Non-Geometric T-duality from Higher Groupoid Bundles with Connections

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Topological T-duality

- String theories on backgrounds with $\mathsf{U}(1)$-isometries:
  $\Rightarrow$ a T-dual partner
- Low-energy limit: corresponding supergravity contains B-field:
  $\Rightarrow$ connective structure on a gerbe

Geometric string background:

- A Riemannian manifold X
- A principal/affine torus bundle $\pi : P \to X$
- An abelian gerbe $\mathscr{G}$ on the total space of P

Topological T-duality

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Topological T-duality follows from exactness of the Gysin sequence:

$$\ldots \to \mathrm{H}^3(X,\mathbb{Z}) \xrightarrow{\pi^*} \mathrm{H}^3(P,\mathbb{Z}) \xrightarrow{\pi_*} \mathrm{H}^2(X,\mathbb{Z}) \xrightarrow{F\cup} \mathrm{H}^4(X,\mathbb{Z}) \to \ldots$$

- Gerbe over P: 3-form $H \in \mathrm{H}^3(P,\mathbb{Z})$
- Fiber integration $\pi_* H = \hat{F} \in \mathrm{H}^2(X,\mathbb{Z})$ with $F \cup \hat{F} = 0$
- $\Rightarrow$ There is $\hat{H} \in \mathrm{H}^3(P,\mathbb{Z})$ with $\pi_* \hat{H} = F$.
- Topological T-duality: $(F, H) \leftrightarrow (\hat{F}, \hat{H})$.
  Note: possibility for topology change!

Bouwknegt, Evslin, Hannabuss, Mathai (2004)

Topological T-duality, geometrically

T-correspondence:

$$\begin{tikzcd}
 & & \mathscr{G}_{\mathrm{C}} = \check{\mathsf{p}}^*\check{\mathscr{G}} \otimes \hat{\mathsf{p}}^*\hat{\mathscr{G}}^{-1} \arrow[d] & & \\
 & & \check{P} \times_X \hat{P} \arrow[dl, "\check{\mathsf{p}}"'] \arrow[dr, "\hat{\mathsf{p}}"] & & \\
\check{\mathscr{G}} \arrow[r] & \check{P} \arrow[dr, "\check{\pi}"] & & \hat{P} \arrow[dl, "\hat{\pi}"'] & \hat{\mathscr{G}} \arrow[l] \\
 & & X & &
\end{tikzcd}$$

Bunke, Rumpf, Schick (2005, 2006)

Principal 2-bundles (without connections):

$$\begin{tikzcd}
 & \mathscr{P}_{\mathrm{C}} \arrow[dl, "\check{\mathsf{p}}"'] \arrow[dr, "\hat{\mathsf{p}}"] & \\
\check{\mathscr{P}} & & \hat{\mathscr{P}}
\end{tikzcd}$$

Nikolaus, Waldorf (2018)

Two open problems

I. T-duality can lead to non-geometric backgrounds:

F^3: H has no legs along fiber
T-duality: identity

F^2: H has 1 leg along fiber
T-duality $\rightarrow$ geometric string background

F^1: H has 2 legs along fiber
T-duality $\rightarrow$ Q-space, (e.g. T-folds) locally geometric

F^0: H has all legs along fiber
T-duality $\rightarrow$ R-space, non-geometric

Nikolaus/Waldorf cover $F^2 \leftrightarrow F^2$ and $F^2 \leftrightarrow F^1$ T-dualities
What about the general case?

II. Differential refinement of this picture

Why is this interesting/hard?

I. need to use suitable groupoids and augmented groupoids

II. connections on principal 2-bundles require adjustment

Outline

- Connections on principal 2-bundles
- T-duality with differentially refined principal 2-bundles
- Explicit example: Nilmanifolds
- The T-duality group from Kaluza–Klein reduction
- Groupoid bundles for T-folds
- Augmented groupoid bundles for R-spaces

Principal 2-bundles or Non-Abelian Gerbes

with Connections

A mathematical structure ("Bourbaki-style") consists of

- Sets • Structure Functions • Structure Equations

"Categorification":

Sets → Categories

Structure Functions → Structure Functors

Structure Equations → Structure Isomorphisms

Example: Group → 2-Group

- Set G → Category $\mathscr{G}$
- product, identity ($\mathbb{1} : * \to \mathsf{G}$), inverse → Functors
- $a(bc) = (ab)c \to$ Associator $\mathsf{a} : a \otimes (b \otimes c) \Rightarrow (a \otimes b) \otimes c$
- $\mathbb{1}a = a\mathbb{1} = a \to$ Unitors $\mathsf{l}_a : a \otimes \mathbb{1} \Rightarrow a$, $\mathsf{r}_a : \mathbb{1} \otimes a \Rightarrow a$
- $aa^{-1} = a^{-1}a = \mathbb{1} \to$ weak inv. $\mathsf{inv}(x) \otimes x \Rightarrow \mathbb{1} \Leftarrow x \otimes \mathsf{inv}(x)$

Note: Process not unique, variants: weak/strict/...

Example: The Lie 2-group $\underline{\mathsf{TD}}_n$

$$\mathbb{R}^{2n} \times \mathbb{Z}^{2n} \times \mathsf{U}(1) \rightrightarrows \mathbb{R}^{2n}$$

$$\begin{tikzcd}
\xi & \xi - m_1 \arrow[l, bend right, "(\xi{,}m_1{,}\phi_1)"'] & \xi - m_1 - m_2 \arrow[l, bend right, "(\xi-m_1{,}m_2{,}\phi_2)"'] \arrow[ll, bend left, "(\xi{,}m_1+m_2{,}\phi_1+\phi_2)"]
\end{tikzcd}$$

$$\mathsf{id}_\xi := (\xi, 0, 0) \;, \quad (\xi, m, \phi)^{-1} := (\xi - m, -m, -\phi)$$

$$(\xi_1, m_1, \phi_1) \otimes (\xi_2, m_2, \phi_2) := (\xi_1 + \xi_2, m_1 + m_2, \phi_1 + \phi_2 - \langle \xi_1, m_2 \rangle)$$

$$\mathsf{inv}(\xi, m, \phi) := (-\xi, -m, -\phi - \langle \xi, m \rangle)$$

This Lie 2-group corresponds to a crossed module of Lie groups:

$$\mathsf{TD}_n \;:=\; \left(\mathbb{Z}^{2n} \times \mathsf{U}(1) \xrightarrow{\;\mathsf{t}\;} \mathbb{R}^{2n}\right)$$

$$\mathsf{t}(m, \phi) := m$$

$$\xi \rhd (m, \phi) := (m, \phi - \langle \xi, m \rangle)$$

Principal 2-Bundles

Categorify bundles over a manifold M subordinate to cover (U_a)

Breen, Messing (2005), Aschieri, Cantini, Jurčo (2005)

Object	Principal G-bundle	Principal $(\mathsf{H} \xrightarrow{\mathsf{t}} \mathsf{G})$-bundle
Cochains	(g_{ab}) valued in G	(g_{ab}) valued in G, (h_{abc}) valued in H
Cocycle	$g_{ab}g_{bc} = g_{ac}$	$\mathsf{t}(h_{abc})g_{ab}g_{bc} = g_{ac}$ $h_{acd}h_{abc} = h_{abd}(g_{ab} \rhd h_{bcd})$
Coboundary	$g_a g'_{ab} = g_{ab}g_b$	$g_a g'_{ab} = \mathsf{t}(h_{ab})g_{ab}g_b$ $h_{ac}h_{abc} = (g_a \rhd h'_{abc})h_{ab}(g_{ab} \rhd h_{bc})$
gauge pot.	$A_a \in \Omega^1(U_a) \otimes \mathfrak{g}$	$A_a \in \Omega^1(U_a) \otimes \mathfrak{g}$, $B_a \in \Omega^2(U_a) \otimes \mathfrak{h}$
Curvature	$F_a = \mathrm{d}A_a + A_a \wedge A_a -$	$\mathcal{F}_a = \mathrm{d}A_a + \frac{1}{2}[A_a, A_a] - \mathsf{t}(B_a) \stackrel{!}{=} 0$ $H_a = \mathrm{d}B_a + A_a \rhd B_a$
Gauge trafos	$\tilde{A}_a := g_a^{-1}A_a g_a + g_a^{-1}\mathrm{d}g_a$	$\tilde{A}_a := g_a^{-1}A_a g_a + g_a^{-1}\mathrm{d}g_a + \mathsf{t}(\Lambda_a)$ $\tilde{B}_a := g_a^{-1} \rhd B_a + \tilde{A}_a \rhd \Lambda_a + \mathrm{d}\Lambda_a - \Lambda_a \wedge \Lambda_a$

Remarks:

- A principal $(1 \xrightarrow{\mathsf{t}} \mathsf{G})$-bundle is a principal G-bundle.
- A principal $(\mathsf{U}(1) \xrightarrow{\mathsf{t}} 1) = \mathsf{BU}(1)$-bundle is an abelian gerbe.

Why should the fake curvature(s) vanish?

$$\mathcal{F} := \mathrm{d}A + \tfrac{1}{2}[A, A] + \mathsf{t}(B) \stackrel{!}{=} 0$$

Without this condition:

- Gauge transformations do not close
- Cocycles do not glue together
- Higher parallel transport is not reparametrization invariant
- 6d Self-duality equation $H = \star H$ is not gauge-covariant:

$$H \to \tilde{H} = g \rhd H - \mathcal{F} \rhd \Lambda$$

With this condition:

- Principal $(1 \xrightarrow{\mathsf{t}} \mathsf{G})$-bundle is flat principal G-bundle.
- Higher connections are locally abelian!

Gastel (2019), CS, Schmidt (2020)

Solution: Adjustment

Many (not all!) higher gauge groups come with

Adjustment of higher group $\mathcal{G}$:

CS, Schmidt (2020), Rist, CS, Wolf (2022)

- Additional map $\kappa : \mathcal{G} \times \mathsf{Lie}(\mathcal{G}) \to \mathsf{Lie}(\mathcal{G})$
- Necessary for consistent definition of invariant polynomials.
- From Alternator ($\Rightarrow EL_\infty$-algebras, Borsten, Kim, CS (2021))

For connections on principal $\mathcal{G}$-bundles:

- Adjustment of curvature/cocycle/coboundary relations
- Can drop fake flatness condition

Example: Heterotic supergravity

- Lie 2-algebra $\mathfrak{g} \times \mathbb{R} \rightrightarrows \mathfrak{g}$ or L_∞-algebra $\mathbb{R} \to \mathfrak{g}$
- $H = \mathrm{d}B - \frac{1}{3!}(A, [A, A]) - (A, F) = \mathrm{d}B + \mathsf{cs}(A)$
- such that F arbitrary and $\mathrm{d}H = (F, F)$ follows

Geometric T-duality

Geometric T-duality: General Picture

$$\begin{tikzcd} & \mathscr{P}_{\mathrm{C}} \arrow[dl, "\check{\mathsf{p}}"'] \arrow[dr, "\hat{\mathsf{p}}"] & \\ \check{\mathscr{P}} & & \hat{\mathscr{P}} \end{tikzcd}$$

- Nikolaus/Waldorf: Topological part:
  - $\check{\mathscr{P}}$ and $\hat{\mathscr{P}}$ are principal $\mathsf{TB}^{\mathsf{F2}}_n$-bundles
  - $\mathscr{P}_C$ is a principal TD_n-bundle
  - $\hat{\mathsf{p}}$ is a projection induced by strict morphism $\hat{\phi} : \mathsf{TD}_n \to \mathsf{TB}^{\mathsf{F2}}_n$
  - $\check{\mathsf{p}}$ induced by $\check{\phi} = \hat{\phi} \circ \phi_{\mathsf{flip}}$, flip morphism $\phi_{\mathsf{flip}} : \mathsf{TD}_n \to \mathsf{TD}_n$
- Differential refinement: (i.e. B-field+metric)
  - $\mathsf{TB}^{\mathsf{F2}}_n$ does not come with adjustment, but
  - TD_n comes with very natural adjustment map
  - Have topological and full connection data on $\mathscr{P}_C$
  - Can reconstruct gerbe and bundle data on $\check{\mathscr{P}}$ and $\hat{\mathscr{P}}$
- (Also: generalization to affine tori.)

Example: Nilmanifolds

Geometry of string background $\check{\mathscr{G}}_\ell \to N_k$:

- Principal circle bundle over T^2 with $c_1 = k$
- Subordinate to $\mathbb{R}^2 \to T^2$ and with $\mathsf{U}(1) \cong \mathbb{R}/\mathbb{Z}$

$$(x,y,z) \sim (x,y+1,z) \sim (x,y,z+1) \sim (x+1,y,z-ky)$$

- Local connection form: $A(x,y) = kx\,\mathrm{d}y \in \Omega^1(\mathbb{R}^2)$
- Kaluza–Klein metric: $g(x,y,z) = \mathrm{d}x^2 + \mathrm{d}y^2 + (\mathrm{d}z + kx\,\mathrm{d}y)^2$

T-duality:

$$(\check{\mathscr{G}}_\ell \to N_k) \quad \longleftrightarrow \quad (\hat{\mathscr{G}}_k \to N_\ell)$$

Have: full interpretation in terms of higher bundle Kim, CS (2022)

Example: Nilmanifolds with principal 2-bundles

$$
\begin{tikzcd}
 & \mathscr{P}_{\rm C} \arrow[dl, "\check{\mathsf{p}}"'] \arrow[dr, "\hat{\mathsf{p}}"] & \\
\check{\mathscr{P}} & & \hat{\mathscr{P}}
\end{tikzcd}
$$

Lie 2-group:

$$\mathsf{TD}_1 \;:=\; \big(\mathbb{Z}^2 \times \mathsf{U}(1) \xrightarrow{\;\mathsf{t}\;} \mathbb{R}^2\big)$$

Topological cocycle data:

$$g = \begin{pmatrix} \hat{g}, & \hat{\xi} \\ \check{g}, & \check{\xi} \end{pmatrix}\,, \quad \begin{aligned} \hat{g}(x,y;x',y') &= \mathbb{1}\,, & \hat{\xi}(x,y;x',y') &= \ell(x'-x)y\,, \\ \check{g}(x,y;x',y') &= \mathbb{1}\,, & \check{\xi}(x,y;x',y') &= k(x'-x)y\,, \end{aligned}$$

$$m = \begin{pmatrix} \hat{m} \\ \check{m} \end{pmatrix}\,, \quad \begin{aligned} \hat{m}(x,y;x',y';x'',y'') &= -\ell(x''-x')(y'-y)\,, \\ \check{m}(x,y;x',y';x'',y'') &= -k(x''-x')(y'-y)\,, \end{aligned}$$

$$\phi = \tfrac{1}{2}k\ell\,\big(y'(xx''-xx'-x'x'') - (x''-x')(y'^2-y^2)x\big)$$

Cocycle data of differential refinement:

$$A = \begin{pmatrix} \check{A} \\ \hat{A} \end{pmatrix} = \begin{pmatrix} kx\,\mathrm{d}y \\ \ell x\,\mathrm{d}y \end{pmatrix}\,, \quad B = 0\,, \quad \Lambda = \tfrac{1}{2}k\ell(xx'\,\mathrm{d}y + (xy + x'y' + y^2(x'-x))\,\mathrm{d}x)$$

Can reconstruct both string backgrounds fully.

The T-duality group from Kaluza–Klein Reduction

The group TD_n from Kaluza–Klein reduction

Observation:

T-duality is intimately linked to Kaluza–Klein reduction:

- Gysin sequence contains fiber integration
- Metric on total space given by Kaluza–Klein metric
- Literature: e.g. Berman (2019), Alfonsi (2019), ...

- Geometric objects from maps into classifying spaces $\mathcal{C}$.
- Note: currying $C^0(X \times T^n, \mathcal{C}) \cong C^0(X, C^0(T^n, \mathcal{C}))$
- Non-trivial fibrations: cyclic torus space: $C^0(T^n, \mathcal{C}) /\!/ \mathsf{U}(1)^n$

Example TD_1 from KK-reduction of gerbe on circle bundle

- Gerbe: $C^0(P, \mathcal{C})$ with $\mathcal{C} = \mathsf{BBU}(1)$
- Cyclic loop space: $L\mathsf{BBU}(1) /\!/ \mathsf{U}(1) \cong \mathsf{B}(\mathsf{BU}(1) \times \mathsf{U}(1) \times \mathsf{U}(1))$
- Replace $\mathsf{U}(1)$ with $\mathbb{Z} \to \mathbb{R}$: $\mathsf{TD}_1 \;:=\; \big(\mathsf{U}(1) \times \mathbb{Z}^2 \xrightarrow{\mathsf{t}} \mathbb{R}^2\big)$
- Iterate: TD_n

Automorphisms of TD_n

Abstract nonsense:

- Natural definition of morphism of 2-groups
- Automorphisms of 2-group form naturally a 2-group
- 2-group action $\mathscr{G} \curvearrowright \mathscr{H}$: morphism $\mathscr{G} \to \mathsf{Aut}(\mathscr{H})$

Automorphisms of the 2-group TD_n:

- Restrict to "reasonable" automorphisms
- These are parameterized by $\mathsf{GO}(n,n;\mathbb{Z}) \times \mathsf{Sym}(2n;\mathbb{Z})$
- Recover T-duality group for affine torus bundles
- Neither this group nor $\mathsf{GO}(n,n;\mathbb{Z})$ fully acts on TD_n
- What works: weak (unital) Lie 2-group

$$\mathscr{GO}(n,n;\mathbb{Z}) := \Big(\ \mathsf{GO}(n,n;\mathbb{Z}) \times \mathbb{Z}^{2n} \Longrightarrow \mathsf{GO}(n,n;\mathbb{Z}) \ \Big)$$

- Explicit: geometric subgroup, B- and β-trafos, T-dualities
- $\Rightarrow$ arrange everything based on $\mathscr{GO}(n,n;\mathbb{Z})$

Groupoid bundles for T-folds

T-folds from groupoid bundles

Recall our construction of TD_1:

- Gerbe: $C^0(P, \mathcal{C})$ with $\mathcal{C} = \mathsf{BBU}(1)$
- Cyclic loop space: $L\mathsf{BBU}(1)//\mathsf{U}(1) \cong \mathsf{B}(\mathsf{BU}(1) \times \mathsf{U}(1) \times \mathsf{U}(1))$
- Replace $\mathsf{U}(1)$ with $\mathbb{R} \times \mathbb{Z} \rightrightarrows \mathbb{R}$: $\mathsf{TD}_1 \;:=\; \big(\mathbb{Z}^2 \times \mathsf{U}(1) \xrightarrow{\mathsf{t}} \mathbb{R}^2\big)$
- Iterate: TD_n

Last point was sloppy, one obtains no 2-group, but 2-groupoid!

For T-folds: at least two T-duality directions $\Rightarrow$ 2-groupoid!

Question: What is the appropriate groupoid here?

The 2-groupoid $\mathscr{T}\mathscr{D}_n$

- Narain moduli space for affine circle bundles:

$$\begin{aligned} GM_n &= \mathsf{GO}(n,n;\mathbb{Z}) \setminus \mathsf{O}(n,n;\mathbb{R}) \ / \ \big(\mathsf{O}(n;\mathbb{R}) \times \mathsf{O}(n;\mathbb{R})\big) \\ &=: \mathsf{GO}(n,n;\mathbb{Z}) \setminus Q_n \ . \end{aligned}$$

- Resolve into action groupoid:

$$\mathsf{GO}(n,n;\mathbb{Z}) \ltimes Q_n \ \rightrightarrows \ Q_n \ .$$

- Extend to $\mathscr{G}\mathscr{O}(n,n;\mathbb{Z})$-action ($\mathscr{G}\mathscr{O}(n,n;\mathbb{Z}) \cong \mathsf{Aut}(\mathsf{TD}_n)$)
- Place TD_n-fiber over every point in Q_n
- Include action of $\mathscr{G}\mathscr{O}(n,n;\mathbb{Z})$ on TD_n
- The result is the 2-groupoid $\mathscr{T}\mathscr{D}_n$

T-duality as $\mathscr{T}\mathscr{D}_n$-bundles

Recall: functorial description of (higher) principal bundles:

- Manifold X
- Cover/surjective submersion $\sigma : Y \to X$
- Cech groupoid $\check{\mathscr{C}}(Y \to X) := \big(Y \times_X Y \rightrightarrows Y\big)$
- Top. principal G-bundle: functor $\check{\mathscr{C}}(Y \to M) \to \mathsf{BG}$

For $\mathscr{T}\mathscr{D}_n$-bundle:

- Replace (higher) group BG by Lie 2-groupoid $\mathscr{T}\mathscr{D}_n$
- For ordinary groupoids: e.g. gauged sigma models

A non-geometric T-duality is simply a $\mathscr{T}\mathscr{D}_n$-bundle.

T-duality as $\mathscr{T}\mathscr{D}_n$-bundles

Remarks:

- The T-duality group $\mathscr{G}\mathscr{O}(n,n;\mathbb{Z}) \supset \mathsf{GO}(n,n;\mathbb{Z})$ is gauged!
- Explicitly visible: $\mathsf{GO}(n,n;\mathbb{Z})$-gluing of local data
- Matches topological discussion in Nikolaus, Waldorf (2018)
- Differential refinement imposes restriction on top. cocycles
- This describes all T-dualities between pairs of T-folds
- Concrete conditions for "half-geometric" T-dualities
- Concrete cycles of the T-fold in the nilmanifold example

To describe Q-spaces/T-folds:
(can) use higher instead of noncommutative geometry.

Augmented groupoid bundles for R-spaces

What about R-spaces?

- T-folds/Q-spaces relatively harmless, as locally geometric
- R-spaces are not even locally geometric
- But perhaps higher description still works?

Note:

- One T-duality direction: B-field $\to$ 2-, 1-forms
  $\Rightarrow$ Lie 2-group TD_n-bundles with connection
- Two T-duality directions: B-field $\to$ 2-, 1-, 0-forms
  $\Rightarrow$ Lie 2-groupoid $\mathscr{T}\mathscr{D}_n$-bundles with connection
- Three T-duality directions: B-field $\to$ 2-, 1-, 0-, (-1)-forms
  $\Rightarrow$ Augmented Lie 2-groupoid $\mathscr{T}\mathscr{D}_n^{\mathsf{aug}}$-bundles with connection

T-duality as $\mathscr{TD}_n^{\mathsf{aug}}$-bundles

Construction of $\mathscr{TD}_n^{\mathsf{aug}}$:

- Augmentation by suitable space of R-fluxes
- Determined by finite version of tensor hierarchy
- Finite embedding tensor $\mathbb{R}^{2n} \to \mathsf{GO}(n,n;\mathbb{Z}) \subset \mathscr{GO}(n,n;\mathbb{Z})$
- plus some standard consistency conditions
- Beyond this, augmentation fairly trivial

Remarks on T-duality with $\mathscr{TD}_n^{\mathsf{aug}}$-bundles:

- Explicit examples, e.g. from nilmanifolds
- Yields consistency conditions between Q- and R-fluxes
- All previously discussed cases included
- All previously discussed also for affine $\mathsf{U}(1)$-bundles

To describe R-spaces:
(can) use higher instead of nonassociative geometry.

Summary

What has been done:

- Top. T-duality can be described using principal 2-bundles
- Differential refinement requires adjusted curvatures
- Explicit description of geometric T-duality with nilmanifolds
- T-duality group is really a 2-group derived from KK-reduction
- Can extend to Q-spaces or T-folds
- Can extend to R-spaces

Future work:

- Link some mathematical results to physical expectations
- Link to pre-NQ-manifold pictures and similar
- Non-abelian T-duality?
- U-duality

Thank You!