Curved Yang-Mills gauge theories and their recent applications

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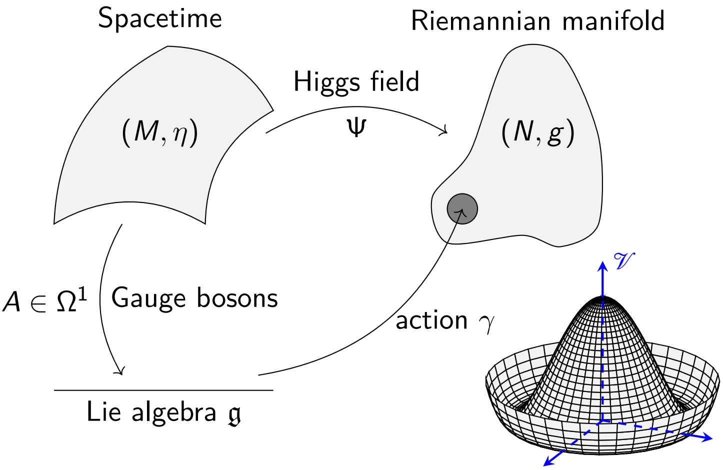
Infinitesimal Version

Infinitesimal curved Yang-Mills-Higgs gauge theory



Guide: Infinitesimal curved Yang-Mills-Higgs gauge theory

Classical formalism	CYMH GT
Lie algebra $\mathfrak{g}$ as $M \times \mathfrak{g}$	Lie algebroid $E \to N$
$\mathfrak{g}$-action γ	Anchor ρ of E & E-connections
Canonical flat connection ∇^0 on $M \times \mathfrak{g}$	General connection ∇ on E

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Remarks (Why a "curved theory"?)

Usually, the field strength F is given by (abelian, for simplicity)

$$F := \mathrm{d}A = \mathrm{d}^{\nabla^0} A.$$

$\rightsquigarrow$ We will use a general connection ∇ instead of ∇^0, and ∇ may not be flat.

Definition (Lie algebroids)

Let $E \to N$ be a vector bundle. Then E is a Lie algebroid, if there is a bundle map $\rho : E \to \mathrm{T}N$, called the **anchor**, and a Lie algebra structure on $\Gamma(E)$ with Lie bracket $[\cdot,\cdot]_E$ satisfying

$$[\mu, f\nu]_E = f[\mu,\nu]_E + \mathscr{L}_{\rho(\mu)}(f)\ \nu \qquad (1)$$

for all $f \in C^\infty(N)$ and $\mu, \nu \in \Gamma(E)$.

Example

- $E = \mathrm{T}N$, $\rho = \mathbb{1}_{\mathrm{T}N}$

Sources: Ana Cannas Da Silva, Alan Weinstein. *Geometric models for noncommutative algebras*, volume 10. American Mathematical Society, 1999.

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The classical formalism will correspond to:

Proposition (Action Lie algebroids)

*Let $\left(\mathfrak{g}, [\cdot,\cdot]_{\mathfrak{g}}\right)$ be a Lie algebra with a $\mathfrak{g}$-action γ on N. Then there is a **unique** Lie algebroid structure on $E := N \times \mathfrak{g}$ as a vector bundle over N such that*

$$\rho(\nu) = \gamma(\nu), \tag{2}$$

$$[\mu, \nu]_E = [\mu, \nu]_{\mathfrak{g}} \tag{3}$$

for all constant sections $\mu, \nu \in \Gamma(E)$.

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Example (E-connection ${}^E\nabla$ on V)

∇' a vector bundle connection on $V \to N$, then

$$ {}^E\nabla_\nu v := \nabla'_{\rho(\nu)} v \tag{4} $$

for all $\nu \in \Gamma(E)$ and $v \in \Gamma(V)$. In short denoted by ∇'_ρ.

Sources
Mohamed Boucetta. Riemannian geometry of Lie algebroids. *Journal of the Egyptian Mathematical Society*, 19(1-2):57–70, 2011.

Example

For ∇ a connection on E we have the **basic connection** given as a pair of E-connections on E and on $\mathrm{T}N$ by

$$\nabla^{\mathrm{bas}}_{\nu}\mu := [\nu, \mu]_E + \nabla_{\rho(\mu)}\nu, \tag{5}$$

$$\nabla^{\mathrm{bas}}_{\nu}X := [\rho(\nu), X] + \rho(\nabla_X \nu) \tag{6}$$

for all $X \in \mathfrak{X}(N)$ and $\nu, \mu \in \Gamma(E)$.

Remarks (Encoding of Lie algebra representations)

Test this with trivial bundles and canonical flat connection ∇^0, *i.e.* $E = N \times \mathfrak{g}$ and $\nabla^0\nu = 0$ for constant sections ν.

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Definition (Basic curvature)

Let ∇ be a connection on E. The **basic curvature** $R^{\mathrm{bas}}_{\nabla}$ is defined as an element of $\Gamma\left(\bigwedge^2 E^* \otimes \mathrm{T}^*N \otimes E\right)$ by

$$R^{\mathrm{bas}}_{\nabla}(\mu,\nu)X := \nabla_X([\mu,\nu]_E) - [\nabla_X\mu,\nu]_E - [\mu,\nabla_X\nu]_E - \nabla_{\nabla^{\mathrm{bas}}_{\nu}X}\mu + \nabla_{\nabla^{\mathrm{bas}}_{\mu}X}\nu, \tag{7}$$

where $\mu,\nu \in \Gamma(E)$ and $X \in \mathfrak{X}(N)$.

Proposition

We recover the curvature of the basic connection:

$$R_{\nabla^{\mathrm{bas}}} = \begin{cases} -R^{\mathrm{bas}}_{\nabla}(\cdot,\cdot)\circ\rho, & \textit{on } E, \\ -\rho\circ R^{\mathrm{bas}}_{\nabla}, & \textit{on } \mathrm{T}N. \end{cases} \tag{8}$$

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Fields are a pair consisting of:

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Definition (Minimal coupling)

Minimal coupling $\mathfrak{D}$, $(\Phi, A) \mapsto \mathfrak{D}(\Phi, A) \in \Omega^1(M; \Phi^* \mathrm{T}N)$, by

$$\mathfrak{D}(\Phi, A) \coloneqq \mathfrak{D}^A \Phi \coloneqq \mathrm{D}\Phi - (\Phi^* \rho)(A), \tag{9}$$

where $\mathrm{D}\Phi : \mathrm{T}M \to \mathrm{T}N$ is the tangent map.

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Definition (Field strength)

Let ∇ be a connection on E. We define the **field strength** F, $(\Phi, A) \mapsto F(\Phi, A) \in \Omega^2(M; \Phi^* E)$, by

$$F(\Phi, A) := \mathrm{d}^{\Phi^*\nabla} A + \frac{1}{2}(\Phi^* t_{\nabla^{\mathrm{bas}}})(A \overset{\wedge}{,} A), \tag{10}$$

where $t_{\nabla^{\mathrm{bas}}}$ is the torsion of ∇^{bas} on E and $\mathrm{d}^{\Phi^*\nabla}$ the exterior covariant derivative of $\Phi^*\nabla$.

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Definition (Generalised field strength)

Let ζ be an element of $\Omega^2(N; E)$, then we define the **generalised field strength** $\mathscr{F}$ by

$$\mathscr{F}(\Phi, A) := F(\Phi, A) + \frac{1}{2}(\Phi^*\zeta)\left(\mathfrak{D}^A \Phi \overset{\wedge}{,} \mathfrak{D}^A \Phi\right). \tag{11}$$

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Definition (Curved Yang-Mills-Higgs (CYMH) Lagrangian)

Let κ be a fibre metric on E, then the **curved Yang-Mills-Higgs Lagrangian** $\mathfrak{L}_{\mathrm{CYMH}}$, $(\Phi, A) \mapsto \mathfrak{L}_{\mathrm{CYMH}}(\Phi, A) \in \Omega^{\dim(M)}(M)$, is defined by

$$\mathfrak{L}_{\mathrm{CYMH}}(\Phi, A) := -\frac{1}{2}(\Phi^*\kappa)\big(\mathscr{F}(\Phi, A) \overset{\wedge}{,} *\mathscr{F}(\Phi, A)\big) + (\Phi^*g)\left(\mathfrak{D}^A\Phi \overset{\wedge}{,} *\mathfrak{D}^A\Phi\right) - *(\Phi^*\mathscr{V}), \quad (12)$$

where $*$ is the Hodge star operator related to the spacetime metric η.

Definition (CYMH GT)

Assume we have additionally the **compatibility conditions**

$$R_\nabla + \mathrm{d}^{\nabla^{\mathrm{bas}}} \zeta = 0, \tag{13}$$

$$R_\nabla^{\mathrm{bas}} = 0, \tag{14}$$

$$\nabla^{\mathrm{bas}} \kappa = 0, \tag{15}$$

$$\nabla^{\mathrm{bas}} g = 0, \tag{16}$$

$$\mathscr{L}_\rho \mathscr{V} = 0, \tag{17}$$

then we say that we have a **curved Yang-Mills-Higgs gauge theory**.

We say that we have a **pre-classical gauge theory**, if ∇ is flat.

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Summary

$$\begin{tikzcd}
\Phi^*E \arrow[d] & (E, [\cdot,\cdot]_E, \kappa, \nabla) \arrow[d] \arrow[dr, "\rho"] & \\
M \arrow[r, "\Phi"] & (N, g) & \mathrm{T}N \arrow[l] \arrow[ul, bend right, "\zeta \in \Omega^2"']
\end{tikzcd}$$

$\rightsquigarrow$ Together with the compatibility conditions we have gauge invariance, that is,

$$\delta_\varepsilon \mathfrak{L}_{\mathrm{CYMH}} = 0. \tag{18}$$

Remarks ([S.-R. F.])

If $\rho \equiv 0$, then $\varepsilon \in \Gamma(\Phi^* E)$ and

$$\delta_\varepsilon \Phi = 0, \qquad \delta_\varepsilon A = [\varepsilon, A]_E - \mathrm{d}^{\Phi^*\nabla} \varepsilon.$$

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Motivation

- Are there CYMH GTs which are neither pre-classical nor classical?
- Difficulty: There is an equivalence relation of CYMH GTs keeping the same Lagrangian and preserving the physics, possibly turning theories into (pre-)classical ones.

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Definition (Field redefinition, [S.-R. F.])

Let $\lambda \in \Omega^1(N; E)$ such that $\Lambda := \mathbb{1}_E - \lambda \circ \rho$ is an automorphism of E. We then define the **field redefinitions** by

$$\widetilde{A}^\lambda := (\Phi^*\Lambda)(A) + \Phi^!\lambda, \tag{19}$$

$$\widetilde{\nabla}^\lambda := \nabla + \left(\Lambda \circ \mathrm{d}^{\nabla^{\mathrm{bas}}} \circ \Lambda^{-1}\right)\lambda, \tag{20}$$

$$\widetilde{\kappa}^\lambda := \kappa \circ \left(\Lambda^{-1}, \Lambda^{-1}\right), \tag{21}$$

$$\widetilde{g}^\lambda := g \circ \left(\widehat{\Lambda}^{-1}, \widehat{\Lambda}^{-1}\right), \tag{22}$$

where $\widehat{\Lambda} := \mathbb{1}_{\mathrm{T}N} - \rho \circ \lambda$, and for all $X, Y \in \mathfrak{X}(N)$ we also define

$$\widetilde{\zeta}^\lambda\left(\widehat{\Lambda}(X), \widehat{\Lambda}(Y)\right)$$
$$:= \Lambda(\zeta(X, Y)) - \left(\mathrm{d}^{\widetilde{\nabla}^\lambda}\lambda\right)(X, Y) + t_{\widetilde{\nabla}^\lambda_\rho}(\lambda(X), \lambda(Y)). \tag{23}$$

Proposition ([S.-R. F.])

- *Field redefinitions define an equivalence relation of CYMH gauge theories*
- $\widetilde{\mathfrak{L}}^{\lambda}_{\mathrm{CYMH}} = \mathfrak{L}_{\mathrm{CYMH}}$

Let us now apply a field redefinition in order to study whether ∇ and ζ can become flat and zero, respectively.

Proposition ([S.-R. F.])

- *Field redefinitions define an equivalence relation of CYMH gauge theories*
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What happens in the case of Lie algebra bundles?

Example (Lie algebra bundles (LABs))

- $E = \mathcal{g}$ an LAB ($\rho \equiv 0$) with a field of Lie brackets $[\cdot,\cdot]_{\mathcal{g}} \in \Gamma\left(\bigwedge^2 \mathcal{g}^* \otimes \mathcal{g}\right)$ which restricts to the bracket of a given Lie algebra $\mathfrak{g}$

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- We need

$$\nabla_Y\left([\mu, \nu]_{\mathcal{g}}\right) = [\nabla_Y \mu, \nu]_{\mathcal{g}} + [\mu, \nabla_Y \nu]_{\mathcal{g}}, \qquad (24)$$

$$R_{\nabla}(Y, Z)\mu = [\zeta(Y, Z), \mu]_{\mathcal{g}} \qquad (25)$$

for all $Y, Z \in \mathfrak{X}(N)$ and $\mu, \nu \in \Gamma(\mathcal{g})$.

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Theorem (Invariant for LABs, [S.-R. F.])

We have

$$\mathrm{d}^{\widetilde{\nabla}^\lambda}\widetilde{\zeta}^\lambda = \mathrm{d}^\nabla\zeta, \tag{26}$$

and $\mathrm{d}^\nabla\zeta$ *has values in the centre of* $\mathcal{g}$.

Behaviour of the field redefinition of ζ

Theorem (Existence of non-classical theories, [S.-R. F.])

If $\mathrm{d}^\nabla \zeta \neq 0$, then there is no field redefinition such that $\widetilde{\zeta}^\lambda = 0$.

Remarks

Starting with a classical theory:
If $\dim(N) \geq 3$ and if Lie algebra $\mathfrak{g}$ has a non-zero centre, then we can always construct a pre-classical CYMH GT which is not a classical one by adding a ζ with $\mathrm{d}^\nabla \zeta \neq 0$.

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However, by $R_\nabla = \mathrm{ad}_{\mathscr{g}} \circ \zeta$ it may still be that ∇ becomes flat.

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Turning to the field redefinition of ∇:

Theorem (Differential on centre-valued forms, [S.-R. F.])

∇ restricts to the centre of $\mathscr{g}$ and induces a differential d^{Ξ} on centre-valued forms. Moreover, d^{Ξ} is independent of the field redefinitions.

Sketch of proof.

Recall

$$\nabla_Y\left([\mu,\nu]_{\mathscr{g}}\right) = [\nabla_Y\mu,\nu]_{\mathscr{g}} + [\mu,\nabla_Y\nu]_{\mathscr{g}},$$
$$R_\nabla(Y,Z)\mu = [\zeta(Y,Z),\mu]_{\mathscr{g}},$$
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Theorem (Closedness of $\mathrm{d}^{\nabla}\zeta$, [S.-R. F.])

We have

$$\mathrm{d}^{\Xi}\mathrm{d}^{\nabla}\zeta = 0. \tag{27}$$

Definition (Obstruction class, [S.-R. F.])

We define the **obstruction class** by

$$\mathrm{Obs}(\Xi) := \left[\mathrm{d}^{\nabla}\zeta\right]_{\mathrm{d}^{\Xi}}. \tag{28}$$

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Proposition ([S.-R. F.])

- *An invariant of the field redefinitions.*
- *If ∇ flat, then $\mathrm{Obs}(\Xi) = 0$.*

Theorem (Closedness of $\mathrm{d}^{\nabla}\zeta$, [S.-R. F.])

We have

$$\mathrm{d}^{\Xi}\mathrm{d}^{\nabla}\zeta = 0. \tag{27}$$

Definition (Obstruction class, [S.-R. F.])

We define the **obstruction class** by

$$\mathrm{Obs}(\Xi) := \left[\mathrm{d}^{\nabla}\zeta\right]_{\mathrm{d}^{\Xi}}. \tag{28}$$

Proposition ([S.-R. F.])

- *An invariant of the field redefinitions.*
- *If ∇ flat, then $\mathrm{Obs}(\Xi) = 0$.*

Theorem (Obstruction for non-pre-classical theories, [S.-R. F.])

If $\mathrm{Obs}(\Xi) \neq 0$*, then there is no field redefinition such that* $\widetilde{\nabla}^{\lambda}$ *is flat.*

Theorem (Locally always pre-classical)

If N *is contractible, then there is a field redefinition such that* $\widetilde{\nabla}^{\lambda}$ *is flat.*

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Second theorem follows as a result by K. Mackenzie (General Theory of Lie Groupoids and Algebroids. *London Mathematical Society Lecture Note Series*, 213, 2005). Mackenzie derived $\mathrm{Obs}(\Xi)$ in the context of extending Lie algebroids by LABs.

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Example (Zero obstruction class not necessarily pre-classical)

Let P be the Hopf fibration

$$\begin{tikzcd} \mathrm{SU}(2) \arrow[r] & \mathbb{S}^7 \arrow[d] \\ & \mathbb{S}^4 \end{tikzcd}$$

Then for the adjoint bundle

$$\mathcal{g} := P \times_{\mathrm{SU}(2)} \mathfrak{su}(2) := \left(\mathbb{S}^7 \times \mathfrak{su}(2)\right) \Big/ \mathrm{SU}(2)$$

we have a non-flat ∇ satisfying the compatibility conditions such that all of its field redefinitions are not flat either, but $\mathrm{Obs}(\Xi) = 0$.

K. Mackenzie. General Theory of Lie Groupoids and Algebroids.
London Mathematical Society Lecture Note Series, 213, 2005.

Summary

Remarks

Locally, LABs are always pre-classical but not necessarily classical. In general, $\mathrm{Obs}(\Xi) = 0$ does not imply a flat connection.

So, what actually happens in the adjoint bundle of $\mathbb{S}^7 \to \mathbb{S}^4$?

$\rightsquigarrow$ Integration

Summary

Remarks

Locally, LABs are always pre-classical but not necessarily classical.
In general, $\mathrm{Obs}(\Xi) = 0$ does not imply a flat connection.

So, what actually happens in the adjoint bundle of $\mathbb{S}^7 \to \mathbb{S}^4$?
$\rightsquigarrow$ Integration

Integrated Version

We will only focus on Yang-Mills theories:

	Classical	Curved
Infinitesimal	Lie algebra $\mathfrak{g}$	LAB[1] $\mathscr{g}$
Integrated	Lie group G	LGB[2] $\mathscr{G}$

$$
\begin{tikzcd}
G \arrow[r] & \mathscr{G} \arrow[d] \\
 & M
\end{tikzcd}
$$

[1]LAB = Lie algebra bundle
[2]LGB = Lie group bundle

Definition (LGB actions, simplified)

$$\begin{array}{ccc} & & \mathscr{G} \\ & & \downarrow \\ \mathscr{P} & \xrightarrow{\pi} & M \end{array}$$

$\mathscr{P} \xrightarrow{\pi} M$ a fibre bundle. A **right-action of $\mathscr{G}$ on $\mathscr{P}$** is a smooth map $\mathscr{P} * \mathscr{G} := \pi^* \mathscr{G} = \mathscr{P} \times_M \mathscr{G} \to \mathscr{P}$, $(p, g) \mapsto p \cdot g$, satisfying the following properties:

$$\pi(p \cdot g) = \pi(p), \tag{29}$$

$$(p \cdot g) \cdot h = p \cdot (gh), \tag{30}$$

$$p \cdot e_{\pi(p)} = p \tag{31}$$

for all $p \in \mathscr{P}$ and $g, h \in \mathscr{G}_{\pi(p)}$, where $e_{\pi(p)}$ is the neutral element of $\mathscr{G}_{\pi(p)}$.

K. Mackenzie. General Theory of Lie Groupoids and Algebroids. *London Mathematical Society Lecture Note Series*, 213, 2005.

Definition (Principal bundle)

Still a fibre bundle

$$\begin{array}{ccc} G & \longrightarrow & \mathscr{P} \\ & & \downarrow{\scriptstyle\pi} \\ & & M \end{array}$$

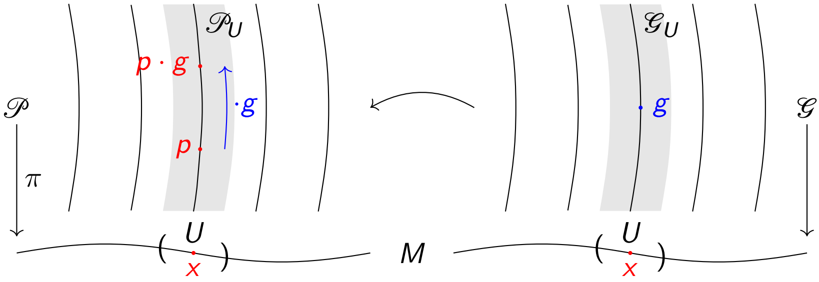
but with $\mathscr{G}$-action

$$\underset{\mathscr{P} * \mathscr{G}}{\cancel{\mathscr{P} \times G}} \rightarrow \mathscr{P}$$

simply transitive on fibres of $\mathscr{P}$, and "suitable" atlas.

Ieke Moerdijk, Janez Mrcun. Introduction to Foliations and Lie Groupoids.
Cambridge Studies in Advanced Mathematics 91, Cambridge University Press, Cambridge, 2003

Connection on $\mathscr{P}$: Idea



But:

$$r_g : \mathscr{P}_x \to \mathscr{P}_x$$

$$\Rightarrow \qquad \mathrm{D}_p r_g \text{ only defined on vertical structure}$$

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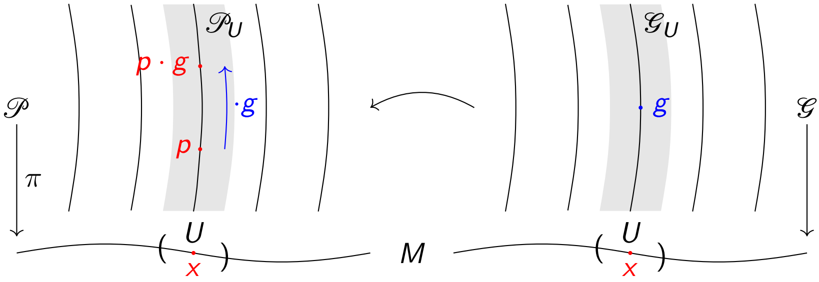

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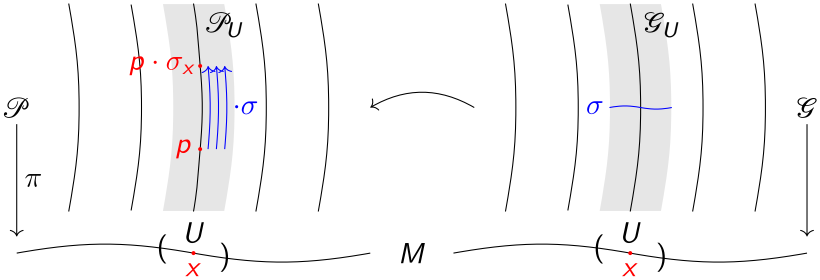
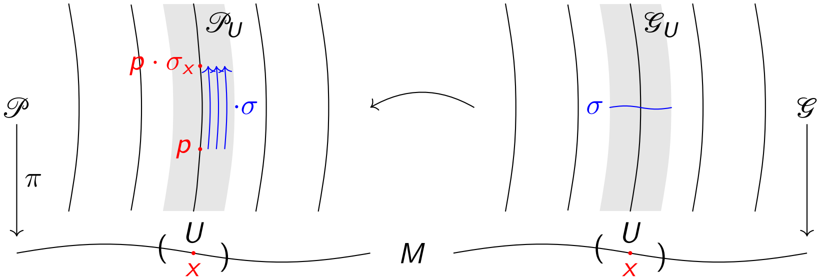


$$\text{Use } \sigma \in \Gamma(\mathscr{G}) : r_\sigma(p) := p \cdot \sigma_x$$

Remarks (Problem!)

Ambiguity in the choice of $\sigma \Rightarrow$ Fix a horizontal distribution

Connection on $\mathscr{P}$: Idea



Use $\sigma \in \Gamma(\mathscr{G}) : r_\sigma(p) := p \cdot \sigma_x$

Remarks (Problem!)

Ambiguity in the choice of $\sigma \Rightarrow$ Fix a horizontal distribution

Definition (Fundamental vector fields)

Fundamental vector fields defined by

$$\overline{\nu}_p := \left.\frac{\mathrm{d}}{\mathrm{d}t}\right|_{t=0} \left(p \cdot \mathrm{e}^{t\nu_x}\right)$$

for all $\nu \in \Gamma(\mathscr{g})$ and $p \in \mathscr{P}_x$, where $\mathscr{g}$ is the LAB of $\mathscr{G}$.

Straightforward generalization of classical definition as in: Mark JD Hamilton. Mathematical Gauge Theory. *Springer*, 2017.

Definition (Darboux derivative)

For $\sigma \in \Gamma(\mathscr{G})$ we define the **Darboux derivative** $\Delta\sigma \in \Omega^1(M; \mathscr{g})$

$$\Delta\sigma = \sigma^! \mu_{\mathscr{G}},$$

where $\mu_{\mathscr{G}}$ is given by

$$\left(\mu_{\mathscr{G}}\right)_g := \mathrm{D}_g L_{g^{-1}} \circ \pi^{v},$$

π^{v} the projection onto the vertical bundle.

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π^{v} the projection onto the vertical bundle.

Remarks

If $\mathscr{G}$ a trivial LGB with canonical flat connection and if Lie group additionally a matrix group, then

$$\Delta\sigma = \sigma^{-1}\mathrm{d}\sigma.$$

Sources

Trivial generalization of classical definition as in: K. Mackenzie. General Theory of Lie Groupoids and Algebroids. *London Mathematical Society Lecture Note Series*, 213, 2005.

Definition (Modified right-pushforward, [S.-R. F.])

Define

$$\mathscr{r}_{g*}(X) := \mathrm{D}_p r_\sigma(X) - \overline{(\pi^! \Delta\sigma)|_p(X)}\Big|_{p \cdot g}$$

for all $(p, g) \in \mathscr{P}_x \times \mathscr{G}_x$ and $X \in \mathrm{T}_p\mathscr{P}$, where σ is any section of $\mathscr{G}$ with $\sigma_x = g$.

Proposition (Well-defined isomorphism, [S.-R. F.])

We have that

$$\begin{aligned} \mathrm{T}\mathscr{P}|_{\mathscr{P}_x} &\to \mathrm{T}\mathscr{P}|_{\mathscr{P}_x}, \\ X &\mapsto \mathscr{r}_{g*}(X), \end{aligned}$$

is a well-defined automorphism over r_g.

Definition (Ehresmann connection, [S.-R. F.])

H a horizontal distribution of $\mathrm{T}\mathscr{P}$ with

$$\mathscr{r}_{g*}(H_p) = H_{p \cdot g}$$

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Definition (Equivalently: Connection 1-form, [S.-R. F.])

$A \in \Omega^1(\mathscr{P}; \pi^* \mathscr{g})$ with

$$A(\overline{\nu}) = \pi^* \nu,$$
$$\mathscr{r}_\sigma^! A = \mathrm{Ad}_{\sigma^{-1}} \circ A$$

for all $\sigma \in \Gamma(\mathscr{G})$ and $\nu \in \Gamma(\mathscr{g})$.

Remarks

$$\left(\mathscr{r}_\sigma^! A\right)_p (X) = A_{p\sigma_x}\left(\mathscr{r}_{\sigma_x *}(X)\right).$$

Proposition (Connection on $\mathscr{g}$, [S.-R. F.])

We have an induced vector bundle connection on $\mathscr{g}$ given by

$$\nabla^{\mathscr{G}}\nu := \left.\frac{\mathrm{d}}{\mathrm{d}t}\right|_{t=0} \Delta \mathrm{e}^{t\nu}.$$

Sources: Similar construction as in: Camille Laurent-Gengoux, Mathieu Stiénon, and Ping Xu. Non-abelian differentiable gerbes. *Advances in Mathematics*, 220(5):1357–1427, 2009.

Remarks

Recall, $\mathscr{G}$ a principal $\mathscr{G}$-bundle.

Definition (Compatibility conditions, [S.-R. F.])

$\mu_{\mathscr{G}}$ a **Yang-Mills connection (w.r.t. $\zeta \in \Omega^2(M; \mathscr{g})$)** if it satisfies the **compatibility conditions**:

1. $\mu_{\mathscr{G}}$ a connection 1-form on $\mathscr{G} \xrightarrow{\pi_{\mathscr{G}}} M$;
2. $\mu_{\mathscr{G}}$ satisfies the **generalised Maurer-Cartan equation**

$$\left(\mathrm{d}^{\pi_{\mathscr{G}}^{*}\nabla^{\mathscr{G}}}\mu_{\mathscr{G}} + \frac{1}{2}[\mu_{\mathscr{G}} \stackrel{\wedge}{,} \mu_{\mathscr{G}}]_{\pi_{\mathscr{G}}^{*}\mathscr{g}}\right)\Big|_g = \mathrm{Ad}_{g^{-1}} \circ \pi_{\mathscr{G}}^{!}\zeta\Big|_g - \pi_{\mathscr{G}}^{!}\zeta\Big|_g$$

Proposition ($\nabla^{\mathscr{G}}$ a Lie bracket derivation)

Let $\mu_{\mathscr{G}}$ be a connection 1-form on $\mathscr{G}$, then

$$\nabla^{\mathscr{G}}\left([\mu,\nu]_{\mathscr{g}}\right) = \left[\nabla^{\mathscr{G}}\mu,\nu\right]_{\mathscr{g}} + \left[\mu,\nabla^{\mathscr{G}}\nu\right]_{\mathscr{g}}.$$

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Theorem (Curvature of LAB connection exact, [S.-R. F.])

$\mu_{\mathscr{G}}$ satisfies the generalized Maurer-Cartan equation w.r.t. ζ if and only if

$$R_{\nabla^{\mathscr{G}}} = \mathrm{ad}\circ\zeta.$$

Sources For the first statement: Camille Laurent-Gengoux, Mathieu Stiénon, and Ping Xu. Non-abelian differentiable gerbes. *Advances in Mathematics*, 220(5):1357–1427, 2009.

Remarks

Both compatibility conditions are related to a cohomology, that is:

1. μ_g closed
2. Curvature of μ_g exact with primitive ζ

Given a Yang-Mills connection on $\mathscr{G}$:

Definition (Generalized curvature/field strength F of A, [S.-R. F.])

We define

$$F := \mathrm{d}^{\pi^*\nabla^{\mathscr{G}}} A + \frac{1}{2}[A \stackrel{\wedge}{,} A]_{\pi^*\mathscr{g}} + \pi^! \zeta.$$

Proposition (Properties of F, [S.-R. F.])

- $F(X, \cdot) = 0$, *if* X *vertical,*
- $\mathcal{r}^!_\sigma F = \mathrm{Ad}_{\sigma^{-1}} \circ F$.

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Theorem (Gauge transformation, [S.-R. F.])

Let s_i, s_j *be two sections of* $\mathscr{P}$ *over* U_i *and* U_j, *respectively, which are open subsets of* M *with* $U_i \cap U_j \neq \emptyset$. *Then over* $U_i \cap U_j$

$$F_{s_i} = \mathrm{Ad}_{\sigma_{ji}^{-1}} \circ F_{s_j},$$

where $F_{s_i} := s_i^! F$ *and* σ_{ji} *a section of* $\mathscr{G}$ *with* $s_i = s_j \cdot \sigma_{ji}$.

Theorem (Lagrangian, [S.-R. F.])

- *κ be an Ad-invariant fibre metric on $\mathscr{g}$,*
- *M a spacetime, and $*$ its Hodge star operator,*
- *$(U_i)_i$ open covering of M with subordinate gauges $s_i \in \Gamma(\mathscr{P}|_{U_i})$.*

Then the Lagrangian $\mathfrak{L}_{\mathrm{CYM}}[A]$, defined locally by

$$\left(\mathfrak{L}_{\mathrm{CYM}}[A]\right)\big|_{U_i} := -\frac{1}{2}\kappa(F_{s_i} \overset{\wedge}{,} *F_{s_i}),$$

is well-defined, and

$$\mathfrak{L}_{\mathrm{CYM}}\left[L^! A\right] = \mathfrak{L}_{\mathrm{CYM}}[A]$$

for all principal bundle automorphisms L.

Back to the roots

1. $\mathscr{G} \cong M \times G$
2. Equip $\mathscr{G}$ with canonical flat connection
3. $\zeta \equiv 0$

Example (Hopf fibration $\mathbb{S}^7 \to \mathbb{S}^4$, [S.-R. F.])

Let P be the Hopf bundle

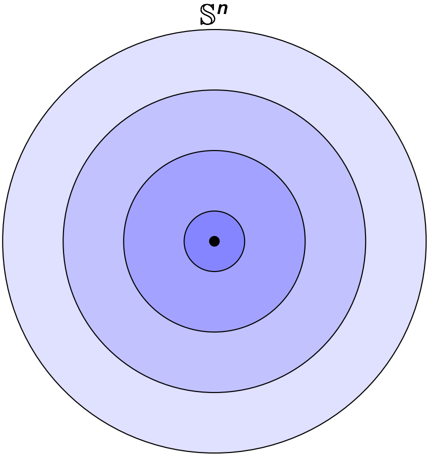
$$
\begin{tikzcd}
\mathrm{SU}(2) \cong \mathbb{S}^3 \arrow[r] & \mathbb{S}^7 \arrow[d] \\
& \mathbb{S}^4
\end{tikzcd}
$$

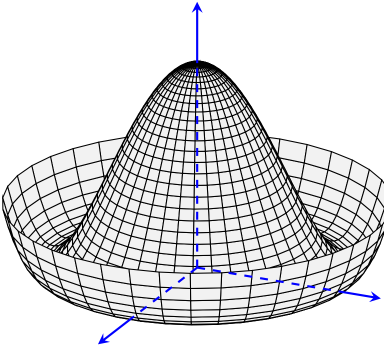
Define $\mathscr{P} := \mathscr{G}$ as the inner group bundle of P,

$$\mathscr{G} := c_{\mathrm{SU}(2)}(P) := \left(P \times \mathrm{SU}(2)\right)\Big/\mathrm{SU}(2).$$

This principal $c_{\mathrm{SU}(2)}(P)$-bundle admits the structure as curved Yang-Mills gauge theory; there is no description as classical gauge theory.

Applications: Singular foliations
(joint work w/ Camille Laurent-Gengoux)





Right diagram made by Mark J.D. Hamilton.

Singular Foliations:

- Gauge Theory
  (Ex.: Singular foliation $\leftrightarrow$ Symmetry breaking $\rightarrow$ Higgs mechanism)
- Poisson Geometry
  (Singular foliation of symplectic leaves)
- Lie groupoids and algebroids
- Dirac structures
- Generalised complex manifolds
- Non-commutative geometry
- ...

Definition (Smooth singular foliation)

A **smooth singular foliation** $\mathscr{F}$ on a smooth manifold is a subspace of $\mathfrak{X}_c(M)$ so that

- it is **involutive**,
- it is **stable under** $C^\infty(M)$**-multiplication**,
- it is **locally finitely generated**.

Sources
Peter Stefan, Accessible sets, orbits, and foliations with singularities. *Proc. London Math. Soc.*, 29, 1974.
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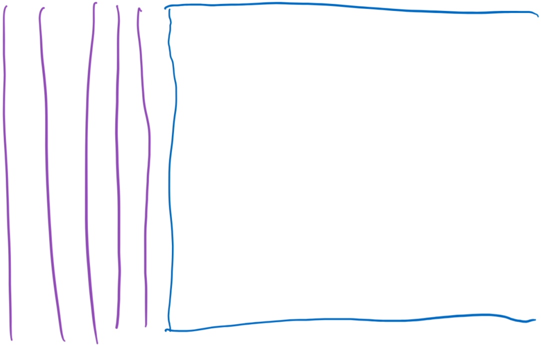
- it is **stable under** $C^\infty(M)$**-multiplication**, *i.e.* $fX \in \mathscr{F}$ *for all* $f \in C^\infty(M)$ *and* $X \in \mathscr{F}$,
- it is **locally finitely generated**, *i.e. around each* $p \in M$ *there is an open neighbourhood* U *and a finite family* $(X^i)_i^r$ $(X^i \in \mathscr{F})$ *such that for all* $X \in \mathscr{F}$ *there are* $f_i \in C^\infty(M)$ *satisfying on* U.

$$X = \sum_i f_i X^i.$$

Sources
Peter Stefan, Accessible sets, orbits, and foliations with singularities. *Proc. London Math. Soc.*, 29, 1974.
Héctor J. Sussmann, Orbits of families of vector fields and integrability of distributions. *Trans. Amer. Math. Soc.*, 180, 1973

Remarks (Leaves)

Following the flows in $\mathscr{F}$, this gives rise to a partition of connected immersed submanifolds in M.



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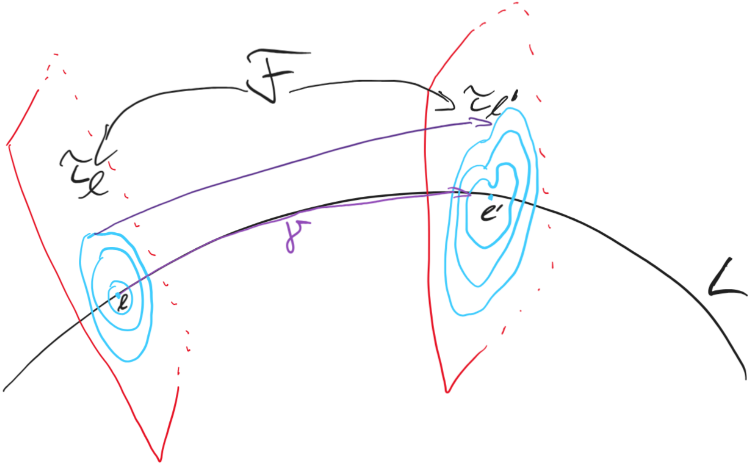
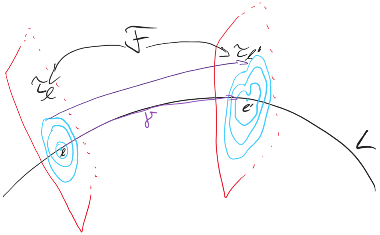
Idea: Relation to gauge theory



Camille Laurent-Gengoux and Leonid Ryvkin, The holonomy of a singular leaf, *Selecta Mathematica 28*, no. 2, 45, 2022.



Theorem ($\mathscr{F}$-connections)

There is a connection on the normal bundle of a leaf L:

- *Horizontal vector fields are in $\mathscr{F}$.*
- *Parallel transport PT_γ has values in $\mathrm{Sym}(\tau_l, \tau_{l'})$.*
- *For a contractible loop γ_0 at l: PT_{γ_0} values in $\mathrm{Inner}(\tau_l)$.*

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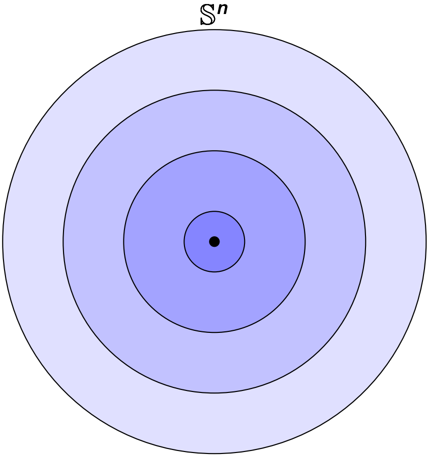
Example of a transverse foliation τ:

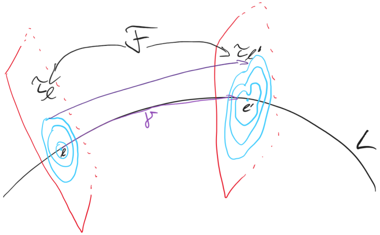


Remarks

- $\mathrm{Inner}(\tau_I)$ maps each circle to itself
- $\mathrm{Sym}(\tau_I)$ allows to exchange circles
- Both preserve τ_I and fix the origin

Camille Laurent-Gengoux and Leonid Ryvkin, The holonomy of a singular leaf, *Selecta Mathematica 28*, no. 2, 45, 2022.

Idea



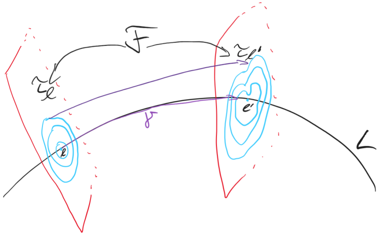
Idea

Generators of $\mathscr{F}$ given by $\mathscr{F}_{\text{projectable}}$:

$$X^{\uparrow} + \overline{\nu},$$

where $X \in \mathfrak{X}(L)$, $X^{\uparrow}$ its projectable horizontal lift, $\nu \in \Gamma(\mathrm{inner}(\tau))$ and $\overline{\nu}$ its fundamental vector field.

Idea



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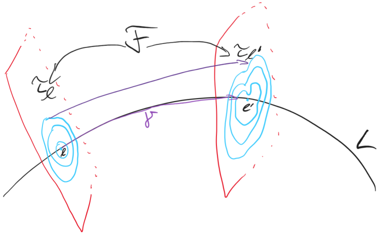

Idea

Fix l and given τ_l: Reconstruct $\mathscr{F}$.

$$\left[X^\uparrow + \overline{\nu}, X'^\uparrow + \overline{\mu}\right] = [X, X']^\uparrow + \dots$$
$$= \underbrace{\left[X^\uparrow, X'^\uparrow\right]}_{\rightsquigarrow \text{ curvature}} + \underbrace{\left[X^\uparrow, \overline{\mu}\right] - \left[X'^\uparrow, \overline{\nu}\right]}_{\rightsquigarrow \text{ connection}} + \overline{[\nu, \mu]}$$

Curved Yang-Mills gauge theory

Curved Yang-Mills gauge theories:

Classical	Curved
Lie group G	Lie group bundle $\mathscr{G}$

$$
\begin{tikzcd}
G \arrow[r] & \mathscr{G} \arrow[d] \\
& L
\end{tikzcd}
$$

Remarks (Why a "curved theory"?)

Usually, the field strength F is given by (abelian, for simplicity)

$$F := \mathrm{d}A = \mathrm{d}^{\nabla^0} A.$$

$\rightsquigarrow$ We will use a general connection ∇ instead of ∇^0, and ∇ may not be flat.

Curved Yang-Mills gauge theories:

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Lie group G	Lie group bundle $\mathscr{G}$

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$$F := \mathrm{d}A = \mathrm{d}^{\nabla^0} A.$$

$\rightsquigarrow$ We will use a general connection ∇ instead of ∇^0, and ∇ may not be flat.

Definition (LGB actions)

$$
\begin{tikzcd}
& \mathscr{G} \arrow[dl, bend right] \arrow[d, "\pi_{\mathscr{G}}"] \\
\mathscr{T} \arrow[r, "\phi"] & L
\end{tikzcd}
$$

A **right-action of $\mathscr{G}$ on $\mathscr{T}$** is a smooth map $\mathscr{T} * \mathscr{G} := \mathscr{T} \,{}_{\phi}\!\times_{\pi_{\mathscr{G}}} \mathscr{G} \to \mathscr{T}$, $(t, g) \mapsto t \cdot g$, satisfying the following properties:

$$
\begin{aligned}
\phi(t \cdot g) &= \phi(t), && (32)\\
(t \cdot g) \cdot h &= t \cdot (gh), && (33)\\
t \cdot e_{\phi(t)} &= p && (34)
\end{aligned}
$$

for all $t \in \mathscr{T}$ and $g, h \in \mathscr{G}_{\phi(t)}$, where $e_{\phi(t)}$ is the neutral element of $\mathscr{G}_{\phi(t)}$.

Sources
K. Mackenzie. General Theory of Lie Groupoids and Algebroids. *London Mathematical Society Lecture Note Series*, 213, 2005.

Definition (Principal bundle)

$$\begin{tikzcd} \mathscr{P} \arrow[d, "\pi_{\mathscr{P}}"] \arrow[dr, "\phi"] & \mathscr{G} \arrow[l, bend right] \arrow[d, "\pi_{\mathscr{G}}"] \\ L' \arrow[r, "\Psi"] & L \end{tikzcd}$$

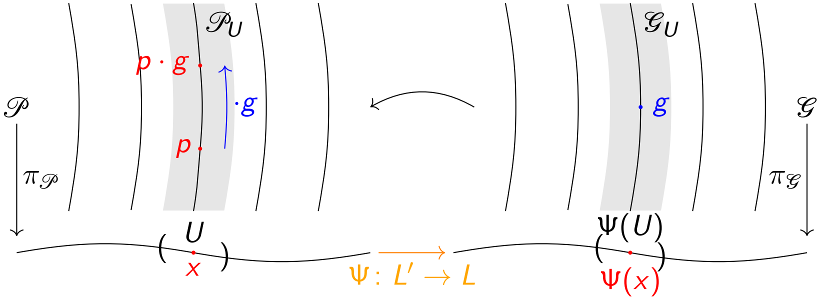
A surjective submersion $\pi_{\mathscr{P}} \colon \mathscr{P} \to L'$, with $\mathscr{G}$-action

$$\underset{\mathscr{P} * \mathscr{G}}{\cancel{\mathscr{P} \times G}} \to \mathscr{P}$$

simply transitive on $\pi_{\mathscr{P}}$-fibres of $\mathscr{P}$, and "suitable" atlas.

Ieke Moerdijk, Janez Mrcun. Introduction to Foliations and Lie Groupoids.
Cambridge Studies in Advanced Mathematics 91, Cambridge University Press, Cambridge, 2003

Connection on $\mathscr{P}$: Idea



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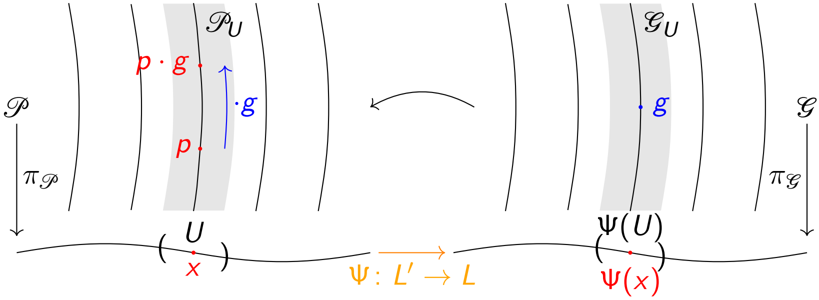

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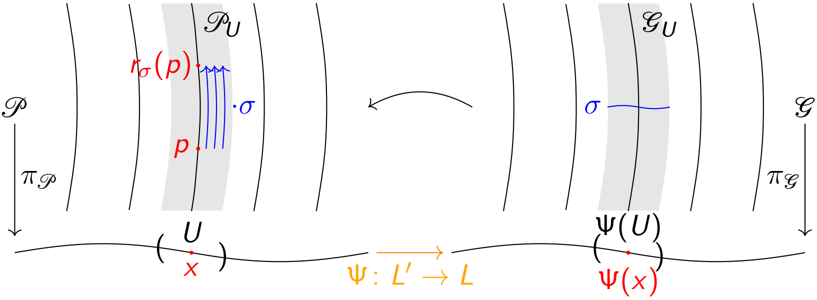
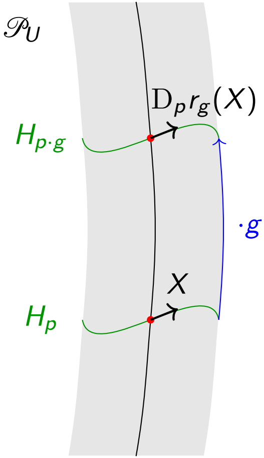


Use $\sigma \in \Gamma(\mathscr{G})$: $r_\sigma(p) := p \cdot \sigma_{\Psi(x)}$

Connection on $\mathscr{P}$: Revisiting the classical setup

If $\mathscr{P}$ a typical principal bundle ($\mathscr{G}$ trivial, $\sigma \equiv g$ constant), and H a connection:



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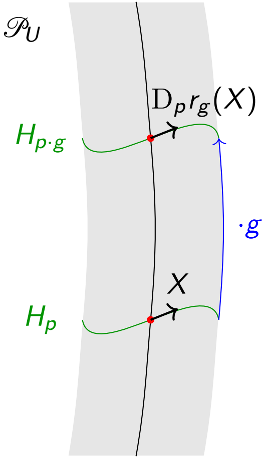

Remarks (Integrated case)

Parallel transport $\mathrm{PT}_\gamma^{\mathscr{P}}$ in $\mathscr{P}$:

$$\mathrm{PT}_\gamma^{\mathscr{P}}(p \cdot g) = \mathrm{PT}_\gamma^{\mathscr{P}}(p) \cdot g$$

where $\gamma : I \to L'$ is a base path

Connection on $\mathscr{P}$: General case

Remarks (Integrated case)

Ansatz: Introduce connection on $\mathscr{G}$,

$$\mathrm{PT}^{\mathscr{P}}_{\gamma}(p \cdot g) = \mathrm{PT}^{\mathscr{P}}_{\gamma}(p) \cdot \mathrm{PT}^{\mathscr{G}}_{\Psi \circ \gamma}(g).$$

Back to the roots

1. $\mathscr{G} \cong L \times G$
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Definition (Ehresmann/Yang-Mills connection, [C. L.-G., S.-R. F.])

A surjective submersion $\pi_{\mathscr{T}} : \mathscr{T} \to L'$ so that one has a commuting diagram

$$\begin{tikzcd} \mathscr{T} \arrow[d, "\pi_{\mathscr{T}}"'] \arrow[dr, "\phi"] & \mathscr{G} \arrow[l, bend right] \arrow[d, "\pi_{\mathscr{G}}"] \\ L' \arrow[r, "\Psi"] & L \end{tikzcd}$$

1. **Ehresmann connection:** $\mathscr{G}$ preserving $\pi_{\mathscr{T}}$ and

$$\mathrm{PT}^{\mathscr{T}}_{\gamma}(t \cdot g) = \mathrm{PT}^{\mathscr{T}}_{\gamma}(t) \cdot \mathrm{PT}^{\mathscr{G}}_{\Psi\circ\gamma}(g)$$

2. **Yang-Mills connection:** Additionally

$$\mathrm{PT}^{\mathscr{T}}_{\gamma_0}(t) = t \cdot g_{\gamma_0}$$

for some $g_{\gamma_0} \in \mathscr{G}_{\phi(t)}$, where γ_0 is a contractible loop.

Definition (Multiplicative YM connection, [S.-R. F.])

On $\mathscr{G}$ there is also the notion of **multiplicative Yang-Mills connections**, that is,

$$\mathrm{PT}^{\mathscr{G}}_{\gamma}(q \cdot g) = \mathrm{PT}^{\mathscr{G}}_{\gamma}(q) \cdot \mathrm{PT}^{\mathscr{G}}_{\gamma}(g),$$
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Definition (Principal bundle connection, [S.-R. F.])

- On $\mathscr{G}$: Multiplicative Yang-Mills connection
- On $\mathscr{P}$: Ehresmann connection

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Remarks

There is a simplicial differential δ on $\mathcal{G} \overset{\pi_{\mathcal{G}}}{\rightarrow} L$ with Lie algebra bundle $\mathscr{g}$

$$\delta : \Omega^\bullet(\underbrace{\mathcal{G} * \ldots * \mathcal{G}}_{k \text{ times}}; \pi_{\mathcal{G}}^* \mathscr{g}) \to \Omega^\bullet(\underbrace{\mathcal{G} * \ldots * \mathcal{G}}_{k+1 \text{ times}}; \pi_{\mathcal{G}}^* \mathscr{g})$$

such that the definition of the multiplicative Yang-Mills connection is equivalent to the **compatibility conditions**

- Connection closed
- Curvature exact ([S.-R. F.])

Sources For differential: Marius Crainic, Maria Amelia Salazar, and Ivan Struchiner. Multiplicative forms and Spencer operators. *Mathematische Zeitschrift*, 279(3):939–979, 2015.

Remarks

On the Lie algebra bundle $\mathcal{g}$ we have a connection $\nabla^{\mathscr{G}}$ with

$$\nabla^{\mathscr{G}}\left([\mu,\nu]_{\mathcal{g}}\right) = \left[\nabla^{\mathscr{G}}\mu,\nu\right]_{\mathcal{g}} + \left[\mu,\nabla^{\mathscr{G}}\nu\right]_{\mathcal{g}},$$

$$R_{\nabla^{\mathscr{G}}} = \mathrm{ad}\circ\zeta. \qquad \text{([S.-R. F.])}$$

Example

Given a short exact sequence of algebroids

$$\mathcal{g} \hookrightarrow E \twoheadrightarrow \mathrm{T}L$$

with splitting $\chi\colon \mathrm{T}L \to E$, then

$$\nabla^{\mathscr{G}}_X\nu = [\chi(X),\nu]_E,$$

$$\zeta(X,X') = [\chi(X),\chi(X')]_E - \chi([X,X']).$$

For the first equation: Camille Laurent-Gengoux, Mathieu Stiénon, and Ping Xu. Non-abelian differentiable gerbes. *Advances in Mathematics*, 220(5):1357–1427, 2009.

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Going back to foliations

Theorem ([C. L.-G., S.-R. F.])

Given a multiplicative Yang-Mills connection on $\mathscr{G}$ and a Yang-Mills connection on $\mathscr{T}$, then there is a natural foliation on $\mathscr{T}$ generated by

$$X^{\uparrow} + \overline{\nu},$$

where $X \in \mathfrak{X}(L)$ and $\nu \in \Gamma(\mathscr{g})$.

Proof.

We have

$$\left[X^{\uparrow}, \overline{\nu}\right] = \overline{\nabla^{\mathscr{G}}_X \nu},$$
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Idea (Leaf L simply connected)

Fix a point $l \in L$ with transverse model $\left(\mathbb{R}^d, \tau_l\right)$:

1. $G = \mathrm{Inn}(\tau_l)$
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Proposition ([C. L.-G., S.-R. F.])

The associated connection on $\mathscr{G}$ is a multiplicative Yang-Mills connection and the one on $\mathscr{T}$ is a corresponding Yang-Mills connection.

Remarks

Thus, we have a singular foliation on $\mathscr{T}$, which, by construction, admits L as a leaf and τ_l as transverse data.

Lemma ([C. L.-G., S.-R. F.])

$\mathscr{P} := (P \times P)\big/G$, *the* ***Atiyah groupoid****, is a principal* $\mathscr{G}$*-bundle*

$$\begin{tikzcd} \mathscr{P} \arrow[d, "(t{,}s)"'] \arrow[dr, "s"] & \mathscr{G} \arrow[l, bend right] \arrow[d] \\ L \times L \arrow[r, "\mathrm{pr}_2"'] & L \end{tikzcd}$$

where t *and* s *are the target and source arrows, respectively.*
A connection on P *induces an Ehresmann connection on* $\mathscr{P}$*.*

Definition (Associated bundles, [C. L.-G., S.-R. F.])

$$\begin{tikzcd}
\mathscr{P} \arrow[d, "{(t,s)}"'] \arrow[dr, "s"] & \mathscr{G} \arrow[l, bend right] \arrow[d, "\pi_{\mathscr{G}}"] \arrow[dr, bend left] & \\
L' \arrow[r, "\mathrm{pr}_2"] & L & \mathscr{T} \arrow[l, "\pi_{\mathscr{T}}"]
\end{tikzcd}$$

Equivalence relation on $\mathscr{P}\ {}_s{\times}_{\pi_{\mathscr{T}}} \mathscr{T}$

$$(p, t) \sim \left(p \cdot g, g^{-1} \cdot t\right)$$

defines the **associated bundle** $\mathscr{P} \tilde{\times} \mathscr{T}$ over L'.

Theorem (Associated connection, [C. L.-G., S.-R. F.])

$$\mathsf{PT}_{\gamma}^{\mathscr{P}\tilde{\times}\mathscr{T}}[p,t] := \left[\mathsf{PT}_{\gamma}^{\mathscr{P}}(p), \mathsf{PT}_{\mathrm{pr}_2\circ\gamma}^{\mathscr{T}}(t)\right]$$

is a well-defined connection.

Remarks ([C. L.-G., S.-R. F.])

Associated connection independent of the choice of connection on P!

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Explicitly, one possible way:

Remarks

Corresponding to $\mathscr{P}$ there is an Atiyah sequence:

$$\mathsf{Ad}(P) \hookrightarrow \mathsf{At}(P) \twoheadrightarrow \mathsf{T}L$$

Via pullback to $\mathscr{T}$ we have a transitive algebroid over $\mathscr{T}$:

$$\pi^!_{\mathscr{T}}\mathsf{Ad}(P) \hookrightarrow \pi^!_{\mathscr{T}}\mathsf{At}(P) \twoheadrightarrow \mathsf{T}\mathscr{T}$$

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Observe

$$\pi^!_{\mathscr{T}}\mathsf{At}(P) \subset \mathrm{T}(\mathscr{P}\ {}_{s}\!\times_{\pi_{\mathscr{T}}} \mathscr{T})$$

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$\mathrm{Ad}(P)$ and $\mathrm{At}(P)$ the adjoint and Atiyah bundle of P, respectively:

$$\begin{tikzcd}
\Gamma^{\text{symmetric}}_{\text{parallel}}\left(\pi^!_{\mathscr{T}}\mathrm{Ad}(P)\right) \arrow[r, hook] \arrow[d] & \Gamma^{\text{symmetric}}_{\text{parallel}}\left(\pi^!_{\mathscr{T}}\mathrm{At}(P)\right) \arrow[r, two heads] \arrow[d] & \mathfrak{X}(L) \arrow[d, equal] \\
\tau \arrow[r, hook] & \mathscr{F}_{\text{projectable}} \arrow[r, two heads] & \mathfrak{X}(L)
\end{tikzcd}$$

Future Prospects

$$
\begin{tikzcd}
 & \mathscr{F} \arrow[dl] \arrow[dr] & \\
\mathrm{At}(P) & & \text{Associated connection}
\end{tikzcd}
$$

Remarks (Why curved gauge theory?)

- Associated connection invariant under choice of $\mathscr{F}$-connection $\nabla^{\mathscr{F}}$
- Associated connection has the form

$$\nabla^{\mathscr{F}} + A\cdot$$

where A is the connection 1-form on $\mathscr{P}$

Thank you!