Semisimple 2-categories

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Goal

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

- The 2-category $\mathcal{M}\mathrm{od}^{\mathit{fin}}_{s.s.}(C)$ 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 $\mathcal{C} \simeq \mathcal{M}\mathrm{od}^{\mathit{fin}}_{s.s.}(C)$

Overview

- direct sum

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- idempotent completion, separable stuff

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- direct sum
- idempotent completion, separable stuff
- simple objects
- ‘Schur lemma’
- main results

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:
for composition of 1-morphisms,

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

for horizontal composition of 2-morphisms,

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

for vertical composition of 2-morphisms,

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

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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

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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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A *zero object* in $\mathcal{C}$ is an object 0 with trivial endomorphism category $\mathcal{C}(0,0)$ (has one object id_0 with only identity morphism $\mathrm{id}_{\mathrm{id}_0}$.

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Definition

2-category $\mathcal{C}$ is *additive* if finite direct sums of objects exist, has a zero object, (and is locally additive).

Additive 2-category, direct sum of objects

Definition (subobject)

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

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- $\mathcal{C}((X_i)_{i \in J}, (Y_j)_{j \in J}) = \bigoplus \mathcal{C}_i(X_i, Y_i)$

Idempotent completeness, separable monads, splittings

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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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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 - the splitting gives $rl \simeq r(\mathrm{id}_Y)l \Rightarrow r(lr)l \simeq (rl)(rl)$

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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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Proposition (Uniqueness of splitting)

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

Idempotent completeness, 2-category

Definition

A 2-category $\mathcal{C}$ is *idempotent complete* if every separable monad admits a splitting and is locally idempotent complete.

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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

Key example:
$\mathcal{B}C$: one object $*$ with endomorphism category $\mathcal{B}C(*,*) = C$ (with $x \otimes y = x \circ y$)

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

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

Proposition ([1]Prop 1.3.13)

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

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

Idempotent completeness, 2-category

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

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-[4]Corollary 2.6.9: When C is multifusion over a field of characterisitc 0, a right C-module category M is separable ($\simeq a\text{-}\mathrm{mod}(C)$ for a separable algebra a) if and only if it is semisimple.

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Idempotent completeness, 2-category

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Fully faithfulness: on free modules: $F(a \otimes c) \simeq F(a) \otimes c$; (right) exactness: $F(m) = F(a \otimes_a m) \simeq F(a) \otimes_a m$

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Idempotent completeness, 2-category

Slightly more detailed proof.

$M_C \simeq a\text{-}\mathrm{mod}(C)$:

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$M_C \simeq a\text{-}\mathrm{mod}(C)$: use C-action on M to enrich $M(m_1, m_2) \in \mathrm{Vec}$ to object $\underline{\mathrm{Hom}}(m_1, m_2) \in C$, "internal hom"

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for left a-module m, separability of a gives section to quotient $a \otimes m \to a \otimes_a m \simeq m$, so m is projective.

Idempotent completeness, 2-category

Slightly more detailed proof.

$M_C \simeq a\text{-}\mathrm{mod}(C)$: use C-action on M to enrich $M(m_1, m_2) \in \mathrm{Vec}$ to object $\underline{\mathrm{Hom}}(m_1, m_2) \in C$, "internal hom"

$$C(c, \underline{\mathrm{Hom}}(m_1, m_2)) \simeq M(m_1 \triangleleft c, m_2)$$

fix some $x \in M$; $a := \underline{\mathrm{Hom}}(x, x)$; composition gives a-module structure on $\underline{\mathrm{Hom}}(x, m)$
$M \ni m \mapsto \underline{\mathrm{Hom}}(x, m) \in a\text{-}\mathrm{mod}(C)$

separable $\Rightarrow$ semisimple:
$\mathbf{1} \in C$ is projective, $a \in a\text{-}\mathrm{mod}(C)$ is projective, free modules $a \otimes c$ are projective
for left a-module m, separability of a gives section to quotient $a \otimes m \to a \otimes_a m \simeq m$, so m is projective.
semisimple $\Rightarrow$ separable is more challenging $\square$

Simple objects

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Proposition (equivalent notions of simple-ness)

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(3) id_X is a simple object in $\mathcal{C}(X, X)$.

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Proof sketch.
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(2) $\Rightarrow$ (3): Contravariant statement is "identity splitting implies object splitting", uses idempotent completeness of $\mathcal{C}$ to split out objects corresponding to summands of id_X (which are separable monads) (see [1]Prop 1.3.16).

(3) $\Rightarrow$ (1): for non-zero fully faithful $r : Y \to X$, with id_X simple, consider the left adjoint $l : X \to Y$, use fully faithfulness to get a preimage $\delta : \mathrm{id}_Y \Rightarrow lr$ of $\eta \circ r : r \Rightarrow rlr$. Show δ is a section of the counit. Etc. (See [1]Prop 1.2.14) $\square$

Semisimple 2-category

Definition ((finite) semisimple 2-category)

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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

Schur's lemma

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$$\begin{tikzcd}
\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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There can be nonzero morphisms between non-equivalent simple objects - weird!

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"2-Morita equivalences" between fusion categories

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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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$$\begin{tikzcd} A \arrow[r, bend left, "f"] & B \arrow[r, "g"] & C \end{tikzcd}$$

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Proof.

$$
\begin{tikzcd}
A \arrow[r, bend left=50, "f"] \arrow[r, phantom, "\overset{\varepsilon}{\Longrightarrow}"] & B \arrow[l, bend left=50, "f^*"] \arrow[r, "g"] & C
\end{tikzcd}
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Proof.

$$
\begin{tikzcd}
A \arrow[r, bend left=60, "f"] \arrow[r, phantom, shift left=1, "\overset{\varepsilon}{\Rrightarrow}"] \arrow[r, phantom, shift right=1, "\underset{\exists\delta}{\Lleftarrow}"'] & B \arrow[l, bend left=60, "f^*"] \arrow[r, "g"] & C
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Proof.

$$\begin{tikzcd} A \arrow[r, bend left=50, "f"] \arrow[r, phantom, "\overset{\varepsilon}{\Rrightarrow}"] \arrow[r, phantom, yshift=-2ex, "\underset{\exists\delta}{\Lleftarrow}"] & B \arrow[l, bend left=50, "f^*"] \arrow[r, "g"] & C \end{tikzcd}$$

$$\mathrm{id}_{\mathrm{id}_B} = \varepsilon \cdot \delta$$

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if $gf \cong 0$, then $id_g = 0$, and $g \cong 0$

$\square$

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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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. $\mathcal{M}\mathrm{od}(C)$ is clearly already additive.

Locally semisimple-ness follows directly from [4]Corollary 2.5.6;

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(explicit right adjoint to ${}_b m_a : a\text{-}\mathrm{mod}(C) \to b\text{-}\mathrm{mod}(C)$ is given by $\underline{\mathrm{Hom}}_B(m, -)$)

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We show $\mathcal{C} \simeq (\mathcal{B}C)^{\nabla}$.

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Proof (Cont.)

Consider the inclusion 2-functor

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is fully faithful. Remains to show other simples are in essential image.

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$$\begin{tikzcd} & & Y \\ * \arrow[r, mapsto, "F^{\nabla}"] & X \arrow[ur, bend left, "f"] & \end{tikzcd}$$

$\square$

Main results

Proof (Cont.)

$$
\begin{tikzcd}
& & Y \arrow[dl, bend left, "g"] \\
* \arrow[r, mapsto, "F^{\nabla}"] & X \arrow[ur, bend left, "f"] \arrow[ur, phantom, "\dashv"] &
\end{tikzcd}
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ε has section

$\Rightarrow$ sep. adj.

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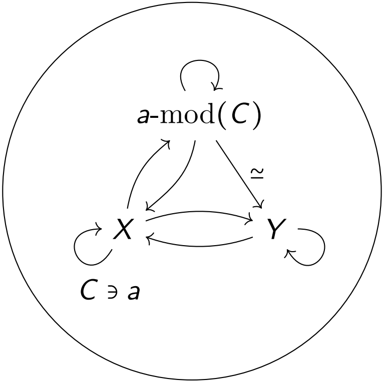
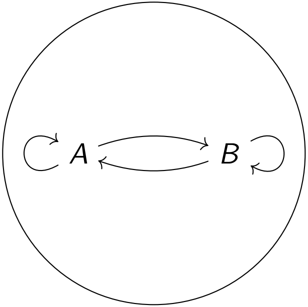
We can also avoid the first step of taking only one component of $\mathcal{C}$, take X with at least one object from each $\mathcal{C}_j$ in its direct sum decomposition.

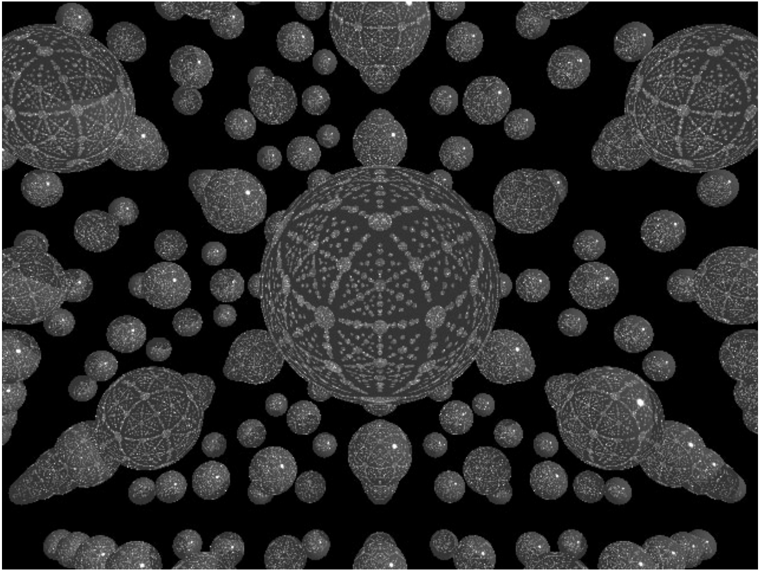
Main results

Every object contains within them the data to reconstruct the whole 2-category.





Indra's Net of Pearls (or $\mathbf{T}^3 \# \mathbf{T}^3$)



Example

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e: trivial algebra $\mathbf{k}_e$ $\quad e\text{-}\mathrm{mod}(C) \simeq C_C$
f: the group algebra $\mathbf{k}[G] = \bigoplus \mathbf{k}_g$ $\quad f\text{-}\mathrm{mod}(C) \simeq \mathrm{Vec}$
(right action on Vec = forget G-grading)

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Next we study the functor categories. Clearly the C-endofunctors of C_C is C itself.

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For $f\text{-}\mathrm{mod}(C)$, an endofunctor is given by some $m \in f\text{-}\mathrm{bimod}\text{-}f(C)$; write $m = \bigoplus m_g$. The right f-action on m makes all the m_g isomorphic in a coherent manner.

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Thus, $\mathcal{M}\mathrm{od}(C)(f, f) \simeq f\text{-}\mathrm{bimod}\text{-}f(C) \simeq \mathsf{Rep}(G)$.

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Thus, $\mathcal{M}\mathrm{od}(C)(f, f) \simeq f\text{-}\mathrm{bimod}\text{-}f(C) \simeq \mathsf{Rep}(G)$.
(Alternatively, one can also check that C-module structure on $m : \mathrm{Vec} \to \mathrm{Vec}$ amounts to G-action on $m(\mathbf{k})$.)

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Next we study the functor categories. Clearly the C-endofunctors of C_C is C itself.
For $f\text{-}\mathrm{mod}(C)$, an endofunctor is given by some $m \in f\text{-}\mathrm{bimod}\text{-}f(C)$; write $m = \bigoplus m_g$. The right f-action on m makes all the m_g isomorphic in a coherent manner. For $h \in G$, conjugation (left action by h and right action by h^{-1}) gives an action of G on m_e; determines m completely.
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(Alternatively, one can also check that C-module structure on $m : \mathrm{Vec} \to \mathrm{Vec}$ amounts to G-action on $m(\mathbf{k})$.)
Thus we have:

$$\mathcal{M}\mathrm{od}(\mathrm{Vec}_G) \simeq \mathcal{M}\mathrm{od}(\mathsf{Rep}(G))$$

Example

For functor categories between them, we see that

$$\mathcal{M}\mathrm{od}(C)(e, f) \simeq f\text{-bimod-}e(C) \simeq f\text{-mod}(C) \simeq \mathrm{Vec}$$

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Note for $G = \mathbb{Z}/2$, $\mathrm{Vec}_{\mathbb{Z}/2} \simeq \mathsf{Rep}(\mathbb{Z}/2)$, don't see difference in endomorphism categories.

Example

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Of course, there are many other objects in $\mathcal{M}\mathrm{od}(C)$, e.g. for a subgroup $H \subseteq G$, have group algebra $\mathbf{k}[H]$.

End!

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