Semisimple 2-categories

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Goal

$$\{\text{multifusion category}\} \xrightarrow[\simeq]{\mathcal{M}\mathrm{od}^{fin}_{s.s.}(-)} \{\text{semisimple 2-cat}\}$$

- The 2-category $\mathcal{M}\mathrm{od}^{fin}_{s.s.}(C)$ of finite semisimple module categories over a multifusion category C is semisimple.
- For any finite semisimple 2-category $\mathcal{C}$, there exists a multifusion category C such that $\mathcal{C} \simeq \mathcal{M}\mathrm{od}^{fin}_{s.s.}(C)$

Conventions

In relation to a 2-category:

- $\mathcal{C}$ (caligraphic font): 2-category;
- X, Y, F (upper case latin): object of 2-category, functor between 2-categories;
- f, g (lower case latin): 1-morphism; we write $\mathcal{C}(X, Y)$ for the category of morphisms from X to Y;
- $\eta, \varepsilon, \delta$ (lower case greek): 2-morphism; for a 2-morphism $\alpha : f \Rightarrow g : X \to Y$, we may write $\alpha \in \mathcal{C}(X, Y)(f, g)$ to indicate its sources and targets, or simply $\alpha \in \mathrm{Hom}(f, g)$ if the objects are clear

Conventions

In relation to a 1-category:

- C, A (upper case latin): category;
- a, b, f, g (lower case latin): objects in category, functor between categories;
- α, β (lower case greek): morphism in category

Conventions

We also compose morphisms from right to left: in a 2-category $\mathcal{C}$, for $\alpha \in \mathcal{C}(X, Y)(f, f'), \beta \in \mathcal{C}(Y, Z)(g, g'), \gamma \in \mathcal{C}(X, Y)(f', f'')$, we write

$$g \circ f, g \circ f', \ldots : X \to Z$$

for composition of 1-morphisms,

$$\beta \circ \alpha : (g \circ f) \Rightarrow (g' \circ f') : X \to Z$$

for horizontal composition of 2-morphisms,

$$\gamma \cdot \alpha : f \Rightarrow f'' : X \to Y$$

for vertical composition of 2-morphisms.

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In general, if P is a property of a 1-category, we say that a 2-category $\mathcal{C}$ is *locally* P if every hom-category $\mathcal{C}(X, Y)$ satisfies P.

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In general, if P is a property of a 1-category, we say that a 2-category $\mathcal{C}$ is *locally* P if every hom-category $\mathcal{C}(X, Y)$ satisfies P.
By 2-category we always mean a weak 2-category that is furthermore locally additive over $\mathbf{k}$.
By 2-functor (sometimes just functor for simplicity) between 2-categories will always be locally $\mathbf{k}$-linear.

Review

Additive 2-category, direct sum of objects

Definition (direct sum of objects in 2-category)

A *direct sum* of two objects A_1, A_2 in $\mathcal{C}$ is an object $A_1 \boxplus A_2$ together with inclusion and projection 1-morphisms $i_k : A_k \rightleftharpoons A_1 \boxplus A_2 : p_k$, such that

- $p_k \circ i_k \simeq \mathrm{id}_{A_k}$,
- $p_2 \circ i_1$, $p_1 \circ i_2$ are zero 1-morphisms,
- $\mathrm{id}_{A_1 \boxplus A_2} \simeq i_1 \circ p_1 \oplus i_2 \circ p_2$

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Proposition

i_k, p_k are two-sided adjoints to each other.

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Definition

A 1-morphism $i : X \to Y$ is *fully faithful* (or (X, i) is a *subobject* of Y) if it induces fully faithful functors between hom-categories by post-composition, i.e. for all objects A, $i \circ - : \mathcal{C}(A, X) \to \mathcal{C}(A, Y)$ is fully faithful.

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Proposition

$i_k : A_k \to A_1 \boxplus A_2$ is fully faithful.

Additive 2-category, direct sum of objects

Definition (Direct sum of 2-categories)

Given 2-categories $\mathcal{C}_j$, $j \in J$, we may consider the direct sum 2-category $\mathcal{C} := \boxplus_{j \in J} \mathcal{C}_j$:

- $\operatorname{Obj} \mathcal{C} = \bigsqcup_{j \in J} \operatorname{Obj} \mathcal{C}_j$
- for $X \in \mathcal{C}_i$, $Y \in \mathcal{C}_j$, $\mathcal{C}(X, Y) = \begin{cases} \mathcal{C}_j(X, Y) & \text{if } i = j \\ 0 \text{ if } i \neq j \end{cases}$

Idempotent completeness, separable monads, splittings

Definition

A *separable algebra* (a, μ, η) in a tensor category C is an algebra that admits an a-a-bimodule section ${}_a a_a \to {}_a a \otimes a_a$ to μ.

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In other words, a separable monad over X is a separable algebra in $\mathcal{C}(X, X)$.

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Definition

Let $r \vdash l : X \to Y$ be an adjunction with unit $\eta : \mathrm{id}_X \Rightarrow rl$ and counit $\varepsilon : lr \Rightarrow \mathrm{id}_Y$. We say the adjunction $l \dashv r$ is *separable* if ε admits a section.

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Clearly, if an adjunction $l \dashv r$ is separable, then the monad rl is separable.

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Let (t, μ, η) be a separable monad on an object $X \in \mathcal{C}$. A *(separable) splitting* of t is a (separable) adjunction $r \vdash l : X \to Y$ together with an isomorphism $\psi : rl \simeq t$ as monads on X.

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Under the right conditions (local idempotent completeness of $\mathcal{C}$), splittings are unique:

Proposition (Uniqueness of splitting)

[[1], Theorem A.3.1] In a locally idempotent complete 2-category $\mathcal{C}$, splittings of a separable monad are unique up to equivalence.

Idempotent completeness, 2-category

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Definition (Idempotent completion)

Let $\mathcal{C}$ be a locally idempotent complete 2-category. The *idempotent completion of* $\mathcal{C}$, denoted $\mathcal{C}^{\nabla}$, with:

- Objects: (X, p) separable monad in $\mathcal{C}$,
- $\mathcal{C}^{\nabla}((X,p),(Y,q)) = q\text{-}\mathrm{bimod}\text{-}p(\mathcal{C}(X,Y))$

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There is a natural 2-functor $I : \mathcal{C} \to \mathcal{C}^{\nabla}$ that is fully faithful.
A 2-functor $F : \mathcal{C} \to \mathcal{D}$ extends to a 2-functor $F^{\nabla} : \mathcal{C}^{\nabla} \to \mathcal{D}^{\nabla}$ that commutes with I's.

Idempotent completeness, 2-category

Proposition

$\mathcal{C}^\nabla$ is idempotent complete. Moreover, if $\mathcal{C}$ is already idempotent complete, then $I : \mathcal{C} \simeq \mathcal{C}^\nabla$ is an equivalence.

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As a consequence, if $\mathcal{D}$ is idempotent complete, then we have equivalences of 2-categories

$$\mathcal{F}un(\mathcal{C}, \mathcal{D}) \simeq \mathcal{F}un(\mathcal{C}^{\nabla}, \mathcal{D}^{\nabla}) \simeq \mathcal{F}un(\mathcal{C}^{\nabla}, \mathcal{D})$$

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Proposition

If $F : \mathcal{C} \to \mathcal{D}$ is fully faithful, then $F^{\nabla} : \mathcal{C}^{\nabla} \to \mathcal{D}^{\nabla}$ is also fully faithful.

Idempotent completeness, 2-category

$$(\mathcal{B}C)^{\nabla} = \begin{cases} \text{Obj}: \ \text{separable algebras in } C \\ \text{Mor}: (\mathcal{B}C)^{\nabla}(a,b) = b\text{-}\mathrm{bimod}\text{-}a(C) \end{cases}$$

Idempotent completeness, 2-category

Proposition ([1]*Prop 1.3.13)

For a multifusion category C, the following 2-functor is an equivalence:

$$\begin{aligned}(-)\text{-}mod(C) : (\mathcal{B}C)^{\nabla} &\to \mathcal{M}od(C)\\ a &\mapsto a\text{-}mod(C)\\ {}_b m_a &\mapsto m \otimes_a -\\ \varphi &\mapsto \varphi \otimes_a -\end{aligned}$$

Proof.

Essential surjectivity follows from:
-[2]*Theorem 1: for a finite semisimple right module category over multifusion C, there exists a semisimple algebra a in C such that $M \simeq a\text{-}\mathrm{mod}(C)$ as right C-module categories; and
-[4]*Corollary 2.6.9: When C is multifusion over a field of characterisitc 0, a right C-module category M is separable

Simple objects

Proposition (equivalent notions of simple-ness)

Let $\mathcal{C}$ be a locally finite semisimple and idempotent complete 2-category, and let $X \in \mathcal{C}$ be a nonzero object. Then the following notions of X being simple are equivalent:

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(2) X cannot be written as a non-trivial direct sum, i.e. if $X = \boxplus X_i$, then $X_i \simeq 0$ for all but one i;
(3) id_X is a simple object in $\mathcal{C}(X, X)$.

Semisimple 2-category

Definition ((finite) semisimple 2-category)

A 2-category $\mathcal{C}$ is *semisimple* if it is:

- locally semisimple,
- admits left and right adjoints for every 1-morphism,
- additive,
- idempotent complete.

It is furthermore *finite semisimple* if it is also locally finite and has finitely many equivalence classes of simple objects.

New Stuff

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\mathrm{Vec}_{\mathbb{Z}/2} \arrow[loop left, "\mathrm{Vec}_{\mathbb{Z}/2}"] \arrow[rr, bend left, "\mathrm{Vec}"] & & \mathrm{Vec} \arrow[loop right, "\mathrm{Vec}_{\mathbb{Z}/2}"] \arrow[ll, bend left, "\mathrm{Vec}"]
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Such nonzero morphisms turn out to be an important aspect of semisimple 2-categories since they capture "2-Morita equivalences" between fusion categories.

Schur's lemma

Proposition (Schur's Lemma, [1]*Prop 1.2.19)

In a semisimple 2-category $\mathcal{C}$*, if* $f : A \to B, g : B \to C$ *are nonzero 1-morphisms between simple objects* A, B, C*, then* $g \circ f$ *is also nonzero.*

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Proof.

$$\begin{tikzcd}
A \arrow[r, bend left=50, "f"] \arrow[r, phantom, "\underset{\exists\delta}{\overset{\varepsilon}{\Longleftrightarrow}}"] & B \arrow[l, bend left=50, "f^*"] \arrow[rr] & & C
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Let $f^* : B \to A$ be a right adjoint to f.

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Proof.

$$\begin{tikzcd}
A \arrow[r, bend left=50, "f"] \arrow[r, phantom, "\overset{\varepsilon}{\Longleftrightarrow}"] \arrow[r, phantom, shift right=3, "\exists\delta"] & B \arrow[l, bend left=50, "f^*"] \arrow[r] & C
\end{tikzcd}$$

Let $f^* : B \to A$ be a right adjoint to f. Since id_B is simple, $\exists$ section $\delta : \mathrm{id}_B \Rightarrow ff^*$ to counit $\varepsilon : ff^* \Rightarrow \mathrm{id}_B$. Postcomposing with g, we have $\mathrm{id}_g = (\mathrm{id}_g \circ \varepsilon) \cdot (\mathrm{id}_g \circ \delta) : g \Rightarrow gff^* \Rightarrow g$. Thus if $gf = 0$, then $\mathrm{id}_g = 0$, contradicting nonzero-ness of B. $\square$

Schur's lemma - components

Definition (component of semisimple 2-category)

In a semisimple 2-category $\mathcal{C}$, we say two simple objects A, B belong to the same *component* if there exists a nonzero 1-morphism $f : A \to B$.

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In a finite semisimple 2-category $\mathcal{C}$, there will be finite set J of components;

full subcategory $\mathcal{C}_j$, $j \in J$: direct sum of simple objects in j gives direct sum decomposition $\mathcal{C} \simeq \boxplus_{j \in J} \mathcal{C}_j$.

Main results

Theorem ([1]*Theorem 1.4.8)

The 2-category of finite semisimple module categories of a multifusion category C is a finite semisimple 2-category.

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Proof.

$\mathcal{M}\mathrm{od}(C) \simeq (\mathcal{B}C)^{\nabla}$ is idempotent complete and locally idempotent complete. $\mathcal{M}\mathrm{od}(C)$ is clearly already additive.
Locally semisimple-ness follows directly from [4]*Corollary 2.5.6, and existence of adjoints for 1-morphisms follows from [3]*Corollary 2.13.

$\square$

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