \xi + \frac{1}{2} y \gamma \eta^2 \xi - \frac{3}{2} T y \gamma \eta^2 \xi + \frac{1}{2} x \gamma \eta \xi^2 - \frac{3}{2} T x \gamma \eta \xi^2 + \frac{\gamma \eta^2 \xi^2}{4 \hbar} - \right. \\
 & \quad \left. \frac{T \gamma \eta^2 \xi^2}{\hbar} + \frac{3 T^2 \gamma \eta^2 \xi^2}{4 \hbar} + x y \gamma \eta \xi \hbar \right) \epsilon + \\
 & \left( 2 a T \gamma \eta^2 \xi^2 - 3 a T^2 \gamma \eta^2 \xi^2 + \frac{1}{8} \gamma^2 \eta^2 \xi^2 - \frac{3}{4} T \gamma^2 \eta^2 \xi^2 + \frac{5}{8} T^2 \gamma^2 \eta^2 \xi^2 + \frac{5}{12} y \gamma^2 \eta^3 \xi^2 - \right. \\
 & \quad \frac{17}{6} T y \gamma^2 \eta^3 \xi^2 + \frac{41}{12} T^2 y \gamma^2 \eta^3 \xi^2 + \frac{5}{12} x \gamma^2 \eta^2 \xi^3 - \frac{17}{6} T x \gamma^2 \eta^2 \xi^3 + \frac{41}{12} T^2 x \gamma^2 \eta^2 \xi^3 + \\
 & \quad \frac{5 \gamma^2 \eta^3 \xi^3}{36 \hbar} - \frac{13 T \gamma^2 \eta^3 \xi^3}{12 \hbar} + \frac{25 T^2 \gamma^2 \eta^3 \xi^3}{12 \hbar} - \frac{41 T^3 \gamma^2 \eta^3 \xi^3}{36 \hbar} - 2 a^2 T \eta \xi \hbar + 3 a T y \gamma \eta^2 \xi \hbar + \\
 & \quad \frac{1}{4} y \gamma^2 \eta^2 \xi \hbar - \frac{5}{4} T y \gamma^2 \eta^2 \xi \hbar + \frac{1}{6} y^2 \gamma^2 \eta^3 \xi \hbar - \frac{7}{6} T y^2 \gamma^2 \eta^3 \xi \hbar + 3 a T x \gamma \eta \xi^2 \hbar + \\
 & \quad \frac{1}{4} x \gamma^2 \eta \xi^2 \hbar - \frac{5}{4} T x \gamma^2 \eta \xi^2 \hbar + \frac{5}{4} x y \gamma^2 \eta^2 \xi^2 \hbar - \frac{21}{4} T x y \gamma^2 \eta^2 \xi^2 \hbar + \frac{1}{6} x^2 \gamma^2 \eta \xi^3 \hbar - \\
 & \quad \left. \frac{7}{6} T x^2 \gamma^2 \eta \xi^3 \hbar + \frac{1}{2} x y \gamma^2 \eta \xi \hbar^2 + \frac{1}{2} x y^2 \gamma^2 \eta^2 \xi \hbar^2 + \frac{1}{2} x^2 y \gamma^2 \eta \xi^2 \hbar^2 + \frac{1}{2} x^2 y^2 \gamma^2 \eta^2 \xi^2 \hbar^2 \right) \epsilon^2 + 0[\epsilon]^3, 6 \}
 \end{aligned}$$



Logos

```
In[*]:= Simp[CU_[specs___, Q_, P_] := CU[specs, CF[Q], CF[P]];
```

Logos

```
In[*]:= ΔU_,k_[{u1_, ω1_, δ_}, {u_, w_}] := Simp@Module[{u, ω, yax, q, p, Q, d},
  {yax, q, p} = List@@ΔU_,k_[{u, ω}, {u, w}];
  CU[yax, Q = (u u + ω w + δ u w + d v ω) / (1 - d δ),
  Expand[(1 - d δ)^-1 e^-Q DP_{u→D_u, ω→D_w}[p][e^Q] + θ_R] /. {d → ∂_{u, ω} Q} /. {u → u1, ω → ω1}];
```

```
Block[{$p = 4, $k = 1},
  {ΔCU, $k}[ħ {ξ, η, δ}, {x, y}],
  Short[lhs = CU@ΔCU[{x, y}, ħ (ξ x + η y + δ x y), 1_{$k}], 5],
  HL@Simp[lhs - CU@ΔCU, $k][ħ {ξ, η, δ}, {x, y}]]
]
```

$$\left\{ \text{CU} \left[ \{y, a, x\}, \frac{xy \delta \hbar + y \eta \hbar + x \xi \hbar - t \eta \xi \hbar^2}{1 + t \delta \hbar}, \right. \right.$$

$$\frac{1}{1 + t \delta \hbar} + \left( (4 a \delta \hbar + 12 a t \delta^2 \hbar^2 + 4 a x y \delta^2 \hbar^2 + 2 t \gamma \delta^2 \hbar^2 - 8 x y \gamma \delta^2 \hbar^2 + 4 a y \delta \eta \hbar^2 - \right.$$

$$4 y \gamma \delta \eta \hbar^2 + 4 a x \delta \xi \hbar^2 - 4 x \gamma \delta \xi \hbar^2 + 4 a \eta \xi \hbar^2 + 12 a t^2 \delta^3 \hbar^3 + 8 a t x y \delta^3 \hbar^3 +$$

$$4 t^2 \gamma \delta^3 \hbar^3 - 12 t x y \gamma \delta^3 \hbar^3 - 4 x^2 y^2 \gamma \delta^3 \hbar^3 + 8 a t y \delta^2 \eta \hbar^3 - 4 t y \gamma \delta^2 \eta \hbar^3 -$$

$$6 x y^2 \gamma \delta^2 \eta \hbar^3 - 2 y^2 \gamma \delta \eta^2 \hbar^3 + 8 a t x \delta^2 \xi \hbar^3 - 4 t x \gamma \delta^2 \xi \hbar^3 - 6 x^2 y \gamma \delta^2 \xi \hbar^3 +$$

$$8 a t \delta \eta \xi \hbar^3 + 4 t \gamma \delta \eta \xi \hbar^3 - 8 x y \gamma \delta \eta \xi \hbar^3 - 2 y \gamma \eta^2 \xi \hbar^3 - 2 x^2 \gamma \delta \xi^2 \hbar^3 - 2 x \gamma \eta \xi^2 \hbar^3 +$$

$$4 a t^3 \delta^4 \hbar^4 + 4 a t^2 x y \delta^4 \hbar^4 + 2 t^3 \gamma \delta^4 \hbar^4 - 4 t^2 x y \gamma \delta^4 \hbar^4 - 3 t x^2 y^2 \gamma \delta^4 \hbar^4 +$$

$$4 a t^2 y \delta^3 \eta \hbar^4 - 4 t x y^2 \gamma \delta^3 \eta \hbar^4 - t y^2 \gamma \delta^2 \eta^2 \hbar^4 + 4 a t^2 x \delta^3 \xi \hbar^4 - 4 t x^2 y \gamma \delta^3 \xi \hbar^4 +$$

$$4 a t^2 \delta^2 \eta \xi \hbar^4 + 4 t^2 \gamma \delta^2 \eta \xi \hbar^4 - 4 t x y \gamma \delta^2 \eta \xi \hbar^4 - t x^2 \gamma \delta^2 \xi^2 \hbar^4 + t \gamma \eta^2 \xi^2 \hbar^4) \epsilon) /$$

$$(2 + 10 t \delta \hbar + 20 t^2 \delta^2 \hbar^2 + 20 t^3 \delta^3 \hbar^3 + 10 t^4 \delta^4 \hbar^4 + 2 t^5 \delta^5 \hbar^5) + 0[\epsilon]^2],$$

$$\left( 1 - t \delta \hbar + t^2 \delta^2 \hbar^2 + t \gamma \delta^2 \epsilon \hbar^2 - t \eta \xi \hbar^2 - t^3 \delta^3 \hbar^3 - 3 t^2 \gamma \delta^3 \epsilon \hbar^3 + 2 t^2 \delta \eta \xi \hbar^3 + \right.$$

$$2 t \gamma \delta \epsilon \eta \xi \hbar^3 + t^4 \delta^4 \hbar^4 + 6 t^3 \gamma \delta^4 \epsilon \hbar^4 - 3 t^3 \delta^2 \eta \xi \hbar^4 -$$

$$\left. 9 t^2 \gamma \delta^2 \epsilon \eta \xi \hbar^4 + \frac{1}{2} t^2 \eta^2 \xi^2 \hbar^4 + \frac{1}{2} t \gamma \epsilon \eta^2 \xi^2 \hbar^4 \right) \text{CU}[\ ] +$$

$$(2 \delta \epsilon \hbar - 4 t \delta^2 \epsilon \hbar^2 + 2 \epsilon \eta \xi \hbar^2 + 6 t^2 \delta^3 \epsilon \hbar^3 - 8 t \delta \epsilon \eta \xi \hbar^3 - 8 t^3 \delta^4 \epsilon \hbar^4 +$$

$$18 t^2 \delta^2 \epsilon \eta \xi \hbar^4 - 2 t \epsilon \eta^2 \xi^2 \hbar^4) \text{CU}[a] +$$

$$\llcorner 37 \gg + \frac{1}{6} \delta^3 \eta \hbar^4 \text{CU}[y, y, y, y, x, x, x] +$$

$$\frac{1}{24} \delta^4 \hbar^4$$

$$\text{CU}[y, y, y, y, x, x, x, x], \mathbf{0} \}$$

```
{ΔQU,2[{ξ, η, δ}, {x, y}], lhs = QU@CQU[{x, y}, ħ (ξ x + η y + δ x y), 1],
HL@SimpT[lhs == QU@ΔQU,1[ħ {ξ, η, δ}, {x, y}]]}
```

$$\left\{ \text{C}_{\text{QU}} \left[ \{y, a, x\}, \frac{\dots 1 \dots}{\dots 1 \dots}, \right. \right.$$

$$\frac{\hbar}{-\delta + T \delta + \hbar} + \left( (-8 a T \delta^4 \hbar^2 + 24 a T^2 \delta^4 \hbar^2 - 24 a T^3 \delta^4 \hbar^2 + 8 a T^4 \delta^4 \hbar^2 + \dots 149 \dots + \right.$$

$$4 x^2 y^2 \gamma \delta^2 \hbar^6 + 4 x y^2 \gamma \delta \eta \hbar^6 + 4 x^2 y \gamma \delta \xi \hbar^6 + 4 x y \gamma \eta \xi \hbar^6) \epsilon) /$$

$$\left( -4 \delta^5 + 20 T \delta^5 - 40 T^2 \delta^5 + 40 T^3 \delta^5 - 20 T^4 \delta^5 + 4 T^5 \delta^5 + \dots 12 \dots + 40 T^3 \delta^3 \hbar^2 + \right.$$

$$40 \delta^2 \hbar^3 - 80 T \delta^2 \hbar^3 + 40 T^2 \delta^2 \hbar^3 - 20 \delta \hbar^4 + 20 T \delta \hbar^4 + 4 \hbar^5) +$$

$$\left. \frac{(\dots 1 \dots)}{\dots 1 \dots} + 0[\epsilon]^3 \right\}, \dots 1 \dots, \text{True} \}$$

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```
{tt = ComposeSeries[(1 + t δ) Last[ΔCU,2[{ξ, η, δ}, {x, y}]], (1 + t δ)4 ε + 0[ε]18];
Together@Log[tt],
Exponent[Normal@Together@Log[tt] /. {ξ → d ξ, η → d η, x → d x, y → d y}, d],
Exponent[Normal@Together@Log[tt] /. {x → d x, y → d y}, d]
} // Expand
```

$$\left\{ \left( 2 a \delta + 6 a t \delta^2 + 2 a x y \delta^2 + t \gamma \delta^2 - 4 x y \gamma \delta^2 + 6 a t^2 \delta^3 + 4 a t x y \delta^3 + 2 t^2 \gamma \delta^3 - 6 t x y \gamma \delta^3 - \right. \right.$$

$$2 x^2 y^2 \gamma \delta^3 + 2 a t^3 \delta^4 + 2 a t^2 x y \delta^4 + t^3 \gamma \delta^4 - 2 t^2 x y \gamma \delta^4 - \frac{3}{2} t x^2 y^2 \gamma \delta^4 + 2 a y \delta \eta -$$

$$2 y \gamma \delta \eta + 4 a t y \delta^2 \eta - 2 t y \gamma \delta^2 \eta - 3 x y^2 \gamma \delta^2 \eta + 2 a t^2 y \delta^3 \eta - 2 t x y^2 \gamma \delta^3 \eta -$$

$$y^2 \gamma \delta \eta^2 - \frac{1}{2} t y^2 \gamma \delta^2 \eta^2 + 2 a x \delta \xi - 2 x \gamma \delta \xi + 4 a t x \delta^2 \xi - 2 t x \gamma \delta^2 \xi - 3 x^2 y \gamma \delta^2 \xi +$$

$$2 a t^2 x \delta^3 \xi - 2 t x^2 y \gamma \delta^3 \xi + 2 a \eta \xi + 4 a t \delta \eta \xi + 2 t \gamma \delta \eta \xi - 4 x y \gamma \delta \eta \xi + 2 a t^2 \delta^2 \eta \xi +$$

$$\left. 2 t^2 \gamma \delta^2 \eta \xi - 2 t x y \gamma \delta^2 \eta \xi - y \gamma \eta^2 \xi - x^2 \gamma \delta \xi^2 - \frac{1}{2} t x^2 \gamma \delta^2 \xi^2 - x \gamma \eta \xi^2 + \frac{1}{2} t \gamma \eta^2 \xi^2 \right) \epsilon +$$

$$\left( 2 a^2 \delta^2 - 2 a \gamma \delta^2 + 12 a^2 t \delta^3 + 4 a^2 x y \delta^3 - 8 a t \gamma \delta^3 - 20 a x y \gamma \delta^3 - 2 t \gamma^2 \delta^3 + 18 x y \gamma^2 \delta^3 + \right.$$

$$30 a^2 t^2 \delta^4 + 20 a^2 t x y \delta^4 - 10 a t^2 \gamma \delta^4 - 88 a t x y \gamma \delta^4 - 13 a x^2 y^2 \gamma \delta^4 - \frac{15}{2} t^2 \gamma^2 \delta^4 +$$

$$64 t x y \gamma^2 \delta^4 + 34 x^2 y^2 \gamma^2 \delta^4 + 40 a^2 t^3 \delta^5 + 40 a^2 t^2 x y \delta^5 - 152 a t^2 x y \gamma \delta^5 - 48 a t x^2 y^2 \gamma \delta^5 -$$

$$10 t^3 \gamma^2 \delta^5 + 86 t^2 x y \gamma^2 \delta^5 + 107 t x^2 y^2 \gamma^2 \delta^5 + 11 x^3 y^3 \gamma^2 \delta^5 + 30 a^2 t^4 \delta^6 + 40 a^2 t^3 x y \delta^6 +$$

$$10 a t^4 \gamma \delta^6 - 128 a t^3 x y \gamma \delta^6 - 66 a t^2 x^2 y^2 \gamma \delta^6 - 5 t^4 \gamma^2 \delta^6 + 54 t^3 x y \gamma^2 \delta^6 + \frac{247}{2} t^2 x^2 y^2 \gamma^2 \delta^6 +$$

$$\frac{80}{3} t x^3 y^3 \gamma^2 \delta^6 + 12 a^2 t^5 \delta^7 + 20 a^2 t^4 x y \delta^7 + 8 a t^5 \gamma \delta^7 - 52 a t^4 x y \gamma \delta^7 - 40 a t^3 x^2 y^2 \gamma \delta^7 +$$

$$16 t^4 x y \gamma^2 \delta^7 + 62 t^3 x^2 y^2 \gamma^2 \delta^7 + \frac{64}{3} t^2 x^3 y^3 \gamma^2 \delta^7 + 2 a^2 t^6 \delta^8 + 4 a^2 t^5 x y \delta^8 + 2 a t^6 \gamma \delta^8 -$$

$$8 a t^5 x y \gamma \delta^8 - 9 a t^4 x^2 y^2 \gamma \delta^8 + \frac{1}{2} t^6 \gamma^2 \delta^8 + 2 t^5 x y \gamma^2 \delta^8 + \frac{23}{2} t^4 x^2 y^2 \gamma^2 \delta^8 + \frac{17}{3} t^3 x^3 y^3 \gamma^2 \delta^8 +$$

$$4 a^2 y \delta^2 \eta - 12 a y \gamma \delta^2 \eta + 6 y \gamma^2 \delta^2 \eta + 20 a^2 t y \delta^3 \eta - 48 a t y \gamma \delta^3 \eta - 20 a x y^2 \gamma \delta^3 \eta +$$

$$14 t y \gamma^2 \delta^3 \eta + 40 x y^2 \gamma^2 \delta^3 \eta + 40 a^2 t^2 y \delta^4 \eta - 72 a t^2 y \gamma \delta^4 \eta - 72 a t x y^2 \gamma \delta^4 \eta + 6 t^2 y \gamma^2 \delta^4 \eta +$$

$$115 t x y^2 \gamma^2 \delta^4 \eta + 23 x^2 y^3 \gamma^2 \delta^4 \eta + 40 a^2 t^3 y \delta^5 \eta - 48 a t^3 y \gamma \delta^5 \eta - 96 a t^2 x y^2 \gamma \delta^5 \eta -$$

$$6 t^3 y \gamma^2 \delta^5 \eta + 118 t^2 x y^2 \gamma^2 \delta^5 \eta + 53 t x^2 y^3 \gamma^2 \delta^5 \eta + 20 a^2 t^4 y \delta^6 \eta - 12 a t^4 y \gamma \delta^6 \eta -$$

$$56 a t^3 x y^2 \gamma \delta^6 \eta - 4 t^4 y \gamma^2 \delta^6 \eta + 51 t^3 x y^2 \gamma^2 \delta^6 \eta + 40 t^2 x^2 y^3 \gamma^2 \delta^6 \eta + 4 a^2 t^5 y \delta^7 \eta -$$

$$\begin{aligned}
 & 12 a t^4 x y^2 \gamma \delta^7 \eta + 8 t^4 x y^2 \gamma^2 \delta^7 \eta + 10 t^3 x^2 y^3 \gamma^2 \delta^7 \eta - 7 a y^2 \gamma \delta^2 \eta^2 + 10 y^2 \gamma^2 \delta^2 \eta^2 - \\
 & 24 a t y^2 \gamma \delta^3 \eta^2 + 24 t y^2 \gamma^2 \delta^3 \eta^2 + 15 x y^3 \gamma^2 \delta^3 \eta^2 - 30 a t^2 y^2 \gamma \delta^4 \eta^2 + \frac{37}{2} t^2 y^2 \gamma^2 \delta^4 \eta^2 + \\
 & 32 t x y^3 \gamma^2 \delta^4 \eta^2 - 16 a t^3 y^2 \gamma \delta^5 \eta^2 + 5 t^3 y^2 \gamma^2 \delta^5 \eta^2 + 22 t^2 x y^3 \gamma^2 \delta^5 \eta^2 - 3 a t^4 y^2 \gamma \delta^6 \eta^2 + \\
 & \frac{1}{2} t^4 y^2 \gamma^2 \delta^6 \eta^2 + 5 t^3 x y^3 \gamma^2 \delta^6 \eta^2 + 3 y^3 \gamma^2 \delta^2 \eta^3 + \frac{17}{3} t y^3 \gamma^2 \delta^3 \eta^3 + \frac{10}{3} t^2 y^3 \gamma^2 \delta^4 \eta^3 + \\
 & \frac{2}{3} t^3 y^3 \gamma^2 \delta^5 \eta^3 + 4 a^2 x \delta^2 \xi - 12 a x \gamma \delta^2 \xi + 6 x \gamma^2 \delta^2 \xi + 20 a^2 t x \delta^3 \xi - 48 a t x \gamma \delta^3 \xi - \\
 & 20 a x^2 y \gamma \delta^3 \xi + 14 t x \gamma^2 \delta^3 \xi + 40 x^2 y \gamma^2 \delta^3 \xi + 40 a^2 t^2 x \delta^4 \xi - 72 a t^2 x \gamma \delta^4 \xi - 72 a t x^2 y \gamma \delta^4 \xi + \\
 & 6 t^2 x \gamma^2 \delta^4 \xi + 115 t x^2 y \gamma^2 \delta^4 \xi + 23 x^3 y^2 \gamma^2 \delta^4 \xi + 40 a^2 t^3 x \delta^5 \xi - 48 a t^3 x \gamma \delta^5 \xi - \\
 & 96 a t^2 x^2 y \gamma \delta^5 \xi - 6 t^3 x \gamma^2 \delta^5 \xi + 118 t^2 x^2 y \gamma^2 \delta^5 \xi + 53 t x^3 y^2 \gamma^2 \delta^5 \xi + 20 a^2 t^4 x \delta^6 \xi - \\
 & 12 a t^4 x \gamma \delta^6 \xi - 56 a t^3 x^2 y \gamma \delta^6 \xi - 4 t^4 x \gamma^2 \delta^6 \xi + 51 t^3 x^2 y \gamma^2 \delta^6 \xi + 40 t^2 x^3 y^2 \gamma^2 \delta^6 \xi + \\
 & 4 a^2 t^5 x \delta^7 \xi - 12 a t^4 x^2 y \gamma \delta^7 \xi + 8 t^4 x^2 y \gamma^2 \delta^7 \xi + 10 t^3 x^3 y^2 \gamma^2 \delta^7 \xi + 4 a^2 \delta \eta \xi - 4 a \gamma \delta \eta \xi + \\
 & 20 a^2 t \delta^2 \eta \xi - 8 a t \gamma \delta^2 \eta \xi - 28 a x y \gamma \delta^2 \eta \xi - 6 t \gamma^2 \delta^2 \eta \xi + 38 x y \gamma^2 \delta^2 \eta \xi + 40 a^2 t^2 \delta^3 \eta \xi + \\
 & 8 a t^2 \gamma \delta^3 \eta \xi - 96 a t x y \gamma \delta^3 \eta \xi - 14 t^2 \gamma^2 \delta^3 \eta \xi + 88 t x y \gamma^2 \delta^3 \eta \xi + 44 x^2 y^2 \gamma^2 \delta^3 \eta \xi + \\
 & 40 a^2 t^3 \delta^4 \eta \xi + 32 a t^3 \gamma \delta^4 \eta \xi - 120 a t^2 x y \gamma \delta^4 \eta \xi - 6 t^3 \gamma^2 \delta^4 \eta \xi + 62 t^2 x y \gamma^2 \delta^4 \eta \xi + \\
 & 93 t x^2 y^2 \gamma^2 \delta^4 \eta \xi + 20 a^2 t^4 \delta^5 \eta \xi + 28 a t^4 \gamma \delta^5 \eta \xi - 64 a t^3 x y \gamma \delta^5 \eta \xi + 6 t^4 \gamma^2 \delta^5 \eta \xi + \\
 & 12 t^3 x y \gamma^2 \delta^5 \eta \xi + 63 t^2 x^2 y^2 \gamma^2 \delta^5 \eta \xi + 4 a^2 t^5 \delta^6 \eta \xi + 8 a t^5 \gamma \delta^6 \eta \xi - 12 a t^4 x y \gamma \delta^6 \eta \xi + \\
 & 4 t^5 \gamma^2 \delta^6 \eta \xi + 14 t^3 x^2 y^2 \gamma^2 \delta^6 \eta \xi - 8 a y \gamma \delta \eta^2 \xi + 6 y \gamma^2 \delta \eta^2 \xi - 24 a t y \gamma \delta^2 \eta^2 \xi + \\
 & 5 t y \gamma^2 \delta^2 \eta^2 \xi + 25 x y^2 \gamma^2 \delta^2 \eta^2 \xi - 24 a t^2 y \gamma \delta^3 \eta^2 \xi - 8 t^2 y \gamma^2 \delta^3 \eta^2 \xi + 45 t x y^2 \gamma^2 \delta^3 \eta^2 \xi - \\
 & 8 a t^3 y \gamma \delta^4 \eta^2 \xi - 7 t^3 y \gamma^2 \delta^4 \eta^2 \xi + 24 t^2 x y^2 \gamma^2 \delta^4 \eta^2 \xi + 4 t^3 x y^2 \gamma^2 \delta^5 \eta^2 \xi + 4 y^2 \gamma^2 \delta \eta^3 \xi + \\
 & 5 t y^2 \gamma^2 \delta^2 \eta^3 \xi + t^2 y^2 \gamma^2 \delta^3 \eta^3 \xi - 7 a x^2 \gamma \delta^2 \xi^2 + 10 x^2 \gamma^2 \delta^2 \xi^2 - 24 a t x^2 \gamma \delta^3 \xi^2 + \\
 & 24 t x^2 \gamma^2 \delta^3 \xi^2 + 15 x^3 y \gamma^2 \delta^3 \xi^2 - 30 a t^2 x^2 \gamma \delta^4 \xi^2 + \frac{37}{2} t^2 x^2 \gamma^2 \delta^4 \xi^2 + 32 t x^3 y \gamma^2 \delta^4 \xi^2 - \\
 & 16 a t^3 x^2 \gamma \delta^5 \xi^2 + 5 t^3 x^2 \gamma^2 \delta^5 \xi^2 + 22 t^2 x^3 y \gamma^2 \delta^5 \xi^2 - 3 a t^4 x^2 \gamma \delta^6 \xi^2 + \frac{1}{2} t^4 x^2 \gamma^2 \delta^6 \xi^2 + \\
 & 5 t^3 x^3 y \gamma^2 \delta^6 \xi^2 - 8 a x \gamma \delta \eta \xi^2 + 6 x \gamma^2 \delta \eta \xi^2 - 24 a t x \gamma \delta^2 \eta \xi^2 + 5 t x \gamma^2 \delta^2 \eta \xi^2 + \\
 & 25 x^2 y \gamma^2 \delta^2 \eta \xi^2 - 24 a t^2 x \gamma \delta^3 \eta \xi^2 - 8 t^2 x \gamma^2 \delta^3 \eta \xi^2 + 45 t x^2 y \gamma^2 \delta^3 \eta \xi^2 - 8 a t^3 x \gamma \delta^4 \eta \xi^2 - \\
 & 7 t^3 x \gamma^2 \delta^4 \eta \xi^2 + 24 t^2 x^2 y \gamma^2 \delta^4 \eta \xi^2 + 4 t^3 x^2 y \gamma^2 \delta^5 \eta \xi^2 - a \gamma \eta^2 \xi^2 - 3 t \gamma^2 \delta \eta^2 \xi^2 + \\
 & 11 x y \gamma^2 \delta \eta^2 \xi^2 + 6 a t^2 \gamma \delta^2 \eta^2 \xi^2 - \frac{5}{2} t^2 \gamma^2 \delta^2 \eta^2 \xi^2 + 12 t x y \gamma^2 \delta^2 \eta^2 \xi^2 + 8 a t^3 \gamma \delta^3 \eta^2 \xi^2 + \\
 & 4 t^3 \gamma^2 \delta^3 \eta^2 \xi^2 + 3 a t^4 \gamma \delta^4 \eta^2 \xi^2 + \frac{7}{2} t^4 \gamma^2 \delta^4 \eta^2 \xi^2 - t^3 x y \gamma^2 \delta^4 \eta^2 \xi^2 + y \gamma^2 \eta^3 \xi^2 - \\
 & t y \gamma^2 \delta \eta^3 \xi^2 - 2 t^2 y \gamma^2 \delta^2 \eta^3 \xi^2 + 3 x^3 \gamma^2 \delta^2 \xi^3 + \frac{17}{3} t x^3 \gamma^2 \delta^3 \xi^3 + \frac{10}{3} t^2 x^3 \gamma^2 \delta^4 \xi^3 + \\
 & \frac{2}{3} t^3 x^3 \gamma^2 \delta^5 \xi^3 + 4 x^2 \gamma^2 \delta \eta \xi^3 + 5 t x^2 \gamma^2 \delta^2 \eta \xi^3 + t^2 x^2 \gamma^2 \delta^3 \eta \xi^3 + x \gamma^2 \eta^2 \xi^3 - t x \gamma^2 \delta \eta^2 \xi^3 - \\
 & 2 t^2 x \gamma^2 \delta^2 \eta^2 \xi^3 - \frac{1}{3} t \gamma^2 \eta^3 \xi^3 + \frac{1}{3} t^2 \gamma^2 \delta \eta^3 \xi^3 + \frac{2}{3} t^3 \gamma^2 \delta^2 \eta^3 \xi^3 \Big) \epsilon^2 + 0[\epsilon]^3, 6, 6 \Big)
 \end{aligned}$$

`{tt = Last[DeltaQu,2[{{xi, eta, delta}, {x, y}]]];`

`Log[tt],`

`Exponent[Normal@Together@Log[tt] /. {xi -> d xi, eta -> d eta, x -> d x, y -> d y}, d] // Expand`

$$\left\{ \text{Log} \left[ \frac{\hbar}{-\delta + T \delta + \hbar} \right] + \left( \frac{2 a T \delta^5 \hbar}{(-\delta + T \delta + \hbar)^5} - \frac{8 a T^2 \delta^5 \hbar}{(-\delta + T \delta + \hbar)^5} + \frac{12 a T^3 \delta^5 \hbar}{(-\delta + T \delta + \hbar)^5} - \frac{8 a T^4 \delta^5 \hbar}{(-\delta + T \delta + \hbar)^5} + \dots 267 \dots + \frac{x^2 y^2 \gamma \delta^2 \hbar^6}{(-\delta + T \delta + \hbar)^5} + \frac{x y^2 \gamma \delta \eta \hbar^6}{(-\delta + T \delta + \hbar)^5} + \frac{x^2 y \gamma \delta \xi \hbar^6}{(-\delta + T \delta + \hbar)^5} + \frac{x y \gamma \eta \xi \hbar^6}{(-\delta + T \delta + \hbar)^5} \right) \epsilon + \left( - \frac{32 a^2 T^2 \delta^{10} \hbar^2}{(\dots 1 \dots)^2} + \dots 8307 \dots + \dots 1 \dots + \frac{144 x^2 y^2 \gamma^2 \eta^2 \xi^2 \hbar^{11}}{\dots 1 \dots} \right) \epsilon^2 + O[\epsilon]^3, 6 \right\}$$

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## Reorderings with Rord

Rord

In[\*]:=

```
Rordui, wj → k [CU[L---, {L---, ui, wj, r---}s, R---, Q-, P-]] :=
Simp@Module[{u, w, δ, Δ1, yax, q, p, kk = P[[5]], δ1 = ∂ui, wj Q},
{yax, q, p} = Echo[List@@ If[δ1 === 0, ΔU, kk [{u, w}, {u, w}],
ΔU, kk [{u, w, δ}, {u, w}]] /. {y → yk, a → ak, x → xk, t → ts, T → Ts}};
CU[L, {L, Sequence@@ yax, r}s, R, q + (Q /. ui | wj → 0), e-q DPui → Du, wj → Dw [P] [p eq]] /.
{u → ∂ui Q /. wj → 0, w → ∂wj Q /. ui → 0, δ → δ1}];
```

Rord

In[\*]:=

```
Rordui, wj → k [CU[L---, {L---, ui, wj, r---}s, R---, Q-, P-]] :=
Simp@Module[{u, w, δ, Δ1, yax, q, p, n, kk = P[[5]], δ1 = ∂ui, wj Q},
{yax, q, p} = List@@ If[δ1 === 0, ΔU, kk [{u, w}, {u, w}], ΔU, kk [{u, w, δ}, {u, w}]] /.
{y → yn, a → an, x → xn, t → ts, T → Ts};
(*Echo@{{ui, v}, {wj, ω}}, P, p eq}; *)
CU[L, {L, Sequence@@ yax, r}s, R, q + (Q /. ui | wj → 0), e-q SPui → v, wj → ω [P p eq]] /.
{n → k, v → ∂ui Q /. wj → 0, w → ∂wj Q /. ui → 0, δ → δ1}];
```

```
With[{co = CCU[{y1, x1}1, {x2, a2, y2}2, ħ t1 a2 + ħ t1-1 (et1 - 1) y1 x2, 12 + ε x1 y2]}],
{Short[rhs = co // Rordx2, a2 → 3, 3], HL[CU[co] = CU[rhs]]}]
{CCU[{y1, x1}1, {a3, x3, y2}2,  $\frac{e^{-\gamma \hbar t_1} (e^{\gamma \hbar t_1} \hbar a_3 t_1^2 - \hbar x_3 y_1 + e^{t_1} \hbar x_3 y_1)}{t_1}$ , 1 + x1 y2 ε + O[ε]3], True}
```

```
With[{co = CCU[{y1, a1, a2}1, {x2, x1, y2}2,
ħ (l11 t1 a1 + l12 t1 a2 + l21 t2 a1 + l22 t2 a2 + γ11 x1 y1 + γ12 x1 y2 + γ21 x2 y1 + γ22 x2 y2),
12 + ε (l1 a1 + l2 a2 + p11 x1 y1 + p12 x1 y2 + p21 x2 y1 + p22 x2 y2)]},
{Short[rhs = co // Rorda1, a2 → 3 // Rordx2, x1 → 4, 3], HL[CU[co] = CU[rhs]]}]
{CCU[{y1, a3}1, {x4, y2}2,
ħ a3 l11 t1 + ħ a3 l12 t1 + ħ a3 l21 t2 + ħ a3 l22 t2 + ħ x4 y1 γ11 + ħ x4 y2 γ12 + ħ x4 y1 γ21 + ħ x4 y2 γ22,
1 + (a3 l1 + a3 l2 + p11 x4 y1 + p21 x4 y1 + p12 x4 y2 + p22 x4 y2) ε + O[ε]3], True}
ħ a3 l11 t1 + ħ a3 l12 t1 + ħ a3 l21 t2 + ħ a3 l22 t2 +
ħ x4 y1 γ11 + ħ x4 y2 γ12 + ħ x4 y1 γ21 + ħ x4 y2 γ22 // Simplify
ħ (a3 (l11 t1 + l12 t1 + (l21 + l22) t2) + x4 (y1 (γ11 + γ21) + y2 (γ12 + γ22)))
```

With [ {c0 = CCU [ {y1, a1, x1}1, {x2, a2, y2}2,  
 $\hbar (l_{11} t_1 a_1 + l_{12} t_1 a_2 + l_{21} t_2 a_1 + l_{22} t_2 a_2 + \gamma_{11} x_1 y_1 + \gamma_{12} x_1 y_2 + \gamma_{21} x_2 y_1 + \gamma_{22} x_2 y_2),$   
 $1_2 + \epsilon (l_1 a_1 + l_2 a_2 + p_{11} x_1 y_1 + p_{12} x_1 y_2 + p_{21} x_2 y_1 + p_{22} x_2 y_2) ] }],$   
 {Short[rhs = c0 // Rord<sub>x<sub>2</sub>, a<sub>2</sub>→3</sub>, 3], HL[CU[c0] = CU[rhs]]}]  
 {CCU [ {y1, a1, x1}1, <<1>>2, <<1>> <<1>>,  
 $1 + e^{-\gamma \hbar l_{12} t_1 - \gamma \hbar l_{22} t_2} (e^{\gamma \hbar l_{12} t_1 + \gamma \hbar l_{22} t_2} a_1 l_1 + e^{\gamma \hbar l_{12} t_1 + \gamma \hbar l_{22} t_2} a_3 l_2 + e^{\gamma \hbar l_{12} t_1 + \gamma \hbar l_{22} t_2} p_{11} x_1 y_1 + p_{21} x_3 y_1 +$   
 $e^{\langle\langle 1 \rangle\rangle + \langle\langle 1 \rangle\rangle} p_{12} x_1 y_2 + p_{22} x_3 y_2 - \gamma \hbar l_2 x_3 y_1 \gamma_{21} - \gamma \hbar l_2 x_3 y_2 \gamma_{22}) \in + O[\epsilon]^3], True}$

With [ {q0 = CQU [ {y1, a1, x1}1, {x2, a2, y2}2,  
 $\hbar (l_{11} t_1 a_1 + l_{12} t_1 a_2 + l_{21} t_2 a_1 + l_{22} t_2 a_2 + \gamma_{11} x_1 y_1 + \gamma_{12} x_1 y_2 + \gamma_{21} x_2 y_1 + \gamma_{22} x_2 y_2),$   
 $1_2 + \epsilon (l_1 a_1 + l_2 a_2 + p_{11} x_1 y_1 + p_{12} x_1 y_2 + p_{21} x_2 y_1 + p_{22} x_2 y_2) ] }],$   
 {Short[rhs = q0 // Rord<sub>x<sub>2</sub>, a<sub>2</sub>→3</sub>, 3], HL[QU[q0] = QU[rhs]]}]  
 {CQU [ {y1, a1, x1}1, <<1>>2, <<1>> <<1>>,  
 $1 + e^{-\gamma \hbar l_{12} t_1 - \gamma \hbar l_{22} t_2} (e^{\gamma \hbar l_{12} t_1 + \gamma \hbar l_{22} t_2} a_1 l_1 + e^{\gamma \hbar l_{12} t_1 + \gamma \hbar l_{22} t_2} a_3 l_2 + e^{\gamma \hbar l_{12} t_1 + \gamma \hbar l_{22} t_2} p_{11} x_1 y_1 + p_{21} x_3 y_1 +$   
 $e^{\langle\langle 1 \rangle\rangle + \langle\langle 1 \rangle\rangle} p_{12} x_1 y_2 + p_{22} x_3 y_2 - \gamma \hbar l_2 x_3 y_1 \gamma_{21} - \gamma \hbar l_2 x_3 y_2 \gamma_{22}) \in + O[\epsilon]^3], True}$

With [ {q0 = CQU [ {y1, a1, x1}1, {x2, a2, y2}2,  
 $\hbar (l_{11} t_1 a_1 + l_{12} t_1 a_2 + l_{21} t_2 a_1 + l_{22} t_2 a_2 + \gamma_{11} x_1 y_1 + \gamma_{12} x_1 y_2 + \gamma_{21} x_2 y_1 + \gamma_{22} x_2 y_2),$   
 $1_2 + \epsilon (l_1 a_1 + l_2 a_2 + p_{11} x_1 y_1 + p_{12} x_1 y_2 + p_{21} x_2 y_1 + p_{22} x_2 y_2) ] }],$   
 {Short[rhs = q0 // Rord<sub>a<sub>2</sub>, y<sub>2</sub>→3</sub>, 3], HL[QU[q0] = QU[rhs]]}]  
 { <<1>>, True}

Timing@With [ {q0 = CQU [ {x1, y1}1, {x2, a2, y2}2,  
 $\hbar (l_{12} t_1 a_2 + l_{22} t_2 a_2 + \gamma_{11} x_1 y_1 + \gamma_{12} x_1 y_2 + \gamma_{21} x_2 y_1 + \gamma_{22} x_2 y_2),$   
 $\theta_2 + \epsilon (l_2 a_2 + p_{11} x_1 y_1 + p_{12} x_1 y_2 + p_{21} x_2 y_1 + p_{22} x_2 y_2) ] }],$   
 {Short[rhs = q0 // Rord<sub>x<sub>1</sub>, y<sub>1</sub>→3</sub>, 5]}]

{116.156, {CQU [ {y3, a3, x3}1, <<1>>2,  $\frac{\langle\langle 1 \rangle\rangle}{1 - \langle\langle 1 \rangle\rangle + \langle\langle 1 \rangle\rangle},$   
 $( (\hbar a_2 l_2 + p_{11} T_1 + \hbar p_{22} x_2 y_2 + \hbar p_{12} x_3 y_2 + \langle\langle 46 \rangle\rangle + 2 \hbar p_{12} T_1 x_2 y_2 \gamma_{11} \gamma_{21} -$   
 $\hbar p_{12} T_1^2 x_2 y_2 \gamma_{11} \gamma_{21} + \hbar p_{11} x_2 y_2 \gamma_{12} \gamma_{21} - 2 \hbar p_{11} T_1 x_2 y_2 \gamma_{12} \gamma_{21} + \hbar p_{11} T_1^2 x_2 y_2 \gamma_{12} \gamma_{21}) \epsilon) /$   
 $(\hbar - 3 \hbar \gamma_{11} + 3 \hbar T_1 \gamma_{11} + 3 \hbar \gamma_{11}^2 - 6 \hbar T_1 \gamma_{11}^2 + 3 \hbar T_1^2 \gamma_{11}^2 - \hbar \gamma_{11}^3 + 3 \hbar T_1 \gamma_{11}^3 - 3 \hbar T_1^2 \gamma_{11}^3 + \hbar T_1^3 \gamma_{11}^3) +$   
 $(8 a_3 p_{11} T_1 + \langle\langle 1 \rangle\rangle + \langle\langle 2726 \rangle\rangle + 3 \gamma \langle\langle 6 \rangle\rangle \gamma_{21}^3) \langle\langle 1 \rangle\rangle) /$   
 $(4 - 28 \gamma_{11} + \langle\langle 48 \rangle\rangle + 4 T_1^7 \gamma_{11}^7) + O[\epsilon]^3 ] }$

$$\begin{aligned} & \text{Timing@With}[\{\mathbf{q}_0 = \mathbb{C}_{\text{QU}}[\{\mathbf{x}_1, \mathbf{y}_1\}_1, \{\mathbf{x}_2, \mathbf{a}_2, \mathbf{y}_2\}_2, \\ & \quad \hbar (\mathbf{l}_{12} \mathbf{t}_1 \mathbf{a}_2 + \mathbf{l}_{22} \mathbf{t}_2 \mathbf{a}_2 + \gamma_{11} \mathbf{x}_1 \mathbf{y}_1 + \gamma_{12} \mathbf{x}_1 \mathbf{y}_2 + \gamma_{21} \mathbf{x}_2 \mathbf{y}_1 + \gamma_{22} \mathbf{x}_2 \mathbf{y}_2), \\ & \quad \mathbf{l}_2 + \epsilon (\mathbf{l}_2 \mathbf{a}_2 + \mathbf{p}_{11} \mathbf{x}_1 \mathbf{y}_1 + \mathbf{p}_{12} \mathbf{x}_1 \mathbf{y}_2 + \mathbf{p}_{21} \mathbf{x}_2 \mathbf{y}_1 + \mathbf{p}_{22} \mathbf{x}_2 \mathbf{y}_2)\}], \\ & \{\text{Short}[\text{rhs} = \mathbf{q}_0 // \text{Rord}_{\mathbf{x}_1, \mathbf{y}_1 \rightarrow 3}, 5], \text{HL@SimpT}[\text{QU}[\mathbf{q}_0] == \text{QU}[\text{rhs}]]\}] \\ & \{388.922, \\ & \left\{ \mathbb{C}_{\text{QU}}[\{\mathbf{y}_3, \mathbf{a}_3, \mathbf{x}_3\}_1, \{\ll 1 \gg\}_2, \frac{\ll 1 \gg}{\ll 1 \gg}, \frac{1}{1 - \gamma_{11} + T_1 \gamma_{11}} + \left( (4 \hbar \mathbf{a}_2 \mathbf{l}_2 + 4 \mathbf{p}_{11} - 4 \mathbf{p}_{11} T_1 + 4 \hbar \mathbf{p}_{22} \mathbf{x}_2 \mathbf{y}_2 + \right. \right. \\ & \quad \left. \left. \ll 339 \gg + \gamma \hbar^4 \mathbf{x}_2^2 \mathbf{y}_2^2 \gamma_{12}^2 \gamma_{21}^2 - 4 \gamma \hbar^4 T_1 \mathbf{x}_2^2 \mathbf{y}_2^2 \gamma_{12}^2 \gamma_{21}^2 + 3 \gamma \hbar^4 T_1^2 \mathbf{x}_2^2 \mathbf{y}_2^2 \gamma_{12}^2 \gamma_{21}^2) \epsilon\right) / \right. \\ & \quad \left. (4 \hbar - 20 \hbar \gamma_{11} + 20 \hbar T_1 \gamma_{11} + 40 \hbar \gamma_{11}^2 - 80 \hbar T_1 \gamma_{11}^2 + 40 \hbar T_1^2 \gamma_{11}^2 - 40 \hbar \gamma_{11}^3 + \ll 13 \gg + \right. \\ & \quad \left. 20 \hbar T_1 \gamma_{11}^5 - 40 \hbar T_1^2 \gamma_{11}^5 + 40 \hbar T_1^3 \gamma_{11}^5 - 20 \hbar T_1^4 \gamma_{11}^5 + 4 \hbar T_1^5 \gamma_{11}^5) + \right. \\ & \quad \left. (576 \mathbf{a}_3 \mathbf{p}_{11} T_1 + \ll 8073 \gg + \ll 1 \gg) \frac{\ll 1 \gg}{\ll 79 \gg + 288 T_1^9 \gamma_{11}^9} + 0[\epsilon]^3\right\}, \text{True} \} \} \end{aligned}$$

$$\begin{aligned} & \text{Timing@With}[\{\mathbf{q}_0 = \mathbb{C}_{\text{QU}}[\{\mathbf{x}_1, \mathbf{y}_1\}_1, \{\mathbf{x}_2, \mathbf{a}_2, \mathbf{y}_2\}_2, \\ & \quad \hbar (\mathbf{l}_{12} \mathbf{t}_1 \mathbf{a}_2 + \mathbf{l}_{22} \mathbf{t}_2 \mathbf{a}_2 + \gamma_{11} \mathbf{x}_1 \mathbf{y}_1 + \gamma_{12} \mathbf{x}_1 \mathbf{y}_2 + \gamma_{21} \mathbf{x}_2 \mathbf{y}_1 + \gamma_{22} \mathbf{x}_2 \mathbf{y}_2), \\ & \quad \mathbf{l}_2 + \epsilon (\mathbf{l}_2 \mathbf{a}_2 + \mathbf{p}_{11} \mathbf{x}_1 \mathbf{y}_1 + \mathbf{p}_{12} \mathbf{x}_1 \mathbf{y}_2 + \mathbf{p}_{21} \mathbf{x}_2 \mathbf{y}_1 + \mathbf{p}_{22} \mathbf{x}_2 \mathbf{y}_2)\}], \\ & \{\text{Short}[\text{rhs} = \mathbf{q}_0 // \text{Rord}_{\mathbf{x}_1, \mathbf{y}_1 \rightarrow 1}, 5], \text{HL@SimpT}[\text{QU}[\mathbf{q}_0] == \text{QU}[\text{rhs}]]\}] \\ & \{336.781, \\ & \left\{ \mathbb{C}_{\text{QU}}[\{\mathbf{y}_1, \mathbf{a}_1, \mathbf{x}_1\}_1, \{\ll 1 \gg\}_2, \frac{\ll 1 \gg}{\ll 1 \gg}, \frac{1}{1 - \gamma_{11} + T_1 \gamma_{11}} + \left( (4 \hbar \mathbf{a}_2 \mathbf{l}_2 + 4 \mathbf{p}_{11} - 4 \mathbf{p}_{11} T_1 + 4 \hbar \mathbf{p}_{11} \mathbf{x}_1 \mathbf{y}_1 + \right. \right. \\ & \quad \left. \left. 4 \hbar \mathbf{p}_{21} \mathbf{x}_2 \mathbf{y}_1 + \ll 338 \gg + \gamma \hbar^4 \mathbf{x}_2^2 \mathbf{y}_2^2 \gamma_{12}^2 \gamma_{21}^2 - 4 \gamma \hbar^4 T_1 \mathbf{x}_2^2 \mathbf{y}_2^2 \gamma_{12}^2 \gamma_{21}^2 + 3 \gamma \hbar^4 T_1^2 \mathbf{x}_2^2 \mathbf{y}_2^2 \gamma_{12}^2 \gamma_{21}^2) \epsilon\right) / \right. \\ & \quad \left. (4 \hbar - 20 \hbar \gamma_{11} + 20 \hbar T_1 \gamma_{11} + 40 \hbar \gamma_{11}^2 - 80 \hbar T_1 \gamma_{11}^2 + 40 \hbar T_1^2 \gamma_{11}^2 - 40 \hbar \gamma_{11}^3 + \ll 10 \gg + \right. \\ & \quad \left. 20 \hbar T_1^4 \gamma_{11}^4 - 4 \hbar \gamma_{11}^5 + 20 \hbar T_1 \gamma_{11}^5 - 40 \hbar T_1^2 \gamma_{11}^5 + 40 \hbar T_1^3 \gamma_{11}^5 - 20 \hbar T_1^4 \gamma_{11}^5 + 4 \hbar T_1^5 \gamma_{11}^5) + \right. \\ & \quad \left. (576 \mathbf{a}_1 \mathbf{p}_{11} T_1 + \ll 8073 \gg + \ll 1 \gg) \frac{\ll 1 \gg}{\ll 79 \gg + 288 T_1^9 \gamma_{11}^9} + 0[\epsilon]^3\right\}, \text{True} \} \} \end{aligned}$$

## Canonical ordering with Cord

Cord

In[\*]:=

```

Cord[C_U[L___, {L___, u_i_, w_j_, r___}_s, R___, Q_, P_]] /;
  OrderedQ[{w, u} /. {y -> 1, a -> 2, x -> 3}] :=
  ((*Echo@{u_i, w_j}; *) Cord[Rord_{u_i, w_j -> Unique[]} [C_U[L, {L, u_i, w_j, r}_s, R, Q, P]]]);
Cord[C_U[specs___, Q_, P_]] := C_U[Sequence @@ Sort@{specs}, Q, P] /.
  Flatten[{specs} /. {yax___}_s -> ({yax} /. u_i_ -> (u_i -> u_s))]
    
```

Cord@C\_U[{x\_1, y\_1}\_1, 0, 0\_1 + x\_1 y\_1]

C\_U[{y\_1, a\_1, x\_1}\_1, 0, (-t\_1 + x\_1 y\_1) + 2 a\_1 \epsilon + 0[\epsilon]^2]

**Block** [ { \$p = 4, \$k = 0, c0 = CU [ { y1, a1, x1, x2, a2, y2 } 1,  $\hbar (l_{11} t_1 a_1 + l_{12} t_1 a_2 + l_{21} t_2 a_1 + l_{22} t_2 a_2 + \gamma_{11} x_1 y_1 + \gamma_{12} x_1 y_2 + \gamma_{21} x_2 y_1 + \gamma_{22} x_2 y_2)$ ,  $1_0 + \epsilon (l_1 a_1 + l_2 a_2 + p_{11} x_1 y_1 + p_{12} x_1 y_2 + p_{21} x_2 y_1 + p_{22} x_2 y_2)$  ] }, **Timing** @ { Short [ Cord [ c0 ], 8 ], HL @ Simp [ CU [ c0 ] - CU [ Cord [ c0 ] ] ] } ]

{ 4.53125,  $\left\{ \text{CU} [ \{ y_1, a_1, x_1 \} ]_1, \left( e^{\gamma \hbar l_{11} t_1 + 2 \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + 2 \gamma \hbar l_{22} t_2} \hbar a_1 l_{11} t_1 + e^{\gamma \hbar l_{11} t_1 + 2 \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + 2 \gamma \hbar l_{22} t_2} \hbar a_1 l_{12} t_1 + \ll 12 \gg + e^{\gamma \hbar l_{11} t_1 + \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + \gamma \hbar l_{22} t_2} \hbar^2 a_1 l_{22} t_1 t_2 \gamma_{22} + \hbar x_1 y_1 \gamma_{22} \right) / \left( e^{\gamma \hbar l_{11} t_1 + 2 \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + 2 \gamma \hbar l_{22} t_2} + e^{\gamma \hbar l_{11} t_1 + \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + \gamma \hbar l_{22} t_2} \hbar t_1 \gamma_{12} + e^{\gamma \hbar l_{11} t_1 + \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + \gamma \hbar l_{22} t_2} \hbar t_1 \gamma_{22} \right), \frac{e^{\gamma \hbar l_{12} t_1 + \gamma \hbar l_{22} t_2}}{e^{\gamma \hbar l_{12} t_1 + \gamma \hbar l_{22} t_2} + \hbar t_1 \gamma_{12} + \hbar t_1 \gamma_{22}} + O[\epsilon]^1, \mathbf{0} \right\}$  }

**Block** [ { \$p = 4, \$k = 1, c0 = CU [ { y1, a1, x1, x2, a2, y2 } 1,  $\hbar (l_{11} t_1 a_1 + l_{12} t_1 a_2 + l_{21} t_2 a_1 + l_{22} t_2 a_2 + \gamma_{11} x_1 y_1 + \gamma_{12} x_1 y_2 + \gamma_{21} x_2 y_1 + \gamma_{22} x_2 y_2)$ ,  $1_1 + \epsilon (l_1 a_1 + l_2 a_2 + p_{11} x_1 y_1 + p_{12} x_1 y_2 + p_{21} x_2 y_1 + p_{22} x_2 y_2)$  ] }, **Timing** @ { Short [ Cord [ c0 ], 8 ], HL @ Simp [ CU [ c0 ] - CU [ Cord [ c0 ] ] ] } ]

{ 81.2656,  $\left\{ \text{CU} [ \{ y_1, a_1, x_1 \} ]_1, \left( e^{\gamma \hbar l_{11} t_1 + 2 \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + 2 \gamma \hbar l_{22} t_2} \hbar a_1 l_{11} t_1 + \ll 14 \gg + \hbar x_1 y_1 \gamma_{22} \right) / \left( e^{\gamma \hbar l_{11} t_1 + 2 \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + 2 \gamma \hbar l_{22} t_2} + e^{\gamma \hbar l_{11} t_1 + \ll 2 \gg + \gamma \hbar \ll 1 \gg} t_2 \hbar t_1 \gamma_{12} + e^{\gamma \hbar l_{11} t_1 + \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + \gamma \hbar l_{22} t_2} \hbar t_1 \gamma_{22} \right), \frac{e^{\gamma \hbar l_{12} t_1 + \gamma \hbar l_{22} t_2}}{e^{\gamma \hbar l_{12} t_1 + \gamma \hbar l_{22} t_2} + \hbar t_1 \gamma_{12} + \hbar t_1 \gamma_{22}} + \left( \left( 2 e^{2 \gamma \hbar l_{11} t_1 + 6 \gamma \hbar l_{12} t_1 + 2 \gamma \hbar l_{21} t_2 + 6 \gamma \hbar l_{22} t_2} a_1 l_1 + \ll 419 \gg \right) \epsilon \right) / \left( 2 e^{2 \gamma \hbar l_{11} t_1 + 6 \gamma \hbar l_{12} t_1 + 2 \gamma \hbar l_{21} t_2 + 6 \gamma \hbar l_{22} t_2} + 1_0 e^{2 \gamma \hbar l_{11} t_1 + 5 \gamma \hbar l_{12} t_1 + 2 \gamma \hbar l_{21} t_2 + 5 \gamma \hbar l_{22} t_2} \hbar t_1 \gamma_{12} + \ll 18 \gg + 2 e^{2 \gamma \hbar l_{11} t_1 + \gamma \hbar l_{12} t_1 + 2 \gamma \hbar l_{21} t_2 + \gamma \hbar l_{22} t_2} \hbar^5 t_1^5 \gamma_{22}^5 \right) + O[\epsilon]^2, \mathbf{0} \right\}$  }

**With** [ { q0 = QU [ { y1, a1, x1, x2, a2, y2 } 1,  $\hbar (l_{11} t_1 a_1 + l_{12} t_1 a_2 + l_{21} t_2 a_1 + l_{22} t_2 a_2 + \gamma_{11} x_1 y_1 + \gamma_{12} x_1 y_2 + \gamma_{21} x_2 y_1 + \gamma_{22} x_2 y_2)$ ,  $1_0 + \epsilon (l_1 a_1 + l_2 a_2 + p_{11} x_1 y_1 + p_{12} x_1 y_2 + p_{21} x_2 y_1 + p_{22} x_2 y_2)$  ] }, **Cord** [ q0 ] ]

$\text{QU} [ \{ y_1, a_1, x_1 \} ]_1,$

$\left( e^{\gamma \hbar l_{11} t_1 + 2 \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + 2 \gamma \hbar l_{22} t_2} \hbar a_1 l_{11} t_1 + e^{\gamma \hbar l_{11} t_1 + 2 \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + 2 \gamma \hbar l_{22} t_2} \hbar a_1 l_{12} t_1 + e^{\gamma \hbar l_{11} t_1 + 2 \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + 2 \gamma \hbar l_{22} t_2} \hbar a_1 l_{21} t_2 + e^{\gamma \hbar l_{11} t_1 + 2 \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + 2 \gamma \hbar l_{22} t_2} \hbar a_1 l_{22} t_2 + e^{\gamma \hbar l_{11} t_1 + \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + \gamma \hbar l_{22} t_2} \hbar x_1 y_1 \gamma_{11} - e^{\gamma \hbar l_{11} t_1 + \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + \gamma \hbar l_{22} t_2} \hbar a_1 l_{11} t_1 \gamma_{12} - e^{\gamma \hbar l_{11} t_1 + \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + \gamma \hbar l_{22} t_2} \hbar a_1 l_{12} t_1 \gamma_{12} - e^{\gamma \hbar l_{11} t_1 + \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + \gamma \hbar l_{22} t_2} \hbar a_1 l_{21} t_2 \gamma_{12} - e^{\gamma \hbar l_{11} t_1 + \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + \gamma \hbar l_{22} t_2} \hbar a_1 l_{22} t_2 \gamma_{12} + e^{\gamma \hbar l_{11} t_1 + \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + \gamma \hbar l_{22} t_2} \hbar a_1 l_{11} t_1 T_1 \gamma_{12} + e^{\gamma \hbar l_{11} t_1 + \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + \gamma \hbar l_{22} t_2} \hbar a_1 l_{12} t_1 T_1 \gamma_{12} + e^{\gamma \hbar l_{11} t_1 + \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + \gamma \hbar l_{22} t_2} \hbar a_1 l_{21} t_2 T_1 \gamma_{12} + e^{\gamma \hbar l_{11} t_1 + \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + \gamma \hbar l_{22} t_2} \hbar a_1 l_{22} t_2 T_1 \gamma_{12} + \hbar x_1 y_1 \gamma_{12} + e^{\gamma \hbar l_{11} t_1 + \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + \gamma \hbar l_{22} t_2} \hbar x_1 y_1 \gamma_{21} - e^{\gamma \hbar l_{11} t_1 + \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + \gamma \hbar l_{22} t_2} \hbar a_1 l_{11} t_1 \gamma_{22} - e^{\gamma \hbar l_{11} t_1 + \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + \gamma \hbar l_{22} t_2} \hbar a_1 l_{12} t_1 \gamma_{22} - e^{\gamma \hbar l_{11} t_1 + \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + \gamma \hbar l_{22} t_2} \hbar a_1 l_{21} t_2 \gamma_{22} - e^{\gamma \hbar l_{11} t_1 + \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + \gamma \hbar l_{22} t_2} \hbar a_1 l_{22} t_2 \gamma_{22} + e^{\gamma \hbar l_{11} t_1 + \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + \gamma \hbar l_{22} t_2} \hbar a_1 l_{11} t_1 T_1 \gamma_{22} + e^{\gamma \hbar l_{11} t_1 + \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + \gamma \hbar l_{22} t_2} \hbar a_1 l_{12} t_1 T_1 \gamma_{22} + e^{\gamma \hbar l_{11} t_1 + \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + \gamma \hbar l_{22} t_2} \hbar a_1 l_{21} t_2 T_1 \gamma_{22} + e^{\gamma \hbar l_{11} t_1 + \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + \gamma \hbar l_{22} t_2} \hbar a_1 l_{22} t_2 T_1 \gamma_{22} + \hbar x_1 y_1 \gamma_{22} \right) / \left( e^{\gamma \hbar l_{11} t_1 + 2 \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + 2 \gamma \hbar l_{22} t_2} - e^{\gamma \hbar l_{11} t_1 + \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + \gamma \hbar l_{22} t_2} t_2 \gamma_{12} + e^{\gamma \hbar l_{11} t_1 + \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + \gamma \hbar l_{22} t_2} T_1 \gamma_{12} - e^{\gamma \hbar l_{11} t_1 + \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + \gamma \hbar l_{22} t_2} t_2 \gamma_{22} + e^{\gamma \hbar l_{11} t_1 + \gamma \hbar l_{12} t_1 + \gamma \hbar l_{21} t_2 + \gamma \hbar l_{22} t_2} T_1 \gamma_{22} \right), \frac{e^{\gamma \hbar l_{12} t_1 + \gamma \hbar l_{22} t_2}}{e^{\gamma \hbar l_{12} t_1 + \gamma \hbar l_{22} t_2} - \gamma_{12} + T_1 \gamma_{12} - \gamma_{22} + T_1 \gamma_{22}} + O[\epsilon]^1 ]$

## Stitching $\mathbb{C}$ 's.

StitchingOEs

```
In[ ]:= mj→k[ $\mathbb{C}_U$ [specs__, Q_, P_]] := Cord[ $\mathbb{C}_U$ [Sequence@@Append[DeleteCases[{specs}, {__}_j|k], Flatten[{Cases[{specs}, {us__}_j :> {us}], Cases[{specs}, {us__}_k :> {us}]}}]_k], Q, P] /. {tj → tk, Tj → Tk}
```

```
co =  $\mathbb{C}_{CU}$ [{y1, a1, x1}1, {y2, a2, x2}2, {y3, a3, x3}3,  $\hbar$  Sum[l10i+j ti aj +  $\Upsilon$ 10i+j yi xj, {i, 3}, {j, 3}], 12];
co // m3→4, HL@Simp[CU[m3→4[co]] - m3→4[CU[co]]]
 $\mathbb{C}_{CU}$ [{y1, a1, x1}1, {y2, a2, x2}2, {y4, a4, x4}4,  $\hbar$  ( a1 l11 t1 + a2 l12 t1 + a4 l13 t1 + a1 l21 t2 + a2 l22 t2 + a4 l23 t2 + a1 l31 t4 + a2 l32 t4 + a4 l33 t4 + x1 y1  $\Upsilon$ 11 + x2 y1  $\Upsilon$ 12 + x4 y1  $\Upsilon$ 13 + x1 y2  $\Upsilon$ 21 + x2 y2  $\Upsilon$ 22 + x4 y2  $\Upsilon$ 23 + x1 y4  $\Upsilon$ 31 + x2 y4  $\Upsilon$ 32 + x4 y4  $\Upsilon$ 33 ), 1 + O[ $\epsilon$ ]3 ], 0 }
```

Verifying that *m* commutes with evaluation, in CU:

```
co =  $\mathbb{C}_{CU}$ [{y1, a1, x1}1, {y2, a2, x2}2, {y3, a3, x3}3,  $\hbar$  Sum[l10i+j ti aj +  $\Upsilon$ 10i+j yi xj, {i, 3}, {j, 3}], 12];
Timing@{co // m2→3, HL@Simp[CU[m2→3[co]] - m2→3[CU[co]]]}
```

$$\left\{ 513.453, \left\{ \mathbb{C}_{CU} \left[ \{y_1, a_1, x_1\}_1, \{y_3, a_3, x_3\}_3, \frac{\dots 1 \dots}{e^{\dots 1 \dots} \dots 1 \dots}, \frac{1}{1 + \hbar t_3 \Upsilon_{32}} + \left( \left( 4 e^{2 \Upsilon \hbar l_{12} t_1 + \dots 4 \dots} + 2 \Upsilon \hbar l_{33} t_3 \hbar^2 a_3 x_1 y_1 \Upsilon_{12} \Upsilon_{31} - 2 \dots 7 \dots \Upsilon_{31} + \dots 154 \dots \right) \epsilon \right) / \left( 2 e^{2 \Upsilon \hbar l_{12} t_1 + 2 \Upsilon \hbar l_{13} t_1 + \dots 3 \dots} + 2 \Upsilon \hbar l_{33} t_3 + 10 e^{\dots 1 \dots} \hbar t_3 \Upsilon_{32} + \dots 2 \dots + \dots 1 \dots + 2 e^{2 \Upsilon \hbar l_{12} t_1 + \dots 4 \dots} + \dots 1 \dots \hbar^5 t_3^5 \Upsilon_{32}^5 \right) + \frac{(\dots 1 \dots)^2}{\dots 1 \dots} + O[\epsilon]^3 \right), \mathbf{0} \right\} \right\}$$

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Verifying that *m* commutes with evaluation, in QU:

```
qo =  $\mathbb{C}_{QU}$ [{y1, a1, x1}1, {y2, a2, x2}2, {y3, a3, x3}3,  $\hbar$  Sum[l10i+j ti aj +  $\Upsilon$ 10i+j yi xj, {i, 3}, {j, 3}], 12];
Timing@{qo // m2→3, HL@SimpT[QU[m2→3[qo]] - m2→3[QU[qo]]]}
```

$$\left\{ 7831.47, \left\{ \mathbb{C}_{QU} \left[ \{y_1, a_1, x_1\}_1, \{y_3, a_3, x_3\}_3, \frac{\dots 1 \dots}{\dots 1 \dots}, \frac{1}{1 - \Upsilon_{32} + T_3 \Upsilon_{32}} + \left( \left( 8 e^{2 \Upsilon \hbar l_{12} t_1 + \dots 4 \dots} + 2 \Upsilon \hbar l_{33} t_3 \hbar^2 a_3 T_3 x_1 y_1 \Upsilon_{12} \Upsilon_{31} + 4 \dots 8 \dots \Upsilon_{31} + \dots 371 \dots \right) \epsilon \right) / \left( 4 e^{2 \Upsilon \hbar l_{12} t_1 + 2 \Upsilon \hbar l_{13} t_1 + \dots 3 \dots} + 2 \Upsilon \hbar l_{33} t_3 - 20 e^{\dots 1 \dots} \Upsilon_{32} + \dots 26 \dots + 4 e^{2 \Upsilon \hbar l_{12} t_1 + \dots 4 \dots} + \dots 1 \dots T_3^5 \Upsilon_{32}^5 \right) + \frac{(\dots 1 \dots)^2}{\dots 79 \dots + \dots 1 \dots} + O[\epsilon]^3 \right), \mathbf{0} \right\} \right\}$$

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In[\*]:=

```
CU[_sp1_, Q1_, P1_] ≡ CU[_sp2_, Q2_, P2_] :=  
Sort[{sp1}] == Sort[{sp2}] ∧ Simplify[Q1 == Q2] ∧ Simplify[Normal[P1 - P2] == 0]
```

Verifying meta-associativity in CU:

```
co = CU[{y1, a1, x1}1, {y2, a2, x2}2,  
  {y3, a3, x3}3, h Sum[λ10i+j ti aj + γ10i+j yi xj, {i, 3}, {j, 3}], 10];  
Timing@HL[(lhs = co // m1,2→1 // m1,3→1) ≡ (rhs = co // m2,3→2 // m1,2→1)]  
{41.9219, True}
```

```
co = CU[{y1, a1, x1}1, {y2, a2, x2}2,  
  {y3, a3, x3}3, h Sum[λ10i+j ti aj + γ10i+j yi xj, {i, 3}, {j, 3}], 11];  
Timing@HL[(lhs = co // m1,2→1 // m1,3→1) ≡ (rhs = co // m2,3→2 // m1,2→1)]  
{30119.8, True}
```

mexamples

```
co = CU[{y1, a1, x1}1, {y2, a2, x2}2, h Sum[l10i+j ti aj + γ10i+j yi xj, {i, 2}, {j, 2}], 11];  
Short[Simplify /@ (cexample = co // m1→2), 12]  
Short[Simplify /@ (qexample = (qo = co /. CU → QU) // m1→2), 12]
```

mexamples

$$\begin{aligned} & \mathbb{C}_{\text{CU}} \left[ \{y_2, a_2, x_2\}_2, \hbar a_2 (l_{11} + l_{12} + l_{21} + l_{22}) t_2 + \frac{1}{1 + \hbar t_2 \gamma_{21}} \right. \\ & \left. e^{-\gamma \hbar (l_{11} + l_{12} + l_{21} + l_{22}) t_2} \hbar x_2 y_2 (\gamma_{21} + e^{\gamma \hbar (l_{11} + l_{12} + l_{21} + l_{22}) t_2} \gamma_{12} (1 + \hbar t_2 \gamma_{21})) + \right. \\ & \left. e^{\gamma \hbar (l_{12} + l_{22}) t_2} \gamma_{22} + \gamma_{11} (e^{\gamma \hbar (l_{11} + l_{21}) t_2} - e^{\gamma \hbar (l_{11} + l_{12} + l_{21} + l_{22}) t_2} \hbar t_2 \gamma_{22}) \right), \\ & \frac{1}{1 + \hbar t_2 \gamma_{21}} + \frac{1}{2 (1 + \hbar t_2 \gamma_{21})^5} e^{-2 \gamma \hbar (l_{11} + l_{12} + l_{21} + l_{22}) t_2} \hbar \left( 4 a_2 (1 + \hbar t_2 \gamma_{21})^2 \right. \\ & \left. (e^{\gamma \hbar (l_{11} + l_{12} + l_{21} + l_{22}) t_2} \hbar (e^{\gamma \hbar (l_{11} + l_{12} + l_{21} + l_{22}) t_2} t_2 + x_2 y_2) \gamma_{21}^2 + e^{2 \gamma \hbar (l_{11} + l_{12} + l_{21} + l_{22}) t_2} \hbar x_2 y_2 \gamma_{11} \gamma_{22} + \right. \\ & \left. \gamma_{21} (e^{2 \gamma \hbar (l_{11} + l_{12} + l_{21} + l_{22}) t_2} + \hbar x_2 y_2 (e^{\gamma \hbar (2 l_{11} + l_{12} + 2 l_{21} + l_{22}) t_2} \gamma_{11} + e^{\gamma \hbar (l_{11} + 2 l_{12} + l_{21} + 2 l_{22}) t_2} \gamma_{22})) \right) - \\ & \left. \gamma \hbar (-2 e^{2 \gamma \hbar (l_{11} + l_{12} + l_{21} + l_{22}) t_2} t_2 \gamma_{21}^2 (1 + \hbar t_2 \gamma_{21})^2 + 4 \ll 5 \gg (\ll 1 \gg) + \right. \\ & \left. \hbar \ll 4 \gg (3 \hbar t_2 \gamma_{21}^2 + 2 e^{\gamma \hbar (l_{12} + l_{22}) t_2} \gamma_{22} + \gamma_{21} (4 + e^{\gamma \ll 3 \gg} \hbar t_2 \gamma_{22}) + \right. \\ & \left. e^{\gamma \hbar (l_{11} + l_{21}) t_2} \gamma_{11} (2 + \hbar t_2 (\gamma_{21} - e^{\gamma \hbar (l_{12} + l_{22}) t_2} \gamma_{22}))) \right) \in + \mathbf{O}[\epsilon]^2 \end{aligned}$$

mexamples

$$\begin{aligned} & \mathbb{C}_{\text{QU}} \left[ \{y_2, a_2, x_2\}_2, \hbar a_2 (l_{11} + l_{12} + l_{21} + l_{22}) t_2 + \right. \\ & \left. \frac{1}{1 + (-1 + T_2) \gamma_{21}} e^{-\gamma \hbar (l_{11} + l_{12} + l_{21} + l_{22}) t_2} \hbar x_2 y_2 (\gamma_{21} + e^{\gamma \hbar (l_{11} + l_{12} + l_{21} + l_{22}) t_2} \gamma_{12} (1 + (-1 + T_2) \gamma_{21})) + \right. \\ & \left. e^{\gamma \hbar (l_{12} + l_{22}) t_2} \gamma_{22} + \gamma_{11} (e^{\gamma \hbar (l_{11} + l_{21}) t_2} - e^{\gamma \hbar (l_{11} + l_{12} + l_{21} + l_{22}) t_2} (-1 + T_2) \gamma_{22}) \right), \\ & \frac{1}{1 + (-1 + T_2) \gamma_{21}} + \frac{1}{4 (1 + (-1 + T_2) \gamma_{21})^5} e^{-2 \gamma \hbar (l_{11} + l_{12} + l_{21} + l_{22}) t_2} \hbar \left( \right. \\ & \left. 8 a_2 T_2 (1 + (-1 + T_2) \gamma_{21})^2 (e^{\gamma \hbar (l_{11} + l_{12} + l_{21} + l_{22}) t_2} (-e^{\gamma \hbar (l_{11} + l_{12} + l_{21} + l_{22}) t_2} + \right. \\ & \left. e^{\gamma \hbar (l_{11} + l_{12} + l_{21} + l_{22}) t_2} T_2 + \hbar x_2 y_2) \gamma_{21}^2 + e^{2 \gamma \hbar (l_{11} + l_{12} + l_{21} + l_{22}) t_2} \hbar x_2 y_2 \gamma_{11} \gamma_{22} + \right. \\ & \left. \gamma_{21} (e^{2 \gamma \hbar (l_{11} + l_{12} + l_{21} + l_{22}) t_2} + \hbar x_2 y_2 (e^{\gamma \hbar (2 l_{11} + l_{12} + 2 l_{21} + l_{22}) t_2} \gamma_{11} + e^{\gamma \hbar (l_{11} + 2 l_{12} + l_{21} + 2 l_{22}) t_2} \gamma_{22})) \right) \right) + \\ & \left. \gamma (2 e^{2 \gamma \hbar (l_{11} + l_{12} + l_{21} + l_{22}) t_2} (1 - 4 T_2 + 3 T_2^2) \gamma_{21}^2 (1 + (-1 + T_2) \gamma_{21})^2 + \right. \\ & \left. 4 e^{\gamma \hbar (l_{11} + l_{12} + l_{21} + l_{22}) t_2} \hbar x_2 y_2 \gamma_{21} (1 + (-1 + T_2) \gamma_{21}) (\ll 1 \gg) - \ll 1 \gg) \right) \in + \mathbf{O}[\epsilon]^2 \end{aligned}$$

## R in QU.

The Faddeev-Quesne formula:

Faddeev

$$\text{In[*]:= } e_{q_-,k_-}[X_-] := e^{\sum_{j=1}^{k+1} \frac{(1-q)^j x^j}{j(1-q^j)}}; e_{q,-}[X_-] := e_{q,\$k}[X]$$

Table[Series[e<sub>q<sub>n</sub>,k</sub>[X], {ε, 0, 4}], {k, 0, 5}] // Column

$$e^x$$

$$e^x - \frac{1}{4} (e^x x^2 \gamma \hbar) \epsilon + \frac{1}{32} e^x x^4 \gamma^2 \hbar^2 \epsilon^2 - \frac{1}{384} (e^x x^2 (-8 + x^4) \gamma^3 \hbar^3) \epsilon^3 + \frac{e^x x^4 (-32+x^4) \gamma^4 \hbar^4 \epsilon^4}{6144} + O[\epsilon]^5$$

$$e^x - \frac{1}{4} (e^x x^2 \gamma \hbar) \epsilon + \frac{1}{288} e^x x^3 (32 + 9x) \gamma^2 \hbar^2 \epsilon^2 - \frac{(e^x x^2 (-24+32x^3+3x^4) \gamma^3 \hbar^3) \epsilon^3}{1152} + \frac{e^x x^3 (-4608-864x+1024x^3+576x^4+27x^5) \gamma^4 \hbar^4 \epsilon^4}{165888} + O[\epsilon]^5$$

$$e^x - \frac{1}{4} (e^x x^2 \gamma \hbar) \epsilon + \frac{1}{288} e^x x^3 (32 + 9x) \gamma^2 \hbar^2 \epsilon^2 - \frac{(e^x x^2 (-24+72x^2+32x^3+3x^4) \gamma^3 \hbar^3) \epsilon^3}{1152} + \frac{e^x x^3 (-4608-864x+3616x^3+576x^4+27x^5) \gamma^4 \hbar^4 \epsilon^4}{165888} + O[\epsilon]^5$$

$$e^x - \frac{1}{4} (e^x x^2 \gamma \hbar) \epsilon + \frac{1}{288} e^x x^3 (32 + 9x) \gamma^2 \hbar^2 \epsilon^2 - \frac{(e^x x^2 (-24+72x^2+32x^3+3x^4) \gamma^3 \hbar^3) \epsilon^3}{1152} + \frac{1}{4147200} \gamma^4 \hbar^4 \epsilon^4 + O[\epsilon]^5$$

$$e^x x^3 (-115200 - 21600x + 165888x^2 + 90400x^3 + 14400x^4 + 675x^5) \gamma^4 \hbar^4 \epsilon^4 + O[\epsilon]^5$$

$$e^x - \frac{1}{4} (e^x x^2 \gamma \hbar) \epsilon + \frac{1}{288} e^x x^3 (32 + 9x) \gamma^2 \hbar^2 \epsilon^2 - \frac{(e^x x^2 (-24+72x^2+32x^3+3x^4) \gamma^3 \hbar^3) \epsilon^3}{1152} + \frac{1}{4147200} \gamma^4 \hbar^4 \epsilon^4 + O[\epsilon]^5$$

$$e^x x^3 (-115200 - 21600x + 165888x^2 + 90400x^3 + 14400x^4 + 675x^5) \gamma^4 \hbar^4 \epsilon^4 + O[\epsilon]^5$$

Table[Together@SeriesCoefficient[e<sub>q<sub>5</sub></sub>[X], {x, 0, n}], {n, 0, 5}]

$$\left\{ 1, 1, \frac{1}{1+q}, \frac{1}{(1+q)(1+q+q^2)}, \frac{1}{(1+q)^2(1+q^2)(1+q+q^2)}, \frac{1}{(1+q)^2(1+q^2)(1+q+q^2+q^3+q^4)} \right\}$$

Table[HL@FunctionExpand[QFactorial[n, q] SeriesCoefficient[e<sub>q<sub>5</sub></sub>[X], {x, 0, n}]], {n, 0, 5}]

{1, 1, 1, 1, 1, 1}

R

$$\text{In[*]:= } QU[R_{i,j}] := OQU[\{y_1, a_1\}_i, \{a_2, x_2\}_j, SS[e^{\hbar b_1 a_2} e_{q_h}[\hbar y_1 x_2] /. b_1 \to \gamma^{-1} (\epsilon a_1 - t_i)]]; QU[R_{i,j}^{-1}] := S_j @ QU[R_{i,j}];$$

QU[R<sub>3,4</sub>] // Short

$$QU[] + \frac{\epsilon \hbar QU[a_3, a_4]}{\gamma} + \hbar QU[y_3, x_4] + \frac{\epsilon \langle\langle 1 \rangle\rangle \langle\langle 1 \rangle\rangle}{\gamma} + \frac{1}{2} \frac{\langle\langle 1 \rangle\rangle \langle\langle 1 \rangle\rangle}{\gamma} - \frac{\langle\langle 1 \rangle\rangle}{\gamma} - \frac{\epsilon \hbar^2 \langle\langle 1 \rangle\rangle t_3}{\gamma^2} - \frac{\hbar^2 QU[y_3, a_4, x_4] t_3}{\gamma} + \frac{\hbar^2 QU[a_4, a_4] t_3^2}{2 \gamma^2}$$

Verifying R2 (~2 secs @ \$p=4, \$k=2):

QU[R<sub>1,2</sub> \*\* R<sub>1,2</sub><sup>-1</sup>] // Simp // HL // Timing

{0.078125, QU[]}

Verifying R3 (~156 secs @ \$p=4, \$k=2):

`{Short[lhs = QU[R1,2 ** R1,3 ** R2,3], HL@SimpT[lhs - QU[R2,3 ** R1,3 ** R1,2]]} // Timing`

$$\left\{ 0.203125, \left\{ \text{QU} \left[ \frac{\epsilon \hbar \text{QU}[a_1, a_2]}{\gamma} + \frac{\epsilon \hbar \text{QU}[a_1, a_3]}{\gamma} + \right. \right. \right. \\ \left. \left. \left. \ll 73 \gg + 2 \epsilon \hbar^2 \text{QU}[y_1, a_2, x_3] T_2 + \text{QU}[y_1, x_3] (\hbar - \hbar T_2), \mathbf{0} \right\} \right\}$$

## R in $\mathbb{C}_{\text{QU}}$ .

RinOE

$$\text{In[*]:= } \mathbb{C}_{\text{QU},k}[\mathbf{R}_{i,j}] := \mathbb{C}_{\text{QU}} \left[ \{y_i, a_i, x_i\}_i, \{y_j, a_j, x_j\}_j, -\hbar \gamma^{-1} t_i a_j + \hbar y_i x_j, \right. \\ \left. \text{Series} \left[ e^{\hbar \gamma^{-1} t_i a_j - \hbar y_i x_j} \left( e^{\hbar b_i a_j} \mathbf{e}_{q_n, k}[\hbar y_i x_j] / . b_i \rightarrow \gamma^{-1} (\epsilon a_i - t_i) \right), \{\epsilon, \mathbf{0}, k\} \right] \right]$$

$\{\mathbb{C}_{\text{QU},1}[\mathbf{R}_{1,2}], \mathbb{C}_{\text{QU},2}[\mathbf{R}_{1,2}]\}$

$$\left\{ \mathbb{C}_{\text{QU}} \left[ \{y_1, a_1, x_1\}_1, \{y_2, a_2, x_2\}_2, -\frac{\hbar a_2 t_1}{\gamma} + \hbar x_2 y_1, 1 + \left( \frac{\hbar a_1 a_2}{\gamma} - \frac{1}{4} \gamma \hbar^3 x_2^2 y_1^2 \right) \epsilon + \mathbf{O}[\epsilon]^2 \right], \right. \\ \left. \mathbb{C}_{\text{QU}} \left[ \{y_1, a_1, x_1\}_1, \{y_2, a_2, x_2\}_2, -\frac{\hbar a_2 t_1}{\gamma} + \hbar x_2 y_1, 1 + \left( \frac{\hbar a_1 a_2}{\gamma} - \frac{1}{4} \gamma \hbar^3 x_2^2 y_1^2 \right) \epsilon + \right. \right. \\ \left. \left. \frac{1}{288 \gamma^2} (144 \hbar^2 a_1^2 a_2^2 - 72 \gamma^2 \hbar^4 a_1 a_2 x_2^2 y_1^2 + 32 \gamma^4 \hbar^5 x_2^3 y_1^3 + 9 \gamma^4 \hbar^6 x_2^4 y_1^4) \epsilon^2 + \mathbf{O}[\epsilon]^3 \right] \right\}$$

## The morphism $\mathbb{C}_{U,k}$ .

MorphismOE

$$\text{In[*]:= } \mathbb{C}_{U,k}[\mathbf{a}_- * \mathbf{b}_-] := \mathbb{C}_{U,k}[\mathbf{a}] \mathbb{C}_{U,k}[\mathbf{b}]; \\ \mathbb{C}_{U,k}[\mathbf{m}_{iS}[\mathbf{a}_-]] := \mathbf{m}_{iS}[\mathbb{C}_{U,k}[\mathbf{a}]];$$

$\mathbb{C}_{\text{QU},1}[\mathbf{R}_{1,2} \mathbf{R}_{3,4} \mathbf{R}_{5,6}]$

$$\mathbb{C}_{\text{QU}} \left[ \{y_1, a_1, x_1\}_1, \{y_2, a_2, x_2\}_2, \{y_3, a_3, x_3\}_3, \{y_4, a_4, x_4\}_4, \right. \\ \left. \{y_5, a_5, x_5\}_5, \{y_6, a_6, x_6\}_6, -\frac{\hbar a_2 t_1}{\gamma} - \frac{\hbar a_4 t_3}{\gamma} - \frac{\hbar a_6 t_5}{\gamma} + \hbar x_2 y_1 + \hbar x_4 y_3 + \hbar x_6 y_5, \right. \\ \left. 1 + \left( \frac{\hbar a_1 a_2}{\gamma} + \frac{\hbar a_3 a_4}{\gamma} + \frac{\hbar a_5 a_6}{\gamma} - \frac{1}{4} \gamma \hbar^3 x_2^2 y_1^2 - \frac{1}{4} \gamma \hbar^3 x_4^2 y_3^2 - \frac{1}{4} \gamma \hbar^3 x_6^2 y_5^2 \right) \epsilon + \mathbf{O}[\epsilon]^2 \right]$$

$\mathbb{C}_{\text{QU},1}[\mathbf{R}_{1,2} \mathbf{R}_{3,4} \mathbf{R}_{5,6} // \mathbf{m}_{1,3 \rightarrow 1} // \mathbf{m}_{2,5 \rightarrow 2} // \mathbf{m}_{4,6 \rightarrow 4}]$

$$\mathbb{C}_{\text{QU}} \left[ \{y_1, a_1, x_1\}_1, \{y_2, a_2, x_2\}_2, \{y_4, a_4, x_4\}_4, \frac{1}{\gamma} \right. \\ \left. (-\hbar a_2 t_1 - \hbar a_4 t_1 - \hbar a_4 t_2 + \gamma \hbar x_2 y_1 + \gamma \hbar x_4 y_1 + e^{\hbar t_2} \gamma \hbar x_4 y_1 - \gamma \hbar T_2 x_4 y_1 + e^{\hbar t_1} \gamma \hbar x_4 y_2), \right. \\ \left. 1 + \frac{1}{4 \gamma} (4 \hbar a_1 a_2 + 4 \hbar a_1 a_4 + 4 \hbar a_2 a_4 - 4 \gamma \hbar^2 a_4 x_2 y_1 - 8 e^{\hbar t_2} \gamma \hbar^2 a_2 x_4 y_1 + \right. \\ \left. 8 \gamma \hbar^2 a_2 T_2 x_4 y_1 - \gamma^2 \hbar^3 x_2^2 y_1^2 + 4 e^{\hbar t_2} \gamma^2 \hbar^3 x_2 x_4 y_1^2 - 4 \gamma^2 \hbar^3 T_2 x_2 x_4 y_1^2 - \gamma^2 \hbar^3 x_4^2 y_1^2 - \right. \\ \left. e^{2 \hbar t_2} \gamma^2 \hbar^3 x_4^2 y_1^2 + \gamma^2 \hbar^3 T_2^2 x_4^2 y_1^2 - 4 e^{\hbar t_1} \gamma \hbar^2 a_1 x_4 y_2 + 4 e^{\hbar t_1} \gamma^2 \hbar^3 x_2 x_4 y_1 y_2 + \right. \\ \left. 4 e^{\hbar t_1 + \hbar t_2} \gamma^2 \hbar^3 x_4^2 y_1 y_2 - 4 e^{\hbar t_1} \gamma^2 \hbar^3 T_2 x_4^2 y_1 y_2 - e^{2 \hbar t_1} \gamma^2 \hbar^3 x_4^2 y_2^2) \epsilon + \mathbf{O}[\epsilon]^2 \right]$$

$$\mathbb{C}_{\text{QU},1} [\mathbf{R}_{1,2} \mathbf{R}_{3,4} \mathbf{R}_{5,6} // \mathbf{m}_{3,1 \rightarrow 1} // \mathbf{m}_{5,2 \rightarrow 2} // \mathbf{m}_{6,4 \rightarrow 4}]$$

$$\begin{aligned} & \mathbb{C}_{\text{QU}} \left[ \{y_1, a_1, x_1\}_1, \{y_2, a_2, x_2\}_2, \{y_4, a_4, x_4\}_4, \frac{1}{\gamma} \right. \\ & \left. (-\hbar a_2 t_1 - \hbar a_4 t_1 - \hbar a_4 t_2 + \gamma \hbar x_2 y_1 + \gamma \hbar x_4 y_1 + e^{\hbar t_1} \gamma \hbar x_4 y_2), \right. \\ & \left. 1 + \frac{1}{4\gamma} (4 \hbar a_1 a_2 + 4 \hbar a_1 a_4 + 4 \hbar a_2 a_4 - 4 \gamma \hbar^2 a_4 x_2 y_1 - \gamma^2 \hbar^3 x_2^2 y_1^2 - \gamma^2 \hbar^3 x_4^2 y_1^2 - \right. \\ & \left. 4 e^{\hbar t_1} \gamma \hbar^2 a_1 x_4 y_2 + 4 e^{\hbar t_1} \gamma^2 \hbar^3 x_2 x_4 y_1 y_2 - e^{2\hbar t_1} \gamma^2 \hbar^3 x_4^2 y_2^2) \in + \mathbf{O}[\epsilon]^2 \right] \end{aligned}$$

$$\mathbb{C}_{\text{QU},1} [\mathbf{R}_{1,2} \mathbf{R}_{3,4} \mathbf{R}_{5,6} // \mathbf{m}_{1,3 \rightarrow 1} // \mathbf{m}_{2,5 \rightarrow 2} // \mathbf{m}_{4,6 \rightarrow 4}] \equiv \mathbb{C}_{\text{QU},1} [\mathbf{R}_{1,2} \mathbf{R}_{3,4} \mathbf{R}_{5,6} // \mathbf{m}_{3,1 \rightarrow 1} // \mathbf{m}_{5,2 \rightarrow 2} // \mathbf{m}_{6,4 \rightarrow 4}]$$

$$\hbar (e^{\hbar t_2} - T_2) x_4 y_1 = \mathbf{0} \&\& \in \hbar (e^{\hbar t_2} - T_2) x_4 y_1 (8 a_2 + \gamma \hbar (-4 x_2 y_1 + x_4 ((e^{\hbar t_2} + T_2) y_1 - 4 e^{\hbar t_1} y_2))) = \mathbf{0}$$

## Exponentials as needed.

```
In[ ]:= Block[{$p = 2, $k = 2}, TableForm[StringSplit[
  "y | a | x | C@y_CU | C@a_CU | C@x_CU | Q@y_QU | Q@a_QU | Q@x_QU | AD@y_QU | AD@a_QU | AD@x_QU | SD@y_QU | SD@a_QU | SD
  @x_QU | S@y_CU | S@a_CU | S@x_CU | S@y_QU | S@a_QU | S@x_QU | Δ@y_CU | Δ@a_CU | Δ@x_CU | Δ@y_QU | Δ@a_QU | Δ@x_QU",
  "" ] /. s_String =>
  {s, Normal@Simplify@Series[ToExpression[s] /. CU | QU → Times, {ε, 0, $k}]}]]
```

Out[ ]//TableForm=

y	y
a	a
x	x
C@y_CU	-x
C@a_CU	-a
C@x_CU	-y
Q@y_QU	$-\frac{x}{\sqrt{T}} - \frac{ax\epsilon\hbar}{\sqrt{T}} - \frac{a^2x\epsilon^2\hbar^2}{2\sqrt{T}}$
Q@a_QU	-a
Q@x_QU	$-\frac{y}{\sqrt{T}} + \frac{y(-a+\gamma)\epsilon\hbar}{\sqrt{T}} - \frac{y(a-\gamma)^2\epsilon^2\hbar^2}{2\sqrt{T}}$
AD@y_QU	$\frac{2}{3}a^2y\epsilon^2\hbar^2 + \frac{1}{6}y(6+3t\hbar+t^2\hbar^2) + \frac{1}{12}y\epsilon\hbar(xy\gamma\hbar - 4a(3+2t\hbar))$
AD@a_QU	a
AD@x_QU	x
SD@y_QU	$y + \frac{1}{48}t^2y\hbar^2 + \frac{1}{24}y(-2at+xy\gamma)\epsilon\hbar^2 + \frac{1}{12}a^2y\epsilon^2\hbar^2$
SD@a_QU	a
SD@x_QU	$\frac{7}{12}a^2x\epsilon^2\hbar^2 + x\left(1 + \frac{t\hbar}{2} + \frac{7t^2\hbar^2}{48}\right) + \frac{1}{24}x\epsilon\hbar(xy\gamma\hbar - 2a(12+7t\hbar))$
S@y_CU	-y
S@a_CU	-a
S@x_CU	-x
S@y_QU	$-\frac{y}{T} + \frac{y(-a+\gamma)\epsilon\hbar}{T} - \frac{y(a-\gamma)^2\epsilon^2\hbar^2}{2T}$
S@a_QU	-a
S@x_QU	$-x - a x \epsilon \hbar - \frac{1}{2} a^2 x \epsilon^2 \hbar^2$
Δ@y_CU	y <sub>1</sub> + y <sub>2</sub>
Δ@a_CU	a <sub>1</sub> + a <sub>2</sub>
Δ@x_CU	x <sub>1</sub> + x <sub>2</sub>
Δ@y_QU	y <sub>1</sub> + T <sub>1</sub> y <sub>2</sub> - εħ a <sub>1</sub> T <sub>1</sub> y <sub>2</sub> + $\frac{1}{2}\epsilon^2\hbar^2 a_1^2 T_1 y_2$
Δ@a_QU	a <sub>1</sub> + a <sub>2</sub>
Δ@x_QU	x <sub>1</sub> + x <sub>2</sub> - εħ a <sub>1</sub> x <sub>2</sub> + $\frac{1}{2}\epsilon^2\hbar^2 a_1^2 x_2$

Exp

Task. Define  $\text{Exp}_{U_i,k}[\xi, P]$  which computes  $e^{\xi Q(P)}$  to  $\epsilon^k$  in the algebra  $U_i$ , where  $\xi$  is a scalar,  $X$  is  $x_i$  or  $y_i$ , and  $P$  is an  $\epsilon$ -dependent near-docile element, giving the answer in  $\mathbb{C}\epsilon$ -form. Should satisfy

$$U @ \text{Exp}_{U_i,k}[\xi, P] == \mathbb{S}_U[e^{\xi X}, x \rightarrow Q(P)].$$

Methodology. If  $P_0 := P_{\epsilon=0}$  and  $e^{\xi Q(P)} = Q(e^{\xi P_0} F(\xi))$ , then  $F(\xi = 0) = 1$  and we have:

$$Q(e^{\xi P_0}(P_0 F(\xi) + \partial_\xi F)) = Q(\partial_\xi e^{\xi P_0} F(\xi)) = \partial_\xi Q(e^{\xi P_0} F(\xi)) = \partial_\xi e^{\xi Q(P_0)} = e^{\xi Q(P_0)} Q(P) = Q(e^{\xi P_0} F(\xi)) Q(P).$$

This is an ODE for  $F$ . Setting inductively  $F_k = F_{k-1} + \epsilon^k \varphi$  we find that  $F_0 = 1$  and solve for  $\varphi$ .

Exp

In[ ]:=

```
(* Bug: The first line is valid only if 0 (e^P0) == e^0 (P0). *)
(* Bug: ξ must be a symbol. *)
ExpU_{i,0}[ξ_, P_] := CU[{y_i, a_i, x_i}_i, Normal@P /. ε → 0, 1 + 0_0];
ExpU_{i,k}[ξ_, P_] := Module[{yax = {y_i, a_i, x_i}, P0, φ, φS, F, j, rhs, at0, atξ},
  P0 = Normal@P /. ε → 0;
  φS =
    Flatten@Table[φ_{j1,j2,j3}[ξ], {j2, 0, k}, {j1, 0, 2 k + 1 - j2}, {j3, 0, 2 k + 1 - j2 - j1}];
  F = Normal@Last@ExpU_{i,k-1}[ξ, P] + e^k φS. (φS /. φ_{js}_[ξ] := Times@@yax^{js});
  rhs = Normal@Last@m_{i,j→i}[CU[yax_i, ξ P0, F + 0_k] m_{i→j}@CU[{y_i, a_i, x_i}_i, 0, P + 0_k]];
  at0 = (# == 0) & /@ Flatten@CoefficientList[F - 1 /. ξ → 0, yax];
  atξ = (# == 0) & /@ Flatten@CoefficientList[(∂_ξ F) + P0 F - rhs, yax];
  CU[yax_i, ξ P0, F + 0_k] /. DSolve[And@@(at0 ∪ atξ), φS, ξ] [[1]] ]
```

In[ ]:=

```
Timing@Block[{$p = 4, $k = 2}, {
  s = S1[QU[y1]] /. QU → Times,
  exps = ExpQU_{i,$k}[η, s], (* Warning: wrong unless $p ≥ $k + 1! *)
  HL@Simp[S1@OQU[{y1}_1, SS[e^h η y1]] - QU@(exps /. η → h η)]
}]
```

Out[ ]:=  $\left\{ 35.8281, \left\{ a_1 \left( -\frac{\epsilon \hbar}{T_1} + \frac{\gamma \epsilon^2 \hbar^2}{T_1} \right) y_1 + \left( -\frac{1}{T_1} + \frac{\gamma \epsilon \hbar}{T_1} - \frac{\gamma^2 \epsilon^2 \hbar^2}{2 T_1} \right) y_1 - \frac{\epsilon^2 \hbar^2 a_1^2 y_1}{2 T_1}, \right. \right.$

$$\left. \mathbb{C}_{QU} \left[ \{y_1, a_1, x_1\}_1, -\frac{\eta y_1}{T_1}, 1 + \frac{(2 \gamma \eta \hbar T_1 y_1 - 2 \eta \hbar a_1 T_1 y_1 - \gamma \eta^2 \hbar y_1^2) \epsilon}{2 T_1^2} + \left( -\frac{\gamma^2 \eta \hbar^2 y_1}{2 T_1} + \frac{\gamma \eta \hbar^2 a_1 y_1}{T_1} - \frac{\eta \hbar^2 a_1^2 y_1}{2 T_1} + \frac{7 \gamma^2 \eta^2 \hbar^2 y_1^2}{4 T_1^2} - \frac{2 \gamma \eta^2 \hbar^2 a_1 y_1^2}{T_1^2} + \frac{\eta^2 \hbar^2 a_1^2 y_1^2}{2 T_1^2} - \frac{\gamma^2 \eta^3 \hbar^2 y_1^3}{T_1^3} + \frac{\gamma \eta^3 \hbar^2 a_1 y_1^3}{2 T_1^3} + \frac{\gamma^2 \eta^4 \hbar^2 y_1^4}{8 T_1^4} \right) \epsilon^2 + O[\epsilon]^3 \right], \mathbf{0} \right\}$$

In[ ]:=

```
Timing@Block[{$p = 4, $k = 2}, {
  s = S1[QU[a1]] /. QU → Times,
  exps = ExpQU_{i,$k}[α, s], (* Warning: wrong unless $p ≥ $k + 1! *)
  HL@Simp[S1@OQU[{a1}_1, SS[e^h α a1]] - QU@(exps /. α → h α)]
}]
```

Out[ ]:=  $\left\{ 33.5938, \left\{ -a_1, \mathbb{C}_{QU} \left[ \{y_1, a_1, x_1\}_1, -\alpha a_1, 1 + O[\epsilon]^3 \right], \mathbf{0} \right\} \right\}$

```
In[ ]:= Timing@Block[{$p = 4, $k = 2}, {
  s = S1[QU[x1]] /. QU → Times,
  exps = ExpQU1,$k[ξ, s], (* Warning: wrong unless $p≥$k+1! *)
  HL@Simp[S1@OQU[{x1}1, SS[eħ ξ x1]] - QU@(exps /. ξ → ħ ξ)]
}]
```

$$\text{Out[ ]} = \left\{ 34.0625, \left\{ -x_1 - \epsilon \hbar a_1 x_1 - \frac{1}{2} \epsilon^2 \hbar^2 a_1^2 x_1, \right. \right.$$

$$\left. \left( \mathbb{E}_{\text{QU}} \left[ \{y_1, a_1, x_1\}_1, -\xi x_1, 1 + \left( -\xi \hbar a_1 x_1 - \frac{1}{2} \gamma \xi^2 \hbar x_1^2 \right) \epsilon + \left( -\frac{1}{2} \xi \hbar^2 a_1^2 x_1 + \frac{1}{4} \gamma^2 \xi^2 \hbar^2 x_1^2 - \right. \right. \right. \right.$$

$$\left. \left. \left. \gamma \xi^2 \hbar^2 a_1 x_1^2 + \frac{1}{2} \xi^2 \hbar^2 a_1^2 x_1^2 - \frac{1}{2} \gamma^2 \xi^3 \hbar^2 x_1^3 + \frac{1}{2} \gamma \xi^3 \hbar^2 a_1 x_1^3 + \frac{1}{8} \gamma^2 \xi^4 \hbar^2 x_1^4 \right) \epsilon^2 + O[\epsilon]^3 \right], \mathbf{0} \right\} \right\}$$

$S(e^{\eta y} e^{\alpha a} e^{\xi x})$

```
In[ ]:= Timing@Block[{$p = 3, $k = 1}, {
  sexp = m3,2,1+1[ExpQU1,$k[η, S1[QU[y1]]] /. QU → Times] ExpQU2,$k[α, S2[QU[a2]]] /. QU → Times]
  ExpQU3,$k[ξ, S3[QU[x3]]] /. QU → Times]] /. {η → ħ η, α → ħ α, ξ → ħ ξ},
  HL@SimpT[QU@sexp - S1@OQU[{y1, a1, x1}1, SS[eħ (η y1 + α a1 + ξ x1)]]]
}]
```

$$\text{Out[ ]} = \left\{ 9.34375, \right.$$

$$\left\{ \mathbb{E}_{\text{QU}} \left[ \{y_1, a_1, x_1\}_1, \frac{1}{\hbar T_1} \left( e^{\alpha \gamma \hbar} \eta \xi \hbar^2 - e^{\alpha \gamma \hbar} \eta \xi \hbar^2 T_1 - \alpha \hbar^2 a_1 T_1 - e^{\alpha \gamma \hbar} \xi \hbar^2 T_1 x_1 - e^{\alpha \gamma \hbar} \eta \hbar^2 y_1 \right), \right. \right.$$

$$1 + \frac{1}{4 \hbar T_1^2} \left( -3 e^{2\alpha \gamma \hbar} \gamma \eta^2 \xi^2 \hbar^4 - 4 e^{\alpha \gamma \hbar} \gamma \eta \xi \hbar^3 T_1 + 4 e^{2\alpha \gamma \hbar} \gamma \eta^2 \xi^2 \hbar^4 T_1 + \right.$$

$$8 e^{\alpha \gamma \hbar} \eta \xi \hbar^3 a_1 T_1 + 4 e^{\alpha \gamma \hbar} \gamma \eta \xi \hbar^3 T_1^2 - e^{2\alpha \gamma \hbar} \gamma \eta^2 \xi^2 \hbar^4 T_1^2 + 6 e^{2\alpha \gamma \hbar} \gamma \eta \xi^2 \hbar^4 T_1 x_1 -$$

$$2 e^{2\alpha \gamma \hbar} \gamma \eta \xi^2 \hbar^4 T_1^2 x_1 - 4 e^{\alpha \gamma \hbar} \xi \hbar^3 a_1 T_1^2 x_1 - 2 e^{2\alpha \gamma \hbar} \gamma \xi^2 \hbar^4 T_1^2 x_1^2 +$$

$$6 e^{2\alpha \gamma \hbar} \gamma \eta^2 \xi \hbar^4 y_1 + 4 e^{\alpha \gamma \hbar} \gamma \eta \hbar^3 T_1 y_1 - 2 e^{2\alpha \gamma \hbar} \gamma \eta^2 \xi \hbar^4 T_1 y_1 -$$

$$4 e^{\alpha \gamma \hbar} \eta \hbar^3 a_1 T_1 y_1 - 4 e^{2\alpha \gamma \hbar} \gamma \eta \xi \hbar^4 T_1 x_1 y_1 - 2 e^{2\alpha \gamma \hbar} \gamma \eta^2 \hbar^4 y_1^2 \left. \right) \epsilon + O[\epsilon]^2, \mathbf{0} \right\}$$

LinearLambda

```
In[ ]:= Timing@Block[{$p = 3, $k = 1}, {
  (sexp = m3,2,1+1[ExpQU1,$k[η, S1[QU[y1]]] /. QU → Times] ExpQU2,$k[α, S2[QU[a2]]] /. QU → Times]
  ExpQU3,$k[ξ, S3[QU[x3]]] /. QU → Times]] /. u_1 → u,
  HL@SimpT[QU@(sexp /. {η → ħ η, α → ħ α, ξ → ħ ξ}) -
  S1@OQU[{y1, a1, x1}1, SS[eħ (η y1 + α a1 + ξ x1)]]]
}]
```

LinearLambda

$$\text{Out[ ]} = \left\{ 15.2969, \left\{ \mathbb{E}_{\text{QU}} \left[ \{y_1, a_1, x_1\}, \frac{1}{T \hbar} \left( e^{\alpha \gamma} \eta \xi - e^{\alpha \gamma} T \eta \xi - a T \alpha \hbar - e^{\alpha \gamma} y \eta \hbar - e^{\alpha \gamma} T x \xi \hbar \right), \right. \right.$$

$$1 + \frac{1}{4 T^2 \hbar} \left( -3 e^{2\alpha \gamma} \gamma \eta^2 \xi^2 + 4 e^{2\alpha \gamma} T \gamma \eta^2 \xi^2 - e^{2\alpha \gamma} T^2 \gamma \eta^2 \xi^2 + 8 a e^{\alpha \gamma} T \eta \xi \hbar - 4 e^{\alpha \gamma} T \gamma \eta \xi \hbar + \right.$$

$$4 e^{\alpha \gamma} T^2 \gamma \eta \xi \hbar + 6 e^{2\alpha \gamma} y \gamma \eta^2 \xi \hbar - 2 e^{2\alpha \gamma} T y \gamma \eta^2 \xi \hbar + 6 e^{2\alpha \gamma} T x \gamma \eta \xi^2 \hbar -$$

$$2 e^{2\alpha \gamma} T^2 x \gamma \eta \xi^2 \hbar - 4 a e^{\alpha \gamma} T y \eta \hbar^2 + 4 e^{\alpha \gamma} T y \gamma \eta \hbar^2 - 2 e^{2\alpha \gamma} y^2 \gamma \eta^2 \hbar^2 -$$

$$4 a e^{\alpha \gamma} T^2 x \xi \hbar^2 - 4 e^{2\alpha \gamma} T x y \gamma \eta \xi \hbar^2 - 2 e^{2\alpha \gamma} T^2 x^2 \gamma \xi^2 \hbar^2 \left. \right) \epsilon + O[\epsilon]^2, \mathbf{0} \right\}$$

$$\Delta_{1 \rightarrow 1,2}(e^{\eta y_1} e^{\alpha a_1} e^{\xi x_1})$$

```
In[*]:= Timing@Block[{$p = 3, $k = 2}, {
  s =  $\Delta_{1 \rightarrow 1,2}$ [QU[y1]] /. QU  $\rightarrow$  Times,
  exps = Prepend[{y2}2]@ExpQu1,$k[\eta, s], (* Warning: wrong unless $p \ge $k+1! *)
  HL@Simp[\Delta_{1 \rightarrow 1,2}@OQu[{y1}1], SS[e^{\hbar \eta y1}] - QU@(exps /. \eta  $\rightarrow$  \hbar \eta)]
}]
```

$$\text{Out[*]} = \left\{ 35.9531, \left\{ y_1 + T_1 y_2 - \epsilon \hbar a_1 T_1 y_2 + \frac{1}{2} \epsilon^2 \hbar^2 a_1^2 T_1 y_2, \right. \right. \\ \left. \left. \mathbb{C}_{\text{Qu}} \left[ \{y_2\}_2, \{y_1, a_1, x_1\}_1, \eta (y_1 + T_1 y_2), 1 + \left( -\eta \hbar a_1 T_1 y_2 + \frac{1}{2} \gamma \eta^2 \hbar T_1 y_1 y_2 \right) \epsilon + \right. \right. \right. \\ \left. \left. \left( \frac{1}{2} \hbar^2 a_1^2 T_1 y_2 (\eta + \eta^2 T_1 y_2) + \frac{1}{2} a_1 y_1 (-\gamma \eta^2 \hbar^2 T_1 y_2 - \gamma \eta^3 \hbar^2 T_1^2 y_2^2) + \frac{1}{12} y_1 \right. \right. \right. \\ \left. \left. \left. \left( 3 \gamma^2 \eta^2 \hbar^2 T_1 y_2 + 2 \gamma^2 \eta^3 \hbar^2 T_1^2 y_2^2 \right) + \frac{1}{24} y_1^2 (4 \gamma^2 \eta^3 \hbar^2 T_1 y_2 + 3 \gamma^2 \eta^4 \hbar^2 T_1^2 y_2^2) \right) \right] \epsilon^2 + \mathcal{O}[\epsilon]^3, \mathbf{0} \right\}$$

```
In[*]:= Timing@Block[{$p = 3, $k = 2}, {
  s =  $\Delta_{1 \rightarrow 1,2}$ [QU[a1]] /. QU  $\rightarrow$  Times,
  exps = Prepend[{a2}2]@ExpQu1,$k[\alpha, s], (* Warning: wrong unless $p \ge $k+1! *)
  HL@Simp[\Delta_{1 \rightarrow 1,2}@OQu[{a1}1], SS[e^{\hbar \alpha a1}] - QU@(exps /. \alpha  $\rightarrow$  \hbar \alpha)]
}]
```

$$\text{Out[*]} = \left\{ 30.5313, \left\{ a_1 + a_2, \mathbb{C}_{\text{Qu}} \left[ \{a_2\}_2, \{y_1, a_1, x_1\}_1, \alpha (a_1 + a_2), 1 + \mathcal{O}[\epsilon]^3, \mathbf{0} \right] \right\} \right\}$$

```
In[*]:= Timing@Block[{$p = 3, $k = 2}, {
  s =  $\Delta_{1 \rightarrow 1,2}$ [QU[x1]] /. QU  $\rightarrow$  Times,
  exps = Prepend[{x2}2]@ExpQu1,$k[\xi, s], (* Warning: wrong unless $p \ge $k+1! *)
  HL@Simp[\Delta_{1 \rightarrow 1,2}@OQu[{x1}1], SS[e^{\hbar \xi x1}] - QU@(exps /. \xi  $\rightarrow$  \hbar \xi)]
}]
```

$$\text{Out[*]} = \left\{ 34.2656, \left\{ x_1 + x_2 - \epsilon \hbar a_1 x_2 + \frac{1}{2} \epsilon^2 \hbar^2 a_1^2 x_2, \mathbb{C}_{\text{Qu}} \left[ \{x_2\}_2, \{y_1, a_1, x_1\}_1, \xi (x_1 + x_2), \right. \right. \right. \\ \left. \left. 1 + \left( -\xi \hbar a_1 x_2 + \frac{1}{2} \gamma \xi^2 \hbar x_1 x_2 \right) \epsilon + \left( \frac{1}{2} \hbar^2 a_1^2 x_2 (\xi + \xi^2 x_2) - \frac{1}{2} \gamma \hbar^2 a_1 x_1 x_2 (\xi^2 + \xi^3 x_2) + \right. \right. \right. \\ \left. \left. \left. \frac{1}{12} \gamma^2 \hbar^2 x_1 x_2 (3 \xi^2 + 2 \xi^3 x_2) + \frac{1}{24} \gamma^2 \hbar^2 x_1^2 x_2 (4 \xi^3 + 3 \xi^4 x_2) \right) \right] \epsilon^2 + \mathcal{O}[\epsilon]^3, \mathbf{0} \right\}$$



LinearLambda

```
In[*]:= Timing@Block[{$p = 4, $k = 2}, {
  sexp = m1,3,5→1@m2,4,6→2@Times[
    Prepend[{y2}2]@ExpQU1,$k[η, Δ1→1,2[QU[y1]] /. QU → Times],
    Prepend[{a4}4]@ExpQU3,$k[α, Δ3→3,4[QU[a3]] /. QU → Times],
    Prepend[{x6}6]@ExpQU5,$k[ξ, Δ5→5,6[QU[x5]] /. QU → Times]
  ] /. {η → ħ η, α → ħ α, ξ → ħ ξ},
  HL@SimpT[QU@sexp - Δ1→1,2@OQU[{y1, a1, x1}1, SS[eħ(η y1+α a1+ξ x1)]]]
}]
```

LinearLambda

```
Out[*]:= {162., {EQU[{y2, a2, x2}2, {y1, a1, x1}1, α ħ a1 + α ħ a2 + ξ ħ x1 + ξ ħ x2 + η ħ y1 + η ħ T1 y2,
  1 + 1/2 (-2 ξ ħ^2 a1 x2 + γ ξ^2 ħ^3 x1 x2 - 2 η ħ^2 a1 T1 y2 + γ η^2 ħ^3 T1 y1 y2) ∈ +
  1/24 (12 ξ ħ^3 a1^2 x2 + 6 γ^2 ξ^2 ħ^4 x1 x2 - 12 γ ξ^2 ħ^4 a1 x1 x2 + 4 γ^2 ξ^3 ħ^5 x1^2 x2 + 12 ξ^2 ħ^4 a1^2 x2^2 +
  4 γ^2 ξ^3 ħ^5 x1 x2^2 - 12 γ ξ^3 ħ^5 a1 x1 x2^2 + 3 γ^2 ξ^4 ħ^6 x1^2 x2^2 + 12 η ħ^3 a1^2 T1 y2 +
  24 η ξ ħ^4 a1^2 T1 x2 y2 - 12 γ η ξ^2 ħ^5 a1 T1 x1 x2 y2 + 6 γ^2 η^2 ħ^4 T1 y1 y2 - 12 γ η^2 ħ^4 a1 T1 y1 y2 -
  12 γ η^2 ξ ħ^5 a1 T1 x2 y1 y2 + 6 γ^2 η^2 ξ^2 ħ^6 T1 x1 x2 y1 y2 + 4 γ^2 η^3 ħ^5 T1 y1^2 y2 + 12 η^2 ħ^4 a1^2 T1^2 y2^2 +
  4 γ^2 η^3 ħ^5 T1^2 y1 y2^2 - 12 γ η^3 ħ^5 a1 T1^2 y1 y2^2 + 3 γ^2 η^4 ħ^6 T1^2 y1^2 y2^2) ∈^2 + O[ε]^3}, 0}}
```

## Zip and Bind

Zip

```
In[*]:= {t*, y*, a*, x*, z*} = {τ, η, α, ξ, ζ};
{τ*, η*, α*, ξ*, ζ*} = {t, y, a, x, z}; (u_{-i})* := (u*)i;
```

Zip

```
In[*]:= Zip_{i}[P_] := P; Zip_{(ξs, ζs___)}[P_] := (Expand[P // Zip_{(ξs)}] /. f_{-} . ξ^{d_{-}} . => ∂_{(ξ*, d)} f) /. ξ* → 0
```

Zip

```
In[*]:= Kδ /: Kδ_{i_, j_} := If[i === j, 1, 0];
E /: ZipExcept[{{___Integer}, ξs_List]@E[Q_, P_] :=
Module[{ξ, z, zs, c, ys, ηs, qt, zrule, Q1, Q2},
  zs = Table[ξ*, {ξ, ξs}];
  c = Q /. Alternatives@@(ξs ∪ zs) → 0;
  ys = Table[∂_ξ (Q /. Alternatives@@zs → 0), {ξ, ξs}];
  ηs = Table[∂_z (Q /. Alternatives@@ξs → 0), {z, zs}];
  qt = Inverse@Table[Kδ_{z, ξ*} - ∂_{z, ξ} Q, {ξ, ξs}, {z, zs}];
  zrule = Thread[zs → qt.(zs + ys)];
  Q1 = c + ηs.zs /. zrule;
  Q2 = Q1 /. Alternatives@@zs → 0;
  Simplify /@ E[Q2, Det[qt] e^{-Q2} Zip_{ξs}[e^{Q1} (P /. zrule)]];
E /: Zip_{is___Integer}[E_E] :=
E // ZipEcho@Flatten@Table[{τi, ai}, {i, {is}}] // ZipEcho@Flatten@Table[{ξi, yi}, {i, {is}}];
```

```
In[*]:= Timing@{E0 = E[Sum[a10 i+j xi xj, {i, 3}, {j, 3}],
  1 + e Sum[fi[x1, x2, x3] xi, {i, 3}] + e Sum[f10 i+j[x1, x2, x3] xi xj, {i, 3}, {j, 3}]],
lhs = Zip[{xi, x2}]@E0,
HL[lhs == Zip[{xi}]@Zip[{xi2}]@E0]}
```

```
Out[*]:= {37.7813,
{E[a11 x1 xi + a21 x2 xi + a31 x3 xi + a12 x1 xi2 + a22 x2 xi2 + a32 x3 xi2 + a13 x1 xi3 + a23 x2 xi3 + a33 x3 xi3,
  1 + e (... 1 ...) + e (xi^2 f11[x1, x2, x3] + xi xi2 f12[x1, x2, x3] + xi xi3 f13[x1, x2, x3] +
  (... 4 ...) + xi2 xi3 f32[x1, x2, x3] + xi^2 f33[x1, x2, x3])], E[... 1 ..., ... 1 ...], True}}
```

large output    show less    show more    show all    set size limit...

```
In[*]:= Timing@{
Eh = E[h Sum[a10 i+j xi xj, {i, 3}, {j, 3}],
  1 + e Sum[fi[x1, x2, x3] xi, {i, 3}] + e Sum[f10 i+j[x1, x2, x3] xi xj, {i, 3}, {j, 3}]],
lhs = Normal[Eh /. E[Q_, P_] -> Series[Pe^Q, {h, 0, 2}]] // Zip[{xi}],
HL@Simplify[lhs == Normal[Zip[{xi}][Eh] /. E[Q_, P_] -> Series[Pe^Q, {h, 0, 2}]]]}
```

```
Out[*]:= {28.7969, {E[
  h (a11 x1 xi + a21 x2 xi + a31 x3 xi + a12 x1 xi2 + a22 x2 xi2 + a32 x3 xi2 + a13 x1 xi3 + a23 x2 xi3 + a33 x3 xi3),
  1 + e (... 1 ...) + e (xi^2 f11[x1, x2, x3] + xi xi2 f12[x1, x2, x3] + (... 5 ...) +
  xi2 xi3 f32[x1, x2, x3] + xi^2 f33[x1, x2, x3])], 1 + (... 579 ...) , True}}
```

large output    show less    show more    show all    set size limit...

Bind

```
In[*]:= E /. E[Q1_, P1_] E[Q2_, P2_] := E[Q1 + Q2, P1 * P2];
BindExcept[[_Integer], xs_List][L_E, R_E] := Module[{n, hidegs, hidezs},
hidegs = Table[xs[[i]] -> S[n+i], {i, Length[xs]}];
hidezs = Table[xs[[i]]* -> Z[n+i], {i, Length[xs]}];
Zip[xs/.hidegs][(L /. hidezs) (R /. hidegs)];
Bind[{is_Integer}[L_E, R_E] := Module[{n},
Times[
  L /. Table[(v : t | a | x | y)_i -> v[n+i], {i, {is}}],
  R /. Table[(v : tau | alpha | xi | eta)_i -> v[n+i], {i, {is}}]
] // ZipFlatten@Table[{tau[n+i], a[n+i]}, {i, {is}}] // ZipFlatten@Table[{xi[n+i], y[n+i]}, {i, {is}}]
];
Bind[E_E] := E;
Bind[LS_., xs_List, R_] := Bind[xs][Bind[LS], R];
```

```
In[*]:= Bind[{xi2}][E[xi(x1 + x2), 1], E[xi2(x2 + x3), 1]]
```

```
Out[*]:= E[xi(x1 + x2 + x3), 1]
```

```
In[*]:= Bind[{xi2}][E[(xi2 + xi3) x2, 1], E[(xi1 + xi2) x, 1]]
```

```
Out[*]:= E[x(xi1 + xi2 + xi3), 1]
```

$In[*]:= \text{Bind}_{\{\xi_1, \xi_2\}} [\mathbb{E} [ (\xi_2 + \xi_3) \mathbf{x}_2 + \xi_1 \mathbf{x}_1, \mathbf{1} ], \mathbb{E} [ (\xi_1 + \xi_2) \mathbf{x}, \mathbf{1} ]]$

$Out[*]:= \mathbb{E} [ \mathbf{x} ( \xi_1 + \xi_2 + \xi_3 ), \mathbf{1} ]$

An  $\mathbf{x}y \rightarrow \mathbf{a}xy \rightarrow \mathbf{a}yx \rightarrow \mathbf{y}ax \equiv \mathbf{x}ay \rightarrow \mathbf{x}ya \rightarrow \mathbf{y}xa \rightarrow \mathbf{y}ax$  test:

$In[*]:= \text{Bind} [\mathbb{E} [ \mathbf{a}_1 \alpha_1 + \mathbf{y}_1 \eta_1 + e^{\gamma \alpha_1} \mathbf{x}_1 \xi_1 + \mathbf{t}_1 \tau_1, \mathbf{1} ]]$

$Out[*]:= \mathbb{E} [ \mathbf{a}_1 \alpha_1 + \mathbf{y}_1 \eta_1 + e^{\gamma \alpha_1} \mathbf{x}_1 \xi_1 + \mathbf{t}_1 \tau_1, \mathbf{1} ]$

$In[*]:= \text{Bind} [\mathbb{E} [ \alpha_1 \mathbf{a}_1 + e^{\gamma \alpha_1} \xi_1 \mathbf{x}_1 + \eta_1 \mathbf{y}_1 + \tau_1 \mathbf{t}_1, \mathbf{1} ], \{\mathbf{1}\}, \mathbb{E} [ \xi_1 \mathbf{x}_1 + \eta_1 \mathbf{y}_1 + \xi_1 \eta_1 \mathbf{t}_1 + \tau_1 \mathbf{t}_1 + \alpha_1 \mathbf{a}_1, \mathbf{1} ]]$

$Out[*]:= \mathbb{E} [ \alpha_1 \mathbf{a}_1 + \mathbf{y}_1 \eta_1 + (1 + e^{\gamma \alpha_1} \gamma \alpha_1) (\mathbf{x}_1 + \mathbf{t}_1 \eta_1) \xi_1 + \mathbf{t}_1 \tau_1, \mathbf{1} ]$

$In[*]:= \text{Cord} [\mathbb{C}_{\text{CU}} [ \{\mathbf{x}_1, \mathbf{a}_1\}_1, \xi_1 \mathbf{x}_1 + \alpha_1 \mathbf{a}_1, \mathbf{1} + \theta_0 ]]$

$Out[*]:= \mathbb{C}_{\text{CU}} [ \{\mathbf{a}_1, \mathbf{x}_1\}_1, e^{-\gamma \alpha_1} (e^{\gamma \alpha_1} \mathbf{a}_1 \alpha_1 + \mathbf{x}_1 \xi_1), \mathbf{1} + 0[\epsilon]^1 ]$

$In[*]:= \text{Cord} [\mathbb{C}_{\text{CU}} [ \{\mathbf{x}_1, \mathbf{y}_1\}_1, \xi_1 \mathbf{x}_1 + \eta_1 \mathbf{y}_1, \mathbf{1} + \theta_0 ]]$

$Out[*]:= \mathbb{C}_{\text{CU}} [ \{\mathbf{y}_1, \mathbf{a}_1, \mathbf{x}_1\}_1, \mathbf{y}_1 \eta_1 + \mathbf{x}_1 \xi_1 - \mathbf{t}_1 \eta_1 \xi_1, \mathbf{1} + 0[\epsilon]^1 ]$

$In[*]:= \text{Cord} [\mathbb{C}_{\text{CU}} [ \{\mathbf{a}_1, \mathbf{y}_1\}_1, \alpha_1 \mathbf{a}_1 + \eta_1 \mathbf{y}_1, \mathbf{1} + \theta_0 ]]$

$Out[*]:= \mathbb{C}_{\text{CU}} [ \{\mathbf{y}_1, \mathbf{a}_1\}_1, e^{-\gamma \alpha_1} (e^{\gamma \alpha_1} \mathbf{a}_1 \alpha_1 + \mathbf{y}_1 \eta_1), \mathbf{1} + 0[\epsilon]^1 ]$

$In[*]:= \mathbf{rxa} = \alpha_1 \mathbf{a}_1 + e^{-\gamma \alpha_1} \xi_1 \mathbf{x}_1 + \eta_1 \mathbf{y}_1 + \tau_1 \mathbf{t}_1;$

$\mathbf{rxy} = \xi_1 \mathbf{x}_1 + \eta_1 \mathbf{y}_1 - \xi_1 \eta_1 \mathbf{t}_1 + \tau_1 \mathbf{t}_1 + \alpha_1 \mathbf{a}_1;$

$\mathbf{ray} = \alpha_1 \mathbf{a}_1 + e^{-\gamma \alpha_1} \eta_1 \mathbf{y}_1 + \xi_1 \mathbf{x}_1 + \tau_1 \mathbf{t}_1;$

$In[*]:= \text{Expand} /@ \text{Bind} [\mathbb{E} [\mathbf{rxa}, \mathbf{1}], \{\mathbf{1}\}, \mathbb{E} [\mathbf{rxy}, \mathbf{1}], \{\mathbf{1}\}, \mathbb{E} [\mathbf{ray}, \mathbf{1}]]$

$Out[*]:= \mathbb{E} [ \mathbf{a}_n\$3192[1] \alpha_1 + \mathbf{a}_1 \alpha_n\$3190[1] + \mathbf{a}_n\$3190[1] \alpha_n\$3192[1] + e^{-\gamma \alpha_1} \mathbf{y}_1 \eta_1 + e^{-\gamma \alpha_n\$3190[1]} \mathbf{x}_1 \xi_1 - e^{-\gamma \alpha_1 - \gamma \alpha_n\$3190[1]} \mathbf{t}_n\$3192[1] \eta_1 \xi_1 + \mathbf{t}_n\$3190[1] \tau_1 + \mathbf{t}_n\$3192[1] \tau_n\$3190[1] + \mathbf{t}_1 \tau_n\$3192[1], \mathbf{1} ]$

$In[*]:= \text{Expand} /@ \text{Bind} [\mathbb{E} [\mathbf{ray}, \mathbf{1}], \{\mathbf{1}\}, \mathbb{E} [\mathbf{rxy}, \mathbf{1}], \{\mathbf{1}\}, \mathbb{E} [\mathbf{rxa}, \mathbf{1}]]$

$Out[*]:= \mathbb{E} [ \mathbf{a}_n\$3197[1] \alpha_1 + \mathbf{a}_1 \alpha_n\$3195[1] + \mathbf{a}_n\$3195[1] \alpha_n\$3197[1] + e^{-\gamma \alpha_n\$3195[1]} \mathbf{y}_1 \eta_1 + e^{-\gamma \alpha_1} \mathbf{x}_1 \xi_1 - \mathbf{t}_n\$3197[1] \eta_1 \xi_1 + \mathbf{t}_n\$3195[1] \tau_1 + \mathbf{t}_n\$3197[1] \tau_n\$3195[1] + \mathbf{t}_1 \tau_n\$3197[1], \mathbf{1} ]$

$In[*]:= \text{Cord} [\mathbb{C}_{\text{CU}} [ \{\mathbf{x}_1, \mathbf{a}_1, \mathbf{y}_1\}_1, \xi_1 \mathbf{x}_1 + \alpha_1 \mathbf{a}_1 + \eta_1 \mathbf{y}_1, \mathbf{1} + \theta_0 ]]$

$Out[*]:= \mathbb{C}_{\text{CU}} [ \{\mathbf{y}_1, \mathbf{a}_1, \mathbf{x}_1\}_1, e^{-\gamma \alpha_1} (e^{\gamma \alpha_1} \mathbf{a}_1 \alpha_1 + \mathbf{y}_1 \eta_1 + \mathbf{x}_1 \xi_1 - \mathbf{t}_1 \eta_1 \xi_1), \mathbf{1} + 0[\epsilon]^1 ]$

$In[*]:= \text{Expand} [e^{-\gamma \alpha_1} (e^{\gamma \alpha_1} \mathbf{a}_1 \alpha_1 + \mathbf{y}_1 \eta_1 + \mathbf{x}_1 \xi_1 - \mathbf{t}_1 \eta_1 \xi_1)]$

$Out[*]:= \mathbf{a}_1 \alpha_1 + e^{-\gamma \alpha_1} \mathbf{y}_1 \eta_1 + e^{-\gamma \alpha_1} \mathbf{x}_1 \xi_1 - e^{-\gamma \alpha_1} \mathbf{t}_1 \eta_1 \xi_1$

## Alternative Algorithms

AllLogos

```
 $In[*]:= \lambda_{\text{alt}, k} [\text{CU}] := \text{If} [k == \mathbf{0}, \mathbf{1}, \text{Module} [ \{\text{eq}, \mathbf{d}, \mathbf{b}, \mathbf{c}, \text{so}\},$ 
 $\text{eq} = \rho @ e^{\xi \mathbf{x}_{\text{cu}}} . \rho @ e^{\eta \mathbf{y}_{\text{cu}}} == \rho @ e^{\mathbf{d} \mathbf{y}_{\text{cu}}} . \rho @ e^{\mathbf{c} (\mathbf{t}_1 \mathbf{c}_{\text{cu}} - 2 \epsilon \mathbf{a}_{\text{cu}})} . \rho @ e^{\mathbf{b} \mathbf{x}_{\text{cu}}};$ 
 $\{\text{so}\} = \text{Solve} [\text{Thread} [\text{Flatten} /@ \text{eq}], \{\mathbf{d}, \mathbf{b}, \mathbf{c}\}] /. \mathbf{C} @ \mathbf{1} \rightarrow \mathbf{0};$ 
 $\text{Series} [e^{-\eta \mathbf{y} - \xi \mathbf{x} + \eta \xi \mathbf{t} + \mathbf{c} \mathbf{t} + \mathbf{d} \mathbf{y} - 2 \epsilon \mathbf{c} \mathbf{a} + \mathbf{b} \mathbf{x}} /. \text{so}, \{\epsilon, \mathbf{0}, k\}]]];$ 
```

`{λa1t,2[CU], HL@Simplify@Normal[λa1t,2[CU] == Last[Δcu,2[{ξ, η}, {x, y}]]]}`

$$\left\{1 + \left(2 a \eta \xi - y \gamma \eta^2 \xi - x \gamma \eta \xi^2 + \frac{1}{2} t \gamma \eta^2 \xi^2\right) \epsilon + \frac{1}{2} \left( \left(2 a \eta \xi - y \gamma \eta^2 \xi - x \gamma \eta \xi^2 + \frac{1}{2} t \gamma \eta^2 \xi^2\right)^2 + 2 \left(-a \gamma \eta^2 \xi^2 + y \gamma^2 \eta^3 \xi^2 + x \gamma^2 \eta^2 \xi^3 - \frac{1}{3} t \gamma^2 \eta^3 \xi^3\right) \right) \epsilon^2 + O[\epsilon]^3, \text{True}\right\}$$


---