Boundaries in finite gauge theory

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Contents

1 Introduction

Let

- G be a finite group,
- $[\omega] \in H^n(G, \mathbb{C}^\times)$,
- and $\mathcal{C}$ a symmetric monoidal (∞, n)-category for some $n \in \mathbb{Z}_+$.

On the one hand, [FHLT] sketches the construction of a fullly extended TQFT

$$\mathrm{Bord}_n \xrightarrow[\text{“classical”}]{I} \mathrm{Fam}_n(\mathcal{C}) \xrightarrow[\text{“quantum”}]{\mathrm{Sum}_n} \mathcal{C} \tag{1.1}$$

based on the data (G, ω), which is viewed as a fully extended version of Dijkgraaf-Witten theory. On the other hand, in [Wi, WWW] a class of boundary conditions for (classical!?) DW theory is proposed in terms of group extensions.

Goal. We want to reformulate the general aspects of the work [Wi, WWW] in the setting of fully extended TQFT. More precisely, we view the bulk theories of [Wi, WWW] as the classical part I in (1.1) with $\mathcal{C} = \boldsymbol{B}^n\mathbb{C}^\times$ (the n-fold delooping of the group $\mathbb{C}^\times$) and then

(i) identify *classical* boundary conditions as 1-morphisms with source $*$ in $\mathrm{Fam}_n(\boldsymbol{B}^n\mathbb{C}^\times)$,

(ii) subsume the boundary conditions of [Wi, WWW] as special cases,

(iii) map classical boundary conditions to quantum ones via Sum_n, and connect them to the known quantum boundary conditions, following the work of Ostrik and Fuchs–Schweigert–Valentino in the case $n = 3$,

(iv) do the above not only for framed, but also for oriented, spin,. . . TQFTs.

Since [FHLT] is very light on details, we first will work out explicitly how (1.1) recovers the known bulk theory for $n \in \{1, 2\}$ and hopefully also $n = 3$. We also want to explain in detail how (G, ω) gives rise to an object in $\mathrm{Fam}_n(\boldsymbol{B}^n\mathbb{C}^\times)$, and how group extensions $1 \to K \to H \xrightarrow{r} G \to 1$ give rise to 1-morphisms $\mathrm{Fam}_n(\boldsymbol{B}^n\mathbb{C}^\times)(*, \boldsymbol{B}G)$.
(A more conceptual approach to boundary conditions and defects would be to start with a bordism category "with singularities" [Lu, Sect. 4.3] instead of Bord_n, but we leave that for another project.)

2 Special objects and 1-morphisms in $\mathrm{Fam}_n(\boldsymbol{B}^n\mathbb{C}^\times)$

TODO:

- spell out definition of $\mathrm{Fam}_n(\mathcal{C})$
- check that n-functor $\boldsymbol{B}G \to \boldsymbol{B}^n\mathbb{C}^\times$ is precisely an n-cocycle
  <u>**Issue**</u>: For $n > 3$, what is a weak n-functor, i. e. precisely what data and constraints are needed?
  <u>**Idea**</u>: Since both n-categories in $\boldsymbol{B}G \to \boldsymbol{B}^n\mathbb{C}^\times$ are close to trivial, most data of the functor will be trivial, and the constraints (whatever they are) will be trivially satisfied. For $n \in \{1, 2, 3\}$ this is true, see Section 3.
- clarify precisely how $\boldsymbol{B}G \to \boldsymbol{B}^n\mathbb{C}^\times$ induces an n-functor $\boldsymbol{B}G \to n\text{-Vect}$, at least for $n \in \{1, 2, 3\}$
- check whether natural transformation from trivial n-functor to $\omega \circ r$ is trivialisation of $r^*\omega$
  <u>**Issue**</u>: induced from issue in second item

3 Bulk theory

3.1 $n = 1$

Since we take the action of G on $\mathbb{C}^\times$ to be trivial, the cocycle

$$\omega = [\omega] \in H^1(G, \mathbb{C}^\times) = \mathrm{Hom}_{\mathrm{Grp}}(G, \mathbb{C}^\times) \tag{3.1}$$

is just a group homomorphism. We consider $\boldsymbol{B}^1\mathbb{C}^\times$ as a subcategory of $\mathrm{Vect}_\mathbb{C}$, and we will use the pair (G, ω) to construct a functor

$$\mathrm{Bord}_1 \xrightarrow{\quad I \quad} \mathrm{Fam}_1(\mathrm{Vect}_\mathbb{C}) \xrightarrow{\quad \mathrm{Sum}_1 \quad} \mathrm{Vect}_\mathbb{C} \ . \tag{3.2}$$

According to the cobordism hypothesis, the composite $\mathrm{Sum}_1 \circ I$ is determined by its value on the point pt_+, so we only need to specify $I(\mathrm{pt}_+)$ and then compute $\mathrm{Sum}_1(I(\mathrm{pt}_+))$. Note that $\boldsymbol{B}^1 G = */\!\!/G$ is the classical action groupoid. We set $I(\mathrm{pt}_+)$ to be the functor

$$\chi^\omega \colon \ */\!\!/G \longrightarrow \mathrm{Vect}_\mathbb{C}\,, \qquad * \longmapsto \mathbb{C}\,, \quad g \longmapsto \omega(g) \in \mathrm{Aut}(\mathbb{C}) \tag{3.3}$$

for all $g \in G$. Then (3.2) recovers the known result reviewed in [FHLT, Sect. 1]:

Lemma 3.1. $\mathrm{Sum}_1(\chi^\omega) = \mathbb{C}$ if $\omega(g) = 1$ for all $g \in G$, and $\mathrm{Sum}_1(\chi^\omega) = 0$ otherwise.

Proof. The statement is a particular case of this more general one: let (V, ρ) be a linear representation of the group G, seen as the functor

$$\chi^\rho \colon \ */\!\!/G \longrightarrow \mathrm{Vect}_\mathbb{C}\,, \qquad * \longmapsto V\,, \quad g \longmapsto \rho(g) \in \mathrm{Aut}(V). \tag{3.4}$$

Then the universal cocone of χ^ρ, viewed as a diagram of shape $*/\!\!/G$ in $\mathrm{Vect}_\mathbb{C}$ is the pair (V_G, π), where V_G is the vector space of coinvariants for the representation ρ, i.e.,

$$V_G = V/\langle v - \rho(g)v \rangle_{g\in G, v\in V}$$

and $\pi \colon V \to V_G$ is the projection to the quotient. Namely, let (W, f) be a cocone for χ^ρ, i.e., a pair consisting of a vector space W together with a linear map $f \colon \chi^\omega(*) = V \to W$ such that

$$\begin{tikzcd} & W & \\ \chi^\omega(*) = V \arrow[ur, "f"] \arrow[rr, "\chi^\rho(g) = \rho(g)"'] & & V = \chi^\omega(*) \arrow[ul, "f"'] \end{tikzcd} \tag{3.5}$$

Then, by definition of V_G, the morphism f uniquely factors through V_G and so we have a commutative diagram

$$\begin{tikzcd}
& W & \\
& V_G \arrow[u, dashed, "\exists!"'] & \\
V \arrow[ur, "\pi"] \arrow[uur, bend left, "f"] \arrow[rr, "\rho(g)"'] & & V \arrow[ul, "\pi"'] \arrow[uul, bend right, "f"']
\end{tikzcd} \tag{3.6}$$

showing that (V_G, π) enjoys the universal property of the universal cocone. $\square$

Corollary 3.2. The linear dual $\mathrm{Hom}_{\mathrm{Vect}_{\mathbb{C}}}(\mathrm{Sum}_1(\chi^\omega), \mathbb{C})$ of $\mathrm{Sum}_1(\chi^\omega)$ is naturally isomorphic to the vector space of natural transformations $\mathrm{Hom}_{[*/\!\!/G, \mathrm{Vect}_{\mathbb{C}}]}(\chi^\omega, \chi^1)$, where $\chi^1\colon */\!\!/G \to \mathrm{Vect}_{\mathbb{C}}$ is the trivial representation of G on the vector space $\mathbb{C}$. In other words, we have

$$\mathrm{Hom}_{\mathrm{Vect}_{\mathbb{C}}}(\mathrm{Sum}_1(\chi^\omega), \mathbb{C}) \cong \left\{ \begin{tikzcd}
*/\!\!/G \arrow[dd, "\chi^\omega"'] \arrow[dr] & \\
\arrow[r, phantom, "\Longrightarrow"] & * \arrow[dl, "\mathbb{C}"] \\
\mathrm{Vect}_{\mathbb{C}} &
\end{tikzcd} \right\}.$$

As a finite dimensional vector space is completely determined by its linear dual, this actually defines $\mathrm{Sum}_1(\chi^\omega)$.

Proof. Again, the statement is true for an aritrary linear representation (V, ρ) of the group G. The natural isomorphism

$$\mathrm{Hom}_{\mathrm{Vect}_{\mathbb{C}}}(V_G, \mathbb{C}) \cong \left\{ \begin{tikzcd}
*/\!\!/G \arrow[dd, "\chi^\rho"'] \arrow[dr] & \\
\arrow[r, phantom, "\Longrightarrow"] & * \arrow[dl, "\mathbb{C}"] \\
\mathrm{Vect}_{\mathbb{C}} &
\end{tikzcd} \right\}$$

is then nothing but the universal property of V_G. Namely, an element in the right hand side is a morphism $f\colon V = \chi^\rho(*) \to \chi^1(*) = \mathbb{C}$ such that all the diagrams

$$\begin{tikzcd}
V \arrow[r, "f"] \arrow[d, "\rho(g)"'] & \mathbb{C} \arrow[d, "\mathrm{id}_{\mathbb{C}}"] \\
V \arrow[r, "f"'] & \mathbb{C}
\end{tikzcd}$$

commute, for any $g \in G$. This is the same as requiring that all the diagrams

$$\begin{tikzcd} & \mathbb{C} & \\ V \arrow[ur, "f"] \arrow[rr, "\rho(g)"'] & & V \arrow[ul, "f"'] \end{tikzcd}$$

commute, and so it is precisely the datum of a morphism $V_G \to \mathbb{C}$ by the argumenti in the proof of Lemma 3.5. □

3.2 $n = 2$

TODO:

- The only non-trivial part of the 2-functor $\chi^\omega \colon \boldsymbol{B}^2 G \to \mathrm{Alg}_{\mathbb{C}}$ is the coherence 2-morphism $\chi^\omega_{g,h} \colon \chi^\omega(g) \otimes \chi^\omega(h) \to \chi^\omega(gh)$, and the constraints (see e. g. [Le, Sect. 1.1] for the definitions) on the $\chi^\omega_{g,h}$ precisely say that they are the components of a 2-cocycle. So we can take $\chi^\omega_{g,h} = \omega(g,h)$.

- compute 2-colimit $\mathrm{Sum}_2(\chi)$ for χ as above, obtain twisted group algebra $\mathbb{C}^\omega[G]$

The datum of the 2-functor $\chi^\omega \colon \boldsymbol{B}^2 G \to \mathrm{Alg}_{\mathbb{C}}$ is a collection of lines (1-dimensional complex vector spaces) L_g, indexed by elements in the group G, together with isomorphisms

$$\rho_{g,h} \colon L_g \otimes L_h \xrightarrow{\sim} L_{gh}$$

subject to the associativity constraint given by the commutativity of the diagrams

$$\begin{tikzcd} L_g \otimes L_h \otimes L_k \arrow[r, "\rho_{g,h} \otimes \mathrm{id}"] \arrow[d, "\mathrm{id} \otimes \rho_{h,k}"'] & L_{gh} \otimes L_k \arrow[d, "\rho_{gh,k}"] \\ L_g \otimes L_{hk} \arrow[r, "\rho_{g,hk}"'] & L_{ghk} \end{tikzcd}$$

where the tensor products are over $\mathbb{C}$. We also require that $L_1 = \mathbb{C}$ and that the isomorphisms $L_1 \otimes L_g \xrightarrow{\sim} L_g$ and $L_g \otimes L_1 \xrightarrow{\sim} L_g$ are the structure isomorphisms for the unit object $\mathbb{C}$ of the monoidal category $\mathrm{Vect}_{\mathbb{C}}$. The associativity constraints imply, and are in fact equivalent to this, that the vector space

$$A_{\chi^\omega} = \bigoplus_{g \in G} L_g$$

has an associative $\mathbb{C}$-algebra structure.

Lemma 3.3. A choice of a basis element x_g for every line L_g defines a $\mathbb{C}^\times$-valued 2-cocycle ω on the group G. A different choice of basis elements leads to a cohomologous cocycle, so that the class $[\omega] \in H^2(G, \mathbb{C}^\times)$ is well defines.

Proof. As $\rho_{g,h}(x_g \otimes x_h)$ is a nonzero element in L_{gh} we have $\rho_{g,h}(x_g \otimes x_h) = \omega(g,h)x_{gh}$ for a unique element $\omega(g,h)$ in $\mathbb{C}^\times$. The associativity constraints are then immediately seen to be equivalent to the cocycle equation

$$\omega(gh,k)\omega(g,h) = \omega(g,hk)\omega(h,k).$$

Finally, if $\{y_g\}_{g\in G}$ is a different basis choice, and $\tilde{\omega}$ is the corresponding 2-cocycle, then we have $y_g = \eta_g x_g$ for some η_g in $\mathbb{C}^\times$ and

$$\tilde{\omega(g,h)} y_{gh} = \rho_{g,h}(y_g \otimes y_h) = \eta_g \eta_h \rho_{g,h}(x_g \otimes x_h) = \eta_g \eta_h \omega(g,h) x_{gh} = \eta_g \eta_h \omega(g,h) \eta_{gh}^{-1} y_{gh}.$$

Therefore

$$\tilde{\omega}(g,h) = \eta_g \eta_{gh}^{-1} \eta_h \omega(g,h),$$

i.e. ω and $\tilde{\omega}$ are cohomologous. $\square$

Corollary 3.4. The algebra A_{χ^ω} is isomorphic to the twisted group algebra $\mathbb{C}^\omega[G]$, defined as the $\mathbb{C}$-vector space on the basis $\{x_g\}_{g\in G}$ with the product $x_g \cdot x_h = \omega(g,h)x_{gh}$ and with $x_1 = 1$.

Lemma 3.5. $\mathrm{Sum}_2(\chi^\omega) \cong \mathbb{C}^\omega[G]$, the twisted group algebra of G.

Proof. Let (A, M) be a cocone for χ^ω, i.e., a pair consisting of a $\mathbb{C}$-algebra A together with a left A-module M (representing a linear functor ${}_{\mathbb{C}}\mathrm{Mod} \to {}_A\mathrm{Mod}$) and homotopy commutative diagrams

$$\begin{tikzcd} & A & \\ \mathbb{C} \arrow[ur, "M"] \arrow[rr, "L_g"'] & \arrow[u, phantom, "\Leftarrow \lambda_g"] & \mathbb{C} \arrow[ul, "M"'] \end{tikzcd}$$

where the λ_g's are isomorphisms of left A-modules

$$\lambda_g \colon M \otimes_{\mathbb{C}} L_g \xrightarrow{\sim} M$$

such that the diagrams

$$\begin{tikzcd} M \otimes L_g \otimes L_h \arrow[r, "\lambda_g \otimes \mathrm{id}"] \arrow[d, "\mathrm{id} \otimes \rho_{g,h}"'] & M \otimes L_h \arrow[d, "\lambda_h"] \\ M \otimes L_{gh} \arrow[r, "\lambda_{gh}"'] & M \end{tikzcd}$$

commute. This implies that the isomorphisms λ_g make M a right A_{χ^ω}-module. Therefore, we can see M as a linear functor

$$ {}_{A_{\chi^\omega}}\mathrm{Mod} \to {}_{A}\mathrm{Mod} $$

i.e., as a morphism from A_{χ^ω} to A in 2-Vect$_{\mathbb{C}}$. The algebra A_{χ^ω} seen as a left A_{χ^ω}-module is a morphism from $\mathbb{C}$ to A_{χ^ω} in 2-Vect$_{\mathbb{C}}$ and the natural isomorphism

$$ {}_{A}M_{\mathbb{C}} \cong {}_{A}M_{A_{\chi^\omega}} \otimes {}_{A_{\chi^\omega}}A_{\chi^\omega}{}_{\mathbb{C}} $$

gives a canonical factorization

$$
\begin{tikzcd}
 & A & \\
 & A_{\chi^\omega} \arrow[u, "M"] & \\
\mathbb{C} \arrow[uur, bend left, "M"] \arrow[ur, "A_{\chi^\omega}"] \arrow[rr, "L_g"'] \arrow[rr, phantom, shift left=4, "\Nearrow \lambda_g"] & & \mathbb{C} \arrow[uul, bend right, "M"'] \arrow[ul, "A_{\chi^\omega}"']
\end{tikzcd}
$$

exhibiting the algebra A_{χ^ω} together with itself seen as a left module over itself as the universal cocone. $\square$

3.3 $n = 3$

TODO:

- The only non-trivial part of the 3-functor $\chi^\omega \colon \boldsymbol{B}^3 G \to \mathrm{TC}_{\mathbb{C}}$ are the coherence 3-morphisms which assemble into the modification (also) called ω in [Sc, Def. A.4.3], and the constraints on ω (see [Sc, Page 219]) seem to be precisely the 3-cocycle condition.

- **Issue**: The notion of a 3-colimit (to really compute Sum_3) is scary. At least we should make some hand-wavy arguments...

4 Boundary conditions

4.1 $n = 2$

TODO

4.2 $n = 3$

TODO

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