

# Geodesic BVP

Consider a geodesic that connects two points  $P_i$  and  $P_j$  with RNC coordinates  $x_i^a$  and  $x_j^a$ . Our aim is to construct a solution  $x^a(s)$  of the geodesic equation such that  $x^a(0) = x_i^a$  and  $x^a(1) = x_j^a$ .

We will do this in two stages. First we will solve

$$x_j^a = x_i^a + y^a - \sum_{k=2}^{\infty} \frac{1}{k!} \Gamma_{\underline{b}_k}^a y^{\underline{b}_k} \quad (1)$$

for  $y^a$  as an explicit polynomial in  $x_i^a$  and  $x_j^a$ . The functions  $\Gamma_{\underline{b}_k}^a$  are the generalised connections for the RNC frame evaluated at  $x^a = x_i^a$ .

In the second stage, we will substitute our expression for  $y^a$  into

$$x^a(s) = x_i^a + sy^a - \sum_{k=2}^{\infty} \frac{1}{k!} \Gamma_{\underline{b}_k}^a y^{\underline{b}_k} s^k \quad (2)$$

to obtain the desired solution to the two point boundary value problem.

## Stage 1: The fixed point iteration scheme

First we rewrite the main equation (1) in the suggestive form

$$y^a = \Delta x^a + \sum_{k=2}^{\infty} \frac{1}{k!} \Gamma_{\underline{b}_k}^a y^{\underline{b}_k}$$

where  $\Delta x^a = x_j^a - x_i^a$ . Our approximate solution for  $y^a$  will be taken to be the partial sums for the infinite series. Thus we will solve

$$y^a = \Delta x^a + \sum_{k=2}^n \frac{1}{k!} \Gamma_{\underline{b}_k}^a y^{\underline{b}_k}$$

for  $y^a$ . Note that in the last term of the sum, the  $\Gamma_{\underline{b}_n}^a$  will contain curvature terms of order  $\mathcal{O}(\epsilon^n)$ . Thus in truncating the series at this point we will lose contributions to the curvature terms of order  $\mathcal{O}(\epsilon^{n+1})$  and higher. So to be consistent we must truncate all terms of the partial sum to order  $\mathcal{O}(\epsilon^n)$  (i.e., exclude any contributions from terms  $\mathcal{O}(\epsilon^{n+1})$  and higher, these are the terms that would couple with the terms that

we excluded when truncating the original infinite series). Let  $\overset{k}{T}$  be the operator that truncates its argument to contain terms no higher than  $\mathcal{O}(\epsilon^n)$ . Then we have the following modified version of the equation for  $\overset{n}{y}^a$

$$\overset{n}{y}^a = \Delta x^a + \sum_{k=2}^n \frac{1}{k!} \overset{k}{T} \left( \Gamma_{b_k}^a \overset{n}{y}^{b_k} \right)$$

Finally we note that since  $\Gamma_{b_k}^a = \mathcal{O}(\epsilon^k)$ , we can use lower order estimates for the  $\overset{k}{y}^a$  in the right hand side of the sum. This allows us to compute  $\overset{n}{y}^a$  by successive approximations such as

$$\begin{aligned} \overset{0}{y}^a &= \Delta x^a \\ \overset{2}{y}^a &= \overset{0}{y}^a + \frac{1}{2!} \overset{2}{T} \left( \Gamma_{bc}^a \overset{0}{y}^b \overset{0}{y}^c \right) \\ \overset{3}{y}^a &= \overset{0}{y}^a + \frac{1}{2!} \overset{3}{T} \left( \Gamma_{bc}^a \overset{2}{y}^b \overset{2}{y}^c \right) + \frac{1}{3!} \overset{3}{T} \left( \Gamma_{bcd}^a \overset{0}{y}^b \overset{0}{y}^c \overset{0}{y}^d \right) \\ \overset{4}{y}^a &= \overset{0}{y}^a + \frac{1}{2!} \overset{4}{T} \left( \Gamma_{bc}^a \overset{3}{y}^b \overset{3}{y}^c \right) + \frac{1}{3!} \overset{4}{T} \left( \Gamma_{bcd}^a \overset{2}{y}^b \overset{2}{y}^c \overset{2}{y}^d \right) + \frac{1}{4!} \overset{4}{T} \left( \Gamma_{bcde}^a \overset{0}{y}^b \overset{0}{y}^c \overset{0}{y}^d \overset{0}{y}^e \right) \\ \overset{5}{y}^a &= \overset{0}{y}^a + \frac{1}{2!} \overset{5}{T} \left( \Gamma_{bc}^a \overset{4}{y}^b \overset{4}{y}^c \right) + \frac{1}{3!} \overset{5}{T} \left( \Gamma_{bcd}^a \overset{3}{y}^b \overset{3}{y}^c \overset{3}{y}^d \right) + \frac{1}{4!} \overset{5}{T} \left( \Gamma_{bcde}^a \overset{2}{y}^b \overset{2}{y}^c \overset{2}{y}^d \overset{2}{y}^e \right) + \frac{1}{5!} \overset{5}{T} \left( \Gamma_{bcdef}^a \overset{0}{y}^b \overset{0}{y}^c \overset{0}{y}^d \overset{0}{y}^e \overset{0}{y}^f \right) \end{aligned}$$

and so on. Note that there are no  $\overset{1}{y}^a$  terms.

## Stage 2: Introduce the generalised connections

This is the final stage – it introduces the generalised connection after the completion of the fixed point scheme.

All that needs be done is to substitute our expression for  $y^a$  into (2) to obtain the desired solution to the two point boundary value problem.

The generalised connections  $\Gamma_{b_k}^a$  are taken from the results of the `genGamma` code.

# Stage 1: The fixed point iteration scheme

```

import time

{a,b,c,d,e,f,g,h,i,j,k,l,m,n,o,p,q,r,s,t,u,v,w#}::Indices(position=independent).

\nabla{#}::Derivative.

g_{a b}::Metric.
g^{a b}::InverseMetric.

R_{a b c d}::RiemannTensor.
R_{a b c d}::Depends(\nabla{#}).

{Gam22^{a}_{b c},Gam23^{a}_{b c},Gam24^{a}_{b c},Gam25^{a}_{b c}}::TableauSymmetry(shape={2}, indices={1,2}).
{Gam33^{a}_{b c d},Gam34^{a}_{b c d},Gam35^{a}_{b c d}}::TableauSymmetry(shape={3}, indices={1,2,3}).
{Gam44^{a}_{b c d e},Gam45^{a}_{b c d e}}::TableauSymmetry(shape={4}, indices={1,2,3,4}).
{Gam55^{a}_{b c d e f}}::TableauSymmetry(shape={5}, indices={1,2,3,4,5}).

{Gam22^{a}_{b c}}::Weight(label=eps,value=2).
{Gam23^{a}_{b c},Gam33^{a}_{b c d}}::Weight(label=eps,value=3).
{Gam24^{a}_{b c},Gam34^{a}_{b c d},Gam44^{a}_{b c d e}}::Weight(label=eps,value=4).
{Gam25^{a}_{b c},Gam35^{a}_{b c d},Gam45^{a}_{b c d e},Gam55^{a}_{b c d e f}}::Weight(label=eps,value=5).

{Dx^{a}}::Weight(label=eps,value=0).

{y00^{a},y20^{a},y30^{a},y40^{a},y50^{a}}::Weight(label=eps,value=0).
{y22^{a},y32^{a},y42^{a},y52^{a}}::Weight(label=eps,value=2).
{y33^{a},y43^{a},y53^{a}}::Weight(label=eps,value=3).
{y44^{a},y54^{a}}::Weight(label=eps,value=4).
{y55^{a}}::Weight(label=eps,value=5).

# Dx{#}::LaTeXForm("{\Dx}"). # LCB: currently causes a bug, it kills ::KeepWeight for Dx

# note: keeping numbering as is (out of order) to ensure R appears before \nabla R etc.
def product_sort (obj):
    substitute (obj,$ x^{a}          -> A001^{a}          $)
    substitute (obj,$ Dx^{a}         -> A002^{a}          $)

```

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substitute (obj,$ g^{a b}                -> A003^{a b}                $)
substitute (obj,$ \nabla_{e f g h}\{R_{a b c d}\} -> A008_{a b c d e f g h} $)
substitute (obj,$ \nabla_{e f g}\{R_{a b c d}\}    -> A007_{a b c d e f g}    $)
substitute (obj,$ \nabla_{e f}\{R_{a b c d}\}      -> A006_{a b c d e f}      $)
substitute (obj,$ \nabla_{e}\{R_{a b c d}\}        -> A005_{a b c d e}        $)
substitute (obj,$ R_{a b c d}                -> A004_{a b c d}                $)
sort_product (obj)
rename_dummies (obj)
substitute (obj,$ A001^{a}                  -> x^{a}                  $)
substitute (obj,$ A002^{a}                  -> Dx^{a}                  $)
substitute (obj,$ A003^{a b}                -> g^{a b}                $)
substitute (obj,$ A004_{a b c d}            -> R_{a b c d}            $)
substitute (obj,$ A005_{a b c d e}          -> \nabla_{e}\{R_{a b c d}\} $)
substitute (obj,$ A006_{a b c d e f}        -> \nabla_{e f}\{R_{a b c d}\} $)
substitute (obj,$ A007_{a b c d e f g}      -> \nabla_{e f g}\{R_{a b c d}\} $)
substitute (obj,$ A008_{a b c d e f g h}    -> \nabla_{e f g h}\{R_{a b c d}\} $)

```

```

return obj

```

```

def get_term (obj,n):

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    tmp := @(obj).
    foo = Ex("eps = " + str(n))
    distribute (tmp)
    keep_weight (tmp, foo)

```

```

    return tmp

```

```

def truncate (obj,n):

```

```

    ans = Ex(0)

```

```

    for i in range (0,n+1):
        foo := @(obj).
        bah = Ex("eps = " + str(i))
        distribute (foo)
        keep_weight (foo, bah)
        ans = ans + foo

```

```

return ans

def substitute_eps (obj):
    substitute (obj, epsy0)
    substitute (obj, epsy2)
    substitute (obj, epsy3)
    substitute (obj, epsy4)
    substitute (obj, epsy5)
    substitute (obj, epsGam2)
    substitute (obj, epsGam3)
    substitute (obj, epsGam4)
    substitute (obj, epsGam5)
    distribute (obj)
    obj = truncate (obj, 5)
    obj = product_sort (obj)
    rename_dummies (obj)
    canonicalise (obj)

    return obj

beg_stage_1 = time.time()

# yn = y expanded to terms upto and including O(eps^n)

y0 := Dx^{a}.
y2 := Dx^{a} + (1/2) Gam^{a}_{b c} y0^{b} y0^{c}.
y3 := Dx^{a} + (1/2) Gam^{a}_{b c} y2^{b} y2^{c}
      + (1/6) Gam^{a}_{b c d} y0^{b} y0^{c} y0^{d}.
y4 := Dx^{a} + (1/2) Gam^{a}_{b c} y3^{b} y3^{c}
      + (1/6) Gam^{a}_{b c d} y2^{b} y2^{c} y2^{d}
      + (1/24) Gam^{a}_{b c d e} y0^{b} y0^{c} y0^{d} y0^{e}.
y5 := Dx^{a} + (1/2) Gam^{a}_{b c} y4^{b} y4^{c}
      + (1/6) Gam^{a}_{b c d} y3^{b} y3^{c} y3^{d}
      + (1/24) Gam^{a}_{b c d e} y2^{b} y2^{c} y2^{d} y2^{e}
      + (1/120) Gam^{a}_{b c d e f} y0^{b} y0^{c} y0^{d} y0^{e} y0^{f}.

# epsyN = y expanded to terms upto and including O(eps^N)

```

```

# yPQ = O(eps^Q) term of epsyP

# expand to O(eps^5)

epsy0 := y0^{a} -> y00^{a}.
epsy2 := y2^{a} -> y20^{a}+y22^{a}.
epsy3 := y3^{a} -> y30^{a}+y32^{a}+y33^{a}.
epsy4 := y4^{a} -> y40^{a}+y42^{a}+y43^{a}+y44^{a}.
epsy5 := y5^{a} -> y50^{a}+y52^{a}+y53^{a}+y54^{a}+y55^{a}.

# epsGamN = gen. gamma with N lower indices (epsGam2 = the connection)
# epsGamPQ = O(eps^Q) term of epsGamP

epsGam2 := Gam^{a}_{b c} -> Gam22^{a}_{b c}+Gam23^{a}_{b c}+Gam24^{a}_{b c}+Gam25^{a}_{b c}.
epsGam3 := Gam^{a}_{b c d} -> Gam33^{a}_{b c d}+Gam34^{a}_{b c d}+Gam35^{a}_{b c d}.
epsGam4 := Gam^{a}_{b c d e} -> Gam44^{a}_{b c d e}+Gam45^{a}_{b c d e}.
epsGam5 := Gam^{a}_{b c d e f} -> Gam55^{a}_{b c d e f}.

y0 = substitute_eps (y0)    # cdb (y0.001,y0)
y2 = substitute_eps (y2)    # cdb (y2.001,y2)
y3 = substitute_eps (y3)    # cdb (y3.001,y3)
y4 = substitute_eps (y4)    # cdb (y4.001,y4)
y5 = substitute_eps (y5)    # cdb (y5.001,y5)

y0 = truncate (y0,1)        # cdb (y0.002,y0)
y2 = truncate (y2,2)        # cdb (y2.002,y2)
y3 = truncate (y3,3)        # cdb (y3.002,y3)
y4 = truncate (y4,4)        # cdb (y4.002,y4)
y5 = truncate (y5,5)        # cdb (y5.002,y5)

defy0 := y0^{a} -> @(y0).
defy2 := y2^{a} -> @(y2).
defy3 := y3^{a} -> @(y3).
defy4 := y4^{a} -> @(y4).
defy5 := y5^{a} -> @(y5).

# -----
def tidy (obj):

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```

    obj = product_sort (obj)
    rename_dummies      (obj)
    canonicalise        (obj)
    return obj

# -----
# y0

y00 := @(y0).          # cdb (y00.101,y00)

defy00 := y00^{a} -> @(y00).

# -----
# y2

substitute (y2,defy00)

distribute (y2)

y20 = get_term (y2,0)   # cdb (y20.101,y20)
y22 = get_term (y2,2)   # cdb (y22.101,y22)

y20 = tidy (y20)        # cdb (y20.201,y20)
y22 = tidy (y22)        # cdb (y22.201,y22)

defy20 := y20^{a} -> @(y20).
defy22 := y22^{a} -> @(y22).

# -----
# y3

substitute (y3,defy00)

substitute (y3,defy20)
substitute (y3,defy22)

distribute (y3)

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```

y30 = get_term (y3,0)    # cdb (y30.101,y30)
y32 = get_term (y3,2)    # cdb (y32.101,y32)
y33 = get_term (y3,3)    # cdb (y33.101,y33)

y30 = tidy (y30)         # cdb (y30.201,y30)
y32 = tidy (y32)         # cdb (y32.201,y32)
y33 = tidy (y33)         # cdb (y33.201,y33)

defy30 := y30^{a} -> @(y30).
defy32 := y32^{a} -> @(y32).
defy33 := y33^{a} -> @(y33).

# -----
# y4

substitute (y4,defy00)

substitute (y4,defy20)
substitute (y4,defy22)

substitute (y4,defy30)
substitute (y4,defy32)
substitute (y4,defy33)

distribute (y4)

y40 = get_term (y4,0)    # cdb (y40.101,y40)
y42 = get_term (y4,2)    # cdb (y42.101,y42)
y43 = get_term (y4,3)    # cdb (y43.101,y43)
y44 = get_term (y4,4)    # cdb (y44.101,y44)

y40 = tidy (y40)         # cdb (y40.201,y40)
y42 = tidy (y42)         # cdb (y42.201,y42)
y43 = tidy (y43)         # cdb (y43.201,y43)
y44 = tidy (y44)         # cdb (y44.201,y44)

defy40 := y40^{a} -> @(y40).
defy42 := y42^{a} -> @(y42).

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defy43 := y43^{a} -> @(y43).
defy44 := y44^{a} -> @(y44).

# -----
# y5

substitute (y5,defy00)

substitute (y5,defy20)
substitute (y5,defy22)

substitute (y5,defy30)
substitute (y5,defy32)
substitute (y5,defy33)

substitute (y5,defy40)
substitute (y5,defy42)
substitute (y5,defy43)
substitute (y5,defy44)

distribute (y5)

y50 = get_term (y5,0)   # cdb (y50.101,y50)
y52 = get_term (y5,2)   # cdb (y52.101,y52)
y53 = get_term (y5,3)   # cdb (y53.101,y53)
y54 = get_term (y5,4)   # cdb (y54.101,y54)
y55 = get_term (y5,5)   # cdb (y55.101,y55)

y50 = tidy (y50)        # cdb (y50.201,y50)
y52 = tidy (y52)        # cdb (y52.201,y52)
y53 = tidy (y53)        # cdb (y53.201,y53)
y54 = tidy (y54)        # cdb (y54.201,y54)
y55 = tidy (y55)        # cdb (y55.201,y55)

defy50 := y50^{a} -> @(y50).
defy52 := y52^{a} -> @(y52).
defy53 := y53^{a} -> @(y53).
defy54 := y54^{a} -> @(y54).

```

```
defy55 := y55^{a} -> @(y55).
```

```
end_stage_1 = time.time()
```

$$y0.001 := Dx^a$$

$$y2.001 := Dx^a + \frac{1}{2} Gam_{22}^a{}_{bc} y_{00}^b y_{00}^c + \frac{1}{2} Gam_{23}^a{}_{bc} y_{00}^b y_{00}^c + \frac{1}{2} Gam_{24}^a{}_{bc} y_{00}^b y_{00}^c + \frac{1}{2} Gam_{25}^a{}_{bc} y_{00}^b y_{00}^c$$

$$y3.001 := Dx^a + \frac{1}{2} Gam_{22}^a{}_{bc} y_{20}^b y_{20}^c + \frac{1}{2} Gam_{23}^a{}_{bc} y_{20}^b y_{20}^c + \frac{1}{6} Gam_{33}^a{}_{bcd} y_{00}^b y_{00}^c y_{00}^d + Gam_{22}^a{}_{bc} y_{20}^b y_{22}^c + \frac{1}{2} Gam_{24}^a{}_{bc} y_{20}^b y_{20}^c \\ + \frac{1}{6} Gam_{34}^a{}_{bcd} y_{00}^b y_{00}^c y_{00}^d + Gam_{23}^a{}_{bc} y_{20}^b y_{22}^c + \frac{1}{2} Gam_{25}^a{}_{bc} y_{20}^b y_{20}^c + \frac{1}{6} Gam_{35}^a{}_{bcd} y_{00}^b y_{00}^c y_{00}^d$$

$$y4.001 := Dx^a + \frac{1}{2} Gam_{22}^a{}_{bc} y_{30}^b y_{30}^c + \frac{1}{2} Gam_{23}^a{}_{bc} y_{30}^b y_{30}^c + \frac{1}{6} Gam_{33}^a{}_{bcd} y_{20}^b y_{20}^c y_{20}^d + Gam_{22}^a{}_{bc} y_{30}^b y_{32}^c + \frac{1}{2} Gam_{24}^a{}_{bc} y_{30}^b y_{30}^c \\ + \frac{1}{6} Gam_{34}^a{}_{bcd} y_{20}^b y_{20}^c y_{20}^d + \frac{1}{24} Gam_{44}^a{}_{bcde} y_{00}^b y_{00}^c y_{00}^d y_{00}^e + Gam_{22}^a{}_{bc} y_{30}^b y_{33}^c + Gam_{23}^a{}_{bc} y_{30}^b y_{32}^c \\ + \frac{1}{2} Gam_{25}^a{}_{bc} y_{30}^b y_{30}^c + \frac{1}{2} Gam_{33}^a{}_{bcd} y_{20}^b y_{20}^c y_{22}^d + \frac{1}{6} Gam_{35}^a{}_{bcd} y_{20}^b y_{20}^c y_{20}^d + \frac{1}{24} Gam_{45}^a{}_{bcde} y_{00}^b y_{00}^c y_{00}^d y_{00}^e$$

$$y5.001 := Dx^a + \frac{1}{2} Gam_{22}^a{}_{bc} y_{40}^b y_{40}^c + \frac{1}{2} Gam_{23}^a{}_{bc} y_{40}^b y_{40}^c + \frac{1}{6} Gam_{33}^a{}_{bcd} y_{30}^b y_{30}^c y_{30}^d + Gam_{22}^a{}_{bc} y_{40}^b y_{42}^c + \frac{1}{2} Gam_{24}^a{}_{bc} y_{40}^b y_{40}^c \\ + \frac{1}{6} Gam_{34}^a{}_{bcd} y_{30}^b y_{30}^c y_{30}^d + \frac{1}{24} Gam_{44}^a{}_{bcde} y_{20}^b y_{20}^c y_{20}^d y_{20}^e + Gam_{22}^a{}_{bc} y_{40}^b y_{43}^c + Gam_{23}^a{}_{bc} y_{40}^b y_{42}^c + \frac{1}{2} Gam_{25}^a{}_{bc} y_{40}^b y_{40}^c \\ + \frac{1}{2} Gam_{33}^a{}_{bcd} y_{30}^b y_{30}^c y_{32}^d + \frac{1}{6} Gam_{35}^a{}_{bcd} y_{30}^b y_{30}^c y_{30}^d + \frac{1}{24} Gam_{45}^a{}_{bcde} y_{20}^b y_{20}^c y_{20}^d y_{20}^e + \frac{1}{120} Gam_{55}^a{}_{bcdef} y_{00}^b y_{00}^c y_{00}^d y_{00}^e y_{00}^f$$

$$y0.002 := Dx^a$$

$$y2.002 := Dx^a + \frac{1}{2} Gam_{22}^a{}_{bc} y_{00}^b y_{00}^c$$

$$y3.002 := Dx^a + \frac{1}{2} Gam_{22}^a{}_{bc} y_{20}^b y_{20}^c + \frac{1}{2} Gam_{23}^a{}_{bc} y_{20}^b y_{20}^c + \frac{1}{6} Gam_{33}^a{}_{bcd} y_{00}^b y_{00}^c y_{00}^d$$

$$y4.002 := Dx^a + \frac{1}{2} Gam_{22}^a{}_{bc} y_{30}^b y_{30}^c + \frac{1}{2} Gam_{23}^a{}_{bc} y_{30}^b y_{30}^c + \frac{1}{6} Gam_{33}^a{}_{bcd} y_{20}^b y_{20}^c y_{20}^d + Gam_{22}^a{}_{bc} y_{30}^b y_{32}^c \\ + \frac{1}{2} Gam_{24}^a{}_{bc} y_{30}^b y_{30}^c + \frac{1}{6} Gam_{34}^a{}_{bcd} y_{20}^b y_{20}^c y_{20}^d + \frac{1}{24} Gam_{44}^a{}_{bcde} y_{00}^b y_{00}^c y_{00}^d y_{00}^e$$

$$y5.002 := Dx^a + \frac{1}{2} Gam_{22}^a{}_{bc} y_{40}^b y_{40}^c + \frac{1}{2} Gam_{23}^a{}_{bc} y_{40}^b y_{40}^c + \frac{1}{6} Gam_{33}^a{}_{bcd} y_{30}^b y_{30}^c y_{30}^d + Gam_{22}^a{}_{bc} y_{40}^b y_{42}^c + \frac{1}{2} Gam_{24}^a{}_{bc} y_{40}^b y_{40}^c \\ + \frac{1}{6} Gam_{34}^a{}_{bcd} y_{30}^b y_{30}^c y_{30}^d + \frac{1}{24} Gam_{44}^a{}_{bcde} y_{20}^b y_{20}^c y_{20}^d y_{20}^e + Gam_{22}^a{}_{bc} y_{40}^b y_{43}^c + Gam_{23}^a{}_{bc} y_{40}^b y_{42}^c + \frac{1}{2} Gam_{25}^a{}_{bc} y_{40}^b y_{40}^c \\ + \frac{1}{2} Gam_{33}^a{}_{bcd} y_{30}^b y_{30}^c y_{32}^d + \frac{1}{6} Gam_{35}^a{}_{bcd} y_{30}^b y_{30}^c y_{30}^d + \frac{1}{24} Gam_{45}^a{}_{bcde} y_{20}^b y_{20}^c y_{20}^d y_{20}^e + \frac{1}{120} Gam_{55}^a{}_{bcdef} y_{00}^b y_{00}^c y_{00}^d y_{00}^e y_{00}^f$$

$$y00.101 := Dx^a$$

$$y20.201 := Dx^a$$

$$y22.201 := \frac{1}{2} Dx^b Dx^c Gam_{22}^a{}_{bc}$$

$$y30.201 := Dx^a$$

$$y32.201 := \frac{1}{2} Dx^b Dx^c Gam_{22}^a{}_{bc}$$

$$y33.201 := \frac{1}{2} Dx^b Dx^c Gam_{23}^a{}_{bc} + \frac{1}{6} Dx^b Dx^c Dx^d Gam_{33}^a{}_{bcd}$$

$$y40.201 := Dx^a$$

$$y42.201 := \frac{1}{2} Dx^b Dx^c Gam_{22}^a{}_{bc}$$

$$y43.201 := \frac{1}{2} Dx^b Dx^c Gam_{23}^a{}_{bc} + \frac{1}{6} Dx^b Dx^c Dx^d Gam_{33}^a{}_{bcd}$$

$$y44.201 := \frac{1}{2} Dx^b Dx^c Dx^d Gam_{22}^a{}_{be} Gam_{22}^e{}_{cd} + \frac{1}{2} Dx^b Dx^c Gam_{24}^a{}_{bc} + \frac{1}{6} Dx^b Dx^c Dx^d Gam_{34}^a{}_{bcd} + \frac{1}{24} Dx^b Dx^c Dx^d Dx^e Gam_{44}^a{}_{bcde}$$

$$y50.201 := Dx^a$$

$$y52.201 := \frac{1}{2} Dx^b Dx^c Gam_{22}^a{}_{bc}$$

$$y53.201 := \frac{1}{2} Dx^b Dx^c Gam_{23}^a{}_{bc} + \frac{1}{6} Dx^b Dx^c Dx^d Gam_{33}^a{}_{bcd}$$

$$y54.201 := \frac{1}{2} Dx^b Dx^c Dx^d Gam_{22}^a{}_{be} Gam_{22}^e{}_{cd} + \frac{1}{2} Dx^b Dx^c Gam_{24}^a{}_{bc} + \frac{1}{6} Dx^b Dx^c Dx^d Gam_{34}^a{}_{bcd} + \frac{1}{24} Dx^b Dx^c Dx^d Dx^e Gam_{44}^a{}_{bcde}$$

$$\begin{aligned} y55.201 := & \frac{1}{2} Dx^b Dx^c Dx^d Gam_{22}^a{}_{be} Gam_{23}^e{}_{cd} + \frac{1}{6} Dx^b Dx^c Dx^d Dx^e Gam_{22}^a{}_{bf} Gam_{33}^f{}_{cde} + \frac{1}{2} Dx^b Dx^c Dx^d Gam_{22}^e{}_{bc} Gam_{23}^a{}_{de} \\ & + \frac{1}{2} Dx^b Dx^c Gam_{25}^a{}_{bc} + \frac{1}{4} Dx^b Dx^c Dx^d Dx^e Gam_{22}^f{}_{bc} Gam_{33}^a{}_{def} + \frac{1}{6} Dx^b Dx^c Dx^d Gam_{35}^a{}_{bcd} \\ & + \frac{1}{24} Dx^b Dx^c Dx^d Dx^e Gam_{45}^a{}_{bcde} + \frac{1}{120} Dx^b Dx^c Dx^d Dx^e Dx^f Gam_{55}^a{}_{bcdef} \end{aligned}$$

## Stage 2a: Introduce the generalised connections, build terms of $y^a$

```
def substitute_gam (obj):

    substitute (obj,defGam22)
    substitute (obj,defGam23)
    substitute (obj,defGam24)
    substitute (obj,defGam25)

    substitute (obj,defGam33)
    substitute (obj,defGam34)
    substitute (obj,defGam35)

    substitute (obj,defGam44)
    substitute (obj,defGam45)

    substitute (obj,defGam55)

    distribute (obj)
    return obj

import cdblib

beg_stage_2a = time.time()

Gam22 = cdblib.get ('genGamma01','genGamma.json')
Gam23 = cdblib.get ('genGamma02','genGamma.json')
Gam24 = cdblib.get ('genGamma03','genGamma.json')
Gam25 = cdblib.get ('genGamma04','genGamma.json')

Gam33 = cdblib.get ('genGamma11','genGamma.json')
Gam34 = cdblib.get ('genGamma12','genGamma.json')
Gam35 = cdblib.get ('genGamma13','genGamma.json')

Gam44 = cdblib.get ('genGamma21','genGamma.json')
Gam45 = cdblib.get ('genGamma22','genGamma.json')

Gam55 = cdblib.get ('genGamma31','genGamma.json')
```

```

# peel off the A^{a}, must then symmetrise over revealed indices

substitute (Gam22,$A^{a}->1$)
substitute (Gam23,$A^{a}->1$)
substitute (Gam24,$A^{a}->1$)
substitute (Gam25,$A^{a}->1$)

substitute (Gam33,$A^{a}->1$)
substitute (Gam34,$A^{a}->1$)
substitute (Gam35,$A^{a}->1$)

substitute (Gam44,$A^{a}->1$)
substitute (Gam45,$A^{a}->1$)

substitute (Gam55,$A^{a}->1$)

# now symmetrise

sym (Gam22,$_{b},_{c}$)
sym (Gam23,$_{b},_{c}$)
sym (Gam24,$_{b},_{c}$)
sym (Gam25,$_{b},_{c}$)

sym (Gam33,$_{b},_{c},_{d}$)
sym (Gam34,$_{b},_{c},_{d}$)
sym (Gam35,$_{b},_{c},_{d}$)

sym (Gam44,$_{b},_{c},_{d},_{e}$)
sym (Gam45,$_{b},_{c},_{d},_{e}$)

sym (Gam55,$_{b},_{c},_{d},_{e},_{f}$)

defGam22 := Gam22^{a}_{b c} -> @(Gam22).
defGam23 := Gam23^{a}_{b c} -> @(Gam23).
defGam24 := Gam24^{a}_{b c} -> @(Gam24).
defGam25 := Gam25^{a}_{b c} -> @(Gam25).

```



```

defGam33 := Gam33^{a}_{b c d} -> @(Gam33).
defGam34 := Gam34^{a}_{b c d} -> @(Gam34).
defGam35 := Gam35^{a}_{b c d} -> @(Gam35).

defGam44 := Gam44^{a}_{b c d e} -> @(Gam44).
defGam45 := Gam45^{a}_{b c d e} -> @(Gam45).

defGam55 := Gam55^{a}_{b c d e f} -> @(Gam55).

# -----
# y2

y22 = substitute_gam (y22)

y22 = tidy (y22) # cdb (y22.301,y22)

y2 := @(y20) + @(y22). # cdb (y2.301,y2)

# -----
# y3

y32 = substitute_gam (y32)
y33 = substitute_gam (y33)

y32 = tidy (y32) # cdb (y32.301,y32)
y33 = tidy (y33) # cdb (y33.301,y33)

y3 := @(y30) + @(y32) + @(y33). # cdb (y3.301,y3)

# -----
# y4

y42 = substitute_gam (y42)
y43 = substitute_gam (y43)
y44 = substitute_gam (y44)

y42 = tidy (y42) # cdb (y42.301,y42)
y43 = tidy (y43) # cdb (y43.301,y43)

```

```

y44 = tidy (y44) # cdb (y44.301,y44)

y4 := @(y40) + @(y42) + @(y43) + @(y44). # cdb (y4.301,y4)

# -----
# y5

y52 = substitute_gam (y52)
y53 = substitute_gam (y53)
y54 = substitute_gam (y54)
y55 = substitute_gam (y55)

y52 = tidy (y52) # cdb (y52.301,y52)
y53 = tidy (y53) # cdb (y53.301,y53)
y54 = tidy (y54) # cdb (y54.301,y54)
y55 = tidy (y55) # cdb (y55.301,y55)

y5 := @(y50) + @(y52) + @(y53) + @(y54) + @(y55). # cdb (y5.301,y5)

# -----
cdblib.create ('geodesic-bvp.json')

cdblib.put ('y2',y2,'geodesic-bvp.json')
cdblib.put ('y3',y3,'geodesic-bvp.json')
cdblib.put ('y4',y4,'geodesic-bvp.json')
cdblib.put ('y5',y5,'geodesic-bvp.json')

cdblib.put ('y20',y20,'geodesic-bvp.json')
cdblib.put ('y22',y22,'geodesic-bvp.json')

cdblib.put ('y30',y30,'geodesic-bvp.json')
cdblib.put ('y32',y32,'geodesic-bvp.json')
cdblib.put ('y33',y33,'geodesic-bvp.json')

cdblib.put ('y40',y40,'geodesic-bvp.json')
cdblib.put ('y42',y42,'geodesic-bvp.json')
cdblib.put ('y43',y43,'geodesic-bvp.json')
cdblib.put ('y44',y44,'geodesic-bvp.json')

```

```
cdblib.put ('y50',y50,'geodesic-bvp.json')
cdblib.put ('y52',y52,'geodesic-bvp.json')
cdblib.put ('y53',y53,'geodesic-bvp.json')
cdblib.put ('y54',y54,'geodesic-bvp.json')
cdblib.put ('y55',y55,'geodesic-bvp.json')

end_stage_2a = time.time()
```

$$\text{y50.301} := Dx^a$$

$$\text{y52.301} := -\frac{1}{3}x^bDx^cDx^dg^{ae}R_{bcde}$$

$$\text{y53.301} := -\frac{1}{12}x^bx^cDx^dDx^eg^{af}\nabla_dR_{becf} - \frac{1}{6}x^bx^cDx^dDx^eg^{af}\nabla_bR_{cdef} + \frac{1}{24}x^bx^cDx^dDx^eg^{af}\nabla_fR_{bdce} - \frac{1}{12}x^bDx^cDx^dDx^eg^{af}\nabla_dR_{bdef}$$

$$\begin{aligned} \text{y54.301} := & -\frac{2}{45}x^bx^cDx^dDx^eDx^fg^{ag}g^{hi}R_{bdeh}R_{cfgi} + \frac{1}{45}x^bx^cDx^dDx^eDx^fg^{ag}g^{hi}R_{bdeh}R_{cifg} - \frac{4}{45}x^bx^cx^dDx^eDx^fg^{ag}g^{hi}R_{befh}R_{cgdi} \\ & + \frac{2}{45}x^bx^cx^dDx^eDx^fg^{ag}g^{hi}R_{bech}R_{difg} + \frac{1}{45}x^bx^cx^dDx^eDx^fg^{ag}g^{hi}R_{bech}R_{dgfi} - \frac{1}{40}x^bx^cx^dDx^eDx^fg^{ag}\nabla_{eb}R_{cfdg} \\ & - \frac{1}{40}x^bx^cx^dDx^eDx^fg^{ag}\nabla_{be}R_{cfdg} - \frac{1}{20}x^bx^cx^dDx^eDx^fg^{ag}\nabla_{bc}R_{defg} - \frac{1}{45}x^bx^cx^dDx^eDx^fg^{ag}g^{hi}R_{bech}R_{dfgi} \\ & + \frac{1}{80}x^bx^cx^dDx^eDx^fg^{ag}\nabla_{gb}R_{cedf} + \frac{1}{80}x^bx^cx^dDx^eDx^fg^{ag}\nabla_{bg}R_{cedf} - \frac{1}{45}x^bx^cDx^dDx^eDx^fg^{ag}g^{hi}R_{bdeh}R_{cgfi} \\ & + \frac{1}{45}x^bx^cDx^dDx^eDx^fg^{ag}g^{hi}R_{bdch}R_{egfi} - \frac{1}{60}x^bx^cDx^dDx^eDx^fg^{ag}\nabla_{de}R_{bfcg} - \frac{1}{40}x^bx^cDx^dDx^eDx^fg^{ag}\nabla_{db}R_{cefg} \\ & - \frac{1}{40}x^bx^cDx^dDx^eDx^fg^{ag}\nabla_{bd}R_{cefg} + \frac{1}{240}x^bx^cDx^dDx^eDx^fg^{ag}\nabla_{gd}R_{becf} + \frac{1}{240}x^bx^cDx^dDx^eDx^fg^{ag}\nabla_{dg}R_{becf} \\ & - \frac{1}{45}x^bDx^cDx^dDx^eDx^fg^{ag}g^{hi}R_{bcdh}R_{egfi} - \frac{1}{60}x^bDx^cDx^dDx^eDx^fg^{ag}\nabla_{cd}R_{befg} \end{aligned}$$

$$\begin{aligned}
\text{y55.301} := & -\frac{7}{540} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{behi} \nabla_f R_{cgdj} - \frac{1}{45} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{behi} \nabla_e R_{dfgj} \\
& + \frac{1}{216} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{behi} \nabla_j R_{cf dg} + \frac{1}{90} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bieh} \nabla_f R_{cgdj} + \frac{1}{90} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bieh} \nabla_e R_{dfgj} \\
& - \frac{17}{1080} x^b x^c D x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bdhi} \nabla_e R_{cf gj} + \frac{1}{135} x^b x^c D x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bidh} \nabla_e R_{cf gj} \\
& - \frac{1}{540} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{befi} \nabla_g R_{chdj} + \frac{1}{108} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{befi} \nabla_j R_{cgdh} \\
& - \frac{1}{45} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{befi} \nabla_e R_{dghj} + \frac{1}{90} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{befi} \nabla_e R_{djgh} - \frac{7}{540} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{befi} \nabla_h R_{cgdj} \\
& - \frac{2}{45} x^b x^c x^d x^e D x^f D x^g g^{ah} g^{ij} R_{bfgi} \nabla_e R_{dhej} - \frac{1}{60} x^b x^c x^d x^e D x^f D x^g g^{ah} g^{ij} R_{bhci} \nabla_f R_{dgej} - \frac{2}{45} x^b x^c x^d x^e D x^f D x^g g^{ah} g^{ij} R_{bhci} \nabla_d R_{efgj} \\
& + \frac{1}{72} x^b x^c x^d x^e D x^f D x^g g^{ah} g^{ij} R_{bhci} \nabla_j R_{dfeg} + \frac{1}{45} x^b x^c x^d x^e D x^f D x^g g^{ah} g^{ij} R_{bifh} \nabla_e R_{dgej} + \frac{1}{90} x^b x^c x^d x^e D x^f D x^g g^{ah} g^{ij} R_{bhf i} \nabla_e R_{dgej} \\
& + \frac{1}{90} x^b x^c x^d x^e D x^f D x^g g^{ah} g^{ij} R_{bfci} \nabla_g R_{dhej} + \frac{1}{45} x^b x^c x^d x^e D x^f D x^g g^{ah} g^{ij} R_{bfci} \nabla_d R_{ejgh} + \frac{1}{90} x^b x^c x^d x^e D x^f D x^g g^{ah} g^{ij} R_{bfci} \nabla_d R_{ehgj} \\
& - \frac{1}{180} x^b x^c x^d x^e D x^f D x^g g^{ah} \nabla_{fbc} R_{dgeh} - \frac{1}{180} x^b x^c x^d x^e D x^f D x^g g^{ah} \nabla_{bfc} R_{dgeh} - \frac{1}{180} x^b x^c x^d x^e D x^f D x^g g^{ah} \nabla_{bcf} R_{dgeh} \\
& - \frac{1}{90} x^b x^c x^d x^e D x^f D x^g g^{ah} \nabla_{bcd} R_{efgh} - \frac{1}{90} x^b x^c x^d x^e D x^f D x^g g^{ah} g^{ij} R_{bfhi} \nabla_e R_{dgej} - \frac{1}{90} x^b x^c x^d x^e D x^f D x^g g^{ah} g^{ij} R_{bfci} \nabla_h R_{dgej} \\
& - \frac{1}{90} x^b x^c x^d x^e D x^f D x^g g^{ah} g^{ij} R_{bfci} \nabla_d R_{eghj} + \frac{1}{360} x^b x^c x^d x^e D x^f D x^g g^{ah} \nabla_{hbc} R_{dfeg} + \frac{1}{360} x^b x^c x^d x^e D x^f D x^g g^{ah} \nabla_{bhc} R_{dfeg} \\
& + \frac{1}{360} x^b x^c x^d x^e D x^f D x^g g^{ah} \nabla_{bch} R_{dfeg} - \frac{7}{1080} x^b x^c D x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bdei} \nabla_f R_{cghj} - \frac{1}{540} x^b x^c D x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bdei} \nabla_f R_{cjgh} \\
& + \frac{1}{108} x^b x^c D x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bdei} \nabla_j R_{cfgh} - \frac{1}{90} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{befi} \nabla_e R_{dhgj} \\
& - \frac{1}{540} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bhei} \nabla_f R_{cgdj} - \frac{11}{540} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bhci} \nabla_e R_{dfgj} - \frac{1}{90} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bhei} \nabla_e R_{dfgj} \\
& + \frac{1}{216} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bhei} \nabla_j R_{cf dg} + \frac{1}{90} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{ehfi} \nabla_b R_{cgdj} + \frac{1}{90} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{beci} \nabla_f R_{djgh} \\
& + \frac{1}{135} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{beci} \nabla_f R_{dhgj} + \frac{1}{90} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{beci} \nabla_d R_{fhgj} - \frac{1}{270} x^b x^c x^d D x^e D x^f D x^g g^{ah} \nabla_{efb} R_{cgdh} \\
& - \frac{1}{270} x^b x^c x^d D x^e D x^f D x^g g^{ah} \nabla_{ebf} R_{cgdh} - \frac{1}{180} x^b x^c x^d D x^e D x^f D x^g g^{ah} \nabla_{ebc} R_{dfgh} - \frac{1}{270} x^b x^c x^d D x^e D x^f D x^g g^{ah} \nabla_{bef} R_{cgdh} \\
& - \frac{1}{180} x^b x^c x^d D x^e D x^f D x^g g^{ah} \nabla_{bec} R_{dfgh} - \frac{1}{180} x^b x^c x^d D x^e D x^f D x^g g^{ah} \nabla_{bce} R_{dfgh} - \frac{1}{270} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{beci} \nabla_h R_{dfgj} \\
& - \frac{1}{270} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{beci} \nabla_f R_{dghj} + \frac{1}{1080} x^b x^c x^d D x^e D x^f D x^g g^{ah} \nabla_{heb} R_{cf dg} + \frac{1}{1080} x^b x^c x^d D x^e D x^f D x^g g^{ah} \nabla_{hbe} R_{cf dg} \\
& + \frac{1}{1080} x^b x^c x^d D x^e D x^f D x^g g^{ah} \nabla_{ehb} R_{cf dg} + \frac{1}{1080} x^b x^c x^d D x^e D x^f D x^g g^{ah} \nabla_{bhe} R_{cf dg} + \frac{1}{1080} x^b x^c x^d D x^e D x^f D x^g g^{ah} \nabla_{ebh} R_{cf dg} \\
& + \frac{1}{1080} x^b x^c x^d D x^e D x^f D x^g g^{ah} \nabla_{beh} R_{cf dg} - \frac{1}{120} x^b x^c D x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bdei} \nabla_f R_{chgj} - \frac{1}{90} x^b x^c D x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bdei} \nabla_e R_{fhgj}
\end{aligned}$$

## Stage 2b: Building the terms of $x^a(s)$

```
def substitute_y (obj):
    substitute (obj,defy00)
    substitute (obj,defy20)
    substitute (obj,defy30)
    substitute (obj,defy32)
    substitute (obj,defy40)
    substitute (obj,defy42)
    substitute (obj,defy43)
    distribute (obj)
    return obj

beg_stage_2b = time.time()

term2 := Gam^{a}_{b c} y4^{b} y4^{c}.
term3 := Gam^{a}_{b c d} y3^{b} y3^{c} y3^{d}.
term4 := Gam^{a}_{b c d e} y2^{b} y2^{c} y2^{d} y2^{e}.
term5 := Gam^{a}_{b c d e f} y0^{b} y0^{c} y0^{d} y0^{e} y0^{f}.

term2 = substitute_eps (term2)    # cdb (term2.401,term2)
term3 = substitute_eps (term3)    # cdb (term3.401,term3)
term4 = substitute_eps (term4)    # cdb (term4.401,term4)
term5 = substitute_eps (term5)    # cdb (term5.401,term5)

term2 = substitute_y (term2)
term3 = substitute_y (term3)
term4 = substitute_y (term4)
term5 = substitute_y (term5)

term2 = substitute_gam (term2)
term3 = substitute_gam (term3)
term4 = substitute_gam (term4)
term5 = substitute_gam (term5)

term2 = tidy (term2)    # cdb (term2.501,term2)
term3 = tidy (term3)    # cdb (term3.501,term3)
term4 = tidy (term4)    # cdb (term4.501,term4)
```

```
term5 = tidy (term5)  # cdb (term5.501,term5)
```

$$\begin{aligned} \text{term2.401} := & Gam_{22}^a{}_{bc}y_{40}^by_{40}^c + Gam_{23}^a{}_{bc}y_{40}^by_{40}^c + 2 Gam_{22}^a{}_{bc}y_{40}^by_{42}^c + Gam_{24}^a{}_{bc}y_{40}^by_{40}^c \\ & + 2 Gam_{22}^a{}_{bc}y_{40}^by_{43}^c + 2 Gam_{23}^a{}_{bc}y_{40}^by_{42}^c + Gam_{25}^a{}_{bc}y_{40}^by_{40}^c \end{aligned}$$

$$\text{term3.401} := Gam_{33}^a{}_{bcd}y_{30}^by_{30}^cy_{30}^d + Gam_{34}^a{}_{bcd}y_{30}^by_{30}^cy_{30}^d + 3 Gam_{33}^a{}_{bcd}y_{30}^by_{30}^cy_{32}^d + Gam_{35}^a{}_{bcd}y_{30}^by_{30}^cy_{30}^d$$

$$\text{term4.401} := Gam_{44}^a{}_{bcde}y_{20}^by_{20}^cy_{20}^dy_{20}^e + Gam_{45}^a{}_{bcde}y_{20}^by_{20}^cy_{20}^dy_{20}^e$$

$$\text{term5.401} := Gam_{55}^a{}_{bcdef}y_{00}^by_{00}^cy_{00}^dy_{00}^ey_{00}^f$$



$$\begin{aligned}
\text{term2.501} := & -\frac{2}{3} x^b D x^c D x^d g^{ae} R_{bcde} - \frac{1}{6} x^b x^c D x^d D x^e g^{af} \nabla_d R_{becf} - \frac{1}{3} x^b x^c D x^d D x^e g^{af} \nabla_b R_{cdef} + \frac{1}{12} x^b x^c D x^d D x^e g^{af} \nabla_f R_{bdce} \\
& - \frac{2}{9} x^b x^c D x^d D x^e D x^f g^{ag} g^{hi} R_{bdeh} R_{cfdgi} + \frac{2}{9} x^b x^c D x^d D x^e D x^f g^{ag} g^{hi} R_{bdeh} R_{cifg} - \frac{8}{45} x^b x^c x^d D x^e D x^f g^{ag} g^{hi} R_{befh} R_{cgdi} \\
& + \frac{4}{45} x^b x^c x^d D x^e D x^f g^{ag} g^{hi} R_{bech} R_{difg} + \frac{2}{45} x^b x^c x^d D x^e D x^f g^{ag} g^{hi} R_{bech} R_{dgfi} - \frac{1}{20} x^b x^c x^d D x^e D x^f g^{ag} \nabla_e R_{cfdg} \\
& - \frac{1}{20} x^b x^c x^d D x^e D x^f g^{ag} \nabla_{be} R_{cfdg} - \frac{1}{10} x^b x^c x^d D x^e D x^f g^{ag} \nabla_{be} R_{defg} - \frac{2}{45} x^b x^c x^d D x^e D x^f g^{ag} g^{hi} R_{bech} R_{dfgi} \\
& + \frac{1}{40} x^b x^c x^d D x^e D x^f g^{ag} \nabla_{gb} R_{cedf} + \frac{1}{40} x^b x^c x^d D x^e D x^f g^{ag} \nabla_{bg} R_{cedf} - \frac{1}{18} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{behi} \nabla_f R_{cgdj} \\
& - \frac{1}{9} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{behi} \nabla_e R_{dfgj} + \frac{1}{36} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{behi} \nabla_j R_{cfdg} + \frac{1}{18} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bieh} \nabla_f R_{cgdj} \\
& + \frac{1}{9} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bieh} \nabla_e R_{dfgj} - \frac{1}{36} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bieh} \nabla_j R_{cfdg} \\
& - \frac{1}{18} x^b x^c D x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bdhi} \nabla_e R_{cfgj} + \frac{1}{18} x^b x^c D x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bidh} \nabla_e R_{cfgj} \\
& + \frac{1}{18} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{befi} \nabla_g R_{chdj} + \frac{1}{18} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{befi} \nabla_j R_{cgdh} - \frac{1}{9} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{befi} \nabla_e R_{dghj} \\
& + \frac{1}{9} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{befi} \nabla_e R_{djgh} - \frac{1}{18} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{befi} \nabla_h R_{cgdj} - \frac{4}{45} x^b x^c x^d x^e D x^f D x^g g^{ah} g^{ij} R_{bfgi} \nabla_e R_{dhej} \\
& - \frac{1}{30} x^b x^c x^d x^e D x^f D x^g g^{ah} g^{ij} R_{bhci} \nabla_f R_{dgej} - \frac{4}{45} x^b x^c x^d x^e D x^f D x^g g^{ah} g^{ij} R_{bhci} \nabla_d R_{efgj} + \frac{1}{36} x^b x^c x^d x^e D x^f D x^g g^{ah} g^{ij} R_{bhci} \nabla_j R_{dfeg} \\
& + \frac{2}{45} x^b x^c x^d x^e D x^f D x^g g^{ah} g^{ij} R_{bifh} \nabla_e R_{dgej} + \frac{1}{45} x^b x^c x^d x^e D x^f D x^g g^{ah} g^{ij} R_{bhfi} \nabla_e R_{dgej} + \frac{1}{45} x^b x^c x^d x^e D x^f D x^g g^{ah} g^{ij} R_{bfc i} \nabla_g R_{dhej} \\
& + \frac{2}{45} x^b x^c x^d x^e D x^f D x^g g^{ah} g^{ij} R_{bfc i} \nabla_d R_{ejgh} + \frac{1}{45} x^b x^c x^d x^e D x^f D x^g g^{ah} g^{ij} R_{bfc i} \nabla_d R_{ehgj} - \frac{1}{90} x^b x^c x^d x^e D x^f D x^g g^{ah} \nabla_{fbc} R_{dgeh} \\
& - \frac{1}{90} x^b x^c x^d x^e D x^f D x^g g^{ah} \nabla_{bfc} R_{dgeh} - \frac{1}{90} x^b x^c x^d x^e D x^f D x^g g^{ah} \nabla_{bcf} R_{dgeh} - \frac{1}{45} x^b x^c x^d x^e D x^f D x^g g^{ah} \nabla_{bcd} R_{efgh} \\
& - \frac{1}{45} x^b x^c x^d x^e D x^f D x^g g^{ah} g^{ij} R_{bfhi} \nabla_e R_{dgej} - \frac{1}{45} x^b x^c x^d x^e D x^f D x^g g^{ah} g^{ij} R_{bfc i} \nabla_h R_{dgej} - \frac{1}{45} x^b x^c x^d x^e D x^f D x^g g^{ah} g^{ij} R_{bfc i} \nabla_d R_{eghj} \\
& + \frac{1}{180} x^b x^c x^d x^e D x^f D x^g g^{ah} \nabla_{hbc} R_{dfeg} + \frac{1}{180} x^b x^c x^d x^e D x^f D x^g g^{ah} \nabla_{bhc} R_{dfeg} + \frac{1}{180} x^b x^c x^d x^e D x^f D x^g g^{ah} \nabla_{bch} R_{dfeg}
\end{aligned}$$

$$\begin{aligned}
\text{term3.501} := & -\frac{1}{2} x^b D x^c D x^d D x^e g^{af} \nabla_c R_{bdef} - \frac{8}{15} x^b x^c D x^d D x^e D x^f g^{ag} g^{hi} R_{bdeh} R_{cifg} - \frac{2}{15} x^b x^c D x^d D x^e D x^f g^{ag} g^{hi} R_{bdeh} R_{cgfi} \\
& + \frac{2}{15} x^b x^c D x^d D x^e D x^f g^{ag} g^{hi} R_{bdch} R_{egfi} - \frac{1}{10} x^b x^c D x^d D x^e D x^f g^{ag} \nabla_{de} R_{bfeg} - \frac{3}{20} x^b x^c D x^d D x^e D x^f g^{ag} \nabla_{db} R_{cefg} \\
& - \frac{3}{20} x^b x^c D x^d D x^e D x^f g^{ag} \nabla_{bd} R_{cefg} + \frac{2}{5} x^b x^c D x^d D x^e D x^f g^{ag} g^{hi} R_{bdeh} R_{cfig} + \frac{1}{40} x^b x^c D x^d D x^e D x^f g^{ag} \nabla_{gd} R_{becf} \\
& + \frac{1}{40} x^b x^c D x^d D x^e D x^f g^{ag} \nabla_{dg} R_{becf} - \frac{1}{6} x^b x^c D x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bdei} \nabla_f R_{cghj} + \frac{1}{6} x^b x^c D x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bdei} \nabla_f R_{cjgh} \\
& + \frac{1}{6} x^b x^c D x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bdei} \nabla_j R_{cfgh} - \frac{8}{45} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{befi} \nabla_g R_{chdj} \\
& - \frac{4}{15} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{befi} \nabla_e R_{djgh} - \frac{1}{15} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{befi} \nabla_e R_{dhgj} - \frac{1}{10} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bieh} \nabla_f R_{cgdj} \\
& - \frac{1}{90} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bhei} \nabla_f R_{cgdj} - \frac{11}{90} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bhci} \nabla_e R_{dfgj} - \frac{4}{15} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bieh} \nabla_e R_{dfgj} \\
& - \frac{1}{15} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bhei} \nabla_e R_{dfgj} + \frac{1}{12} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bieh} \nabla_j R_{cf dg} + \frac{1}{36} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bhei} \nabla_j R_{cf dg} \\
& + \frac{1}{15} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{ehfi} \nabla_b R_{cgdj} + \frac{1}{15} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{beci} \nabla_f R_{djgh} + \frac{2}{45} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{beci} \nabla_f R_{dhgj} \\
& + \frac{1}{15} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{beci} \nabla_d R_{fhgj} - \frac{1}{45} x^b x^c x^d D x^e D x^f D x^g g^{ah} \nabla_{efb} R_{cgdh} - \frac{1}{45} x^b x^c x^d D x^e D x^f D x^g g^{ah} \nabla_{ebf} R_{cgdh} \\
& - \frac{1}{30} x^b x^c x^d D x^e D x^f D x^g g^{ah} \nabla_{ebc} R_{dfgh} - \frac{1}{45} x^b x^c x^d D x^e D x^f D x^g g^{ah} \nabla_{bef} R_{cgdh} - \frac{1}{30} x^b x^c x^d D x^e D x^f D x^g g^{ah} \nabla_{bec} R_{dfgh} \\
& - \frac{1}{30} x^b x^c x^d D x^e D x^f D x^g g^{ah} \nabla_{bce} R_{dfgh} + \frac{4}{45} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{behi} \nabla_f R_{cgdj} + \frac{1}{5} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{behi} \nabla_e R_{dfgj} \\
& + \frac{4}{45} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{befi} \nabla_h R_{cgdj} - \frac{1}{45} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{beci} \nabla_h R_{dfgj} + \frac{1}{5} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{befi} \nabla_e R_{dghj} \\
& - \frac{1}{45} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{beci} \nabla_f R_{dghj} + \frac{1}{180} x^b x^c x^d D x^e D x^f D x^g g^{ah} \nabla_{heb} R_{cf dg} + \frac{1}{180} x^b x^c x^d D x^e D x^f D x^g g^{ah} \nabla_{hbe} R_{cf dg} \\
& + \frac{1}{180} x^b x^c x^d D x^e D x^f D x^g g^{ah} \nabla_{ehb} R_{cf dg} + \frac{1}{180} x^b x^c x^d D x^e D x^f D x^g g^{ah} \nabla_{bhe} R_{cf dg} + \frac{1}{180} x^b x^c x^d D x^e D x^f D x^g g^{ah} \nabla_{ebh} R_{cf dg} \\
& + \frac{1}{180} x^b x^c x^d D x^e D x^f D x^g g^{ah} \nabla_{beh} R_{cf dg} - \frac{1}{9} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{befi} \nabla_j R_{cgdh} - \frac{1}{18} x^b x^c x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{behi} \nabla_j R_{cf dg}
\end{aligned}$$

$$\begin{aligned}
\text{term4.501} := & -\frac{8}{15} x^b D x^c D x^d D x^e D x^f g^{ag} g^{hi} R_{bcdh} R_{egfi} - \frac{2}{5} x^b D x^c D x^d D x^e D x^f g^{ag} \nabla_{cd} R_{befg} - \frac{32}{45} x^b x^c D x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bdei} \nabla_f R_{cjgh} \\
& - \frac{1}{5} x^b x^c D x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bdei} \nabla_f R_{chgj} - \frac{4}{15} x^b x^c D x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bdei} \nabla_e R_{fhgj} \\
& - \frac{2}{45} x^b x^c D x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{dhei} \nabla_f R_{bgcj} - \frac{22}{45} x^b x^c D x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bidh} \nabla_e R_{cfgj} \\
& - \frac{1}{5} x^b x^c D x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bhdi} \nabla_e R_{cfgj} - \frac{4}{15} x^b x^c D x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{dhei} \nabla_b R_{cfgj} \\
& + \frac{1}{9} x^b x^c D x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{dhei} \nabla_j R_{bfcg} + \frac{8}{45} x^b x^c D x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bdci} \nabla_e R_{fhgj} - \frac{1}{15} x^b x^c D x^d D x^e D x^f D x^g g^{ah} \nabla_{def} R_{bgch} \\
& - \frac{4}{45} x^b x^c D x^d D x^e D x^f D x^g g^{ah} \nabla_{deb} R_{cfgh} - \frac{4}{45} x^b x^c D x^d D x^e D x^f D x^g g^{ah} \nabla_{dbe} R_{cfgh} - \frac{4}{45} x^b x^c D x^d D x^e D x^f D x^g g^{ah} \nabla_{bde} R_{cfgh} \\
& + \frac{13}{45} x^b x^c D x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bdhi} \nabla_e R_{cfgj} + \frac{1}{15} x^b x^c D x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bdei} \nabla_h R_{cfgj} \\
& + \frac{23}{45} x^b x^c D x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bdei} \nabla_f R_{cghj} + \frac{1}{90} x^b x^c D x^d D x^e D x^f D x^g g^{ah} \nabla_{hde} R_{bfcg} \\
& + \frac{1}{90} x^b x^c D x^d D x^e D x^f D x^g g^{ah} \nabla_{dhe} R_{bfcg} + \frac{1}{90} x^b x^c D x^d D x^e D x^f D x^g g^{ah} \nabla_{deh} R_{bfcg} - \frac{4}{9} x^b x^c D x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bdei} \nabla_j R_{cfgh} \\
\text{term5.501} := & -x^b D x^c D x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{bcdi} \nabla_e R_{fhgj} - x^b D x^c D x^d D x^e D x^f D x^g g^{ah} g^{ij} R_{chdi} \nabla_e R_{bfgj} - \frac{1}{3} x^b D x^c D x^d D x^e D x^f D x^g g^{ah} \nabla_{cde} R_{bfgh}
\end{aligned}$$

```

# Check:
#   x^{a} at s=1 should equal x^{a} + Dx^{a}
#   but x^{a}(s) = x^{a} + s y^{a} - \sum (1/n!) @ (termn) s^n
#   thus foo should equal Dx^{a} and it does (yeah)

foo := @(y5)
      - (1/2) @(term2)
      - (1/6) @(term3)
      - (1/24) @(term4)
      - (1/120) @(term5).

distribute      (foo)
obj = product_sort (foo)
rename_dummies  (foo)
canonicalise     (foo)      # cdb (foo.001,foo)

term2 := (1/2) @(term2).    # cdb(term2.502,term2)
term3 := (1/6) @(term3).    # cdb(term3.502,term3)
term4 := (1/24) @(term4).   # cdb(term4.502,term4)
term5 := (1/120) @(term5).  # cdb(term5.502,term5)

end_stage_2b = time.time()

```

$$\text{foo.001} := Dx^a$$

$$y2.301 := Dx^a - \frac{1}{3} x^b Dx^c Dx^d g^{ae} R_{bcde}$$

$$\begin{aligned}
y3.301 := & Dx^a - \frac{1}{3} x^b Dx^c Dx^d g^{ae} R_{bcde} - \frac{1}{12} x^b x^c Dx^d Dx^e g^{af} \nabla_d R_{becf} - \frac{1}{6} x^b x^c Dx^d Dx^e g^{af} \nabla_b R_{cdef} \\
& + \frac{1}{24} x^b x^c Dx^d Dx^e g^{af} \nabla_f R_{bdce} - \frac{1}{12} x^b Dx^c Dx^d Dx^e g^{af} \nabla_c R_{bdef}
\end{aligned}$$

$$\begin{aligned}
\text{y4.301} := & Dx^a - \frac{1}{3} x^b Dx^c Dx^d g^{ae} R_{bcde} - \frac{1}{12} x^b x^c Dx^d Dx^e g^{af} \nabla_d R_{becf} - \frac{1}{6} x^b x^c Dx^d Dx^e g^{af} \nabla_b R_{cdef} + \frac{1}{24} x^b x^c Dx^d Dx^e g^{af} \nabla_f R_{bdce} \\
& - \frac{1}{12} x^b Dx^c Dx^d Dx^e g^{af} \nabla_e R_{bdef} - \frac{2}{45} x^b x^c Dx^d Dx^e Dx^f g^{ag} g^{hi} R_{bdeh} R_{cfgi} + \frac{1}{45} x^b x^c Dx^d Dx^e Dx^f g^{ag} g^{hi} R_{bdeh} R_{cifg} \\
& - \frac{4}{45} x^b x^c x^d Dx^e Dx^f g^{ag} g^{hi} R_{befh} R_{cgdi} + \frac{2}{45} x^b x^c x^d Dx^e Dx^f g^{ag} g^{hi} R_{bech} R_{difg} + \frac{1}{45} x^b x^c x^d Dx^e Dx^f g^{ag} g^{hi} R_{bech} R_{dgfi} \\
& - \frac{1}{40} x^b x^c x^d Dx^e Dx^f g^{ag} \nabla_{eb} R_{cfdg} - \frac{1}{40} x^b x^c x^d Dx^e Dx^f g^{ag} \nabla_{be} R_{cfdg} - \frac{1}{20} x^b x^c x^d Dx^e Dx^f g^{ag} \nabla_{bc} R_{defg} \\
& - \frac{1}{45} x^b x^c x^d Dx^e Dx^f g^{ag} g^{hi} R_{bech} R_{dfgi} + \frac{1}{80} x^b x^c x^d Dx^e Dx^f g^{ag} \nabla_{gb} R_{cedf} + \frac{1}{80} x^b x^c x^d Dx^e Dx^f g^{ag} \nabla_{bg} R_{cedf} \\
& - \frac{1}{45} x^b x^c Dx^d Dx^e Dx^f g^{ag} g^{hi} R_{bdeh} R_{cgfi} + \frac{1}{45} x^b x^c Dx^d Dx^e Dx^f g^{ag} g^{hi} R_{bdch} R_{egfi} - \frac{1}{60} x^b x^c Dx^d Dx^e Dx^f g^{ag} \nabla_{de} R_{bfcg} \\
& - \frac{1}{40} x^b x^c Dx^d Dx^e Dx^f g^{ag} \nabla_{db} R_{cefg} - \frac{1}{40} x^b x^c Dx^d Dx^e Dx^f g^{ag} \nabla_{bd} R_{cefg} + \frac{1}{240} x^b x^c Dx^d Dx^e Dx^f g^{ag} \nabla_{gd} R_{becf} \\
& + \frac{1}{240} x^b x^c Dx^d Dx^e Dx^f g^{ag} \nabla_{dg} R_{becf} - \frac{1}{45} x^b Dx^c Dx^d Dx^e Dx^f g^{ag} g^{hi} R_{bcdh} R_{egfi} - \frac{1}{60} x^b Dx^c Dx^d Dx^e Dx^f g^{ag} \nabla_{cd} R_{befg}
\end{aligned}$$

## Stage 3: Reformatting and output

```
def get_Rterm (obj,n):

# I would like to assign different weights to \nabla_{a}, \nabla_{a b}, \nabla_{a b c} etc. but no matter
# what I do it appears that Cadabra assigns the same weight to all of these regardless of the number of subscripts.
# It seems that the weight is assigned to the symbol \nabla alone. So I'm forced to use the following substitution trick.

    Q_{a b c d}::Weight(label=numR,value=2).
    Q_{a b c d e}::Weight(label=numR,value=3).
    Q_{a b c d e f}::Weight(label=numR,value=4).
    Q_{a b c d e f g}::Weight(label=numR,value=5).

    tmp := @(obj).

    distribute (tmp)

    substitute (tmp, $\nabla_{e f g}\{R_{a b c d}\} \rightarrow Q_{a b c d e f g}\$)
    substitute (tmp, $\nabla_{e f}\{R_{a b c d}\} \rightarrow Q_{a b c d e f}\$)
    substitute (tmp, $\nabla_e\{R_{a b c d}\} \rightarrow Q_{a b c d e}\$)
    substitute (tmp, $R_{a b c d} \rightarrow Q_{a b c d}\$)

    foo := @(tmp).
    bah = Ex("numR = " + str(n))
    keep_weight (foo, bah)

    substitute (foo, $Q_{a b c d e f g} \rightarrow \nabla_{e f g}\{R_{a b c d}\}\$)
    substitute (foo, $Q_{a b c d e f} \rightarrow \nabla_{e f}\{R_{a b c d}\}\$)
    substitute (foo, $Q_{a b c d e} \rightarrow \nabla_e\{R_{a b c d}\}\$)
    substitute (foo, $Q_{a b c d} \rightarrow R_{a b c d}\$)

    return foo

def reformat (obj,scale):
    foo = Ex(str(scale))
    bah := @(foo) @(obj).
    distribute (bah)
    bah = product_sort (bah)
```

```

rename_dummies (bah)
canonicalise   (bah)
substitute     (bah,$Dx^{b}->zzz^{b}$)
factor_out     (bah,$x^{a?},zzz^{b?}$)
substitute     (bah,$zzz^{b}->Dx^{b}$)
ans := @(bah) / @(foo).
return ans

def rescale (obj,scale):
    foo = Ex(str(scale))
    bah := @(foo) @(obj).
    distribute  (bah)
    substitute  (bah,$Dx^{b}->zzz^{b}$)
    factor_out  (bah,$x^{a?},zzz^{b?}$)
    substitute  (bah,$zzz^{b}->Dx^{b}$)
    return bah

beg_stage_3 = time.time()

Rterm22 = get_Rterm (term2,2)      # cdb(Rterm22.101,Rterm22)
Rterm23 = get_Rterm (term2,3)      # cdb(Rterm23.101,Rterm23)
Rterm24 = get_Rterm (term2,4)      # cdb(Rterm24.101,Rterm24)
Rterm25 = get_Rterm (term2,5)      # cdb(Rterm25.101,Rterm25)

Rterm32 = get_Rterm (term3,2)      # cdb(Rterm32.101,Rterm32) # zero
Rterm33 = get_Rterm (term3,3)      # cdb(Rterm33.101,Rterm33)
Rterm34 = get_Rterm (term3,4)      # cdb(Rterm34.101,Rterm34)
Rterm35 = get_Rterm (term3,5)      # cdb(Rterm35.101,Rterm35)

Rterm42 = get_Rterm (term4,2)      # cdb(Rterm42.101,Rterm42) # zero
Rterm43 = get_Rterm (term4,3)      # cdb(Rterm43.101,Rterm43) # zero
Rterm44 = get_Rterm (term4,4)      # cdb(Rterm44.101,Rterm44)
Rterm45 = get_Rterm (term4,5)      # cdb(Rterm45.101,Rterm45)

Rterm52 = get_Rterm (term5,2)      # cdb(Rterm52.101,Rterm52) # zero
Rterm53 = get_Rterm (term5,3)      # cdb(Rterm53.101,Rterm53) # zero
Rterm54 = get_Rterm (term5,4)      # cdb(Rterm54.101,Rterm54) # zero
Rterm55 = get_Rterm (term5,5)      # cdb(Rterm55.101,Rterm55)

```

```
Rterm22 = rescale ( reformat (Rterm22,  -3),  -3 ) # cdb(Rterm22.102,Rterm22)
Rterm23 = rescale ( reformat (Rterm23, -24), -24 ) # cdb(Rterm23.102,Rterm23)
Rterm24 = rescale ( reformat (Rterm24, -720), -720 ) # cdb(Rterm24.102,Rterm24)
Rterm25 = rescale ( reformat (Rterm25, -360), -360 ) # cdb(Rterm25.102,Rterm25)

Rterm33 = rescale ( reformat (Rterm33, -12),  -12 ) # cdb(Rterm33.102,Rterm33)
Rterm34 = rescale ( reformat (Rterm34, -720), -720 ) # cdb(Rterm34.102,Rterm34)
Rterm35 = rescale ( reformat (Rterm35,-1080), -1080 ) # cdb(Rterm35.102,Rterm35)

Rterm44 = rescale ( reformat (Rterm44, -180), -180 ) # cdb(Rterm44.102,Rterm44)
Rterm45 = rescale ( reformat (Rterm45,-2160), -2160 ) # cdb(Rterm45.102,Rterm45)

Rterm55 = rescale ( reformat (Rterm55, -360), -360 ) # cdb(Rterm55.102,Rterm55)
```



```

# -----
# bvp to terms linear in R

tmp2 := -(1/3) @(Rterm22).

bvp2 := x^{a}
      + s Dx^{a}
      + (s-s**2) @(tmp2).                                # cdb(bvp.601,bvp2)

cdblib.put ('bvp2',bvp2,'geodesic-bvp.json')
cdblib.put ('bvp22',tmp2,'geodesic-bvp.json')

y2 := Dx^{a} + @(tmp2).                                # cdb(y2.600,y2)

# -----
# bvp to terms linear in dR

tmp2 := -(1/3) @(Rterm22) - (1/24) @(Rterm23).
tmp3 := -(1/12) @(Rterm33).

bvp3 := x^{a}
      + s Dx^{a}
      + (s-s**2) @(tmp2)
      + (s-s**3) @(tmp3).                                # cdb(bvp.602,bvp3)

cdblib.put ('bvp3',bvp3,'geodesic-bvp.json')
cdblib.put ('bvp32',tmp2,'geodesic-bvp.json')
cdblib.put ('bvp33',tmp3,'geodesic-bvp.json')

y3 := Dx^{a} + @(tmp2) + @(tmp3).                        # cdb(y3.600,y3)

# -----
# bvp to terms linear in d^2 R

tmp2 := -(1/3) @(Rterm22) - (1/24) @(Rterm23) - (1/720) @(Rterm24).
tmp3 := -(1/12) @(Rterm33) - (1/720) @(Rterm34).
tmp4 := -(1/180) @(Rterm44).

```

```

bvp4 := x^{a}
      + s Dx^{a}
      + (s-s**2) @(tmp2)
      + (s-s**3) @(tmp3)
      + (s-s**4) @(tmp4).                                     # cdb(bvp.603,bvp4)

cdblib.put ('bvp4',bvp4,'geodesic-bvp.json')
cdblib.put ('bvp42',tmp2,'geodesic-bvp.json')
cdblib.put ('bvp43',tmp3,'geodesic-bvp.json')
cdblib.put ('bvp44',tmp4,'geodesic-bvp.json')

y4 := Dx^{a} + @(tmp2) + @(tmp3) + @(tmp4).                  # cdb(y4.600,y4)

# -----
# bvp to terms linear in d^3 R

tmp2 := @(term2).
tmp3 := @(term3).
tmp4 := @(term4).
tmp5 := @(term5).

bvp5 := x^{a}
      + s Dx^{a}
      + (s-s**2) @(tmp2)
      + (s-s**3) @(tmp3)
      + (s-s**4) @(tmp4)
      + (s-s**5) @(tmp5).                                     # cdb(bvp.604,bvp5)

cdblib.put ('bvp5',bvp5,'geodesic-bvp.json')
cdblib.put ('bvp52',term2,'geodesic-bvp.json')
cdblib.put ('bvp53',term3,'geodesic-bvp.json')
cdblib.put ('bvp54',term4,'geodesic-bvp.json')
cdblib.put ('bvp55',term5,'geodesic-bvp.json')

y5 := Dx^{a} + @(tmp2) + @(tmp3) + @(tmp4) + @(tmp5).        # cdb(y5.600,y5)

end_stage_3 = time.time()

```

```
# cdbBeg (timing)
print ("Stage 1:  {:7.1f} secs\\hfill\\break".format(end_stage_1-beg_stage_1))
print ("Stage 2a: {:7.1f} secs\\hfill\\break".format(end_stage_2a-beg_stage_2a))
print ("Stage 2b: {:7.1f} secs\\hfill\\break".format(end_stage_2b-beg_stage_2b))
print ("Stage 3:  {:7.1f} secs\\hfill\\break".format(end_stage_3-beg_stage_3))
# cdbEnd (timing)
```

## Non-unit tangent vectors at $P$

These are not unit vectors, their length is the geodesic distance from  $P$  to  $Q$

$$\begin{aligned}
y2.600 &:= Dx^a - \frac{1}{3} x^b Dx^c Dx^d g^{ae} R_{bcde} \\
y3.600 &:= Dx^a - \frac{1}{3} x^b Dx^c Dx^d g^{ae} R_{bcde} - \frac{1}{24} x^b x^c Dx^d Dx^e (2 g^{af} \nabla_d R_{becf} + 4 g^{af} \nabla_b R_{cdef} - g^{af} \nabla_f R_{bdce}) - \frac{1}{12} x^b Dx^c Dx^d Dx^e g^{af} \nabla_c R_{bdef} \\
y4.600 &:= Dx^a - \frac{1}{3} x^b Dx^c Dx^d g^{ae} R_{bcde} - \frac{1}{24} x^b x^c Dx^d Dx^e (2 g^{af} \nabla_d R_{becf} + 4 g^{af} \nabla_b R_{cdef} - g^{af} \nabla_f R_{bdce}) \\
&\quad - \frac{1}{720} x^b x^c Dx^d Dx^e Dx^f (80 g^{ag} g^{hi} R_{bdeh} R_{cfgi} - 80 g^{ag} g^{hi} R_{bdeh} R_{cifg}) \\
&\quad - \frac{1}{720} x^b x^c x^d Dx^e Dx^f (64 g^{ag} g^{hi} R_{befh} R_{cgdi} - 32 g^{ag} g^{hi} R_{bec h} R_{difg} - 16 g^{ag} g^{hi} R_{bec h} R_{dgfi} + 18 g^{ag} \nabla_{eb} R_{cfdg} + 18 g^{ag} \nabla_{be} R_{cfdg} \\
&\quad \quad \quad + 36 g^{ag} \nabla_{bc} R_{defg} + 16 g^{ag} g^{hi} R_{bec h} R_{dfgi} - 9 g^{ag} \nabla_{gb} R_{cedf} - 9 g^{ag} \nabla_{bg} R_{cedf}) - \frac{1}{12} x^b Dx^c Dx^d Dx^e g^{af} \nabla_c R_{bdef} \\
&\quad - \frac{1}{720} x^b x^c Dx^d Dx^e Dx^f (64 g^{ag} g^{hi} R_{bdeh} R_{cifg} + 16 g^{ag} g^{hi} R_{bdeh} R_{cgfi} - 16 g^{ag} g^{hi} R_{bdch} R_{egfi} + 12 g^{ag} \nabla_{de} R_{bfcg} + 18 g^{ag} \nabla_{db} R_{cefg} \\
&\quad \quad \quad + 18 g^{ag} \nabla_{bd} R_{cefg} - 48 g^{ag} g^{hi} R_{bdeh} R_{cfgi} - 3 g^{ag} \nabla_{gd} R_{becf} - 3 g^{ag} \nabla_{dg} R_{becf}) - \frac{1}{180} x^b Dx^c Dx^d Dx^e Dx^f (4 g^{ag} g^{hi} R_{bcdh} R_{egfi} + 3 g^{ag} \nabla_{cd} R_{befg})
\end{aligned}$$

## Geodesic boundary value problem to terms linear in $R$

$$x^a(s) = x^a + sDx^a - \frac{1}{3} (s - s^2) x^b Dx^c Dx^d g^{ae} R_{bcde} + \mathcal{O}(s^3, \epsilon^3)$$

$$x^a(s) = x^a + sDx^a + (s - s^2)x_2^a + \mathcal{O}(s^3, \epsilon^3)$$

$$x_2^a = \overset{2}{x}_2^a + \mathcal{O}(\epsilon^3)$$

$$-3\overset{2}{x}_2^a = x^b Dx^c Dx^d g^{ae} R_{bcde}$$

## Geodesic boundary value problem to terms linear in $\nabla R$

$$x^a(s) = x^a + sDx^a + (s - s^2) \left( -\frac{1}{3} x^b Dx^c Dx^d g^{ae} R_{bcde} - \frac{1}{24} x^b x^c Dx^d Dx^e (2g^{af} \nabla_d R_{becf} + 4g^{af} \nabla_b R_{cdef} - g^{af} \nabla_f R_{bdce}) \right) \\ - \frac{1}{12} (s - s^3) x^b Dx^c Dx^d Dx^e g^{af} \nabla_e R_{bdef} + \mathcal{O}(s^4, \epsilon^4)$$

$$x^a(s) = x^a + sDx^a + (s - s^2)x_2^a + (s - s^3)x_3^a + \mathcal{O}(s^4, \epsilon^4)$$

$$x_2^a = \overset{2}{x}_2^a + \overset{3}{x}_2^a + \mathcal{O}(\epsilon^4)$$

$$-3\overset{2}{x}_2^a = x^b Dx^c Dx^d g^{ae} R_{bcde}$$

$$-24\overset{3}{x}_2^a = x^b x^c Dx^d Dx^e (2g^{af} \nabla_d R_{becf} + 4g^{af} \nabla_b R_{cdef} - g^{af} \nabla_f R_{bdce})$$

$$x_3^a = \overset{3}{x}_3^a + \mathcal{O}(\epsilon^4)$$

$$-12\overset{3}{x}_3^a = x^b Dx^c Dx^d Dx^e g^{af} \nabla_e R_{bdef}$$

## Geodesic boundary value problem to terms linear in $\nabla^2 R$

$$\begin{aligned}
x^a(s) = & x^a + sDx^a + (s - s^2) \left( -\frac{1}{3} x^b Dx^c Dx^d g^{ae} R_{bcde} - \frac{1}{24} x^b x^c Dx^d Dx^e (2g^{af} \nabla_d R_{becf} + 4g^{af} \nabla_b R_{cdef} - g^{af} \nabla_f R_{bdce}) \right. \\
& - \frac{1}{720} x^b x^c Dx^d Dx^e Dx^f (80g^{ag} g^{hi} R_{bdeh} R_{cfgi} - 80g^{ag} g^{hi} R_{bdeh} R_{cifg}) - \frac{1}{720} x^b x^c x^d Dx^e Dx^f (64g^{ag} g^{hi} R_{befh} R_{cgdi} - 32g^{ag} g^{hi} R_{bech} R_{difg} \\
& \left. - 16g^{ag} g^{hi} R_{bech} R_{dgfi} + 18g^{ag} \nabla_{eb} R_{cfdg} + 18g^{ag} \nabla_{be} R_{cfdg} + 36g^{ag} \nabla_{bc} R_{defg} + 16g^{ag} g^{hi} R_{bech} R_{dfgi} - 9g^{ag} \nabla_{gb} R_{cedf} - 9g^{ag} \nabla_{bg} R_{cedf}) \right) \\
& + (s - s^3) \left( -\frac{1}{12} x^b Dx^c Dx^d Dx^e g^{af} \nabla_c R_{bdef} - \frac{1}{720} x^b x^c Dx^d Dx^e Dx^f (64g^{ag} g^{hi} R_{bdeh} R_{cifg} + 16g^{ag} g^{hi} R_{bdeh} R_{cgfi} - 16g^{ag} g^{hi} R_{bdch} R_{egfi} \right. \\
& \left. + 12g^{ag} \nabla_{de} R_{bfcg} + 18g^{ag} \nabla_{db} R_{cefg} + 18g^{ag} \nabla_{bd} R_{cefg} - 48g^{ag} g^{hi} R_{bdeh} R_{cfgi} - 3g^{ag} \nabla_{gd} R_{becf} - 3g^{ag} \nabla_{dg} R_{becf}) \right) \\
& \left. - \frac{1}{180} (s - s^4) x^b Dx^c Dx^d Dx^e Dx^f (4g^{ag} g^{hi} R_{bcdh} R_{egfi} + 3g^{ag} \nabla_{cd} R_{befg}) + \mathcal{O}(s^5, \epsilon^5) \right)
\end{aligned}$$

$$x^a(s) = x^a + sDx^a + (s - s^2)x_2^a + (s - s^3)x_3^a + (s - s^4)x_4^a + \mathcal{O}(s^5, \epsilon^5)$$

$$x_2^a = \dot{x}_2^a + \ddot{x}_2^a + \ddot{x}_2^a + \mathcal{O}(\epsilon^5)$$

$$-3\ddot{x}_2^a = x^b Dx^c Dx^d g^{ae} R_{bcde}$$

$$-24\ddot{x}_2^a = x^b x^c Dx^d Dx^e (2g^{af} \nabla_d R_{becf} + 4g^{af} \nabla_b R_{cdef} - g^{af} \nabla_f R_{bdce})$$

$$\begin{aligned}
-720\ddot{x}_2^a = & x^b x^c Dx^d Dx^e Dx^f (80g^{ag} g^{hi} R_{bdeh} R_{cfgi} - 80g^{ag} g^{hi} R_{bdeh} R_{cifg}) + x^b x^c x^d Dx^e Dx^f (64g^{ag} g^{hi} R_{befh} R_{cgdi} - 32g^{ag} g^{hi} R_{bech} R_{difg} \\
& - 16g^{ag} g^{hi} R_{bech} R_{dgfi} + 18g^{ag} \nabla_{eb} R_{cfdg} + 18g^{ag} \nabla_{be} R_{cfdg} + 36g^{ag} \nabla_{bc} R_{defg} + 16g^{ag} g^{hi} R_{bech} R_{dfgi} - 9g^{ag} \nabla_{gb} R_{cedf} - 9g^{ag} \nabla_{bg} R_{cedf})
\end{aligned}$$

$$x_3^a = \dot{x}_3^a + \ddot{x}_3^a + \mathcal{O}(\epsilon^5)$$

$$-12\ddot{x}_3^a = x^b Dx^c Dx^d Dx^e g^{af} \nabla_c R_{bdef}$$

$$\begin{aligned}
-720\ddot{x}_3^a = & x^b x^c Dx^d Dx^e Dx^f (64g^{ag} g^{hi} R_{bdeh} R_{cifg} + 16g^{ag} g^{hi} R_{bdeh} R_{cgfi} - 16g^{ag} g^{hi} R_{bdch} R_{egfi} + 12g^{ag} \nabla_{de} R_{bfcg} + 18g^{ag} \nabla_{db} R_{cefg} + 18g^{ag} \nabla_{bd} R_{cefg} \\
& - 48g^{ag} g^{hi} R_{bdeh} R_{cfgi} - 3g^{ag} \nabla_{gd} R_{becf} - 3g^{ag} \nabla_{dg} R_{becf})
\end{aligned}$$

$$x_4^a = x_4^a + \mathcal{O}(\epsilon^5)$$

$$-180x_4^a = x^b D x^c D x^d D x^e D x^f \left( 4 g^{ag} g^{hi} R_{bcdh} R_{egfi} + 3 g^{ag} \nabla_{cd} R_{befg} \right)$$



# Geodesic boundary value problem to terms linear in $\nabla^3 R$

The geodesic that connects the points with RNC coordinates  $x^a$  and  $x^a + Dx^a$  is described, for  $0 \leq s \leq 1$ , by

$$x^a(s) = x^a + sDx^a + (s - s^2)x_2^a + (s - s^3)x_3^a + (s - s^4)x_4^a + (s - s^5)x_5^a + \mathcal{O}(s^6, \epsilon^6)$$

$$x_2^a = \overset{2}{x}_2^a + \overset{3}{x}_2^a + \overset{4}{x}_2^a + \overset{5}{x}_2^a + \mathcal{O}(\epsilon^6)$$

$$-3\overset{2}{x}_2^a = x^b Dx^c Dx^d g^{ae} R_{bcde}$$

$$-24\overset{3}{x}_2^a = x^b x^c Dx^d Dx^e (2g^{af} \nabla_d R_{becf} + 4g^{af} \nabla_b R_{cdef} - g^{af} \nabla_f R_{bdce})$$

$$\begin{aligned} -720\overset{4}{x}_2^a = & x^b x^c Dx^d Dx^e Dx^f (80g^{ag} g^{hi} R_{bdeh} R_{cfgi} - 80g^{ag} g^{hi} R_{bdeh} R_{cifg}) + x^b x^c x^d Dx^e Dx^f (64g^{ag} g^{hi} R_{befh} R_{cgdi} - 32g^{ag} g^{hi} R_{bech} R_{difg} \\ & - 16g^{ag} g^{hi} R_{bech} R_{dghi} + 18g^{ag} \nabla_{eb} R_{cfdg} + 18g^{ag} \nabla_{be} R_{cfdg} + 36g^{ag} \nabla_{bc} R_{defg} + 16g^{ag} g^{hi} R_{bech} R_{dfgi} - 9g^{ag} \nabla_{gb} R_{cedf} - 9g^{ag} \nabla_{bg} R_{cedf}) \end{aligned}$$

$$\begin{aligned} -360\overset{5}{x}_2^a = & x^b x^c x^d Dx^e Dx^f Dx^g (10g^{ah} g^{ij} R_{behi} \nabla_f R_{cgdj} + 20g^{ah} g^{ij} R_{behi} \nabla_c R_{dfgj} - 5g^{ah} g^{ij} R_{behi} \nabla_j R_{cfdg} - 10g^{ah} g^{ij} R_{bieh} \nabla_f R_{cgdj} \\ & - 20g^{ah} g^{ij} R_{bieh} \nabla_c R_{dfgj} + 5g^{ah} g^{ij} R_{bieh} \nabla_j R_{cfdg} - 10g^{ah} g^{ij} R_{befi} \nabla_g R_{chdj} - 10g^{ah} g^{ij} R_{befi} \nabla_j R_{cgdh} + 20g^{ah} g^{ij} R_{befi} \nabla_c R_{dghj} \\ & - 20g^{ah} g^{ij} R_{befi} \nabla_e R_{djgh} + 10g^{ah} g^{ij} R_{befi} \nabla_h R_{cgdj}) + x^b x^c Dx^d Dx^e Dx^f Dx^g (10g^{ah} g^{ij} R_{bdhi} \nabla_e R_{cfgj} - 10g^{ah} g^{ij} R_{bidh} \nabla_e R_{cfgj}) \\ & + x^b x^c x^d x^e Dx^f Dx^g (16g^{ah} g^{ij} R_{bfgi} \nabla_c R_{dhej} + 6g^{ah} g^{ij} R_{bhci} \nabla_f R_{dgej} + 16g^{ah} g^{ij} R_{bhci} \nabla_d R_{efgj} - 5g^{ah} g^{ij} R_{bhci} \nabla_j R_{dfeg} \\ & - 8g^{ah} g^{ij} R_{bifh} \nabla_c R_{dgej} - 4g^{ah} g^{ij} R_{bhfi} \nabla_c R_{dgej} - 4g^{ah} g^{ij} R_{bfci} \nabla_g R_{dhej} - 8g^{ah} g^{ij} R_{bfci} \nabla_d R_{ejgh} - 4g^{ah} g^{ij} R_{bfci} \nabla_d R_{ehgj} + 2g^{ah} \nabla_{fbc} R_{dgeh} \\ & + 2g^{ah} \nabla_{bfc} R_{dgeh} + 2g^{ah} \nabla_{bcf} R_{dgeh} + 4g^{ah} \nabla_{bcd} R_{efgh} + 4g^{ah} g^{ij} R_{bfhi} \nabla_c R_{dgej} + 4g^{ah} g^{ij} R_{bfci} \nabla_h R_{dgej} + 4g^{ah} g^{ij} R_{bfci} \nabla_d R_{eghj} \\ & - g^{ah} \nabla_{hbc} R_{dfeg} - g^{ah} \nabla_{bhc} R_{dfeg} - g^{ah} \nabla_{bch} R_{dfeg}) \end{aligned}$$

$$x_3^a = \bar{x}_3^a + \bar{x}_3^a + \bar{x}_3^a + \mathcal{O}(\epsilon^6)$$

$$-12\bar{x}_3^a = x^b D x^c D x^d D x^e g^{af} \nabla_c R_{bdef}$$

$$-720\bar{x}_3^a = x^b x^c D x^d D x^e D x^f (64 g^{ag} g^{hi} R_{bdeh} R_{cifg} + 16 g^{ag} g^{hi} R_{bdeh} R_{cgfi} - 16 g^{ag} g^{hi} R_{bdch} R_{egfi} + 12 g^{ag} \nabla_{de} R_{bfcg} + 18 g^{ag} \nabla_{db} R_{cefg} + 18 g^{ag} \nabla_{bd} R_{cefg} \\ - 48 g^{ag} g^{hi} R_{bdeh} R_{cfigi} - 3 g^{ag} \nabla_{gd} R_{becf} - 3 g^{ag} \nabla_{dg} R_{becf})$$

$$-1080\bar{x}_3^a = x^b x^c D x^d D x^e D x^f D x^g (30 g^{ah} g^{ij} R_{bdei} \nabla_f R_{cghj} - 30 g^{ah} g^{ij} R_{bdei} \nabla_f R_{cjgh} - 30 g^{ah} g^{ij} R_{bdei} \nabla_j R_{cfgh}) \\ + x^b x^c x^d D x^e D x^f D x^g (32 g^{ah} g^{ij} R_{befi} \nabla_g R_{chdj} + 48 g^{ah} g^{ij} R_{befi} \nabla_c R_{djgh} + 12 g^{ah} g^{ij} R_{befi} \nabla_c R_{dhgj} + 18 g^{ah} g^{ij} R_{bieh} \nabla_f R_{cgdj} \\ + 2 g^{ah} g^{ij} R_{bhei} \nabla_f R_{cgdj} + 22 g^{ah} g^{ij} R_{bhci} \nabla_e R_{dfgj} + 48 g^{ah} g^{ij} R_{bieh} \nabla_e R_{dfgj} + 12 g^{ah} g^{ij} R_{bhei} \nabla_e R_{dfgj} - 15 g^{ah} g^{ij} R_{bieh} \nabla_j R_{cf dg} \\ - 5 g^{ah} g^{ij} R_{bhei} \nabla_j R_{cf dg} - 12 g^{ah} g^{ij} R_{ehfi} \nabla_b R_{cgdj} - 12 g^{ah} g^{ij} R_{beci} \nabla_f R_{djgh} - 8 g^{ah} g^{ij} R_{beci} \nabla_f R_{dhgj} - 12 g^{ah} g^{ij} R_{beci} \nabla_d R_{fhgj} \\ + 4 g^{ah} \nabla_{efb} R_{cgdh} + 4 g^{ah} \nabla_{ebf} R_{cgdh} + 6 g^{ah} \nabla_{ebc} R_{dfgh} + 4 g^{ah} \nabla_{bef} R_{cgdh} + 6 g^{ah} \nabla_{bec} R_{dfgh} + 6 g^{ah} \nabla_{bce} R_{dfgh} - 16 g^{ah} g^{ij} R_{behi} \nabla_f R_{cgdj} \\ - 36 g^{ah} g^{ij} R_{behi} \nabla_e R_{dfgj} - 16 g^{ah} g^{ij} R_{befi} \nabla_h R_{cgdj} + 4 g^{ah} g^{ij} R_{beci} \nabla_h R_{dfgj} - 36 g^{ah} g^{ij} R_{befi} \nabla_e R_{dghj} + 4 g^{ah} g^{ij} R_{beci} \nabla_f R_{dghj} - g^{ah} \nabla_{heb} R_{cf dg} \\ - g^{ah} \nabla_{hbe} R_{cf dg} - g^{ah} \nabla_{ehb} R_{cf dg} - g^{ah} \nabla_{bhe} R_{cf dg} - g^{ah} \nabla_{ebh} R_{cf dg} - g^{ah} \nabla_{beh} R_{cf dg} + 20 g^{ah} g^{ij} R_{befi} \nabla_j R_{cgdh} + 10 g^{ah} g^{ij} R_{behi} \nabla_j R_{cf dg})$$

$$x_4^a = \bar{x}_4^a + \bar{x}_4^a + \mathcal{O}(\epsilon^6)$$

$$-180\bar{x}_4^a = x^b D x^c D x^d D x^e D x^f (4 g^{ag} g^{hi} R_{bcdh} R_{egfi} + 3 g^{ag} \nabla_{cd} R_{befg})$$

$$-2160\bar{x}_4^a = x^b x^c D x^d D x^e D x^f D x^g (64 g^{ah} g^{ij} R_{bdei} \nabla_f R_{cjgh} + 18 g^{ah} g^{ij} R_{bdei} \nabla_f R_{chgj} + 24 g^{ah} g^{ij} R_{bdei} \nabla_e R_{fhgj} + 4 g^{ah} g^{ij} R_{dhei} \nabla_f R_{bgcj} \\ + 44 g^{ah} g^{ij} R_{bidh} \nabla_e R_{cf gj} + 18 g^{ah} g^{ij} R_{bhdi} \nabla_e R_{cf gj} + 24 g^{ah} g^{ij} R_{dhei} \nabla_b R_{cf gj} - 10 g^{ah} g^{ij} R_{dhei} \nabla_j R_{bfcg} - 16 g^{ah} g^{ij} R_{bdci} \nabla_e R_{fhgj} \\ + 6 g^{ah} \nabla_{def} R_{bgch} + 8 g^{ah} \nabla_{deb} R_{cf gh} + 8 g^{ah} \nabla_{dbe} R_{cf gh} + 8 g^{ah} \nabla_{bde} R_{cf gh} - 26 g^{ah} g^{ij} R_{bdhi} \nabla_e R_{cf gj} - 6 g^{ah} g^{ij} R_{bdei} \nabla_h R_{cf gj} \\ - 46 g^{ah} g^{ij} R_{bdei} \nabla_f R_{cghj} - g^{ah} \nabla_{hde} R_{bfcg} - g^{ah} \nabla_{dhe} R_{bfcg} - g^{ah} \nabla_{deh} R_{bfcg} + 40 g^{ah} g^{ij} R_{bdei} \nabla_j R_{cf gh})$$

$$x_5^a = \bar{x}_5^a + \mathcal{O}(\epsilon^6)$$

$$-360\bar{x}_5^a = x^b D x^c D x^d D x^e D x^f D x^g (3 g^{ah} g^{ij} R_{bcdi} \nabla_e R_{fhgj} + 3 g^{ah} g^{ij} R_{chdi} \nabla_e R_{bf gj} + g^{ah} \nabla_{cde} R_{bf gh})$$

```

tmp2 := 8 @(Rterm22) + @(Rterm23).
tmp3 := @(Rterm33).

factor_out      (tmp2,$Dx^{a?}$) # cdb(tmp2.001,tmp2)
rename_dummies (tmp2)
factor_out      (tmp2,$Dx^{a?}$) # cdb(tmp2.002,tmp2)

bvp4 := x^{a}
      + \lam Dx^{a}
      - (1/24) (\lam-\lam**2) @(tmp2)
      - (1/12) (\lam-\lam**3) @(tmp3).      # cdb(bvp4,bvp4)

cdblib.create ('geodesic-bvp.export')

# 4th order bvp
cdblib.put ('bvp4',bvp4,'geodesic-bvp.export')

# 6th order bvp terms, scaled
cdblib.put ('bvp622',Rterm22,'geodesic-bvp.export')
cdblib.put ('bvp623',Rterm23,'geodesic-bvp.export')
cdblib.put ('bvp624',Rterm24,'geodesic-bvp.export')
cdblib.put ('bvp625',Rterm25,'geodesic-bvp.export')

cdblib.put ('bvp633',Rterm33,'geodesic-bvp.export')
cdblib.put ('bvp634',Rterm34,'geodesic-bvp.export')
cdblib.put ('bvp635',Rterm35,'geodesic-bvp.export')

cdblib.put ('bvp644',Rterm44,'geodesic-bvp.export')
cdblib.put ('bvp645',Rterm45,'geodesic-bvp.export')

cdblib.put ('bvp655',Rterm55,'geodesic-bvp.export')

checkpoint.append (bvp4)

checkpoint.append (Rterm22)
checkpoint.append (Rterm23)
checkpoint.append (Rterm24)
checkpoint.append (Rterm25)

```

```
checkpoint.append (Rterm33)
checkpoint.append (Rterm34)
checkpoint.append (Rterm35)

checkpoint.append (Rterm44)
checkpoint.append (Rterm45)

checkpoint.append (Rterm55)
```

# Timing

Stage 1: 0.8 secs

Stage 2a: 13.9 secs

Stage 2b: 14.9 secs

Stage 3: 2.8 secs