Journal of Homotopy and Related Structures, vol. 3(1), 2008, pp.193–244

THE INNER AUTOMORPHISM 3-GROUP OF A STRICT 2-GROUP

DAVID MICHAEL ROBERTS AND URS SCHREIBER

(*communicated by Ronald Brown*)

Abstract

Any group G gives rise to a 2-group of inner automorphisms, $\mathrm{INN}(G)$. It is an old result by Segal that the nerve of this is the universal G-bundle. We discuss that, similarly, for every 2-group $G_{(2)}$ there is a 3-group $\mathrm{INN}(G_{(2)})$ and a slightly smaller 3-group $\mathrm{INN}_0(G_{(2)})$ of inner automorphisms. We describe these for $G_{(2)}$ any strict 2-group, discuss how $\mathrm{INN}_0(G_{(2)})$ can be understood as arising from the mapping cone of the identity on $G_{(2)}$ and show that its underlying 2-groupoid structure fits into a short exact sequence

$$G_{(2)} \longrightarrow \mathrm{INN}_0(G_{(2)}) \longrightarrow \mathbf{B}G_{(2)} \ .$$

As a consequence, $\mathrm{INN}_0(G_{(2)})$ encodes the properties of the universal $G_{(2)}$ 2-bundle.

Contents

1 Introduction **194**

2 n-Groups in terms of groups **199**
2.1 Conventions for strict 2-groups and crossed modules 199
2.2 3-Groups and 2-crossed modules 202
2.3 Mapping cones of crossed modules 203

3 Main results **204**
3.1 The exact sequence $G_{(2)} \to \mathrm{INN}_0(G_{(2)}) \to \mathbf{B}G_{(2)}$ 204

We are grateful to Jim Stasheff for helpful discussions and for emphasizing the importance of the mapping cone construction in the present context. We profited from general discussion with Danny Stevenson and thank him for his help on the references to Segal's work. We also thank Christoph Schweigert and Zoran Škoda for helpful comments on the manuscript, Tim Porter for reminding us of Norrie's work. We are grateful to Todd Trimble for discussion about the simplicial aspects of our construction and its relation to décalage, and to two anonymous referees for pointers to the literature and for making the remark which appears in 7.3.2.
DMR is supported by an Australian Postgraduate Award.
Received September 5, 2007, revised Febuary 13, 2008; published on June 30, 2008.
2000 Mathematics Subject Classification: 18B40, 20L05
Key words and phrases: 2-groups, 3-groups, crossed complexes, crossed squares, automorphisms, universal 2-bundles
© 2008, David Michael Roberts and Urs Schreiber. Permission to copy for private use granted.

3.2 $\mathrm{INN}_0(G_{(2)})$ from a mapping cone 205

4 Inner automorphism $(n+1)$-groups **205**
4.1 Exact sequences of strict 2-groupoids 206
4.2 Tangent 2-categories 206
4.3 Inner automorphisms 210
4.4 Inner automorphism 2-groups 213
4.5 Inner automorphism 3-groups. 213

5 The 3-group $\mathrm{INN}_0(G_{(2)})$ **216**
5.1 Objects 217
5.2 Morphisms 217
5.3 2-Morphisms 220

6 Properties of $\mathrm{INN}_0(G_{(2)})$ **224**
6.1 Structure morphisms 224
6.2 Trivializability 225
6.3 Universality 226
6.4 The corresponding 2-crossed module 226

7 Universal n-bundles **234**
7.1 Universal 1-bundles in terms of $\mathrm{INN}(G)$ 234
7.2 Universal 2-bundles in terms of $\mathrm{INN}_0(G_{(2)})$ 236
7.3 Relation to simplicial bundles 238

8 Appendix: Crossed squares **242**

1. Introduction

The theory of groups and their principal fiber bundles generalizes to that of categorical groups and their categorical principal fiber bundles. In fact, using higher categories, one has for each integer n the notion of n-groups and their principal n-bundles.

The reader may have encountered principal 2-bundles mostly in the language of (nonabelian) gerbes, which are to 2-bundles essentially like sheaves are to ordinary bundles. The concept of a 2-bundle proper is described in [**6, 5**].

These n-bundles are certainly interesting already in their own right. One crucial motivation for considering them comes from the study of n-dimensional quantum field theory. In this case one is interested in n-dimensional analogs of the concept of parallel transport in fiber bundles with connection [**3, 29, 30**].

In that context a curious phenomenon occurs: whenever one investigates n-dimensional quantum field theory governed by an n-group $G_{(n)}$, it turns out [**28**] that the situation is governed by an $(n+1)$-group associated to $G_{(n)}$. In fact, it is appropriate to call this $(n+1)$-group $\mathrm{INN}_0(G_{(n)})$, because, as the notation suggests, it is related to inner automorphisms of the original n-group $G_{(n)}$.

One of our aims here is to define what inner automorphisms of a 2-group are and to give a concise definition as well as a detailed description of the 3-group $\mathrm{INN}_0(G_{(2)})$ for any strict 2-group $G_{(2)}$. We then prove that $\mathrm{INN}_0(G_{(2)})$ has a couple of rather peculiar properties; it is *contractible* (equivalent, as a 2-group, to the trivial 2-group), and fits into a short exact sequence

$$G_{(2)} \hookrightarrow \mathrm{INN}_0(G_{(2)}) \twoheadrightarrow \mathbf{B}G_{(2)}$$

of 2-groupoids. To appreciate this result, it is helpful to first consider the analogous statement for ordinary groups.

1.0.0.1. The statement for ordinary groups. For any ordinary group G, various constructions of interest, like that of the universal G-bundle, are closely related to a certain groupoid determined by G.

There are several different ways to think of this groupoid. The simplest way to describe its structure is to say that it is the codiscrete groupoid over the elements of G, namely the groupoid whose objects are the elements of G and which has precisely one morphism from any element to any other.

The relevance of this groupoid is better understood by thinking of it as the action groupoid $G//G$ of the action of G on itself by left multiplication. As such, we may write any of its morphisms as

$$g \xrightarrow{h} hg$$

for $g, h \in G$ and hg being the product of h and g in G.

While this way of thinking about our groupoid already makes it more plausible that it is related to G-actions and hence possibly to G-bundles, one more property remains to be made manifest: there is also a monoidal structure on our groupoid. For any two morphisms,

$$g_1 \xrightarrow{h_1} h_1 g_1$$

and

$$g_2 \xrightarrow{h_2} h_2 g_2,$$

we can form the product morphism

$$g_2 g_1 \xrightarrow{h_2 \mathrm{Ad}_{g_2}(h_1)} h_2 g_2 h_1 g_1,$$

and this assignment is functorial in both arguments. Moreover, to every morphism

$$g \xrightarrow{h} hg$$

there is a morphism

$$g^{-1} \xrightarrow{\mathrm{Ad}_{g^{-1}}(h)^{-1}} (hg)^{-1},$$

which is its inverse with respect to this product operation.

This makes $G//G$ a strict 2-group [**2**]. A helpful way to make the 2-group structure on $G//G$ more manifest is to relate it to inner automorphisms of G. To see

this, consider another groupoid canonically associated to any group G, namely the groupoid

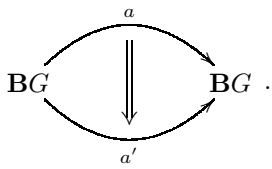
$$\mathbf{B}G = \{ \bullet \xrightarrow{g} \bullet \ | g \in G \}$$

which has a single object $\bullet$, one morphism for each element of G and where composition of morphisms is just the product in the group.

Automorphisms

$$a : \mathbf{B}G \to \mathbf{B}G$$

(i.e. invertible functors) of this groupoid are nothing but group automorphisms of G. But now there are also isomorphisms between two such morphisms a and a', namely natural transformations:

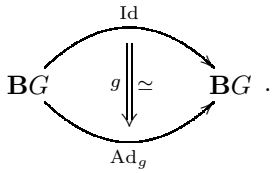


This way for every ordinary group G we have not just its ordinary group of automorphisms, but actually a 2-group

$$\mathrm{AUT}(G) := \mathrm{Aut}_{\mathrm{Cat}}(\mathbf{B}G) \,.$$

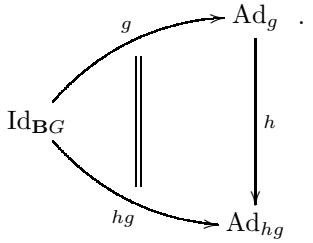
This is a groupoid, whose objects are group automorphisms of G. The 2-group structure on this groupoid is manifest from the horizontal composition of the natural transformations above. Hence the ordinary automorphism group of G is the group of objects of $\mathrm{AUT}(G)$.

By writing out the definition of a natural transformation, one sees that there is a morphism between two objects in $\mathrm{AUT}(G)$ whenever the two underlying ordinary automorphisms of G differ by conjugation with an element of G. It follows in particular that the *inner* automorphisms of G correspond to those autofunctors of $\mathbf{B}G$ which are isomorphic to the identity:



Therefore consider the groupoid $\mathrm{INN}(G)$: its objects are pairs, consisting of an automorphisms together with a transformation connecting it to the identity. A

morphism from (g, Ad_g) to (gh, Ad_{gh}) is a commuting triangle



This is again exactly the groupoid $G//G$ which we are discussing

$$\mathrm{INN}(G) = G//G\,.$$

In this formulation the natural notion of composition of group automorphisms nicely explains the monoidal structure on $G//G$.

Notice that $\mathrm{INN}(G)$ remembers the center of the group. We will discuss that it sits inside an exact sequence

$$1 \to Z(G) \to \mathrm{INN}(G) \to \mathrm{AUT}(G) \to \mathrm{OUT}(G) \to 1$$

of 2-groups, and that this is what generalizes to higher n.

If we think of the group G just as a discrete category, whose objects are the elements of G and which has only identity morphisms, then there is an obvious monomorphic functor

$$G \to \mathrm{INN}(G)\,.$$

Moreover, there is an obvious epimorphic functor

$$\mathrm{INN}(G) \to \mathbf{B}G$$

from our groupoid to the group G, but now with the latter regarded as a category with a single object. This simply forgets the source and target labels and recalls only the group element which is acting.

These two functors are such that the image of the former is precisely the collection of morphisms which get sent to the identity morphism by the latter. Therefore we say that we have a short exact sequence

$$G \to \mathrm{INN}(G) \to \mathbf{B}G \tag{1}$$

of groupoids.

Notice that G and $\mathrm{INN}(G)$ are groupoids which are also 2-groups (the first one, being an ordinary group, is a degenerate case of a 2-group), and that the morphism $G \to \mathrm{INN}(G)$ is also a morphism of 2-groups. But $\mathbf{B}G$ is in general just a groupoid without monoidal structure – it has the structure of a 2-group if and only if G is abelian.

Even though all this is rather elementary, the exact sequence (1) is important. We can apply the functor $|\cdot|$ to our sequence, which takes the nerve of a category and then forms the geometric realization. Note that when K is a 2-group, $|K|$ is a

topological group. Under this functor, (1) becomes the universal G-bundle

$$G \to EG \to BG,$$

even when G is a topological or Lie group. The fact that $BG \simeq |\mathbf{B}G|$ is the very definition of the classifying space BG of a group G in [**31**]. That $EG \simeq |\mathrm{INN}(G)|$ is contractible follows from the existence of an equivalence of groupoids $\mathrm{INN}(G) \xrightarrow{\sim} *$. Finally, the inclusion $G \to \mathrm{INN}(G)$ together with the monoidal structure on $\mathrm{INN}(G)$ gives the free G-action of G on EG whose quotient is exactly BG. The observation that $|\mathrm{INN}(G)|$ is a model for EG is originally due to Segal [**31**], who proved the remaining nontrivial statement: that $|\mathrm{INN}(G)| \to BG$ is locally trivial when G is a well-pointed group.[1]

Our first main result is the higher categorical analogue of (1), obtained by starting with a strict 2-group $G_{(2)}$ in place of the ordinary group G.

Here we do not consider geometric realizations of our categories and 2-categories (for more on that see the closely related article [**4**] as well as [**27**]) but instead focus on the existence of these sequences of 1- and 2-groupoids. We comment on further aspects of the topic of universal n-bundles in §7. More details will be given in [**26**].

1.0.0.2. The formulation in terms of crossed modules. For many purposes, like doing explicit computations and for applying the rich toolbox of simplicial methods, it is possible (and useful!) to express n-groups in terms of n-term complexes of ordinary groups with extra structure on them. For instance strict 2-groups are well known to be equivalent to crossed modules of two ordinary groups: one describes the group of objects, the other the group of morphisms of the 2-group.

This pattern continues, but there is a bifurcation of constructions, all of which are (homotopy) equivalent. Sufficiently strict 3-groups – "Gray groups" – are described by 2-crossed modules, which involve three ordinary groups forming a normal complex, and also by crossed squares, which look like crossed modules of crossed modules of groups. We will primarily use the former, and only mention crossed squares when we cannot avoid it.[2] The way we use these two models can be illustrated in one lower categorical dimension by comparing the *map*

$$G \xrightarrow{\mathrm{id}} G$$

to the *crossed module*

$$G \xrightarrow{\mathrm{id}} G \xrightarrow{\mathrm{Ad}} \mathrm{Aut}(G)$$

using that map. The crossed module can be thought of as the mapping cone (=homotopy quotient) of the identity map.

The translation between n-groups and their corresponding n-term complexes of ordinary groups sheds light on both of these points of view. The analogue of our

[1] That is, the inclusion of the identity element is a closed cofibration.

[2] As one goes to higher categorical dimensions (which we do not do here), there are multiple directions in which to extend the relevant diagrams, so there are a number of different models for n-groups. There is a sort of nonabelian Dold-Kan theorem, due to Carrasco and Cegarra [**11**], which can be used to characterise n-groups by n-term complexes of (possibly nonabelian) groups with the structure they call a hypercrossed complex.

statement about the 3-group $\mathrm{INN}_0(G_{(2)})$ is our second main result: the complex of groups describing $\mathrm{INN}_0(G_{(2)})$ is the mapping cone of the identity on the complex of groups describing $G_{(2)}$ itself.

This fact was anticipated from considerations in the theory of Lie n-algebras [**28**], where the Lie $(n+1)$-algebra corresponding to a Lie $(n+1)$-group $\mathrm{INN}_0(G_{(n)})$ has proven to be crucial for understanding connections with values in Lie n-algebras. There one finds that inner derivation Lie $(n+1)$-algebras govern Lie $(n+1)$-algebras of Chern-Simons type. The fact that $\mathrm{INN}_0(G_{(2)})$ arises from a mapping cone of the identity is crucial in this context.

1.0.0.3. THE PLAN OF THIS ARTICLE. The main content of this work is as follows – first a concise and natural definition of inner automorphisms of 2-groups, relating them to the full automorphism $(n+1)$-group and to the categorical center. Then we apply this definition to the case that $G_{(2)}$ is a strict 2-group and work out in full detail what $\mathrm{INN}_0(G_{(2)})$ looks like, i.e. how the various composition operations work, thus extracting its description in terms of complexes of ordinary groups. We state and prove the main properties of $\mathrm{INN}_0(G_{(2)})$.

The plan of our discussion is as follows.

- In part 2 we recall the relation between 2- and 3-groups and crossed modules of ordinary groups. This serves to set up our convention for the precise choice of identification of 2-group morphisms with ordinary group elements.
- In part 3 we state our two main results.
- In part 4 we define inner automorphism n-groups and prove some important general properties of them.
- In part 5 we apply our definition of inner automorphisms to an arbitrary strict 2-group $G_{(2)}$, to form the 3-group $\mathrm{INN}_0(G_{(2)})$. We then work out in detail the description of $\mathrm{INN}_0(G_{(2)})$ in terms of ordinary groups, spelling out the nature of the various composition and product operations.
- In part 6 we state and prove the main properties of $\mathrm{INN}_0(G_{(2)})$, including our two main results.
- In part 7 we close by indicating in more detail how inner automorphism $(n+1)$-groups play the role of universal n-bundles. We also relate our construction here to analogous simplicial constructions.

2. n-Groups in terms of groups

Sufficiently strict n-groups are equivalent to certain structures – crossed modules and generalizations thereof – involving just collections of ordinary groups with certain structure on them.

2.1. Conventions for strict 2-groups and crossed modules

An ordinary group G may be regarded as a one object category. If we regard G as such a category, we write $\mathbf{B}G$ in order to emphasize that we are thinking of the monoidal 0-category G as a one object 1-category.

This way we obtain a notion of n-groups from any notion of n-categories: an n-group $G_{(n)}$ is a monoidal $(n-1)$-category such that when regarded as a one-object (n)-category $\mathbf{B}G_{(n)}$ it becomes a one-object n-groupoid. An n-groupoid is an n-category all whose k-morphisms are equivalences, for all $1 \leqslant k \leqslant n$.

Here we shall be concerned with strict 2-groups and with 3-groups which are Gray-categories. A strict 2-group $G_{(2)}$ is one such that $\mathbf{B}G_{(2)}$ is a strict one-object 2-groupoid. A Gray-groupoid is a 3-groupoid which is strict except for the exchange law of 2-morphisms.

The standard reference for 2-groups is [**2**]. A discussion of Gray-groupoids useful for our context is in [**22**]. We come to Gray-groups in 2.2.

It is well known that strict 2-groups are equivalent to crossed modules of ordinary groups. This was first established in [**10**]. The relation to category objects in groups was also discussed in [**23**]. The notion of a crossed module is originally due to [**32**].

Definition 1. *A* **crossed module of groups** *is a diagram*

$$H \xrightarrow{t} G \xrightarrow{\alpha} \mathrm{Aut}(H)$$

in Grp *such that*

$$\begin{array}{ccc} H & \xrightarrow{\mathrm{Ad}} & \mathrm{Aut}(H) \\ & {\scriptstyle t}\searrow \quad \nearrow{\scriptstyle \alpha} & \\ & G & \end{array}$$

and

$$\begin{array}{ccc} G \times H & \xrightarrow{\mathrm{Id}\times t} & G \times G \\ \downarrow{\scriptstyle \alpha} & & \downarrow{\scriptstyle \mathrm{Ad}} \\ H & \xrightarrow{t} & G \end{array} .$$

Definition 2. *A* **strict 2-group** $G_{(2)}$ *is any of the following equivalent entities*

- *a group object in* Cat
- *a category object in* Grp
- *a strict 2-groupoid with a single object*

A detailed discussion can be found in [**2**].

One identifies

- G is the group of objects of $G_{(2)}$.
- H is the group of morphism of $G_{(2)}$ starting at the identity object.
- $t : H \to G$ is the target homomorphism so that $h : \mathrm{Id} \to t(h)$ for all $h \in H$.
- $\alpha : G \to \mathrm{Aut}(H)$ is conjugation with identity morphisms:

$$\mathrm{Ad}_{\mathrm{Id}_g}(\ \mathrm{Id} \xrightarrow{h} t(h)\ ) = \ \mathrm{Id} \xrightarrow{\alpha(h)(h)} t(\alpha(g)(h))$$

for all $g \in G$, $h \in H$.

We often abbreviate

$$ {}^{g}h := \alpha(g)(h) \,. $$

Beyond that there are 2×2 choices to be made when identifying a strict 2-group $G_{(2)}$ with a crossed module of groups.

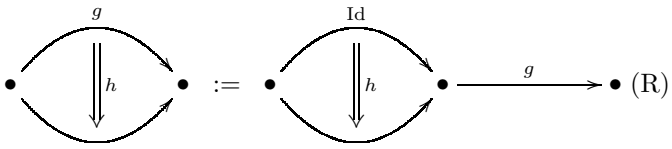
The first choice to be made is in which order to multiply elements in G. For $\bullet \xrightarrow{g_1} \bullet$ and $\bullet \xrightarrow{g_2} \bullet$ two morphisms in $\mathbf{B}G_{(2)}$, we can either set

$$ \bullet \xrightarrow{g_1} \bullet \xrightarrow{g_2} \bullet \;:=\; \bullet \xrightarrow{g_1 g_2} \bullet \quad \text{(F)} $$

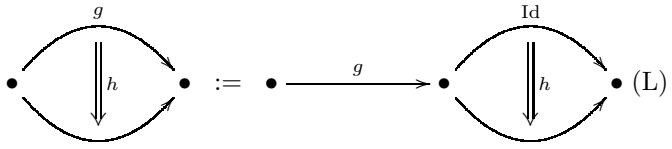
or

$$ \bullet \xrightarrow{g_1} \bullet \xrightarrow{g_2} \bullet \;:=\; \bullet \xrightarrow{g_2 g_1} \bullet \quad \text{(B)} \,. $$

The other choice to be made is how to describe arbitrary morphisms by an element in the semidirect product group $G \ltimes H$: every morphism of $G_{(2)}$ may be written as the product of one starting at the identity object with an identity morphism on some object. The choice of ordering here yields either



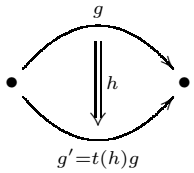
or



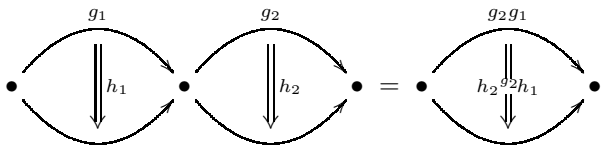
Here we choose the convention

$$ LB \,. $$

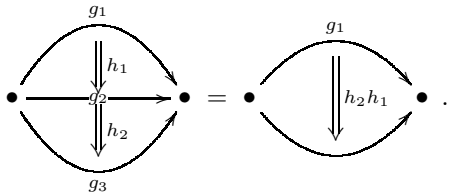
This implies



for all $g \in G$, $h \in H$, as well as the following two equations for horizontal and vertical composition in $\mathbf{B}G_{(2)}$, expressed in terms of operations in the crossed module



and



2.2. 3-Groups and 2-crossed modules

As we are considering strict models in this paper, we will assume that all 3-groups are as strict as possible. This means they will be one-object Gray-categories, or *Gray-monoids* [**15**]. A Gray-monoid is a (strict) 2-category $\mathcal{M}$ such that the product 2-functor

$$\mathcal{M} \otimes \mathcal{M} \to \mathcal{M}$$

uses the Gray tensor product [**17, 16**], not the usual Cartesian product of 2-categories. Thus non-identity coherence morphisms only appear when we use the monoidal structure on $\mathcal{M}$. So from now on a "3-group" $G_{(3)}$ will mean a 3-group such that regarded as a one-object 3-groupoid $\mathbf{B}G_{(3)}$ it is a one-object Gray-groupoid.

Just as a 2-group gives rise to a crossed module, a 3-group gives rise to a 2-crossed module. Roughly, this is a complex of groups

$$L \to M \to N,$$

and a function

$$M \times M \to L \tag{2}$$

such that $L \to M$ is a crossed module, and (2) measures the failure of $M \to N$ to be a crossed module. An example is when $L = 1$, and then we have a crossed module.

The relation between 3-groups and 2-crossed modules was described in [**22**]. The precise definition of a 2-crossed module is as follows, see also [**14**].

Definition 3. *A* **2-crossed module** *is a normal complex of length 2*

$$L \xrightarrow{\partial_2} M \xrightarrow{\partial_1} N$$

of N-groups (N acting on itself by conjugation) and an N-equivariant function

$$\{\cdot,\cdot\} : M \times M \to L\,,$$

called a Peiffer lifting, satisfying these conditions:

1. $\partial_2\{m, m'\} = (mm'm^{-1})({}^{\partial_1 m}m')^{-1}$,
2. $\{\partial_2 l, \partial_2 l'\} = [l, l'] := ll'l^{-1}l'^{-1}$
3. (a) $\{m, m'm''\} = \{m, m'\}^{mm'm^{-1}}\{m, m''\}$
   (b) $\{mm', m''\} = \{m, m'm''m'^{-1}\}^{\partial_1 m}\{m', m''\}$,
4. $\{m, \partial_2 l\} = ({}^m l)({}^{\partial_1 m}l)^{-1}$
5. ${}^n\{m, m'\} = \{{}^n m, {}^n m'\}$,

where $l, l' \in L,\ m, m', m'' \in M$ *and* $n \in N$.

Here ${}^m l$ denotes the action

$$\begin{aligned} M \times L &\to L \\ (m, l) &\mapsto {}^m l := l\{\partial_2 l^{-1}, m\}\,. \end{aligned} \tag{3}$$

A *normal* complex is one in which $im\ \partial$ is normal in $ker\ \partial$ for all differentials.

It follows from these conditions that $\partial_2 : L \to M$ is a crossed module with the action (3).

To get from a 3-group $G_{(3)}$ to a 2-crossed module [**22**], we emulate the construction of a crossed module from a 2-group: one identifies

- N is the group of objects of $G_{(3)}$.
- M is the group of 1-morphisms of $G_{(3)}$ starting at the identity object.
- L is the group of 2-morphisms starting at the identity 1-arrow of the identity object
- $\partial_1 : M \to N$ is the target homomorphism such that $m : \mathrm{Id} \to \partial_1(m)$ for all $m \in M$.
- $\partial_2 : L \to M$ is the target homomorphism such that $l : \mathrm{Id}_{\mathrm{Id}} \to \partial_2(l)$ for all $l \in L$.
- The various actions arise by whiskering, analogously to the case of a 2-group.

We will not go into the proof that this gives rise to a 2-crossed module for all 3-groups, but only in the case we are considering. One reason to consider 2-crossed modules is that the homotopy groups of $G_{(3)}$ can be calculated as the homology of the sequence underlying the 2-crossed module.

2.3. Mapping cones of crossed modules

Another notion related to 3-groups [**1**] is crossed modules internal to crossed modules (more technically known as crossed squares, [**18**],[**23**]). More generally, consider a map ϕ of crossed modules:

Definition 4 (nonabelian mapping cone [23]). *For*

$$\begin{array}{ccc} H_2 & \xrightarrow{\phi_H} & H_1 \\ \downarrow{\scriptstyle t_2} & & \downarrow{\scriptstyle t_1} \\ G_2 & \xrightarrow{\phi_G} & G_1 \end{array}$$

a 2-term complex of crossed modules ($t_i : H_i \to G_i$), we say its mapping cone is the complex of groups

$$H_2 \xrightarrow{\partial_2} G_2 \ltimes H_1 \xrightarrow{\partial_1} G_1 \ , \tag{4}$$

where

$$\partial_1 : (g_2, h_1) \mapsto t_1(h_1)\phi_G(g_2)$$

and

$$\partial_2 : h_2 \mapsto (t_2(h_2), \phi_H(h_2)^{-1}) \, .$$

Here G_2 acts on H_1 by way of the morphism $\phi_G : G_2 \to G_1$.

When no structure is imposed on ϕ, (4) is merely a complex. However, if ϕ is a crossed square, the mapping cone is a 2-crossed module (originally shown in [**13**], but see [**14**]). We will not need to define crossed squares here but just note they come equipped with a map

$$h : G_2 \times H_1 \to H_2$$

satisfying conditions similar to the Peiffer lifting. The details can be found in [**14**], which we recall in our appendix. The only crossed square we will see in this paper is the identity map on a crossed module

$$\begin{array}{ccc} H & \xrightarrow{\mathrm{id}} & H \\ {\scriptstyle t}\downarrow & & \downarrow{\scriptstyle t} \\ G & \xrightarrow{\mathrm{id}} & G \end{array}$$

with the structure map

$$h : G \times H \to H \tag{5}$$

$$(g, h) \mapsto h^g h^{-1}. \tag{6}$$

This concept of "crossed modules of crossed modules" is explored in Norrie's thesis [**25**] on 'actors' of crossed modules, with a focus on categorifying group theory, rather than geometry. Automorphisms of crossed modules of groups and groupoids have been discussed in [**9**] and [**8**].

3. Main results

3.1. The exact sequence $G_{(2)} \to \mathrm{INN}_0(G_{(2)}) \to \mathbf{B}G_{(2)}$

We describe the 3-group $\mathrm{INN}_0(G_{(2)})$ for $G_{(2)}$ any strict 2-group, and show that it plays the role of the universal principal $G_{(2)}$-bundle in that

- $\mathrm{INN}_0(G_{(2)})$ is equivalent to the trivial 3-group (hence "contractible").
- $\mathrm{INN}_0(G_{(2)})$ fits into the short exact sequence

$$G_{(2)} \hookrightarrow \mathrm{INN}_0(G_{(2)}) \twoheadrightarrow \mathbf{B}G_{(2)}$$

of strict 2-groupoids.

3.2. $\mathrm{INN}_0(G_{(2)})$ from a mapping cone

We show that the 3-group $\mathrm{INN}_0(G_{(2)})$ comes from a 2-crossed module

$$H \longrightarrow G \ltimes H \longrightarrow G$$

which is the mapping cone of

$$\begin{array}{ccc} H & \xrightarrow{\mathrm{Id}} & H \\ {\scriptstyle t}\downarrow & & \downarrow{\scriptstyle t} \\ G & \xrightarrow{\mathrm{Id}} & G \end{array} ,$$

the identity map of the crossed module $(t : H \to G)$ which determines $G_{(2)}$.

Notice that this harmonizes with the analogous result for Lie 2-algebras discussed in [**28**].

4. Inner automorphism $(n+1)$-groups

An automorphism of an n-group $G_{(n)}$ is simply an automorphism of the n-category $\mathbf{B}G_{(n)}$. We want to say that such an automorphism q is *inner* if it is equivalent to the identity automorphism

$$\mathbf{B}G_{(n)} \quad \overset{\mathrm{Id}}{\underset{q}{\Downarrow \sim}} \quad \mathbf{B}G_{(n)} \,.$$

Notice that we really do mean automorphisms here, and not auto-equivalences: we require an autmorphism to be an endo-n-functor with a *strict* inverse.

Automorphisms (of crossed modules) connected to the identity appear in definition 2.3 of [**8**] under the name "free derivations". Since the naturality diagram for the transformation connecting an automorphism to the identity implies that this automorphism arises from conjugations, we think of them as *inner automorphisms* here and reserve the term "(inner) derivations" for the image of these automorphisms as one passes from Lie n-groups to Lie n-algebras [**28**].

A useful way to think of the n-groupoid of inner automorphisms is in terms of what we call "tangent categories", a slight variation of the concept of comma categories.

Tangent categories in general happen to live in interesting exact sequences. In order to be able to talk about these, we first quickly set up a our definitions for exact sequences of strict 2-groupoids.

Remember that we work entirely within the Gray-category whose objects are strict 2-groupoids, whose morphisms are strict 2-functors, whose 2-morphisms are pseudonatural transformations and whose 3-morphisms are modifications of these.

4.1. Exact sequences of strict 2-groupoids

Inner automorphism n-groups turn out to live in interesting *exact sequences of* $(n+1)$*-groups*. Therefore we want to talk about generalizations of exact sequences of groups to the world of n-groupoids. Since for our purposes here only strict 2-groupoids matter, we shall be content with just using a definition applicable to that case.

Definition 5 (exact sequence of strict 2-groupoids). *A collection of composable morphisms*

$$C_0 \xrightarrow{f_1} C_1 \xrightarrow{f_2} \cdots \xrightarrow{f_n} C_n$$

of strict 2-groupoids C_i is called an exact sequence if, as ordinary maps between spaces of 2-morphisms,

- f_1 *is injective*
- f_n *is surjective*
- *the image of f_i is the preimage under f_{i+1} of the collection of all identity 2-morphisms on identity 1-morphisms in* $\mathrm{Mor}_2(C_{i+1})$*, for all* $1 \leqslant i < n$.

In order to make this harmonize with our distinction between n-groups $G_{(n)}$ and the corresponding 1-object n-groupoids $\mathbf{B}G_{(n)}$ we add to that

Definition 6 (exact sequences of strict 2-groups). *A collection of composable morphisms*

$$G_0 \xrightarrow{f_1} G_1 \xrightarrow{f_2} \cdots \xrightarrow{f_n} G_n$$

of strict 2-groups is called an exact sequence if the corresponding chain

$$\mathbf{B}G_0 \xrightarrow{\mathbf{B}f_1} \mathbf{B}G_1 \xrightarrow{\mathbf{B}f_2} \cdots \xrightarrow{\mathbf{B}f_n} \mathbf{B}G_n$$

is an exact sequence of strict 2-groupoids.

4.1.0.4. Remark. Ordinary exact sequences of groups thus precisely correspond to exact sequences of strict 2-groups all whose morphisms are identities.

4.2. Tangent 2-categories

We present a simple but useful way describe 2-categories of morphisms with coinciding source. We find it helpful to refer to this construction as *tangent categories* for reasons to become clear. It is not hard to see that this is the globular analog of the simplicial construction known as *décalage*, as will be discussed more in 7.3. In the context of higher categories it has been considered (over single objects) in section 3.2 of [**22**].

Definition 7. *Denote by*

$$\mathrm{pt} := \{\bullet\}$$

the strict 2-category with a single object and no nontrivial morphisms and by

$$I := \{ \bullet \xrightarrow{\sim} \circ \},$$

the strict 2-category consisting of two objects connected by a 1-isomorphism.

Of course I is equivalent to pt – but not isomorphic. We fix one injection

$$i : \mathrm{pt} \hookrightarrow I$$

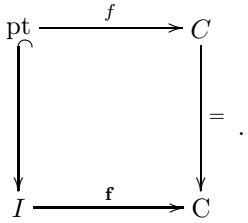
$$i : \bullet \mapsto \bullet$$

once and for all.

It is useful to think of morphisms

$$\mathbf{f} : I \to C$$

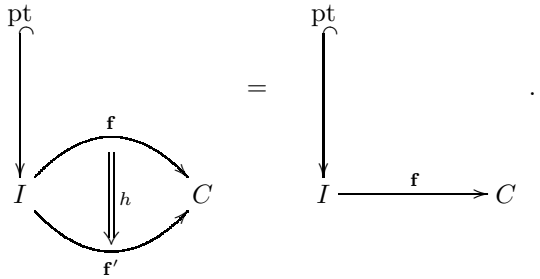
from I to some codomain C as labeled by the corresponding image of the ordinary point



Definition 8 (tangent 2-bundle). *Given any strict 2-category C, we define its tangent 2-bundle*

$$TC \subset \mathrm{Hom}_{2\mathrm{Cat}}(I, C)$$

to be that sub 2-category of morphisms from I into C which collapses to a 0-category when pulled back along the fixed inclusion $i : \mathrm{pt} \hookrightarrow I$: the morphisms h in $T\,C$ are all those for which



The tangent 2-bundle is a disjoint union

$$TC = \bigoplus_{x \in \mathrm{Obj}(C)} T_x C$$

of tangent 2*-categories at each object* x *of* C*. In this way it is a* 2*-bundle*

$$p : TC \longrightarrow \mathrm{Obj}(C)$$

over the space of objects of C*.*

As befits a tangent bundle, the tangent 2-bundle has a canonical section

$$e_{\mathrm{Id}} : \mathrm{Obj}(C) \to TC$$

which sends every object of C to the Identity morphism on it.

4.2.0.5. Remark. The groupoid I plays the role of the interval in topology and underlies the homotopy theory for groupoids, as described in [**21**]. The terminology "tangent category" finds further justification when the discussion here is done for smooth n-groups which are then sent to the corresponding Lie n-algebras: indeed, as indicated in figure 3 of [**28**], one finds a close relation between maps from the interval I, inner automorphisms, the notion of universal n-bundles and tangency relations.

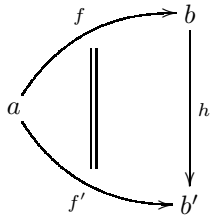
4.2.0.6. Example (slice categories). For C any 1-groupoid, i.e. a strict 2-groupoid with only identity 2-morphisms, its tangent 1-category is the comma category

$$TC = ((\mathrm{Obj}(C) \hookrightarrow C) \downarrow \mathrm{Id}_C) \,.$$

This is the disjoint union of all co-over categories on all objects of C

$$TC = \bigoplus_{a \in \mathrm{Obj}(C)} (a \downarrow C)$$

Objects of TC are morphisms $f : a \to b$ in C, and morphisms $f \xrightarrow{h} f'$ in TC are commuting triangles

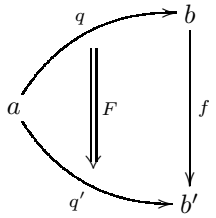


in C.

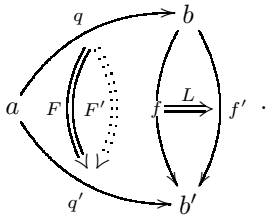
4.2.0.7. Example (strict tangent 2-groupoids). The example which we are mainly interested in is that where C is a strict 2-groupoid. For a any object in C, an object of $T_a C$ is a morphism

$$a \xrightarrow{q} b \,.$$

A 1-morphism in T_aC is a filled triangle



in C. Finally, a 2-morphism in T_aC looks like



The composition of these 2-morphisms is the obvious one. We give a detailed description for the case the $C = \mathbf{B}G_{(2)}$ in 5.

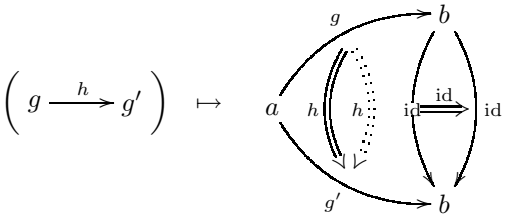
Proposition 1. *For any strict* 2*-category* C*, its tangent* 2*-bundle* TC *fits into an exact sequence*

$$\mathrm{Mor}(C) \hookrightarrow TC \twoheadrightarrow C$$

of strict 2-categories.

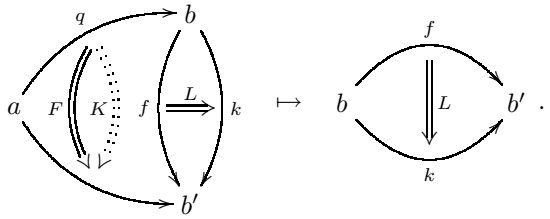
Here $\mathrm{Mor}(C) := \mathrm{Disc}(\mathrm{Mor}(C))$ is the 1-category of morphisms of C, regarded as a strict 2-category with only identity 2-morphisms.

Proof. The strict inclusion 2-functor on the left is



for $g, g' : a \to b$ any two parallel morphisms in C and h any 2-morphism between them.

The strict surjection 2-functor on the right is



The image of the injection is precisely the preimage under the surjection of the identity 2-morphism on the identity 1-morphisms . This means the sequence is exact. □

4.3. Inner automorphisms

Often, for G any group, inner and outer automorphisms are regarded as sitting in a short exact sequence

$$\mathrm{Inn}(G) \longrightarrow \mathrm{Aut}(G) \longrightarrow \mathrm{Out}(G)$$

of ordinary groups.

But we will find shortly that we ought to be regarding the conjugation automorphisms by two group elements which differ by an element in the center of the group as *different* inner automorphisms.

So adopting this point of view for ordinary groups, one gets instead the exact sequence

$$\mathrm{Z}(G) \longrightarrow \mathrm{Inn}'(G) \longrightarrow \mathrm{Aut}(G) \longrightarrow \mathrm{Out}(G) \ .$$

Of course this means setting $\mathrm{Inn}'(G) \simeq G$, which seems to make this step rather ill motivated. But it turns out that this degeneracy of concepts is a coincidence of low dimensions and will be lifted as we pass to inner automorphisms of higher groups.

First recall the standard definitions of center and automorphism of 2-groupoids:

Definition 9. *Given any strict* 2*-groupoid* C*,*

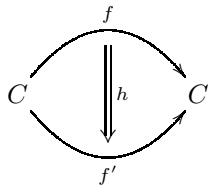
- *the automorphism* 3*-group*

$$\mathrm{AUT}(C) := \mathrm{Aut}_{2\mathrm{Cat}}(C)$$

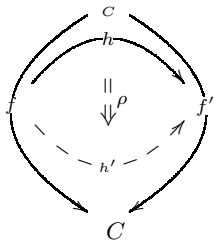
is the 2*-groupoid of isomorphisms on* C*: objects are the strict and strictly invertible 2-functors*

$$C \xrightarrow[\simeq]{f} C \ ,$$

morphisms are pseudonatural transformations



between these and 2-morphisms are modifications



between those – the product on the 3-group comes from the composition of autofunctors;

- *the center of* C

$$Z(C) := \mathbf{B}\mathrm{AUT}(\mathrm{Id}_C)$$

is the (suspended) automorphism 2-group of the identity on C*, i.e. the full subgroupoid of* $\mathrm{AUT}(C)$ *on the single object* Id_C*.*

4.3.0.8. Example. The automorphism 2-group of any ordinary group G (regarded as a 2-group $\mathrm{Disc}(G)$ with only identity morphisms)

$$\mathrm{AUT}(G) := \mathrm{AUT}(\mathbf{B}G)$$

is that coming from the crossed module

$$G \xrightarrow{\mathrm{Ad}} \mathrm{Aut}(G) \xrightarrow{\mathrm{Id}} \mathrm{Aut}(G)\,.$$

The center

$$Z(G) := Z(\mathbf{B}G)$$

of any ordinary group is indeed the ordinary center of the group, regarded as a 1-object category.

4.3.0.9. Example. The automorphism 3-group of a strict 2-group (conceived in terms of crossed modules and 2-crossed modules) is discussed in theorem 4.3 of [**8**].

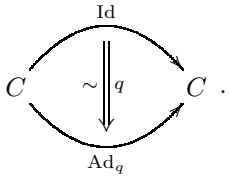
To these two standard definitions, we add the following one, which is supposed to be the proper 2-categorical generalization of the concept of inner automorphisms.

Definition 10 (inner automorphisms). *Given any strict* 2*-groupoid* C*, the tangent* 2*-groupoid*

$$\mathrm{INN}(C) := T_{\mathrm{Id}_C}(\mathrm{Aut}_{2\mathrm{Cat}}(C))$$

is called the 2*-groupoid of inner automorphisms of* C*, and as such thought of as being equipped with the monoidal structure inherited from* $\mathrm{End}(C)$*.*

If the transformation starting at the identity is denoted q, it makes good sense to call the inner automorphism being the target of that transformation Ad_q:



A bigon of this form is an object in $\mathrm{INN}(C)$. The product of two such objects is the horizontal composition of these bigons in 2Cat. We shall spell this out in great detail for the case $C = \mathbf{B}G_{(2)}$ in 5.

Proposition 2. *For* C *any strict 2-category, we have canonical morphisms*

$$\mathrm{Z}(C) \hookrightarrow \mathrm{INN}(C) \longrightarrow \mathrm{AUT}(C)$$

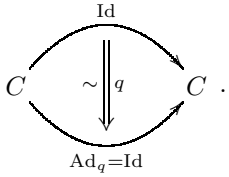
of strict 2-categories whose composition sends everything to the identity 2-morphism on the identity 1-morphism on the identity automorphism of C*.*

Moreover, this sits inside the exact sequence from proposition 1 as

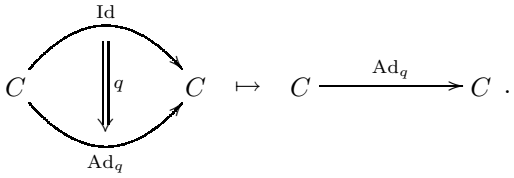
$$\begin{array}{ccccc} Z(C) & \longrightarrow & \mathrm{INN}(C) & \longrightarrow & \mathrm{AUT}(C) \\ \downarrow & & \downarrow & & \downarrow \\ \mathrm{Mor}(\mathbf{C}) & \longrightarrow & T\mathbf{C} & \longrightarrow & \mathbf{C} \end{array} ,$$

where $\mathbf{C} := \mathrm{Aut}_{2\mathrm{Cat}}(C)$*.*

Proof. Recall that a morphism in $Z(C)$ is a transformation of the form



This gives the obvious inclusion $Z(G) \hookrightarrow \mathrm{INN}(G)$. The morphism $\mathrm{INN}(G) \to \mathrm{AUT}(G)$ maps



□

4.3.0.10. REMARK. One would now want to define and construct the cokernel $\mathrm{OUT}(C)$ of the morphism $\mathrm{INN}(C) \to \mathrm{AUT}(C)$ and then say that

$$Z(C) \longrightarrow \mathrm{INN}(C) \longrightarrow \mathrm{AUT}(C) \longrightarrow \mathrm{OUT}(C) \tag{7}$$

is an exact sequence of 3-groups. We shall not consider $\mathrm{OUT}(C)$ here for proper 3-groups. Restricted to just 2-groups, however, one obtains the situation described in the next section.

4.4. Inner automorphism 2-groups

Even though inner automorphism 2-groups of ordinary (1-)groups are just a special case of the inner automorphism 3-groups of strict 2-groups to be discussed in the following, it may be helpful to spell out this simpler case in detail, in order to see how it connects with familiar examples of crossed modules.

For G any (ordinary) group, the sequence 7 is the exact sequence of 2-groups

$$1 \longrightarrow Z(G) \longrightarrow \mathrm{INN}(G) \longrightarrow \mathrm{AUT}(G) \longrightarrow \mathrm{OUT}(G) \longrightarrow 1$$

$$(1 \to 1) \to (1 \to Z(G)) \to (G \stackrel{\mathrm{Id}}{\to} G) \to (G \stackrel{\mathrm{Ad}}{\to} \mathrm{Aut}(G)) \to (1 \to \mathrm{Out}(G)) \to (1 \to 1)$$

corresponding to the exact sequence of crossed modules given in the second line.

Notice that there exists also the crossed module $(\mathrm{Inn}(G) \to \mathrm{Aut}(G))$, which however does not appear in the above sequence. In particular, this crossed module is not the one corresponding to our 2-group $\mathrm{INN}(G)$, which we had described in detail in the introduction.

4.5. Inner automorphism 3-groups.

Now we apply the general concept of inner automorphisms to 2-groups. The following definition just establishes the appropriate shorthand notation.

Definition 11. *For $G_{(2)}$ a strict 2-group, we write*

$$\mathrm{INN}(G_{(2)}) := \mathrm{INN}(\mathbf{B}G_{(2)})$$

for its 3-group of inner automorphisms.

In general this notation could be ambiguous, since one might want to consider the inner automorphisms of just the 1-groupoid underlying $G_{(2)}$. However, in the present context this will never occur and using the above definition makes a couple of expressions more manifestly appear as generalizations of familiar ones.

4.5.0.11. EXAMPLE. For G an ordinary group, regarded as a discrete 2-group, one finds that

$$\mathrm{INN}(G) := T_{\mathrm{Id}_{\mathbf{B}G}}(n\mathrm{Cat}) \simeq T_\bullet(\mathbf{B}G)$$

is the codiscrete groupoid over the elements of G. Its nature as a groupoid is manifest from its realization as

$$\mathrm{INN}(G) = T_\bullet(\mathbf{B}G)\,.$$

But it is also a (strict) 2-group. The monoidal structure is that coming from its realization as $\mathrm{INN}(G) := T_{\mathrm{Id}_{\mathbf{B}G}}(n\mathrm{Cat})$. The crossed module corresponding to this strict 2-group is

$$G \xrightarrow{\mathrm{Id}} G \xrightarrow{\mathrm{Ad}} \mathrm{Aut}(G)\,.$$

The main point of interest for us is the generalization of this fact to strict 2-groups. One issue that one needs to be aware of then is that the above isomorphism $T_{\mathrm{Id}_{\mathbf{B}G}}(n\mathrm{Cat}) \simeq T_\bullet(\mathbf{B}G)$ becomes a mere inclusion.

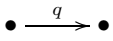
Proposition 3. *For $G_{(2)}$ any strict 2-group, we have an inclusion*

$$T_\bullet \mathbf{B}G_{(2)} \subset T_{\mathrm{Id}_{\mathbf{B}G_{(2)}}}(\mathrm{Aut}_{2\mathrm{Cat}}(\mathbf{B}G_{(2)}))$$

of strict 2-groupoids.

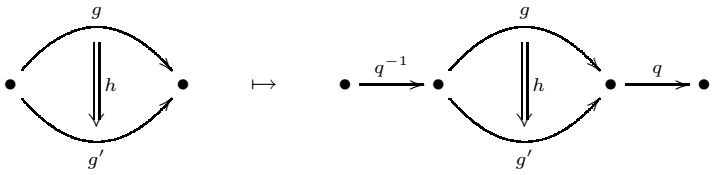
This realizes $T_\bullet \mathbf{B}G_{(2)}$ as a sub 2-groupoid of $T_{\mathrm{Id}_{\mathbf{B}G_{(2)}}}(\mathrm{Aut}_{2\mathrm{Cat}}(\mathbf{B}G_{(2)}))$.

Proof. The inclusion is essentially fixed by its action on objects: we define that an object in $T_\bullet \mathbf{B}G_{(2)}$, which is a morphism

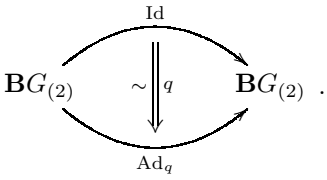


in $\mathbf{B}G$, is sent to the conjugation automorphism

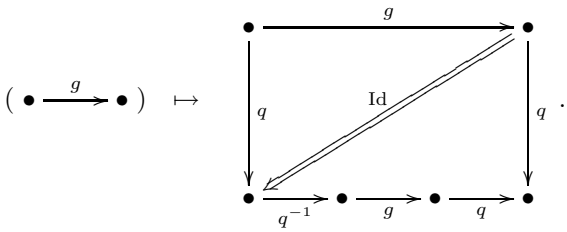
$\mathrm{Ad}_q \quad : \quad \mathbf{B}G_{(2)} \quad \to \quad \mathbf{B}G_{(2)}$



The transformation

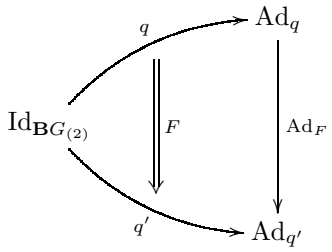


connecting this to the identity is given by the component map



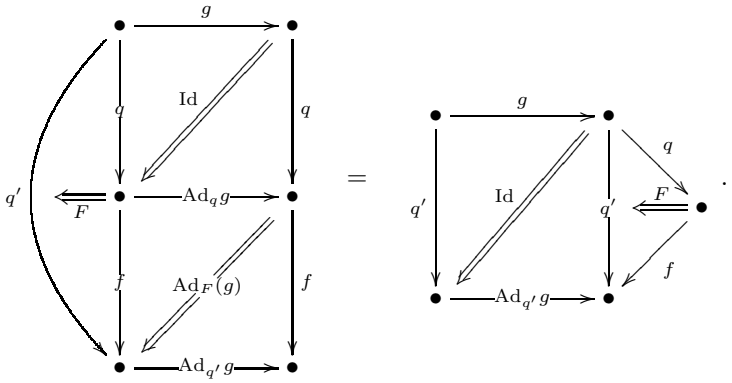
In general one could consider transformations whose component maps involve here a non-identity 2-morphism. The inclusion we are describing picks out exactly those transformations whose component map only involves identity 2-morphisms.

The crucial point to realize now is the form of the component maps of morphisms

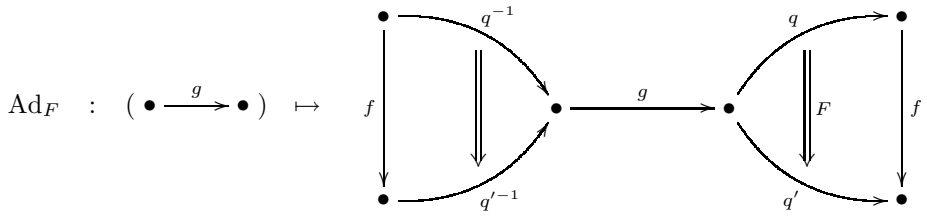


in $T_{\mathrm{Id}_{\mathbf{B}G_{(2)}}}(\mathrm{Aut}_{2\mathrm{Cat}}(\mathbf{B}G_{(2)}))$.

The corresponding component map equation is

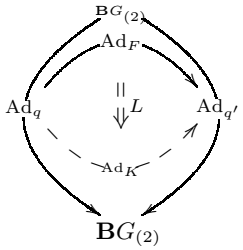


Solving this for Ad_F shows that this is given by conjugation

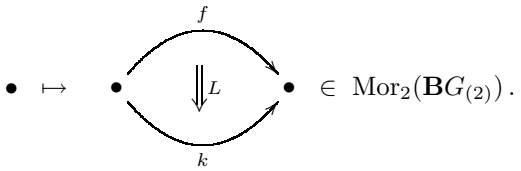


with a morphism in $T_\bullet(\mathbf{B}G_{(2)})$. And each such morphism in $T_\bullet(\mathbf{B}G_{(2)})$ yields a morphism in $T_{\mathrm{Id}_{\mathbf{B}G_{(2)}}}(\mathrm{Aut}_{2\mathrm{Cat}}(\mathbf{B}G_{(2)}))$ this way.

Finally, 2-morphisms in $T_{\mathrm{Id}_{\mathbf{B}G_{(2)}}}(\mathrm{Aut}_{2\mathrm{Cat}}(\mathbf{B}G_{(2)}))$ between these morphisms

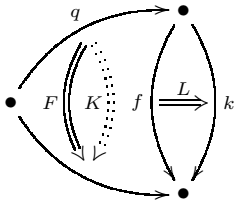


come from component maps



$\in \mathrm{Mor}_2(\mathbf{B}G_{(2)})$.

A sufficient condition for these component maps to solve the required condition for modifications of pseudonatural transformations is that they make



2-commute. But this defines a 2-morphism in $T_\bullet \mathbf{B}G_{(2)}$. And each such 2-morphism in $T_\bullet(\mathbf{B}G_{(2)})$ yields a 2-morphism in $T_{\mathrm{Id}_{\mathbf{B}G_{(2)}}}(\mathrm{Aut}_{2\mathrm{Cat}}(C))$ this way. □

The crucial point is that by the embedding

$$T_\bullet \mathbf{B}G_{(2)} \subset T_{\mathrm{Id}_{\mathbf{B}G_{(2)}}}(\mathrm{Aut}_{2\mathrm{Cat}}(\mathbf{B}G_{(2)}))$$

the former 2-category inherits the monoidal structure of the latter and hence becomes a 3-group in its own right. This 3-group is the object of interest here.

5. The 3-group $\mathrm{INN}_0(G_{(2)})$

Definition 12 ($\mathrm{INN}_0(G_{(2)})$). *For $G_{(2)}$ any strict 2-group, the 3-group $\mathrm{INN}_0(G_{(2)})$ is, as a 2-groupoid, given by*

$$\mathrm{INN}_0(G_{(2)}) := T_\bullet \mathbf{B}G_{(2)}$$

and equipped with the monoidal structure inherited from the embedding of proposition 3.

We now describe $\mathrm{INN}_0(G_{(2)})$ for $G_{(2)}$ coming from the crossed module

$$H \xrightarrow{t} G \xrightarrow{\alpha} \mathrm{Aut}(H)$$

in more detail, in particular spelling out the monoidal structure. We extract the operations in the crossed module corresponding to the various compositions in $\mathrm{INN}_0(G_{(2)})$ and then finally identify the 2-crossed module encoded by this.

5.1. Objects

The objects of $\mathrm{INN}_0(G_{(2)})$ are exactly the objects of $G_{(2)}$, hence the elements of G:

$$\mathrm{Obj}(\mathrm{INN}(G_{(2)})) = G\,.$$

The product of two objects in $\mathrm{INN}(G_{(2)})$ is just the product in G.

5.2. Morphisms

The morphisms

$$g \to h$$

in $\mathrm{INN}(G_{(2)})$ are

$$\mathrm{Mor}(\mathrm{INN}_0(G_{(2)})) = \left\{ \begin{array}{c|c} \begin{array}{ccc} & \overset{g}{\longrightarrow} & \\ \bullet & \Downarrow F & \downarrow f \\ & \underset{h}{\longrightarrow} & \end{array} & \begin{array}{c} f,g,h \in G,\ F \in H \\ h = t(F)fg \end{array} \end{array} \right\}$$

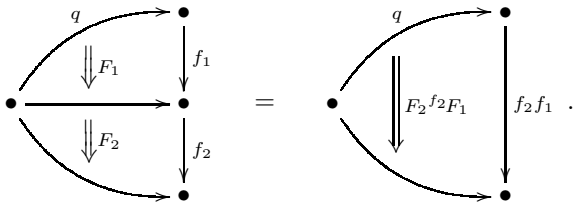
$$= \{(f, F; g) \mid f, g \in G, F \in H\}\,.$$

5.2.1. Composition

The composition of two such morphisms

$$\begin{array}{ccc} & \overset{q_1}{\longrightarrow} & \\ & \Downarrow F_1 \quad \downarrow f_1 & \\ \bullet & \overset{q'}{\longrightarrow} \bullet & \\ & \Downarrow F_2 \quad \downarrow f_2 & \\ & \underset{q''}{\longrightarrow} & \end{array} .$$

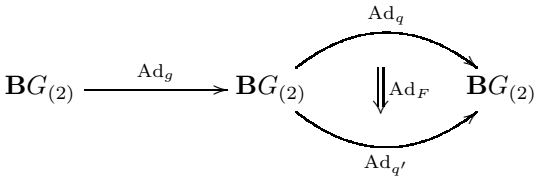
is in terms of group labels given by



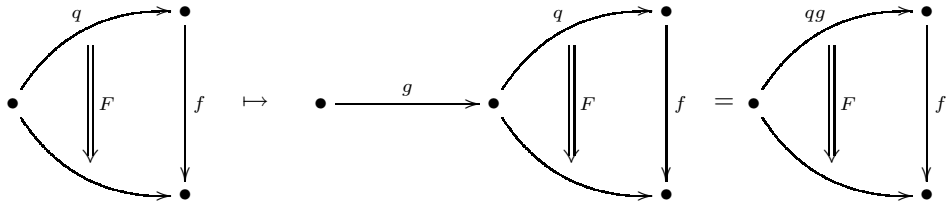
5.2.2. Product

Horizontal composition of automorphisms $\mathbf{B}G_{(2)} \to \mathbf{B}G_{(2)}$ gives the product in the 3-group $\mathrm{INN}(G_{(2)})$

Left whiskering of pseudonatural transformations

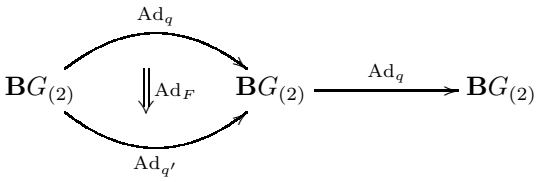


amounts to the operation

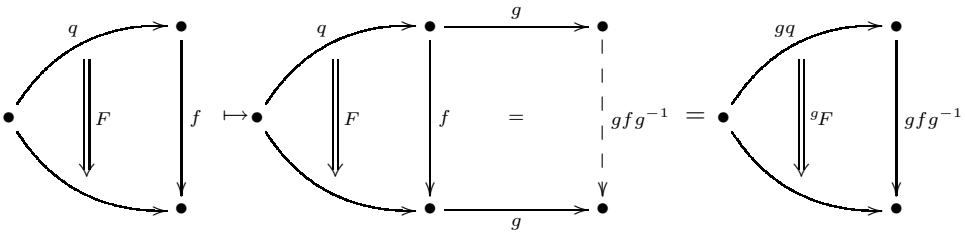


on the corresponding triangles.

Right whiskering of pseudonatural transformations

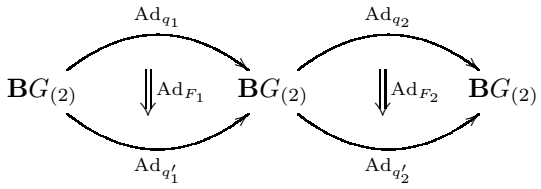


amounts to the operation

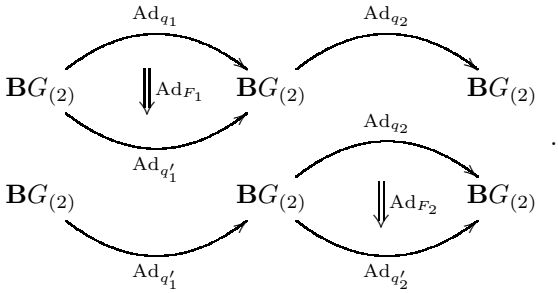


on the corresponding triangles.

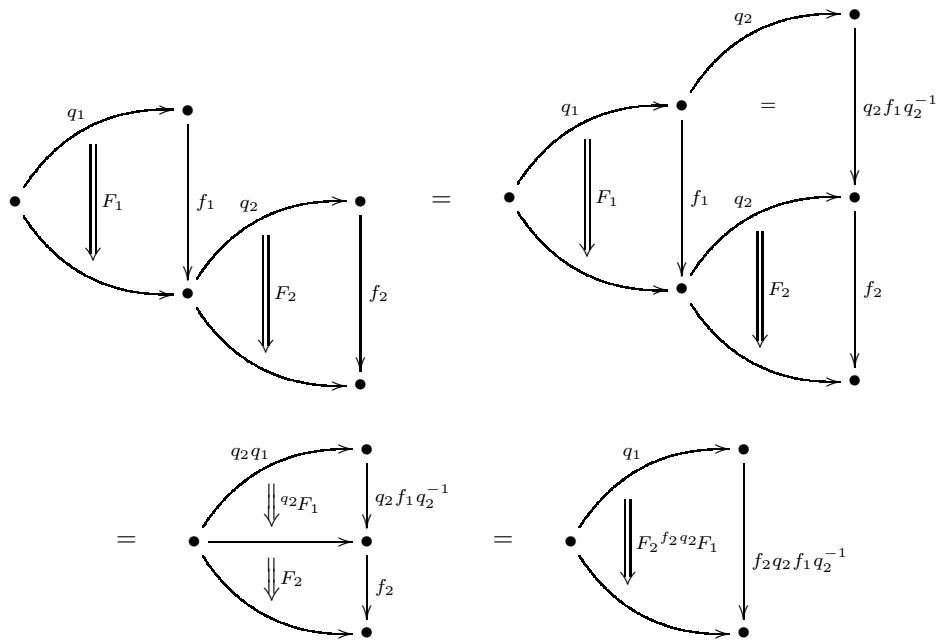
Since 2Cat is a Gray-category, the horizontal composition of pseudonatural transformations



is ambiguous. We shall agree to read this as



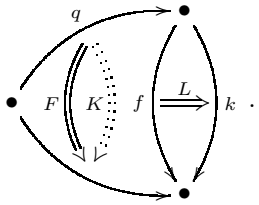
The corresponding operation on triangles labelled in the crossed module is



The non-identitcal isomorphism which relates this to the other possible way to evaluate the horizontal composition of pseudonatural transformations gives rise to the Peiffer lifting of the corresponding 2-crossed module. This is discussed in 6.4.

5.3. 2-Morphisms

The 2-morphisms in $\mathrm{INN}_0(G_{(2)})$ are given by diagrams

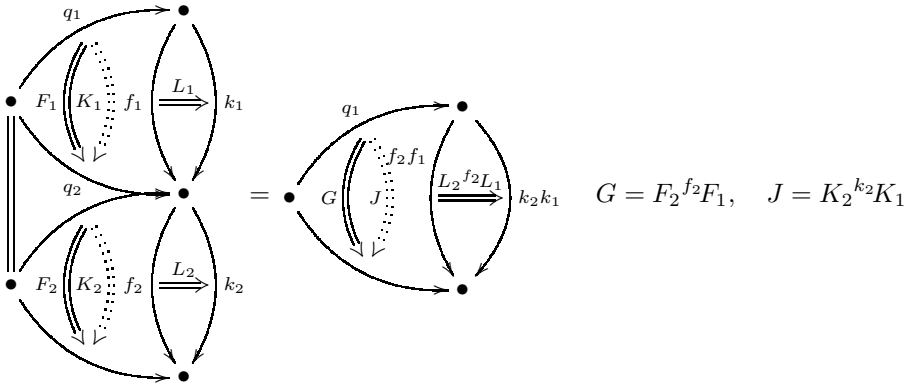


In terms of the group labels this means that $L \in H$ satisfies

$$L = K^{-1}F\,. \tag{8}$$

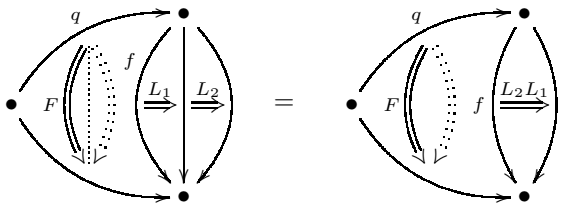
5.3.1. Composition

The horizontal composition of 2-morphisms in $\mathrm{INN}_0(G_{(2)})$ is given by



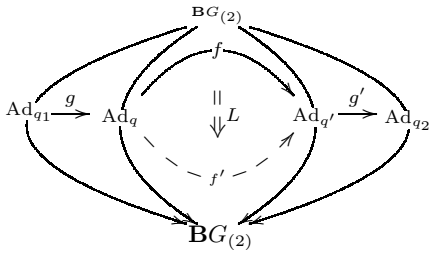
$$G = F_2{}^{f_2}F_1, \quad J = K_2{}^{k_2}K_1$$

and vertical composition by

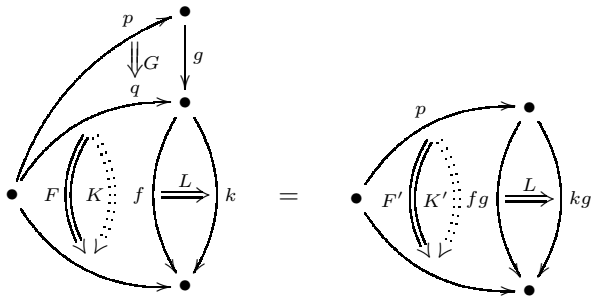


(Notice that these compositions do go horizontally and vertically, respectively, once we rotate such that the bigons have the standard orientation.)

Notice that whiskering along 1-morphisms

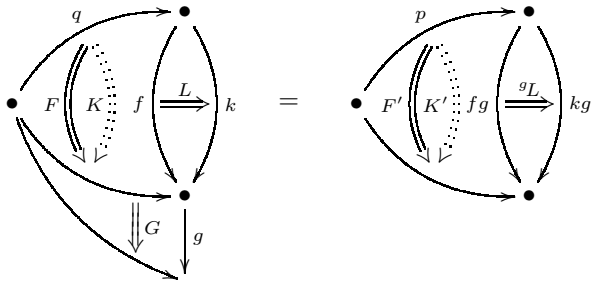


acts on the component maps as



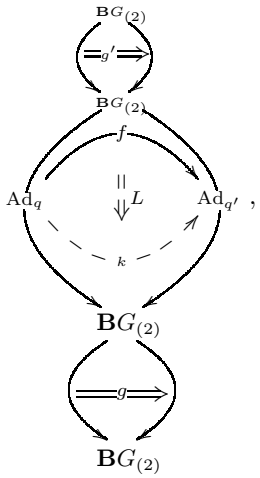
$$F' = F^f G, \quad K' = K^k G$$

and

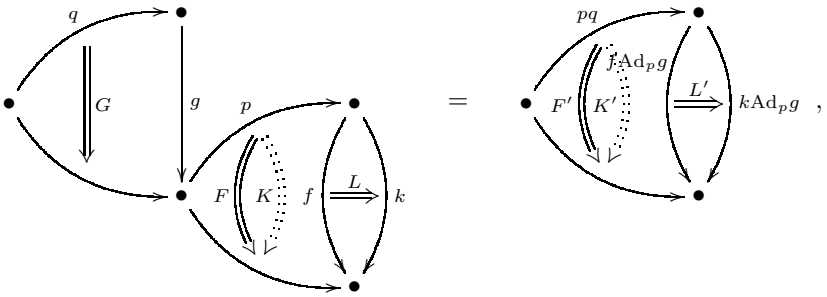


$$F' = G^g F, \quad K' = G^k K\,.$$

There is one more type of whiskering possible with 2-morphisms,



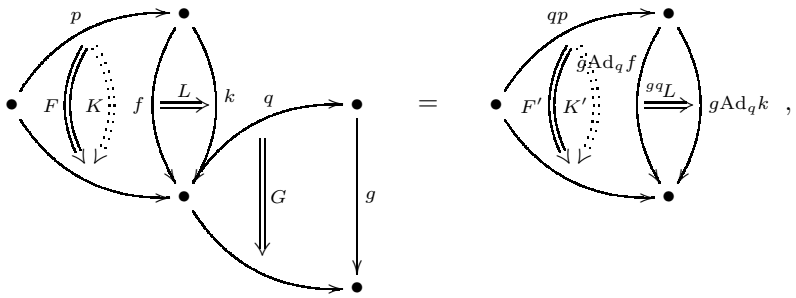
which acts in the following way on the components:



where

$$F' = F^{fp}G,$$
$$K' = K^{kp}G,$$
$$L' = {}^{kp}G^{-1}L^{fp}G.$$

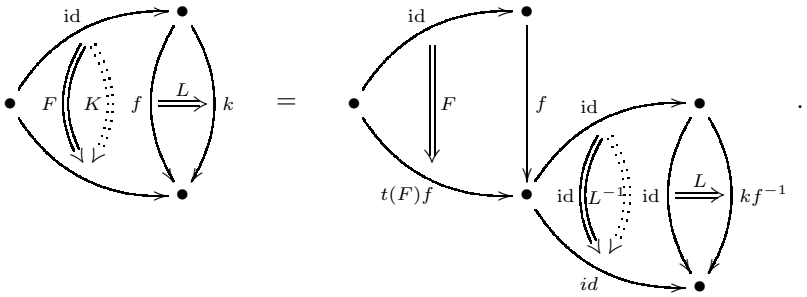
and



where

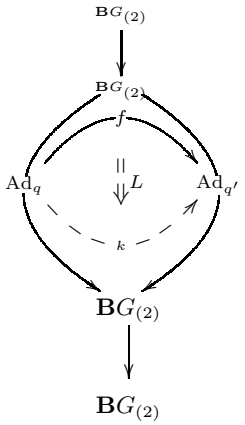
$$F' = G^{gq}F,$$
$$K' = G^{gq}K.$$

An important case of this is:



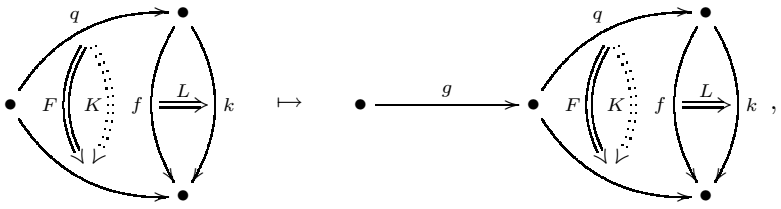
5.3.2. Product

The whiskering along objects

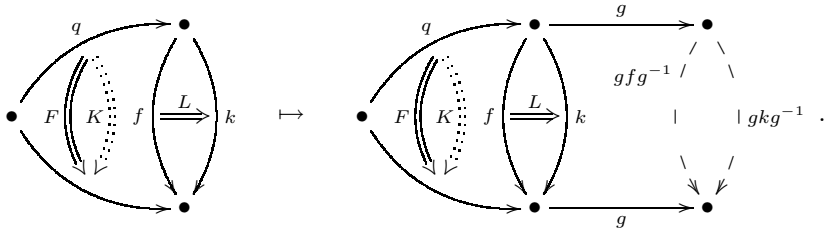


gives the product of objects with 2-morphisms in the 3-group $\mathrm{INN}(G_{(2)})$. Its action on 2-morphisms, which we have already discussed, extends in a simple way to 3-morphisms:

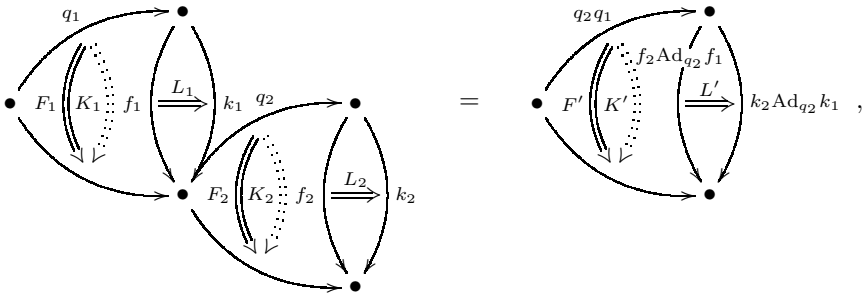
left whiskering along an object acts as



while right whiskering along an object acts as



To calculate the product of a pair of 2-morphisms, we use the fact that a 2-morphism is uniquely determined by its source and target.



with

$$F' = F_2{}^{f_2 q_2} F_1$$
$$K' = K_2{}^{k_2 q_2} K_1$$
$$L' = L_2{}^{f_2 q_2} L_1$$

6. Properties of $\mathrm{INN}_0(G_{(2)})$

6.1. Structure morphisms

We have defined $\mathbf{B}(\mathrm{INN}_0(G_{(2)}))$ essentially as a sub 3-category of 2Cat. The latter is a Gray-category, in that it is a 3-category which is strict except for the exchange law for composition of 2-morphisms. Accordingly, also $\mathbf{B}(\mathrm{INN}_0(G_{(2)}))$ is strict except for the exchange law for 2-morphisms.

This means that as a mere 2-groupoid (forgetting the monoidal structure) $\mathrm{INN}_0(G_{(2)})$ is strict.

6.1.1. Strictness as a 2-groupoid

Proposition 4. *The underlying 2-groupoid of* $\mathrm{INN}_0(G_{(2)})$ *is strict.*

Proof. This follows from the rules for horizontal and vertical composition of 2-morphisms in $\mathrm{INN}_0(G_{(2)})$ – displayed in 5.3.1 – and the fact that $G_{(2)}$ itself is a strict 2-group, by assumption. □

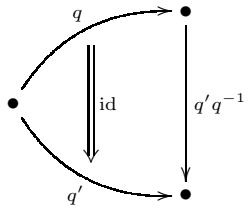
But the product 2-functor on $\mathrm{INN}_0(G_{(2)})$ respects horizontal composition in $\mathrm{INN}_0(G_{(2)})$ only weakly. In the language of 2-groups, this corresponds to a failure of the Peiffer identity

6.2. Trivializability

Proposition 5. *The 2-groupoid* $\mathrm{INN}_0(G_{(2)})$ *is connected,*

$$\pi_0(\mathrm{INN}_0(G_{(2)})) = 1\,.$$

Proof. For any two objects q and q' there is the morphism



□

Proposition 6. *The Hom-groupoids of the 2-category* $\mathrm{INN}_0(G_{(2)})$ *are codiscrete, meaning that they have precisely one morphism for every ordered pair of objects.*

Proof. By equation (8) there is at most one 2-morphism between any parallel pair of morphisms in $\mathrm{INN}_0(G_{(2)})$. For there to be any such 2-morphism at all, the two group elements f and k in the diagram above (8) have to satisfy $kf^{-1} \in \mathrm{im}(t)$. But by using the source-target matching condition for F and K one readily sees that this is always the case. □

Theorem 1. *The 3-group* $\mathrm{INN}_0(G_{(2)})$ *is equivalent to the trivial 3-group. If* $G_{(2)}$ *is a Lie 2-group, then* $\mathrm{INN}_0(G_{(2)})$ *is equivalent to the trivial Lie 3-group even as a Lie 3-group.*

Proof. Equivalence of 3-groups $G_{(3)}$, $G'_{(3)}$ is, by definition, that of the corresponding 1-object 3-groupoids $\mathbf{B}G_{(3)}$, $\mathbf{B}G'_{(3)}$. For showing equivalence with the trivial 3-group, it suffices to exhibit a pseudonatural transformation of 3-functors

$$\mathrm{id}_{\mathbf{B}(\mathrm{INN}_0(G_{(2)}))} \to I_{\mathbf{B}(\mathrm{INN}_0(G_{(2)}))}\,,$$

where $I_{\mathbf{B}(\mathrm{INN}_0(G_{(2)}))}$ sends everything to the identity on the single object of $\mathbf{B}\mathrm{INN}_0(G_{(2)})$. Such a transformation is obtained by sending the single object to the identity 1-morphism on that object and sending any 1-morphism q to the 2-morphism $q \to \mathrm{id}$ from prop 5. By prop 6 this implies the existence of a unique assignment of a 3-morphism to any 2-morphism such that we do indeed obtain the component map of a pseudonatural transformation of 3-functors. By construction, this is clearly smooth when $G_{(2)}$ is Lie. □

6.3. Universality

Theorem 2. *We have a short exact sequence of strict 2-groupoids*

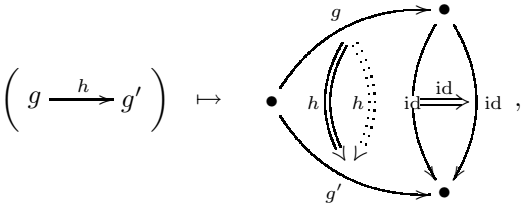
$$G_{(2)} \hookrightarrow \mathrm{INN}_0(G_{(2)}) \twoheadrightarrow \mathbf{B}G_{(2)} \ .$$

Proof. This is just proposition 1, after noticing that

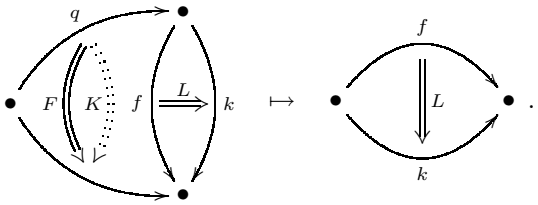
$$\mathrm{Mor}(\mathbf{B}G_{(2)}) = G_{(2)} \, .$$

□

So the strict inclusion 2-functor on the left is



while the strict surjection 2-functor on the right is



6.4. The corresponding 2-crossed module

We now extract the structure of a 2-crossed module from $\mathrm{INN}_0(G_{(2)})$. First, let

$$\mathrm{Mor}_1^I = \mathrm{Mor}_1(\mathrm{INN}_0(G_{(2)}))|_{s^{-1}(\mathrm{Id})}$$

and

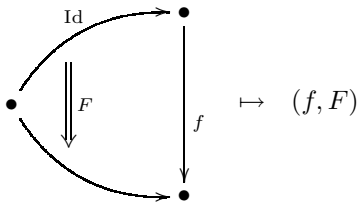
$$\mathrm{Mor}_2^I = \mathrm{Mor}_2(\mathrm{INN}_0(G_{(2)}))|_{s^{-1}(\mathrm{id}_{\mathrm{Id}})}$$

be subgroups of the 1- and 2-morphisms of $\mathrm{INN}_0(G_{(2)})$ respectively.

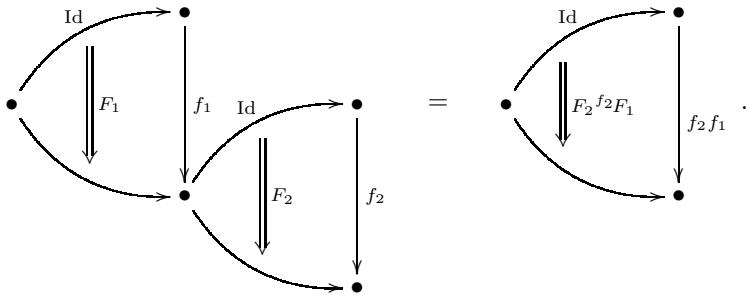
Proposition 7. *The group of 1-morphisms in* $\mathrm{INN}_0(G_{(2)})$ *starting at the identity object form the semidirect product group*

$$\mathrm{Mor}_1^I = G \ltimes H$$

under the identitfication



in that

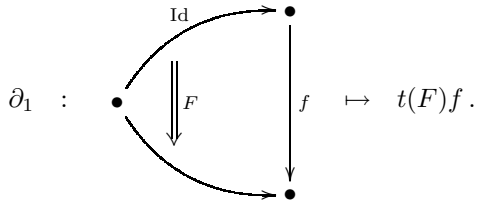


Proof. Use composition in $\mathbf{B}G_{(2)}$. □

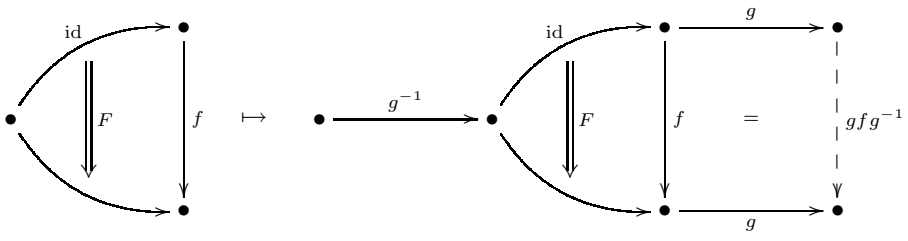
We have the obvious group homomorphism which is just the restriction of the target map

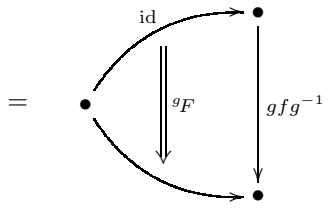
$$\partial_1 : \mathrm{Mor}_1^I \to \mathrm{Obj} := \mathrm{Obj}(\mathrm{INN}_0(G_{(2)}))$$

given by



This and the following constructions are to be compared with definition 4. There is an obvious action on Mor_1^I:



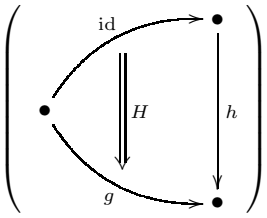


(9)

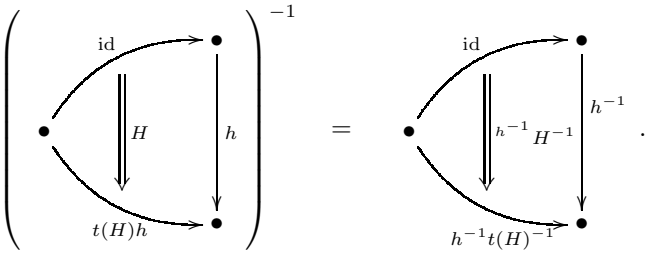
This action almost gives us a crossed module $\mathrm{Mor}_1^I \to \mathrm{Obj}$. But not quite, since the Peiffer identity holds only up to 3- isomorphism.

To see this, let

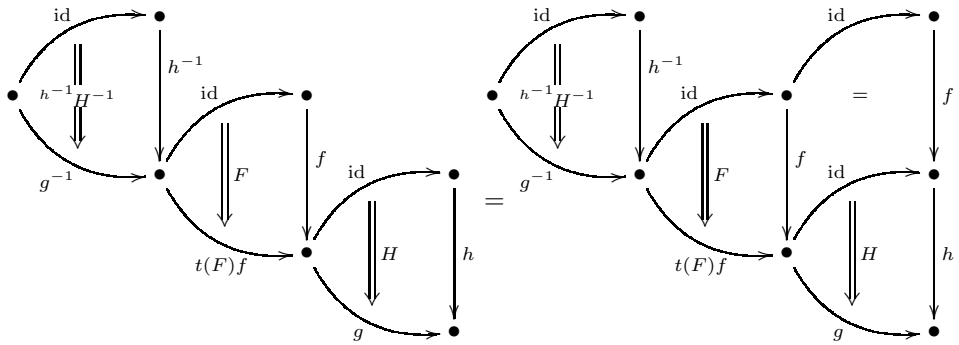
$$g \quad = \quad \partial_1 \left(\right. \quad = \quad t(H)h.$$

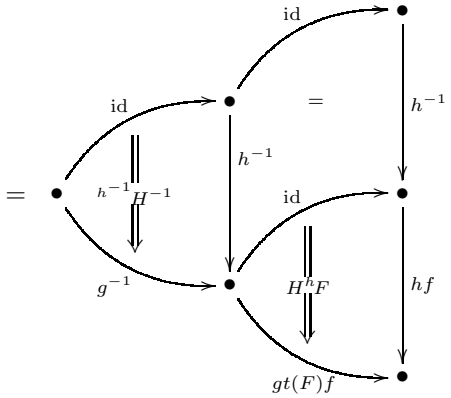


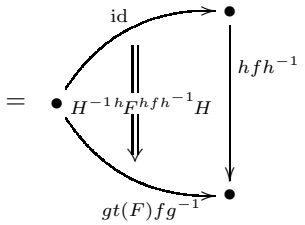
For the Peiffer identity to hold we need the action (6.4) to be equal to the adjoint action of the 2-cell $(h, H; id)$. To see that this fails, first notice that the inverse of the appropriate 2-cell considered as an element in the group Mor_1^I is



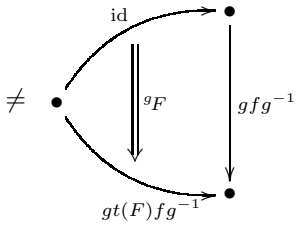
Therefore the conjugation is


id
h^{-1}
$_h{}^{-1}H^{-1}$
id
g^{-1}
F
f
id
$t(F)f$
H
h
g
=
id
h^{-1}
$_h{}^{-1}H^{-1}$
id
g^{-1}
F
f
id
=
f
id
$t(F)f$
H
h
g


=
id
id
=
h^{-1}
h^{-1}
$_h{}^{-1}H^{-1}$
id
g^{-1}
H^hF
hf
$gt(F)f$

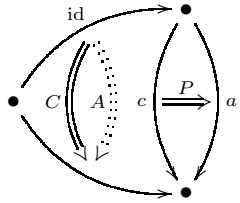

=
id
hfh^{-1}
$H^{-1\,h}F^{hfh^{-1}}H$
$gt(F)fg^{-1}$

(10)


≠
id
^gF
gfg^{-1}
$gt(F)fg^{-1}$

(11)

Though the Peiffer identity does not hold, both actions give rise to 2-cells with the same source and target, and hence define a 3-cell P. Denote the 2-cell (10) by $(c, C; id)$ and the 2-cell (11) by $(a, A; id)$ (for *c*onjugation and *a*ction respectively).



Then

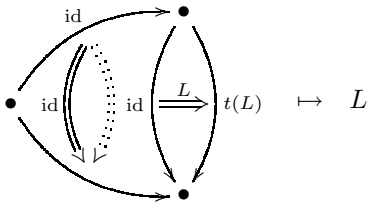
$$\begin{aligned} P &= A^{-1}C \\ &= {}^{g}F^{-1}\left(H^{h}F^{hfh^{-1}}H^{-1}\right) \\ &= {}^{g}F^{-1}\left({}^{t(H)h}FH^{hfh^{-1}}H^{-1}\right) \\ &= {}^{g}F^{-1}\left({}^{g}FH^{hfh^{-1}}H^{-1}\right) \\ &= H^{hfh^{-1}}H^{-1} \end{aligned}$$

However, what we really want is the Peiffer lifting, which will be a 3-cell with source the identity 2-cell. Hence,

Proposition 8. *The group of 2-morphisms in* $\mathrm{INN}_0(G_{(2)})$ *starting at the identity arrow on the identity object form the group*

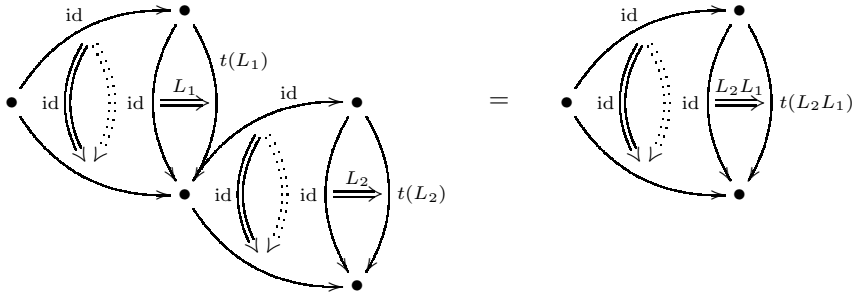
$$\mathrm{Mor}_2^I = H$$

under the identitfication



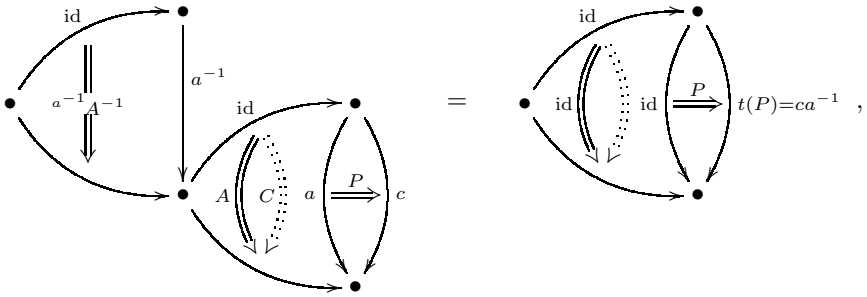
$\mapsto \quad L$

in that



Proof. Use the multiplication of 2-morphisms. □

So, we whisker the 3-cell $(P; a, A; \mathrm{id})$ above with the inverse of $(a, A; \mathrm{id})$:

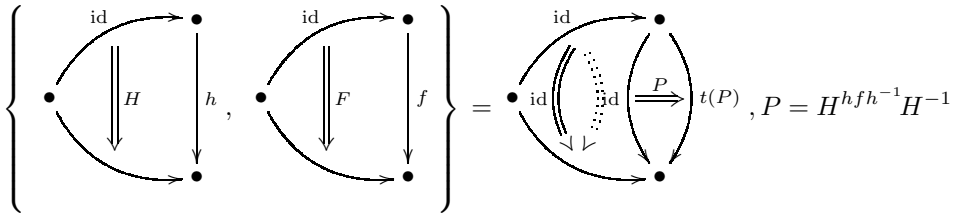


and the back face is necessarily P^{-1}.

Definition 13 (Peiffer lifting). *Define the map*

$$\{\cdot,\cdot\} : \mathrm{Mor}_1^I \times \mathrm{Mor}_1^I \to \mathrm{Mor}_2^I$$

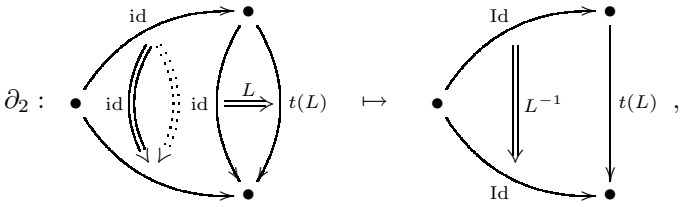
by



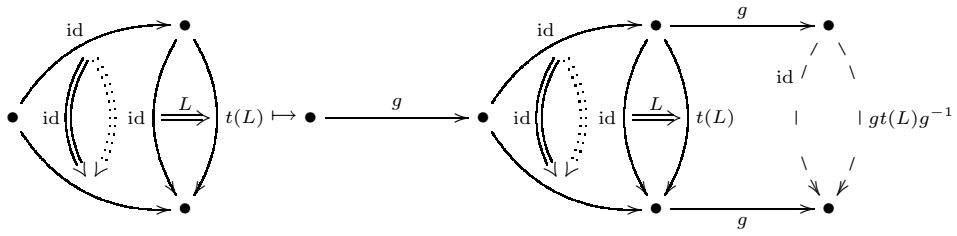
Now define the homomorphism

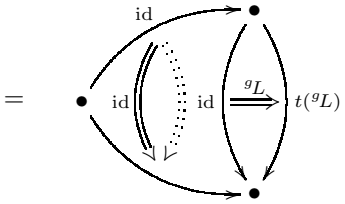
$$\partial_2 : \mathrm{Mor}_2^I \to \mathrm{Mor}_1^I$$

by



which is again the restriction of the target map. Note there is an action of Obj on Mor_2^I:





(12)

Clearly $\partial_2 \circ \partial_1$ is the constant map at the identity, and im ∂_2 is a normal subgroup of ker ∂_1, so

$$\mathrm{Mor}_2^I \xrightarrow{\partial_2} \mathrm{Mor}_1^I \xrightarrow{\partial_1} \mathrm{Obj} \tag{13}$$

is a sequence. We let the action of Obj on the other two groups be as described above in (6.4) and (6.4), and the maps ∂_2 and ∂_1 are clearly equivariant for this action.

Proposition 9. *The map $\{\cdot,\cdot\}$ does indeed satisfy the properties of a Peiffer lifting, and (13) is a 2- crossed module.*

Proof. The first condition holds by definition, the second and the last one are easy to check. The others are tedious. It is easy, using the crossed module properties of $H \to G$, to calculate that the actions of Mor_1^I on Mor_2^I as defined from $\mathrm{INN}_0(G_{(2)})$ and as defined via $\{\cdot,\cdot\}$ are the same. □

Since im $\partial_2 = \ker \partial_1$, ∂_2 is injective and ∂_1 is onto, this shows that (13) has trivial homology and provides us with another proof that $\mathrm{INN}_0(G_{(2)})$ is contractible.

6.4.1. Relation to the mapping cone of $H \to G$
Given a crossed square

$$\begin{array}{ccc} L & \xrightarrow{f} & M \\ {\scriptstyle u}\downarrow & & \downarrow{\scriptstyle v} \\ N & \xrightarrow{g} & P \end{array}$$

with structure map $h : N \times M \to L$, Conduché [**14**]gives the Peiffer lifting of the mapping cone

$$L \longrightarrow N \ltimes M \longrightarrow P$$

as

$$\{(g,h),(k,l)\} = h(gkg^{-1},h).$$

Recall from 2.3 that the identity map on $t : H \to G$ is a crossed square with

$$h(g,h) = h^g h^{-1},$$

so the mapping cone is a 2-crossed module

$$H \xrightarrow{\partial_2} G \ltimes H \xrightarrow{\partial_1} G,$$

where

$$d_2(h) = (t(h), h^{-1}), \qquad d_1(g,h) = t(h)g,$$

and with Peiffer lifting

$$\{(g_1,h_1),(g_2,h_2)\} = h_1{}^{g_1 g_2 g_1^{-1}} h_1^{-1}.$$

which is what we found for $\mathrm{INN}_0(G_{(2)})$.

More precisely,

Definition 14. *A morphism ψ of 2-crossed modules is a map of the underlying complexes*

$$\begin{array}{ccccc} L_1 & \xrightarrow{\partial_2} & M_1 & \xrightarrow{\partial_1} & N_1 \\ {\scriptstyle \psi_L}\downarrow & & {\scriptstyle \psi_M}\downarrow & & {\scriptstyle \psi_N}\downarrow \\ L_2 & \xrightarrow[\partial_2]{} & M_2 & \xrightarrow[\partial_1]{} & N_2 \end{array}$$

such that ψ_L, ψ_M and ψ_N are equivariant for the N- and M-actions, and

$$\{\psi_M(\cdot), \psi_M(\cdot)\}_2 = \psi_L(\{\cdot,\cdot\}_1).$$

Using propositions 7 and 8, we have a map

$$\begin{array}{ccccc} \mathrm{Mor}_2^I & \xrightarrow{\partial_2} & \mathrm{Mor}_1^I & \xrightarrow{\partial_1} & \mathrm{Obj} \\ \simeq\downarrow & & \downarrow\simeq & & \downarrow\simeq \\ H & \xrightarrow[d_2]{} & G \ltimes H & \xrightarrow[d_1]{} & G \end{array}$$

and the actions and Peiffer lifting agree, so

Proposition 10. *The 2-crossed module associated to* $\mathrm{INN}_0(G_{(2)})$ *is isomorphic to the mapping cone of the identity map on the crossed module associated to* $G_{(2)}$*.*

7. Universal n-bundles

In order to put the relevance of the 3-group $\mathrm{INN}_0(G_{(2)})$ in perspective, we further illuminate our statement, 3.1, that $\mathrm{INN}_0(G_{(2)})$ *plays the role of the universal* $G_{(2)}$*-bundle*. An exhaustive discussion will be given elsewhere.

7.1. Universal 1-bundles in terms of $\mathrm{INN}(G)$

Let $\pi : Y \to X$ be a good cover of a space X and write $Y^{[2]} := Y \times_X Y$ for the corresponding groupoid.

Definition 15 (G-cocycles). *A G-(1-)cocycle on X is a functor*

$$g : Y^{[2]} \to \mathbf{B}G\,.$$

This functor can be understood as arising from a choice

$$\pi^* P \xrightarrow[\sim]{t} Y \times G$$

of trivialization of a principal right G-bundle $P \to X$ (which is essentially just a map to G) as

$$g := \pi_2^* t \circ \pi_1^* t^{-1}\,,$$

by noticing that G-equivariant isomorphisms

$$G \to G$$

are in bijection with elements of G

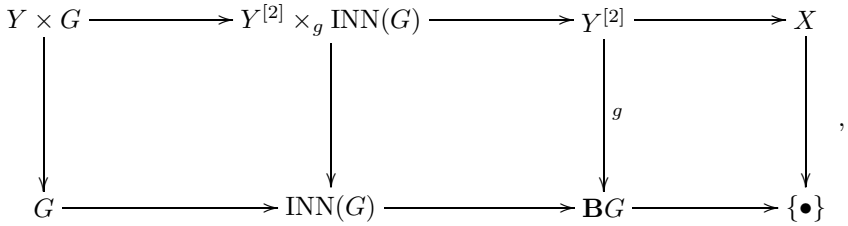
$$g(x,y) : h \mapsto g(x,y)h$$

acting from the left.

Observation 1 (G-bundles as morphisms of sequences of groupoids). *Given a G-cocycle on X as above, its pullback along the exact sequence*

$$G \longrightarrow \mathrm{INN}(G) \longrightarrow \mathbf{B}G\ ,$$

which we write as



produces the bundle of groupoids

$$Y^{[2]} \times_g \mathrm{INN}(G) \longrightarrow Y^{[2]}$$

which plays the role of the total space of the G-bundle classified by g.

This should be compared with the simplicial constructions described, for instance, in [**20**].

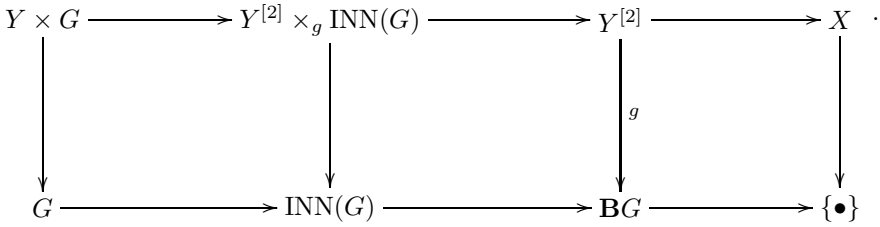
7.1.0.1. Remark. Using the fact that $\mathrm{INN}(G)$ is a 2-group, and using the injection $G \to \mathrm{INN}(G)$ we naturally obtain the G-action on $Y^{[2]} \times_g \mathrm{INN}(G)$.

7.1.0.2. Remark. Notice that this is closely related to the integrated Atiyah sequence

$$\mathrm{Ad}P \longrightarrow P \times_G P \longrightarrow X \times X$$

of groupoids over $X \times X$ coming from the G-principal bundle $P \to X$:

$$\mathrm{Ad}P \longrightarrow P \times_G P \longrightarrow X \times X$$



We now make precise in which sense, in turn, $Y^{[2]} \times_g \mathrm{INN}(G)$ plays the role of the total space of the G-bundle characterized by the cocycle g.

To reobtain the G-bundle $P \to X$ from the groupoid $Y^{[2]} \times_g \mathrm{INN}(G)$ we form

the pushout of

$$\begin{array}{ccc} Y^{[2]} \times_g \mathrm{INN}(G) & \xrightarrow{\text{target}} & Y \times G \\ \Big\downarrow{\scriptstyle \text{source}} & & \\ Y \times G & & \end{array} . \tag{14}$$

Proposition 11. *If g is the cocycle classifying a G-bundle P on X, then the pushout of 14 is (up to isomorphism) that very G-bundle P.*

Proof. Consider the square

$$\begin{array}{ccccc} Y^{[2]} \times_g \mathrm{INN}(G) & \xrightarrow{\text{target}} & Y \times G & & \\ \Big\downarrow{\scriptstyle \text{source}} & & \Big\downarrow{\scriptstyle t^{-1}} & & \\ Y \times G & \xrightarrow{t^{-1}} & \pi^* P & \longrightarrow & P \end{array} ,$$

where $t : \pi^* P \xrightarrow{\sim} Y \times G$ is the local trivialization of P which gives rise to the transition function g. Then the diagram commutes by the very definition of g. Since t is an isomorphism and since $\pi^* P \to P$ is locally an isomorphism, it follows that this is the universal pushout. □

7.2. Universal 2-bundles in terms of $\mathrm{INN}_0(G_{(2)})$

Now let $G_{(2)}$ be any strict 2-group. Let $Y^{[3]}$ be the 2-groupoid whose 2-morphisms are triples of lifts to Y of points in X. A principal $G_{(2)}$-2-bundle [**6, 5**] has local trivializations characterized by 2-functors

$$g : Y^{[3]} \to \mathbf{B}G_{(2)} .$$

Definition 16 ($G_{(2)}$-cocycles). *A $G_{(2)}$-(2-)cocycle on X is a 2-functor*

$$g : Y^{[3]} \to \mathbf{B}G_{(2)} .$$

(Instead of 2-functors on $Y^{[3]}$ one could use pseudo functors on $Y^{[2]}$.)

As before, we can pull these back along our exact sequence of 2-groupoids 3.1

$$G_{(2)} \longrightarrow \mathrm{INN}(G_{(2)}) \longrightarrow \mathbf{B}G_{(2)}$$

to obtain

$$\begin{array}{ccccccc} Y \times G_{(2)} & \longrightarrow & Y^{[3]} \times_g \mathrm{INN}(G_{(2)}) & \longrightarrow & Y^{[3]} & \longrightarrow & X \\ \downarrow & & \downarrow & & \downarrow{\scriptstyle g} & & \downarrow \\ G_{(2)} & \longrightarrow & \mathrm{INN}(G_{(2)}) & \longrightarrow & \mathbf{B}G_{(2)} & \longrightarrow & \{\bullet\} \end{array} .$$

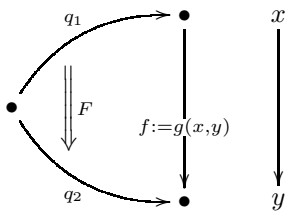
We reconstruct the total 2-space of the 2-bundle by forming the weak pushout of

$$\begin{array}{ccc} Y^{[3]} \times_g \mathrm{INN}(G_{(2)}) & \xrightarrow{\text{target}} & Y \times G_{(2)} \\ \downarrow{\scriptstyle \text{source}} & & \\ Y \times G_{(2)} & & \end{array} . \qquad (15)$$

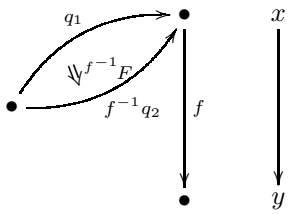
Here "source" and "target" are defined relative to the inclusion

$$Y \times G_{(2)} \hookrightarrow Y^{[2]} \times_g \mathrm{INN}(G_{(2)}) .$$

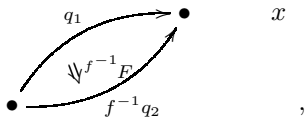
This means that for a given 1-morphism



in $Y^{[3]} \times_g \mathrm{INN}(G_{(2)})$ (for any $x, y \in Y$ with $\pi(x) = \pi(y)$ and for $g(x,y)$ the corresponding component of the given 2-cocycle) which we may equivalently rewrite as

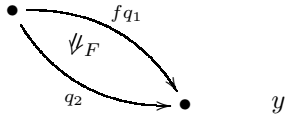


the source in this sense is



,

regarded as a morphism in $Y \times G_{(2)}$, while the target is



regarded as a morphism in $Y \times G_{(2)}$.

This way the transition function $g(x, y)$ acts on the copies of $G_{(2)}$ which appear as the trivialized fibers of the $G_{(2)}$-bundle.

Bartels [**6**][proof of prop. 22] gives a reconstruction of total space of principal 2-bundle from their 2-cocycles which is closely related to $Y^{[3]} \times_g \mathrm{INN}(G_{(2)})$.

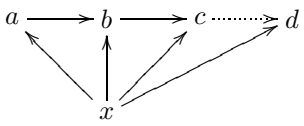
As an anonymous referee pointed out, our construction in the case of 1-groups is related to the universal cover. Since $\mathbf{B}G$ is a (model of a) connected 1-type, and $\mathrm{INN}_0(G)$ is contractible, it can be considered as (a model of) the universal cover. Indeed, one of the motivations for the first author was to understand 2-connected 'universal covers' for 2-types. The connections with such a notion will be treated in [**26**], as well as generalisations.

7.3. Relation to simplicial bundles

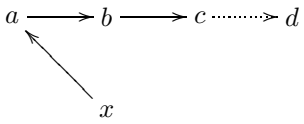
Our considerations can be translated, along the nerve or double nerve functor, to the world of simplicial sets. Under this translation one finds that the tangent category construction corresponds to the simplicial operation known as décalage, and $\mathrm{INN}_0(G)$ corresponds to the simplicial set denoted WG. It does not appear to be well known that a group structure can be put on WG, and one way of seeing this for simplicial groups which are nerves of 2-groups is via our construction. There is a general description of this group structure bypassing $\mathrm{INN}_0(G)$ altogether [**27**].

7.3.1. Tangent categories and décalage

For C any category, notice that a sequence of k composable morphisms



in TC is, since all triangles commute, the same as a sequence



of $k+1$ composable morphisms in C.

To formalize this observation, let Δ denote, as usual the simplicial category whose objects are the catgories

$$[n] = \{0 \to 1 \to \cdots \to n\}$$

for all $n \in \mathbb{N}$ and whose morphisms are the functors between these. Write $[\Delta^{op}, \mathrm{Set}]$ for the category of simplicial sets.

Denote by

$$[(-)+1] : \Delta^{\mathrm{op}} \to \Delta^{\mathrm{op}}$$

the obvious functor which acts on objects as

$$[n] \mapsto [n+1]$$

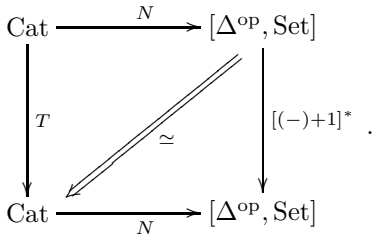
(shifts everything up by one). The induced map on simplicial sets,

$$[(-)+1]^* : [\Delta^{\mathrm{op}}, \mathrm{Set}] \to [\Delta^{\mathrm{op}}, \mathrm{Set}]$$

is called *décalage* [**19**] and is denoted Dec^1. From a more pedestrian viewpoint, Dec^1 strips off the first face and first degeneracy map[3] from each level of a simplicial object X, re-indexes the rest and moves the sets of simplices down one level:

$$(\mathrm{Dec}^1 X)_n = X_{n+1}\,.$$

Proposition 12. *The tangent category construction from definition 8 is taken by the nerve functor $N : \mathrm{Cat} \to [\Delta^{\mathrm{op}}, \mathrm{Set}]$ to the décalage construction in that we have a weakly commuting square*



Proof. This is not hard to see by chasing explicit elements through this diagram. A little more abstractly, we see as follows that the assignment of $(n+1)$-simplices in C to n-simplices in TC is functorial.

---

[3]It is a matter of convention that the first face and degeneracy maps are removed. The décalage is sometimes defined by removing the last face and degeneracy maps, but our tangent category construction is related to the former convention.

Notice that n-simplices in TC are commuting squares

$$\begin{array}{ccc} [n] & \longrightarrow & I \times [n] \\ \downarrow & & \downarrow \\ [0] & \longrightarrow & C \end{array}$$

but the pushout of this co-cone is $[n+1]$:

$$\begin{array}{ccc} [n] & \longrightarrow & I \times [n] \\ \downarrow & & \downarrow f \\ [0] & \longrightarrow & [n+1] \end{array} ,$$

where

$$f \;:\; \begin{array}{ccccccc} (\circ,0) & \to & (\circ,1) & \to & (\circ,2) & \cdots\!\!\to & (\circ,n) \\ \uparrow & & \uparrow & & \uparrow & & \uparrow \\ (\bullet,0) & \to & (\bullet,1) & \to & (\bullet,2) & \cdots\!\!\to & (\bullet,n) \end{array} \mapsto \begin{array}{ccccccc} (\circ,0) & \to & (\circ,1) & \to & (\circ,2) & \cdots\!\!\to & (\circ,k) \\ & \nwarrow & \uparrow & \nearrow & \nearrow & & \\ & & (\bullet,0) & & & & \end{array}$$

$$\mapsto \begin{array}{ccccccc} (\circ,0) & \to & (\circ,1) & \to & (\circ,2) & \cdots\!\!\to & (\circ,n) \\ & \nwarrow & & & & & \\ & & (\bullet,0) & & & & \end{array} .$$

Hence we functorially assign $(n+1)$-simplices in C to n-simplices in TC by using the universality of the pushout:

$$\begin{array}{ccc} [n] & \longrightarrow & I \times [n] \\ \downarrow & \overset{f}{\searrow} & \downarrow \\ [0] & \overset{}{\nearrow}_{[n+1]} \overset{!}{\searrow} & C \end{array} .$$

□

7.3.2. Universal simplicial bundles

If G is a simplicial group in sets, there is a notion of principal bundle internal to sSet [**24**], and for such bundles there is a classifying simplicial set $\overline{W}G$ completely anal-

ogous to the case of topological bundles. As such, there is a contractible simplicial set WG which is the total space of a simplicial bundle

$$\begin{array}{c} WG \\ \downarrow \\ \overline{W}G \end{array}$$

and in fact $WG \simeq \mathrm{Dec}^1\overline{W}G$.

It is a short calculation to show that $\overline{W}G = N\mathbf{B}G$ and $WG = N\mathrm{INN}(G)$ when G is a constant simplicial group. To recover a similar result for strict 2-groups (in Set), we recall that for 2-categories there is a functor $\mathcal{N}$ called the *double nerve*, which forms a bisimplicial set whose geometric realization is called the classifying space of the 2-category.

Definition 17. *Recalling that strict 2-groups are the same as categories internal to groups, the double nerve $\mathcal{N}G_{(2)}$ of a strict 2-group $G_{(2)}$ is defined to be its image under*

$$\mathcal{N}:\ \mathrm{Cat(Gp)} \xrightarrow{N} [\Delta^{\mathrm{op}}, \mathrm{Gp}] \longrightarrow [\Delta^{\mathrm{op}}, [\Delta^{\mathrm{op}}, \mathrm{Set}]]\ ,$$

with groups considered as one-object groupoids.

Explicitly, let $G_{(2)}$ be the strict 2-group coming from the crossed module $t : H \to G$. Recalling that then $\mathrm{Obj}(G_{(2)}) = G$ and $\mathrm{Mor}(G_{(2)}) = H \rtimes G$ we find that $\mathcal{N}G_{(2)}$ is the bisimplicial set given by

$$\begin{aligned}
(\mathcal{N}G_{(2)})_{0n} &= \{\cdot\} \\
(\mathcal{N}G_{(2)})_{1n} &= (NG_{(2)})_n = \begin{cases} G, & n = 0; \\ H \rtimes G & n = 1; \\ (H \rtimes G) \times_G \overset{n}{\cdots} \times_G (H \rtimes G), & n > 1 \end{cases} \\
(\mathcal{N}G_{(2)})_{kn} &= (\mathcal{N}G_{(2)})_{1n} \times \overset{k}{\cdots} \times (\mathcal{N}G_{(2)})_{1n} \qquad k > 1\,.
\end{aligned}$$

So for each n, $(\mathcal{N}G_{(2)})_{\bullet n}$ is the nerve of the group of sequences of n composable morphisms in $G_{(2)}$. Applying Dec^1 to each of these, i.e. forming the bisimplicial set $\mathrm{Dec}^1\mathcal{N}G_{(2)}$ in the image of

$$\mathrm{Dec}^1\mathcal{N}:\ \mathrm{Cat(Gp)} \xrightarrow{N} [\Delta^{\mathrm{op}}, \mathrm{Gp}] \longrightarrow [\Delta^{\mathrm{op}}, [\Delta^{\mathrm{op}}, \mathrm{Set}]] \xrightarrow{[\Delta^{\mathrm{op}}, \mathrm{Dec}^1]} [\Delta^{\mathrm{op}}, [\Delta^{\mathrm{op}}, \mathrm{Set}]]$$

we obtain a surjection $\mathrm{Dec}^1\mathcal{N}G_{(2)} \to \mathcal{N}G_{(2)}$ whose kernel is the bisimplicial set which has just the fiber, namely the group of sequences of n-morphisms, in each row:

$$(N'G_{(2)})_{kn} := (NG_{(2)})_n \qquad \forall k \in \mathbb{N}\,.$$

Hence we have an exact sequence

$$N'G_{(2)} \to \mathrm{Dec}^1\mathcal{N}G_{(2)} \to \mathcal{N}G_{(2)}\,.$$

The realization $|\cdot|$ of a bisimplicial set is the ordinary realization of the diagonal simplicial space $\underline{n} \mapsto (\mathcal{N}G_{(2)})_{nn}$. It is hence clear that $|N'G_{(2)}| = |NG_{(2)}|$ and, by

definition, $|\mathcal{N}G_{(2)}| = BG_{(2)}$. Moreover, since each row of $\mathrm{Dec}^1\mathcal{N}G_{(2)}$ is contractible, $|\mathrm{Dec}^1\mathcal{N}G_{(2)}|$ is also contractible.[4]

This relates to our construction by the fact that $\mathrm{Dec}^1\mathcal{N}G_{(2)}$ is the nerve of a double groupoid (in fact a cat^2-group [**23**]) constructed from the crossed square

$$\begin{array}{ccc} H & \xrightarrow{\mathrm{id}} & H \\ {\scriptstyle t}\downarrow & & \downarrow{\scriptstyle t} \\ G & \xrightarrow{\mathrm{id}} & G \end{array} .$$

8. Appendix: Crossed squares

As noted above, crossed squares were introduced in [**18**]. We include the definition for completeness:

Definition 18 (crossed square). *A crossed square is a commutative square of P-groups*

$$\begin{array}{ccc} L & \xrightarrow{f} & M \\ {\scriptstyle u}\downarrow & & \downarrow{\scriptstyle v} \\ N & \xrightarrow{g} & P \end{array}$$

(with P acting on itself by conjugation, actions denoted by ${}^a b$) and a function $M \times N \to L$ such that

1. *f and u are P-equivariant, and $N \longrightarrow P$, $M \longrightarrow P$, $L \longrightarrow P$. are crossed modules,*
2. *$f(h(x,y)) = x^{g(y)}x^{-1}$, $\qquad u(h(x,y)) = {}^{v(x)}yy^{-1}$,*
3. *$h(f(z),y) = z^{g(y)}z^{-1}$, $\qquad h(x,u(z)) = {}^{v(x)}zz^{-1}$,*
4. *$h(xx',y) = {}^{v(x)}h(x',y)h(x,y)$, $\qquad h(x,yy') = h(x,y)^{g(y)}h(x,y')$,*
5. *h is P-equivariant for the diagonal action of P on $M \times N$.*

It follows from the definition that $L \to M$ and $L \to N$ are crossed modules where M, N act on L via the maps to P. The reader is encouraged to note the analogies between these axioms and those in Definition 3.

[4]The realization of a bisimplicial set can also be calculated as first taking the ordinary realization of the rows then realizing the resulting simplicial space - this results in a space homeomorphic to the previous description.

References

[**1**] Z. Arvasi, E. Ulualan, *On algebraic models for homotopy 3-types*, JHRS vol. 1, no. 1 (2006), pp. 1–17.

[**2**] J. Baez, A. Lauda, *Higher-Dimensional Algebra V: 2-Groups*, Th. and App. of Cat. 12 (2004), pp. 423–491, available as `math/0307200`.

[**3**] J. Baez, U. Schreiber, *Higher Gauge Theory*, in *Noncommutative Geometry and Representation Theory in Mathematical Physics*, Contemporary Mathematics 391, availabvle as `math/0511710`.

[**4**] J. Baez, D. Stevenson, *The classifying space of a topological 2-group*, available as `arXiv:0801.3843`

[**5**] I. Baković, *Bigroupoid bitorsors*, PhD Thesis.

[**6**] T. Bartels, *2-Bundles*, PhD Thesis, available as `math/0410328`.

[**7**] L. Breen, W. Messing, *Differential geometry of gerbes*, Adv. in Mathematics, vol 198, 2 (2005), pp. 732–846.

[**8**] R. Brown, I. Icen, *Homotopies and automorphisms of crossed modules of groupoids*, Appl. Categ. Structures, 11 (2) (2003), pp. 185–203.

[**9**] R. Brown, N. D. Gilbert, *Algebraic models of 3-types and automorphism structures for crossed modules*, Proc. London Math. Soc. (3) 59 (1) (1989), pp. 51–73.

[**10**] R. Brown, C. B. Spencer, *$\mathcal{G}$-groupoids, crossed modules and the classifying space of a topological group*, Proc. Kon. Akad. v. Wet. 79, pp. 296–302

[**11**] P. Carrasco, A. M. Cegarra, *Group-theoretic algebraic models for homotopy types*, J. Pure Appl. Algebra **75** (1991), pp. 195–235.

[**12**] D. Conduché, *Modules croisés généralisés de longueur 2*, J. Pure Appl. Algebra **34** (1984), pp. 155–178.

[**13**] D. Conduché, *Unpublished letter to R. Brown and J.-L. Loday*, 1984.

[**14**] D. Conduché, *Simplicial crossed modules and mapping cones*, Georgian Mathematical Journal **10** (2003), pp. 623–636.

[**15**] B.Day, R. Street, *Monoidal bicategories and Hopf algebroids*, Adv. Math **129** (1997), pp. 99–157.

[**16**] R. Gordon, A. J. Power, R. Street, *Coherence for tricategories* Memoirs of the AMS, vol. 117, no. 558 (1995).

[**17**] J. W. Gray, *Formal Category Theory: Adjointness for 2-Categories* Springer (1974).

[**18**] D. Guin-Waléry and J.-L. Loday, *Obstructions à l'Excision en K-théorie Algébrique*, Springer Lecture Notes in Math., 854 (1981), pp. 179–216.

[**19**] L. Illusie, *Complexe cotangent et déformation II*, Lecture Notes in Mathematics 283, Springer-Verlag, Berlin-New York, (1972).

[**20**] B. Jurčo, *Crossed Module Bundle Gerbes; Classification, String Group and Differential Geometry*, available as `math/0510078`.

[**21**] K. H. Kamps and T. Porter, *Abstract Homotopy and Simple Homotopy Theory*, World Scientific (1997).

[**22**] K. H. Kamps and T. Porter, *2-Groupoid enrichments in homotopy theory and algebra*, K-Theory 25 (2002), pp. 373–409.

[**23**] J.-L. Loday, *Spaces with finitely many homotopy groups*, J. Pure Appl. Algebra **24** (1982), pp. 179–202.

[**24**] J. P. May, *Simplicial objects in algebraic topology* Van Nostrand (1967).

[**25**] K. Norrie, *Actions and automorphisms of crossed modules.* Bulletin de la Société Mathématique de France, **118** no. 2 (1990), pp. 129–146.

[**26**] D. M. Roberts, work in progress.

[**27**] D. M. Roberts and D. Stevenson, *On realizations of simplicial bundles*, in preparation.

[**28**] H. Sati, U. Schreiber, J. Stasheff, L_∞ *algebra connections and applications to String- and Chern-Simons n-transport*, available as `arXiv:0801.3480`.

[**29**] U. Schreiber, K. Waldorf, *Parallel transport and functors*, available as `arXiv:0705.0452`.

[**30**] U. Schreiber, K. Waldorf, *Smooth 2-Functors vs. Differential Forms*, available as `arXiv:0802.0663`.

[**31**] G. B. Segal, *Classifying spaces and spectral sequences*, Publ. Math. IHES No. 34 (1968), pp. 105–112

[**32**] J. H. C. Whitehead, *Note on a previous paper entitled "On adding relations to homotopy groups"*, Ann. Math. **47**, pp. 806–810 (1946)

This article may be accessed via WWW at `http://jhrs.rmi.acnet.ge`

David Michael Roberts
`droberts@maths.adelaide.edu.au`

School of Mathematical Sciences
The University of Adelaide
SA, 5005, Australia

Urs Schreiber
`urs.schreiber@math.uni-hamburg.de`

Department Mathematik
Universität Hamburg
Bundesstraße 55
20146 Hamburg, Germany