# Independence of gauge-fixing in a higher-order BV formalism

Klaus Bering Collaborator: Igor A. Batalin

Masaryk U, Brno, CZ

Lebedev PI, Moscow, RU

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Δ Operator Motivation BV Path Int./Partition Fct. in *W-X* Formalism Transposed Operator Original 2nd-Order BV

# Independence of gauge-fixing in a higher-order BV formalism



Independence of Gauge-Fixing

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# $\Delta$ Operator

#### Diff. Op.

$$\Delta(\hbar, z, \partial)$$

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# Planck number grading

$$\mathsf{PI}(\hbar) = 1 \qquad \qquad \mathsf{PI}(z) = 0$$

$$\mathsf{PI}(\partial) \;=\; \left\{ egin{array}{ccc} 0 & ext{if} & \partial & ext{acts inside} & \Delta \ & & & \ -1 & ext{if} & \partial & ext{acts outside} & \Delta \end{array} 
ight.$$

Super AdditivityTriangular form
$$PI(FG) \ge PI(F) + PI(G)$$
 $PI(\Delta) \ge -2$  $PI([F, G]) \ge PI(F) + PI(G) + 1$  $PI(\Delta) \ge -2$ 

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Higher-Order  $\Delta$  Operator, triangular form

$$\Delta = \sum_{n=-2}^{\infty} \sum_{m=0}^{n+2} \left(\frac{\hbar}{i}\right)^n \Delta_{n,m}$$

$$\Delta_{n,m} = \Delta_{n,m}^{A_1...A_m}(z) \overrightarrow{\partial}_{A_m} \cdots \overrightarrow{\partial}_{A_1}$$

 $\Delta_{0,2}$  original standard 2nd-order BV op.

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# Motivation

# 1. Closed SFT, higher antibrackets, $L_{\infty}$ , ... 2.

Operator Formalism

 $\longleftrightarrow$ 

Path Int. Formalism

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### Example: (Oversimplified) Point particle in curved space

Op. Formalism

$$\langle x_f | \exp \left\{ -\frac{i}{\hbar} \hat{H} \Delta t \right\} | x_i \rangle = \langle x_f, t_f | x_i, t_i \rangle$$

#### Path Int. Formalism

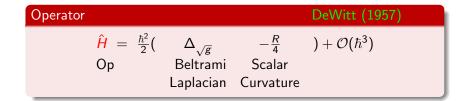
 $\sim$ 

$$\int_{x(t_i)=x_i}^{x(t_f)=x_f} [dx] [dp] \exp\left\{\frac{i}{\hbar} \int_{t_i}^{t_f} dt \left(p_A \dot{x}^A - H_{cl}\right)\right\}$$

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### Hamiltonian: Point particle in curved space

 $\leftrightarrow$ 

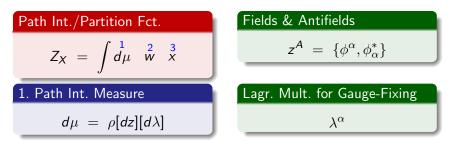


Function  
$$\frac{H_{cl}}{F_{ct}} = \frac{1}{2} p_A g^{AB} p_B$$
Fct

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# W-X Formalism



2. Gauge-generating QME

$$w \equiv e^{\frac{i}{\hbar}W}$$
  $(\Delta w) = 0$   $PI(W) \ge 0$ 

#### 3. Gauge-Fixing QME

$$x \equiv e^{\frac{i}{\hbar}X}$$
  $(\Delta^T x) = 0$   $PI(X) > 0$ 

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Transposed Operator (Int. by parts)

Transposed Operator  $F^{T}$ 

$$\int d\mu \ (F^T f) \ g = (-1)^{fF} \int d\mu \ f \ (Fg)$$

$$(F+G)^{T} = F^{T} + G^{T}$$

$$(z^{A})^{T} = z^{A}$$

$$(FG)^{T} = (-1)^{FG} G^{T} F^{T}$$

$$(\partial_{A})^{T} = -\rho^{-1} \overrightarrow{\partial}_{A} \rho$$

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### Transposed Operator (Int. by parts)

Affine Leibniz rule

$$\partial_A^T(fg) = (\partial_A^T f)g - (-1)^{Af}f(\partial_A g)$$

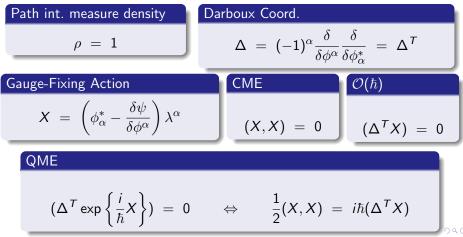
Transposed  $\Delta$  operator also nilpotent

$$(\Delta^T)^2 = 0$$

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Original 2nd-Order BV (Int. out  $\lambda \& \phi^*$ )



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### Original 2nd-Order BV



#### Path Int./Partition Fct.

$$Z_{\psi} = \int [d\phi] \exp\left\{rac{i}{\hbar} W(\phi, \phi^* = rac{\delta\psi}{\delta\phi}
ight\})$$

#### QME

$$(\Delta \exp\left\{\frac{i}{\hbar}W\right\}) = 0 \qquad \Leftrightarrow \qquad \frac{1}{2}(W,W) = i\hbar(\Delta W)$$

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# Independence of gauge-fixing in a higher-order BV formalism



2 Independence of Gauge-Fixing



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### Finite Deformation of Solution to QME

$$x \longrightarrow x' = \left(e^{[\Delta^T, \Psi]}x\right)$$
$$= x + \left([\Delta^T, \Psi]x\right) + \frac{1}{2}\left([\Delta^T, \Psi][\Delta^T, \Psi]x\right) + \dots$$

$$(\Delta^T x) = 0 \longrightarrow (\Delta^T x') = 0$$

#### Deformation generating operator

$$\Psi(\hbar,z,\partial)$$
  $\operatorname{Pl}(\Psi) \geq 0$   $\varepsilon(\Psi) = 1$ 

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### Infinitesimal Deformation of Solution to QME

$$\Delta^{T} \text{-closed}$$

$$(\Delta^{T} \delta x) = 0$$

$$\delta x = ([\Delta^{T}, \Psi]x) = (\Delta^{T} \Psi x)$$
Assumption

No  $\Delta^{T}$ -cohomology in pertinent sector

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### Independence of Gauge-Fixing: Int. by parts

Batalin, Damgaard & KB (1996)

$$\delta Z \equiv Z_{X+\delta X} - Z_X = \int d\mu \ w \ \delta x$$
$$= \int d\mu \ w \ (\Delta^T \Psi x) = \int d\mu \ (\Delta w) \ (\Psi x) = 0$$

#### Question

Int. by parts

Can we construct proof using change of int. var. instead?

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Homotopy operator  $\stackrel{\rightarrow}{h}^{A}(\Delta)$ 

 $\Delta$  operator

$$\Delta(\partial, z) = \sum_{m=0}^{\infty} \Delta_m(\partial, z)$$

#### Anti-normal order

$$\Delta_m(\partial, z) = \stackrel{\rightarrow}{\partial}_{A_m} \dots \stackrel{\rightarrow}{\partial}_{A_1} \Delta_m^{A_1 \dots A_m}(z)$$

#### Homotopy operator

 $\rightsquigarrow$  Extended by linearity

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### Homotopy Formula

$$(-1)^A \stackrel{\rightarrow}{\partial}_A \stackrel{\rightarrow}{h}^A (\Delta(\partial, z)) = \Delta(\partial, z) - \Delta(0, z)$$

$$\stackrel{\rightarrow A \rightarrow B}{h}_{h}(\Delta) = (-1)^{AB} \stackrel{\rightarrow B \rightarrow A}{h}_{h}(\Delta)$$

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Bilinear Homotopy Operator  $B^A(f, \Delta)$ 

$$(-1)^{Af} B^{A}(f, \Delta) = f : \frac{1}{1 - \overset{\leftarrow}{\partial}_{B}} \overset{\rightarrow}{h}^{F} : \overset{\rightarrow}{h}^{A}(\Delta) 1$$
  
$$\equiv f : \sum_{n=0}^{\infty} \left( \overset{\leftarrow}{\partial}_{B} \overset{\rightarrow}{h}^{B} \right)^{n} : \overset{\rightarrow}{h}^{A}(\Delta) 1$$
  
$$= f \underbrace{\overset{\rightarrow}{h}}_{n=0}^{A}(\Delta) 1 + \underbrace{(f \overset{\leftarrow}{\partial}_{B})}_{n=1} \overset{\rightarrow}{h} \overset{A}{h}(\Delta) 1$$
  
$$+ \underbrace{(f \overset{\leftarrow}{\partial}_{B} \overset{\rightarrow}{\partial}_{C})}_{n=2} \overset{\rightarrow}{h} \overset{\leftarrow}{h} \overset{A}{h}(\Delta) 1 + \dots$$

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### **Bilinear Homotopy Formula**

 $(-1)^{A}\left(\partial_{A}^{T}B^{A}(f,\Delta)\right) = (-1)^{f\Delta}(\Delta^{T}f) - f(\Delta 1)$ 

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### Infinitesimal change of Int. Variables

$$\delta z^{A} = \frac{1}{wx} B^{A}(\Psi x, \stackrel{\rightarrow}{\Delta} w)$$

 $\Psi$  infinitesimal & Grassmann-odd op.

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### Divergence

$$\operatorname{div}_{\rho_{WX}} \delta z = \frac{(-1)^{A}}{\rho_{WX}} (\overrightarrow{\partial}_{A} \rho_{XW} \, \delta z^{A}) = -\frac{(-1)^{A}}{w_{X}} (\overrightarrow{\partial}_{A}^{T} B^{A}(\Psi_{X}, \overrightarrow{\Delta}^{} w))$$
$$= \frac{1}{w_{X}} \left\{ (\Psi_{X}) \underbrace{(\Delta w)}_{=0} + w(\Delta^{T} \Psi_{X}) \right\} = \frac{\delta x}{x}$$

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### Independence of Gauge-Fixing

Change of Int. Variables  $z'^A = z^A + \delta z^A$ 

$$0 = \int [d\lambda] [dz'] \rho[z'] w[z'] x[z'] - \int [d\lambda] [dz] \rho[z] w[z] x[z]$$
$$= \int [d\lambda] [dz] (-1)^{A} (\overrightarrow{\partial}_{A} \rho x w \ \delta z^{A}) = \int d\mu w x \operatorname{div}_{\rho x w} \delta z$$
$$= \int d\mu w \ \delta x = Z_{X+\delta X} - Z_{X} \equiv \delta Z$$

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# Conclusions

- The formal higher-order BV path int/partition fct Z<sub>X</sub> does not depend on the gauge-fixing condition X.
- Proof either via int. by parts or change of int. variables.
- It is possible to generalize to BRST/anti-BRST Sp(2)-symmetric theories.
- Recently, finite BRST transformations have been considered by Batalin, Lavrov, Tyutin & KB.

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Classical 2nd-order case (from now on)

$\Delta$ Operator							
	$\Delta \;=\;$	$\Delta_{ ho}$	+	V	+	ν	
		Odd		Odd		Odd	
		Lapla-		vector		scalar	
		cian		field		curvature	

Nilpotent
$$\Delta^2 = 0$$

$$\begin{array}{l} {\sf Transposed} \\ {\sf \Delta}^{{\cal T}} \ = \ {\sf \Delta}_{\rho} - {\sf V} + \nu \end{array}$$

Classical 2nd-order case



$$\frac{1}{2}(W,W) + \frac{\hbar}{i}\left(\left(\Delta_{\rho} + V\right)W\right) + \left(\frac{\hbar}{i}\right)^{2}\nu = 0$$

$$\frac{1}{2}(X,X) + \frac{\hbar}{i}\left(\left(\Delta_{\rho} - V\right)X\right) + \left(\frac{\hbar}{i}\right)^{2}\nu = 0$$

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### **Q** BRST

$$\sigma_{W}f = (W, f) + \frac{\hbar}{i} \left( \left( \Delta_{\rho} + V \right) f \right)$$
  
$$\sigma_{X}f = (X, f) + \frac{\hbar}{i} \left( \left( \Delta_{\rho} - V \right) f \right)$$

$$\sigma_W^2 = 0$$

$$\sigma_X^2 = 0$$

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The Odd Scalar 1

Infinitesimal Change of Int. Var.

$$2 \,\delta z^{A} = \frac{i}{\hbar} \psi \, (\sigma_{W} z^{A} - \sigma_{X} z^{A}) - (\psi, z^{A})$$

 $\psi$  infinitesimal & Grassmann-odd fct.

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# The Odd Scalar $u_ ho$

	(KB 2006)
$ u_{ ho} \; := \;  u_{ ho}^{(0)} + rac{ u^{(1)}}{8} - rac{ u^{(2)}}{24} $	
$\nu_{\rho} := \nu_{\rho}^{+} + \frac{1}{8} - \frac{1}{24}$	

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# The Odd Scalar $\nu_{\rho}$

Odd Scalar in Antisymplectic Geometry

$$\nu_{\rho} := \nu_{\rho}^{(0)} + \frac{\nu^{(1)}}{8} - \frac{\nu^{(2)}}{24}$$

### Terms built from *E* and $\rho$

$$u^{(\mathbf{0})}_{
ho} := rac{1}{\sqrt{
ho}} (\Delta_1 \sqrt{
ho})$$

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# The Odd Scalar $\nu_{\rho}$

Odd Scalar in Antisymplectic Geometry(KB 2006) $u_{\rho} := \nu_{\rho}^{(0)} + \frac{\nu^{(1)}}{8} - \frac{\nu^{(2)}}{24}$ 

#### Terms built from E and $\rho$

$$\begin{split} \nu_{\rho}^{(0)} &:= \frac{1}{\sqrt{\rho}} (\Delta_1 \sqrt{\rho}) \\ \nu^{(1)} &:= (-1)^{\varepsilon_A} (\frac{\overrightarrow{\partial^{\ell}}}{\partial z^A} E^{AB} \frac{\overleftarrow{\partial^{r}}}{\partial z^B}) (-1)^{\varepsilon_B} \end{split}$$

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# The Odd Scalar $\nu_{\rho}$

Odd Scalar in Antisymplectic Geometry(KB 2006) $u_{\rho} := \nu_{\rho}^{(0)} + \frac{\nu^{(1)}}{8} - \frac{\nu^{(2)}}{24}$ 

#### Terms built from E and $\rho$

$$\nu_{\rho}^{(0)} := \frac{1}{\sqrt{\rho}} (\Delta_{1}\sqrt{\rho}) \\
\nu^{(1)} := (-1)^{\varepsilon_{A}} (\frac{\overrightarrow{\partial^{\ell}}}{\partial z^{A}} E^{AB} \frac{\overleftarrow{\partial^{r}}}{\partial z^{B}}) (-1)^{\varepsilon_{B}} \\
\nu^{(2)} := -(-1)^{\varepsilon_{B}} (\frac{\overrightarrow{\partial^{\ell}}}{\partial z^{A}} E_{BC}) (z^{C}, (z^{B}, z^{A}))$$

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# The Odd Scalar $\nu_{\rho}$

Terms built from E and  $\rho$ 

$$\begin{split} \nu_{\rho}^{(0)} &:= \frac{1}{\sqrt{\rho}} (\Delta_{1}\sqrt{\rho}) \\ \nu^{(1)} &:= (-1)^{\varepsilon_{A}} (\frac{\overrightarrow{\partial^{\ell}}}{\partial z^{A}} E^{AB} \frac{\overleftarrow{\partial^{r}}}{\partial z^{B}}) (-1)^{\varepsilon_{B}} \\ \nu^{(2)} &:= -(-1)^{\varepsilon_{B}} (\frac{\overrightarrow{\partial^{\ell}}}{\partial z^{A}} E_{BC}) (z^{C}, (z^{B}, z^{A})) \\ &= (-1)^{\varepsilon_{A} \varepsilon_{D}} (\frac{\overrightarrow{\partial^{\ell}}}{\partial z^{D}} E^{AB}) E_{BC} (E^{CD} \frac{\overleftarrow{\partial^{r}}}{\partial z^{A}} E^{AB}) \end{split}$$

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# Odd scalar curvature

- $\nu_{\rho}$  is constructed from antisymplectic structure  $E^{AB}$  and  $\rho$ .
- $\nu_{\rho}$  transforms as a scalar.
- $\nu_{\rho} = 0$  can be viewed as a compatibility condition between  $E^{AB}$  and  $\rho$ .
- $\nu_{\rho}=-\frac{R}{8}$  is an odd scalar curvature for any tangent space connection, that is
  - torsionfree,
  - antisymplectic,
  - $\bigcirc$  compatible with  $\rho$ .

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