

ENRICHED ∞ -OPERADS AS MARKED ALGEBRAS

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ABSTRACT. The following is a preliminary and partial draft (last modified 01.11.25); an up-to-date version is maintained at www.markus-zetto.com/enriched-operads.pdf.

We prove that an enriched ∞ -operad is completely determined by its category of right modules together with a ‘marking’ by the representable modules. This description allows for a direct comparison of (colored) S -enriched ∞ -operads, defined as algebras in symmetric sequences, and Lurie’s model of ∞ -operads. Additionally, we show that the categories of algebras and right modules defined in both models agree.

We develop the theory of enriched ∞ -operads by defining a Boardman-Vogt product, operadic weighted colimits and free algebras; and consider the question how much about a V -enriched ∞ -operad \mathcal{O} can be recovered from $\text{Alg}_{\mathcal{O}}(V)$ or from its category of right modules, leading to an operadic version of Cauchy-completion. This resolves questions about the Morita-theory of ∞ -operads posed in [KM01].

Finally, we provide a new proof that the envelope functor from ∞ -operads to symmetric monoidal ∞ -categories is a subcategory inclusion, and investigate when this is the case for general enrichment.

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1. INTRODUCTION

The notion of a (*colored*) *operad*, or multicategory, generalizes that of a category by allowing for *k*-ary *multimorphisms* with *k* sources and a single target, for any *k* ≥ 0 . Operads were originally introduced in algebraic topology to encode the algebraic structure on iterated loop spaces [BV06], [May06]. The *little cubes operads* \mathbb{E}_n introduced for this purpose already indicated two fundamental features that a general theory of operads should accommodate:

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- The sets of n -ary multimorphisms often carry additional structure, in this case they are chain complexes. One is thus naturally led to enriched operads, which generalize enriched categories.
- For a morphism of operads to be an equivalence it should suffice for it to induce quasi-isomorphisms between the multimorphism chain complexes, i.e. in modern language we want to homotopy coherently enrich in the derived category of chain complexes $D(k)$.

Lurie's approach in [Lur17] incorporates the second approach while circumventing the first: He defines a fully homotopy-theoretic (and non-linear) version of operads, called ∞ -operads, of which the \mathbb{E}_n -operads are central examples. At first sight this may suggest that the k -linear structure inherent in the approach via dg-operads is superfluous — but there is more to this story.

The duality between grouplike \mathbb{E}_n -spaces and pointed n -connected spaces (i.e. n -fold loop spaces) is a specific instance of *Koszul duality* between augmented \mathbb{E}_n -algebras and augmented \mathbb{E}_n -coalgebras, see 5.2.6. Conceptually, this relies on the fact that the \mathbb{E}_n -operad is Koszul self-dual — a statement that only makes sense if we regard \mathbb{E}_n as an enriched ∞ -operad. Koszul duality is typically formulated for operads enriched in a semiadditive ∞ -category, since this allows us to view non-unital cooperads as coalgebras in symmetric sequences [Hei24a, Corollary 2.27]. It is particularly well-behaved for enrichment in a stable ∞ -category, where Koszul duality enhances to an equivalence between reduced non-unital operads and cooperads [Chi12], [Heu24, Thm. 3.4], [Hei24a, Prop. 3.6]. For instance, the \mathbb{E}_∞ -operad enriched in spectra is Koszul dual to the *spectral Lie operad*, which has no incarnation as an ordinary ∞ -operad — already the ordinary or dg Lie operads require linear enrichment.

Further applications of enriched operads, particularly in vector spaces or chain complexes, arise in mathematical physics (related to factorization algebras and chiral algebras), geometric representation theory, deformation theory and algebraic geometry; see the introduction of [Hau22] for further references.

1.1. Enriched ∞ -operads. Unfortunately, Lurie's definition of ∞ -operads as certain fibrations over the category Fin_* of finite pointed sets does not directly extend to the enriched setting. We therefore adopt a different approach, originating with [BD98] for classical coloured operads and extended to single-coloured ∞ -operads in [Bra17]; see §1.2 of [Hau22] for a more detailed historical account.

Fix a presentably symmetric monoidal ∞ -category $\mathcal{V} \in \text{CAlg}(\text{Pr})$ as our enrichment category. Any space X freely generates a presentably symmetric monoidal \mathcal{V} -module ∞ -category $\mathcal{PSym}(X) \otimes \mathcal{V} \simeq \prod_{k \geq 0} \text{Fun}(B\Sigma_k, \mathcal{V})$, where Σ_k denotes the symmetric group on k elements. This means that there is an equivalence

$$\text{End}_{\mathcal{V}}^{\text{L}, \otimes}(\mathcal{PSym}(X) \otimes \mathcal{V}) \simeq \text{Fun}(X, \mathcal{PSym}(X) \otimes \mathcal{V}) \simeq \text{Fun}(X \times \text{Sym}X, \mathcal{V}).$$

Transporting the composition of endofunctors along this equivalence induces a monoidal structure on the right, (the reverse of) which is often referred to as the *composition product* or *plethysm product* \oplus on the category of *X-colored symmetric sequences*. We describe it in Corollary 2.5.

A functor $\text{Mul}_\mathcal{O} \in \text{Fun}(X \times \text{Sym}X, \mathcal{V})$ assigns to a colour in X and a finite symmetric tuple of colours an object of \mathcal{V} —exactly the data of multimorphisms in a \mathcal{V} -enriched operad. Giving $\text{Mul}_\mathcal{O}$ an algebra structure with respect to \oplus encodes homotopy-coherent composition and identities. This motivates the following definition:

Definition 1.1. A \mathcal{V} -enriched operad with space of colors X is a monad on $\mathcal{PSym}(X) \otimes \mathcal{V}$ in the $(\infty, 2)$ -category $\mathbf{CAlg}(\mathbf{RMod}_{\mathcal{V}}(\mathbf{Pr}))$. In other words, it is an algebra for the composition product \otimes on $\mathbf{Fun}(X \times \mathbf{Sym}X, \mathcal{V})$.

1.2. Marked algebras. We follow the main idea of [RZ25] to rewrite this definition. Given an $(\infty, 2)$ -category that admits Eilenberg-Moore objects, to any monad in it we may associate a monadic adjunction — in particular to a \mathcal{V} -enriched operad $\mathcal{O} \in \mathbf{End}_{\mathcal{V}}^{\mathbf{L}, \otimes}(\mathcal{PSym}(X) \otimes \mathcal{V})$ we obtain

$$\mathcal{PSym}(X) \otimes \mathcal{V} \leftrightarrows \mathbf{LMod}_{\mathcal{O}}(\mathcal{PSym}(X) \otimes \mathcal{V}) =: \mathcal{P}_{\mathcal{V}}^{\otimes}(\mathcal{O})$$

where we refer to the Eilenberg-Moore object $\mathcal{P}_{\mathcal{V}}^{\otimes}(\mathcal{O}) \in \mathbf{CAlg}(\mathbf{RMod}_{\mathcal{V}}(\mathbf{Pr}))$ as the *operadic presheaf category* of \mathcal{O} ¹. Conversely, this monadic adjunction lets us recover the original monad. Characterizing the monadic 1-morphisms in $\mathbf{CAlg}(\mathbf{RMod}_{\mathcal{V}}(\mathbf{Pr}))$, which we do in Proposition 4.1, therefore recovers an alternative description of enriched operads:

Theorem A (Corollary 4.4). Assigning to a \mathcal{V} -enriched operad \mathcal{O} the composition $X \subseteq \mathbf{Sym}(X) \subseteq \mathcal{PSym}(X) \rightarrow \mathcal{PSym}(X) \otimes \mathcal{V} \rightarrow \mathcal{P}_{\mathcal{V}}^{\otimes}(\mathcal{O})$, sending x to the free module on $\mathfrak{L}_{(x)}$, induces a fully faithful embedding

$$v\mathcal{O}p_X(\mathcal{V}) = \mathbf{Alg}(\mathbf{End}_{\mathcal{V}}^{\mathbf{L}, \otimes}((\mathcal{P}(\mathbf{Sym}X) \otimes \mathcal{V}))) \hookrightarrow \mathbf{CAlg}(\mathbf{Pr}_{\mathcal{V}})_X/$$

whose image consists those functors $\mathfrak{L} : X \rightarrow \mathcal{M}$ with $\mathcal{M} \in \mathbf{CAlg}(\mathbf{RMod}_{\mathcal{V}}(\mathbf{Pr}))$ such that:

- The unique extension $Y : \mathcal{PSym}(X) \otimes \mathcal{V} \rightarrow \mathcal{M}$ is an internally left adjoint 1-morphism in $\mathbf{CAlg}(\mathbf{RMod}_{\mathcal{V}}(\mathbf{Pr}))$,
- The image of \mathfrak{L} generates \mathcal{M} under colimits, symmetric monoidal structure and \mathcal{V} -tensoring.

We refer to the functors $X \rightarrow \mathcal{M}$ in the image of this embedding as *marked \mathcal{V} -algebras*.

We use this result to define the category of *valent \mathcal{V} -enriched operads* as the fully subcategory of the pullback $\widehat{\mathbf{Arr}(\mathbf{Cat})} \times_{\widehat{\mathbf{Cat}}} \mathbf{CAlg}(\mathbf{Pr}_{\mathcal{V}})$ on the marked \mathcal{V} -algebras. The term *valent* as opposed to univalent indicates that the space of objects X we have chosen need not agree with the actual underlying space of our operad — to find the correct underlying space, by the Yoneda lemma, we have to ensure that it embeds into $\mathcal{P}_{\mathcal{V}}^{\otimes}(\mathcal{O})$ as a subcategory:

Definition 1.2. A \mathcal{V} -enriched operad \mathcal{O} is called *univalent* if its associated marked algebra $\mathfrak{L} : \mathbf{col}\mathcal{O} \rightarrow \mathcal{P}_{\mathcal{V}}^{\otimes}(\mathcal{O})$ is a subcategory inclusion, in other words $\mathbf{col}\mathcal{O} \simeq \mathbf{Im}(\mathfrak{L})^{\simeq}$. Denote by $\mathcal{O}p(\mathcal{V}) \subseteq v\mathcal{O}p(\mathcal{V})$ the full subcategory on the univalent \mathcal{V} -operads.

Theorem B (Theorem 5.9, Corollary 5.12). The category $v\mathcal{O}p(\mathcal{S})$ of univalent \mathcal{S} -enriched operads is equivalent to the category of flagged ∞ -operads, i.e. pairs of an ∞ -operad O in the sense of Lurie and a surjective functor $X \rightarrow \mathbf{col}O$ into its underlying category from some space X .

The category $\mathcal{O}p(\mathcal{S})$ of univalent \mathcal{S} -enriched operads is equivalent to Lurie's category of ∞ -operads $\mathcal{O}p$.

Let us sketch how this comparison works. First, given a flagged ∞ -operad $X \rightarrow O$, we explain how to associate to it a monad in $\mathbf{CAlg}(\mathbf{Pr})$. We begin by applying the envelope functor \mathbf{Env} as well as the presheaf category functor, regarding X as an operad without

¹Usually, this is called the category of *right modules* for \mathcal{O} .

higher multimorphisms so $\text{Env } X \simeq \text{Sym } X \in \text{CAlg}(\mathcal{C}\text{at})$. This yields an adjunction

$$\begin{array}{ccc} & \text{Env}(i)_! & \\ \text{PSym}(col\mathcal{O}) & \begin{array}{c} \swarrow \otimes, L \\ \downarrow \\ \uparrow \otimes, L \\ \searrow \end{array} & \mathcal{P} \text{Env } \mathcal{O} \\ & \text{Env}(i)^* & \end{array}$$

where the left adjoint is symmetric monoidal and the right adjoint preserves colimits. We prove in Theorem 3.36, using an argument communicated to us by Jan Steinebrunner, that the induced lax symmetric monoidal structure on the right adjoint is strong, enhancing this to an adjunction in $\text{CAlg}(\text{Pr})$. We obtain a symmetric monoidal colimit-preserving monad

$$(\text{Env } f)^*(\text{Env } f)_! \in \text{Alg} \left(\text{End}^{L, \otimes}(\text{PSym}(col\mathcal{O})) \right) \simeq \text{Alg}(\text{Fun}(X \times \text{Sym } X, \mathcal{V})) .$$

Explicitly, under the latter equivalence,

$$(\text{Env } f)^*(\text{Env } f)_!(\mathfrak{L}_{(o)}) = (\text{Env } f)^* \mathfrak{L}_{(o)} = \text{Map}_{\text{Env}(\mathcal{O})}(-, (o)) \circ \text{Env}(f)$$

which sends a symmetric tuple $(o_1, \dots, o_n) \in \text{Sym}(col\mathcal{O})$ to

$$\text{Map}_{\text{Env}(\mathcal{O})}((o_1, \dots, o_n), (o)) \simeq \text{Mul}_{\mathcal{O}}(o_1, \dots, o_n; o)$$

as expected, i.e. we have enhanced $\text{Mul}_{\mathcal{O}}$ to an algebra in $\text{Fun}(X \times \text{Sym } X, \mathcal{V})$. By construction, the marked algebra associated to this operad is $X \rightarrow \mathcal{P} \text{Env } \mathcal{O}$, since the extension $\mathcal{P} \text{Sym } X \rightarrow \mathcal{P} \text{Env } \mathcal{O}$ is a monadic 1-morphism in $\text{CAlg}(\text{RMod}_{\mathcal{V}}(\text{Pr}))$. Hence this proof identifies $\mathcal{P} \text{Env } \mathcal{O}$ with the operadic presheaf category of \mathcal{O} , from which we deduce that the categories of algebras that can be defined in both settings are equivalent.

Conversely, to any marked algebra $\mathfrak{L} : X \rightarrow \mathcal{M}$, we can associate the flagged operad $X \rightarrow \text{Im}(\mathfrak{L})$ since the essential image of \mathfrak{L} , as a subcategory of the symmetric monoidal category \mathcal{M} , inherits an operad structure.

Proving that these constructions are inverse relies on having an understanding of $\mathcal{M} \in \text{CAlg}(\text{RMod}_{\mathcal{V}}(\text{Pr}))$ arise as operadic presheaf categories for some enriched operad; similarly to the characterization [RZ25, Rem. 5.10] that $\mathcal{N} \in \text{RMod}_{\mathcal{V}}(\text{Pr})$ arises as an enriched presheaf category iff it is atomically generated. A priori, there are the following different ways we could define what it means for $\mathcal{M} \in \text{CAlg}(\text{Pr}_{\mathcal{V}})$ to be \otimes -atomically generated, ordered by increasing strength:

- (1) \mathcal{M} is generated under colimits, \mathcal{V} -tensoring and symmetric monoidal structure by its full subcategory (or equivalently, any full subcategory) of \otimes -atomic objects, i.e. objects $m \in \mathcal{M}$ such that the unique morphism $\text{PSym}(\ast) \otimes \mathcal{V} \rightarrow \mathcal{M}$ sending $\ast \mapsto m$ is internally left adjoint,
- (2) There exists a small full subcategory $\mathcal{M}_0 \subseteq \mathcal{M}$ generating \mathcal{M} under the above, such that the unique extension $\text{PSym}(\mathcal{M}_0) \otimes \mathcal{V} \rightarrow \mathcal{M}$ to a morphism in $\text{CAlg}(\text{Pr}_{\mathcal{V}})$ is internally left adjoint,
- (3) \mathcal{M} is generated under the above by its full subcategory $\mathcal{M}^{\otimes \text{at}}$ of \otimes -atomic objects, and the unique extension $\text{PSym}(\mathcal{M}^{\otimes \text{at}}) \otimes \mathcal{V} \rightarrow \mathcal{M}$ is internally left adjoint.

The analogous notions in $\text{Pr}_{\mathcal{V}}$ are immediately seen to be equivalent [RZ25, Prop. 3.32]. However for us, (1) is too weak as we will see in Warning 3.16. We show in Corollary 7.23 that conditions (2) and (3) are in fact equivalent, but proving this uses the machinery of Cauchy-complete operads we develop much later in the paper (in fact, this equivalence makes sure that there exists a Cauchy-completion functor for operads).

1.3. Applications. We use the marked-module picture to develop the higher algebra of enriched ∞ -operads, for instance we introduce:

- An envelope functor $\text{Env}_{\mathcal{V}} : \text{Op}(\mathcal{V}) \rightarrow \text{CAlg}(\text{Cat}(\mathcal{V}))$ from enriched operads to symmetric monoidal \mathcal{V} -categories in Construction 2.7 and Definition 9.3,
- A Boardman-Vogt product \otimes_{BV} on \mathcal{V} -operads that is adjoint to taking \mathcal{V} -categories of algebras, see Proposition 6.2,
- Operadic weighted colimits in Definition 6.6, with factorization homology as a specific example Example 6.9,
- Free algebras over \mathcal{V} -operads in Proposition 6.8,

generalizing the respective constructions for ∞ -operads in [Lur17].

1.4. Recovering on operad from its algebras. We will study the question how much information about an operad \mathcal{O} can be recovered from its categories of algebras $\text{Alg}_{\mathcal{O}}(\mathcal{M})$ where $\mathcal{M} \in \text{CAlg}(\text{RMod}_{\mathcal{V}}(\text{Pr}))$. The following is more or less immediate from the above marked algebra description:

Proposition (??). Let $f : \mathcal{O} \rightarrow \mathcal{P}$ be a map of valent \mathcal{V} -enriched operads whose underlying map on spaces of colors $\text{col}\mathcal{O} \rightarrow \text{col}\mathcal{P}$ is an equivalence. If the induced precomposition map $f^* : \text{Alg}_{\mathcal{P}}(\mathcal{M}) \rightarrow \text{Alg}_{\mathcal{O}}(\mathcal{M})$ is an equivalence for any $\mathcal{M} \in \text{CAlg}(\text{Pr}_{\mathcal{V}})$, then f is already an equivalence.

However, we might now always be given a comparison map f , but only the category $\text{Alg}_{\mathcal{O}}(\mathcal{V})$ itself. Certainly, we can not fully recover \mathcal{O} in this case:

- Let C be a category and \hat{C}^{idc} its idempotent completion. Then
$$\text{Alg}_{\text{Triv}_{\mathcal{V}}(C)}(\mathcal{M}) \simeq \text{Fun}(C, \mathcal{M}) \simeq \text{Fun}(\hat{C}^{\text{idc}}, \mathcal{M}) \simeq \text{Alg}_{\text{Triv}_{\mathcal{V}}(\hat{C}^{\text{idc}})}(\mathcal{M}).$$
- Given a spectral operad \mathcal{O} , we can define its r -fold shift $\mathcal{O}[r]$ whose multimorphism objects are given by the shifts

$$\text{Mul}_{\mathcal{O}[r]}(o_1, \dots, o_n; o) \simeq \text{Mul}_{\mathcal{O}}(o_1, \dots, o_n; o)[r \cdot (1-n)],$$

consider [Hei24a, Constr. 2.34] for a single-colored version of this construction. The auto-equivalence $[-r] : \mathcal{V} \xrightarrow{\sim} \mathcal{V}$ induces, for any $\mathcal{M} \in \text{CAlg}(\text{Pr}_{\text{st}})$, an equivalence $\text{Alg}_{\mathcal{O}}(\mathcal{M}) \simeq \text{Alg}_{\mathcal{O}[r]}(\mathcal{M})$.

- Let \mathcal{V} be semiadditive. Then to any single-colored \mathcal{V} -operad \mathcal{O} , we can associate its r -matrix operad $\text{Mat}_r(\mathcal{O})$, whose multimorphisms are given by

$$\text{Mat}_r(\mathcal{O})(n) = \mathcal{O}(n)^{\oplus r^{n+1}}$$

regarded as matrices with n ingoing and one outgoing indices, and composition given by matrix products and composition in \mathcal{O} . In the case of dg-operads, [KM01] proves that $\text{Alg}_{\mathcal{O}}(\mathcal{M}) \simeq \text{Alg}_{\text{Mat}_r(\mathcal{O})}(\mathcal{M})$. We will see that the analogy of this statement with the fact that every ring is Morita-equivalent to its matrix ring is not accidental.

These examples indicate that how much about \mathcal{O} we can recover is highly dependent on \mathcal{V} , and more specifically *absolute weighted colimits* in \mathcal{V} -enriched category theory. A weight $W \in \mathcal{P}_{\mathcal{V}}(\mathcal{C})$ on some \mathcal{V} -category \mathcal{C} is called *absolute* if W -weighted colimits are preserved by any \mathcal{V} -enriched functor, and \mathcal{C} is called *Cauchy-complete* if any absolute weight on it (which are precisely the atomic objects in the enriched presheaf category $\mathcal{P}_{\mathcal{V}}\mathcal{C}$) is representable, c.f. [Hei24b, Prop. 5.51], [RZ26]. For instance, idempotent splittings are absolute colimits over \mathcal{S} , shifts are over $\mathcal{S}p$, and direct sums are over $\mathcal{S}p^{\text{cn}}$, which is closely related to the above constructions.

Analogously, we call an enriched operad Cauchy-complete if every \otimes -atomic object in $\mathcal{P}_V^\otimes(\mathcal{O})$ is representable. These form a full subcategory $\mathcal{O}_+(\mathcal{V}) \subseteq v\mathcal{O}p(\mathcal{V})$ whose inclusion admits a left adjoint $(\widehat{-})^\mathcal{V}$. We prove the following characterization:

Proposition 1.3. Given \mathcal{V} -operads $\mathcal{O}, \mathcal{P} \in v\mathcal{O}p(\mathcal{V})$, the following are equivalent:

- (1) The functors $\text{Alg}_{\mathcal{O}}(-), \text{Alg}_{\mathcal{P}}(-) : \text{CAlg}(\text{Pr}_{\mathcal{V}}) \rightarrow \widehat{\mathcal{C}\text{at}}$ are equivalent,
- (2) The categories of algebras $\text{Alg}_{\mathcal{O}}(\text{Fun}(\bigsqcup_{k \geq 0} B\Sigma_k, \mathcal{V})) \simeq \text{Alg}_{\mathcal{P}}(\text{Fun}(\bigsqcup_{k \geq 0} B\Sigma_k, \mathcal{V}))$ are equivalent,
- (3) The categories of operadic presheaves $\mathcal{P}_V^\otimes(\mathcal{O}) \simeq \mathcal{P}_V^\otimes(\mathcal{P})$ are equivalent,
- (4) The Cauchy-completions $\widehat{\mathcal{O}}^\mathcal{V} \simeq \widehat{\mathcal{P}}^\mathcal{V}$ are equivalent.

In this case, we call \mathcal{O} and \mathcal{P} *Morita-equivalent*.

Further, we prove in Theorem 7.20 that a \mathcal{V} -operad \mathcal{O} is Cauchy-complete iff its underlying \mathcal{V} -category $\text{Col}_{\mathcal{V}}(\mathcal{O})$ is. This shows, for instance:

- Given two ∞ -operads \mathcal{O}, \mathcal{P} whose underlying ∞ -categories are idempotent complete, then $\mathcal{O} \simeq \mathcal{P}$ iff $\text{Alg}_{\mathcal{O}}(\mathcal{S}) \simeq \text{Alg}_{\mathcal{P}}(\mathcal{S})$. For instance, this is true for the \mathbb{E}_k -operad and its variants with tangential structures, and for the \mathbb{E}_X -operad classifying constructible factorization algebras on a stratified manifold X (since exit-path categories are always idempotent complete).
- Given spectral ∞ -operads \mathcal{O}, \mathcal{P} whose underlying ∞ -categories are stable and idempotent complete, then $\mathcal{O} \simeq \mathcal{P}$ iff $\text{Alg}_{\mathcal{O}}(\mathcal{Sp}) \simeq \text{Alg}_{\mathcal{P}}(\mathcal{Sp})$. Similarly for operads enriched over the derived category of a ring (e.g. dg-operads).

In fact, studying the idempotent completion lets us classify all single-colored operads Morita-equivalent to a given single-colored $\mathcal{O} \in v\mathcal{O}p(\mathcal{V})$. Namely, they are completely specified by an algebra $\mathcal{P}(1) \in \text{Alg}(\mathcal{V})$ that is Morita-equivalent to the algebra $\mathcal{O}(1)$ of 1-ary operations in \mathcal{O} ; or equivalently a dualizable generator in $\text{Mod}_{\mathcal{O}(1)}(\mathcal{V})$. For instance:

- If $\mathcal{V} = \text{Vec}_k$ over a field k and given a single-colored Vec_k -enriched operad $\mathcal{O} \in v\mathcal{O}p(\text{Vec}_k)$ such that $\mathcal{O}(1) \simeq k$, then any single-colored operad $\mathcal{P} \in v\mathcal{O}p(\text{Vec}_k)$ such that $\text{Alg}_{\mathcal{O}}(\text{Vec}_k) \simeq \text{Alg}_{\mathcal{P}}(\text{Vec}_k)$ is equivalent to $\text{Mat}_r(\mathcal{O})$ for some $r \geq 0$.
- If $\mathcal{V} = D(k)$ and $\mathcal{O} \in v\mathcal{O}p(D(k))$ a single-colored dg-operad with $\mathcal{O}(1) \simeq k[0]$, then for any nonzero finite-dimensional graded vector space N we construct a generalized matrix operad $\text{Mat}_N(\mathcal{O})$ that is Morita-equivalent to \mathcal{O} . We show in Example 8.13 that any operad Morita-equivalent to \mathcal{O} arises like this; for instance the shifts $\mathcal{O}[r]$ correspond to $N = k[r]$, while $\text{Mat}_r(\mathcal{O})$ corresponds to $k^{\oplus r}[0]$.

1.5. Recovering an operad from its envelope. We have seen that while we generally can not recover an enriched operad \mathcal{O} from its operadic presheaf category, knowing which presheaves are representable is (by our definition of univalence) enough to recover the univaluation of our operad. What if we are instead given the envelope of \mathcal{O} , i.e. the full subcategory of operadic presheaves that are generated by the representables under the symmetric monoidal structure?

It is a well-established result in the non-enriched setting [HK24], [BS22] that the envelope functor $\text{Env} : \mathcal{O}p \rightarrow \text{CAlg}(\mathcal{C}\text{at})$ is a subcategory inclusion, in particular if $\text{Env}(\mathcal{O}) \simeq \text{Env}(\mathcal{P})$ then $\mathcal{O} \simeq \mathcal{P}$. Its image can be characterized in several ways; for instance as consisting of \otimes -disjunctive symmetric monoidal categories and \otimes -disjunctive symmetric monoidal functors, compare Definition 3.30. We generalize the latter notion to symmetric monoidal \mathcal{V} -enriched functors and prove the following statement about the enriched envelope functor:

Theorem 1.4. Let $\text{CAlg}(v\mathcal{C}\text{at}(\mathcal{V}))^{\otimes\text{-disj}}$ be the wide subcategory of $\text{CAlg}(v\mathcal{C}\text{at}(\mathcal{V}))$ on \otimes -disjunctive enriched functors, and similarly $\text{CAlg}(\mathcal{C}\text{at}(\mathcal{V}))^{\otimes\text{-disj}}$. Then, the envelope functor

$$\text{Env}_{\mathcal{V}} : \mathcal{O}\mathcal{P}(\mathcal{V}) \rightarrow \text{CAlg}(\mathcal{C}\text{at}(\mathcal{V}))^{\otimes\text{-disj}}$$

admits a right adjoint, which we call the singlett functor $\text{sing}_{\mathcal{V}}$.

- The counit $\text{Env}_{\mathcal{V}} \text{sing}_{\mathcal{V}} \mathcal{C} \rightarrow \mathcal{C}$ of this adjunction is always fully faithful, and an isomorphism iff \mathcal{C} is generated under its symmetric monoidal structure by its singletts, i.e. the \otimes -atomic objects in $\mathcal{P}_{\mathcal{V}}(\mathcal{C}) \in \text{CAlg}(\mathcal{P}\mathcal{V})$.
- The unit $\mathcal{O} \rightarrow \text{sing}_{\mathcal{V}} \text{Env}_{\mathcal{V}} \mathcal{O}$ is always fully faithful, and an isomorphism iff the full sub- \mathcal{V} -category $\text{Col}_{\mathcal{V}}(\mathcal{O}) \subseteq \text{Env}_{\mathcal{V}}(\mathcal{O})$ is closed under absolute colimits for \mathcal{V} -enrichment².

This yields an alternative proof that the envelope functor $\text{Env}_{\mathcal{S}} : \mathcal{O}\mathcal{P}(\mathcal{S}) \rightarrow \text{CAlg}(\mathcal{C}\text{at}(\mathcal{S}))^{\otimes\text{-disj}} \hookrightarrow \text{CAlg}(\mathcal{C}\text{at}(\mathcal{S}))$ is a subcategory inclusion for ordinary operads Example 9.17. Also we deduce that it is rarely a subcategory inclusion if \mathcal{V} is semiadditive Example 9.18, in particular for neither Vec_k , $\mathcal{S}p^{\text{cn}}$ or $\mathcal{S}p$.

The best we can recover from $\text{Env}_{\mathcal{V}}(\mathcal{O})$ is $\text{sing}_{\mathcal{V}} \text{Env}_{\mathcal{V}}(\mathcal{O}) =: \mathcal{O}^{\text{env}}$, which we call the *envelope completion* of \mathcal{O} . Explicitly, this is the intersection of the Cauchy-completion and the envelope

$$\mathcal{O}^{\text{env}} := \widehat{\mathcal{O}}^{\mathcal{V}} \cap \text{Env}_{\mathcal{V}}(\mathcal{O}) \subseteq \mathcal{P}_{\mathcal{V}}^{\otimes}(\mathcal{O}).$$

We have $\text{Env}_{\mathcal{V}}(\mathcal{O}) \simeq \text{Env}_{\mathcal{V}}(\mathcal{P})$ iff $\mathcal{O}^{\text{env}} \simeq \mathcal{P}^{\text{env}}$; and $\text{Env}_{\mathcal{V}}$ restricts to a subcategory inclusion on envelope-complete \mathcal{V} -operads.

Remark 1.5. It is crucial in this discussion that we work with univalent \mathcal{V} -operads and symmetric monoidal univalent \mathcal{V} -categories. The valent version of the envelope functor in Definition 9.3 is evidently a subcategory inclusion since one can recover a space X from the \mathbb{E}_{∞} -space $\text{Sym}(X)$, c.f. Theorem 9.13.

1.6. Relation to other work. In [Hau20], Haugseng proves that ∞ -operads in the sense of Lurie are equivalent to algebras in symmetric sequences. However, his construction of the composition product differs from the one obtained by identifying symmetric sequences with an endomorphism object in $\text{CAlg}(\mathcal{R}\text{Mod}_{\mathcal{V}}(\mathcal{P}))$, and he does not supply a comparison between the two. As he notes in §1.2, this left open the question of whether this notion of enriched ∞ -operads agrees with this more widely used one, which Theorem 5.9 resolves (the issue of comparing the monoidal structures still remains).

There is unpublished work proving this comparison for single-colored ∞ -operads predating our result: Gijs Heuts and Lukas Brantner [BH] are preparing a proof using the theory of analytic monads. Also Thomas Blom, Connor Malin and Niall Taggart [BMT] give a proof that is closely to ours and describe Koszul duality in their formalism. Finally, Jan Steinebrunner and Shaul Barkan are working on a similar framework that extends to enriched ∞ -properads.

1.7. Plan of the paper. In Section 2 we introduce enriched ∞ -operads as monads in the 2-category $\text{CAlg}(\mathcal{P}\mathcal{V})$, which is constructed and studied in Appendix A. The subsequent Section 3 is concerned with understanding internally left adjoint morphisms in it, in particular \otimes -atomic objects and markings. This is applied in Section 4 to obtain our marked-algebra description, and compare it with Lurie's ∞ -operads in Section 5.

Section 6 considers further applications of our approach, defining a Boardman-Vogt product and operadic weighted colimits. In Section 7 we introduce Cauchy-completions

²Absolute colimits are those weighted colimits that are preserved by any \mathcal{V} -enriched functor.

of enriched ∞ -operads, which is maybe the technically most subtle part of this paper. It is applied in Section 8 to study the Morita-theory of operads, and in Section 9 to study enriched envelopes.

1.8. Acknowledgements.

1.9. Notation and Conventions.

2. ENRICHED OPERADS

For $\mathcal{V} \in \text{CAlg}(\text{Pr})$ a presentably symmetric monoidal category, in order to define \mathcal{V} -enriched operads we make use of the 2-category $\text{CAlg}(\mathbb{P}_{\mathcal{V}})$ whose

- underlying 1-category is the category $\text{CAlg}(\mathbb{P}_{\mathcal{V}}) := \text{CAlg}(\text{RMod}_{\mathcal{V}}(\text{Pr}))$ of presentably symmetric monoidal \mathcal{V} -module categories,
- morphism categories $\text{Fun}_{\mathcal{V}}^{\text{L}, \otimes}(\mathcal{M}, \mathcal{N})$ consist of symmetric monoidal \mathcal{V} -linear colimit-preserving functors.

Constructing and studying this 2-category relies on a symmetric monoidal structure $\otimes_{\mathcal{V}}$ on it that we introduce in Appendix A; here we summarize some of its properties:

- By Observation A.28 the forgetful 2-functors

$$\text{CAlg}(\mathbb{P}_{\mathcal{V}}) \rightarrow \text{CAlg}(\text{Pr}) \rightarrow \widehat{\text{CAlg}(\text{Cat})} \rightarrow \widehat{\text{Cat}}$$

admit (partially) left adjoint 2-functors

$$\text{Cat} \xrightarrow{\text{Sym}} \text{CAlg}(\text{Cat}) \xrightarrow{\mathcal{P}} \text{CAlg}(\text{Pr}) \xrightarrow{- \otimes \mathcal{V}} \text{CAlg}(\mathbb{P}_{\mathcal{V}})$$

by which we mean in particular that for a given $C \in \text{Cat}$ and $\mathcal{M} \in \text{CAlg}(\mathbb{P}_{\mathcal{V}})$, precomposing with the canonical functor $C \subseteq \text{Sym}(C) \subseteq \mathcal{P}\text{Sym}(C) \rightarrow \mathcal{P}\text{Sym}(C) \otimes \mathcal{V}$ induces an equivalence

$$\text{Fun}_{\mathcal{V}}^{\text{L}, \otimes}(\mathcal{P}(\text{Sym}C) \otimes \mathcal{V}, \mathcal{M}) \simeq \text{Fun}(C, \mathcal{M}) .$$

Since \mathcal{P} , Sym and $- \otimes \mathcal{V}$ merely enhance the respective 1-functors, we calculate

$$\mathcal{P}(\text{Sym}C) \otimes \mathcal{V} \simeq \text{Fun}(\text{Sym}C^{\text{op}}, \mathcal{V}) \simeq \prod_{n \geq 0} \text{Fun}((C^{\text{op}})_{h\Sigma_n}^{\times n}, \mathcal{V}) .$$

- The 2-category $\text{CAlg}(\mathbb{P}_{\mathcal{V}})$ admits all partially (op)lax colimits. In particular it admits Eilenberg-Moore-objects, which are created by all of the above forgetful 2-functors.

Definition 2.1. Given a space $X \in \mathcal{S}$, a \mathcal{V} -enriched operad with colors X is a monad on $\mathcal{P}(\text{Sym}X) \otimes \mathcal{V} \simeq \text{Fun}(\text{Sym}X^{\text{op}}, \mathcal{V})$ in the 2-category $\text{CAlg}(\text{RMod}_{\mathcal{V}}(\text{Pr}))$. Using the above adjunction and that $X^{\text{op}} \simeq X$, this unwinds to an algebra in

$$\text{End}_{\mathcal{V}}^{\text{L}, \otimes}(\mathcal{P}(\text{Sym}X) \otimes \mathcal{V}) \simeq \text{Fun}(X, \text{Fun}(\text{Sym}X^{\text{op}}, \mathcal{V})) \simeq \text{Fun}(X \times \text{Sym}X, \mathcal{V}) .$$

We refer to $\text{sSeq}_X(\mathcal{V}) := \text{Fun}(X \times \text{Sym}X, \mathcal{V})$, equipped with the monoidal structure \otimes it obtains as an endomorphism object via composition, as the category of X -colored symmetric sequences in \mathcal{V} .

Given a \mathcal{V} -enriched operad \mathcal{O} , we call its underlying functor $\text{Mul}_{\mathcal{O}} : X \times \text{Sym}X \rightarrow \mathcal{V}$ the *multigraph* of \mathcal{O} , and denote its evaluation on a tuple $(x, (x_1, \dots, x_n))$ by $\text{Mul}_{\mathcal{O}}(x_1, \dots, x_n; x) \in \mathcal{V}$. Its points $1_{\mathcal{V}} \rightarrow \text{Mul}_{\mathcal{O}}(x_1, \dots, x_n; x)$ are called *n-ary morphisms* in \mathcal{O} .

Warning 2.2. From the explicit formula in Corollary 2.5 we will see that the monoidal structure \otimes on $sSeq_X(\mathcal{V})$ is reverse to what is commonly called the composition product on symmetric sequences, which we denote \oplus . Of course, their categories of algebras are equivalent.

Notation 2.3. We write \underline{x} for a symmetric tuple $(x_1, \dots, x_n) \in \text{Sym}X$. If $X = *$ and $\mathcal{O} \in sSeq_*(\mathcal{V})$, we write $\mathcal{O}(n)$ for $\mathcal{O}(*; *, \dots, *) \in \mathcal{V}$ evaluating on the unique n -tuple.

Lemma 2.4. Let $X \in \mathcal{C}at$ and $\mathcal{M} \in \mathcal{C}Alg(\mathcal{P}r_{\mathcal{V}})$. Under the equivalence $\text{Fun}(X, \mathcal{M}) \simeq \text{Fun}_{\mathcal{V}}^{L, \otimes}(\mathcal{P}SymX \otimes \mathcal{V}, \mathcal{M})$ from Observation A.28, a functor $A : X \rightarrow \mathcal{M}$ is sent to the morphism $\bar{A} : \text{Fun}(\text{Sym}X^{\text{op}}, \mathcal{V}) \rightarrow \mathcal{M}$ in $\mathcal{C}Alg(\mathcal{P}r_{\mathcal{V}})$ which maps

$$(W : \text{Sym}X^{\text{op}} \rightarrow \mathcal{V}) \mapsto \oint^{\underline{x} \in \text{Sym}X} A(x_1) \otimes \cdots \otimes A(x_n) \otimes W(\underline{x}).$$

Proof. As a first step, A extends to a unique symmetric monoidal functor $\text{Sym}X \rightarrow \mathcal{M}$ sending $(x_1, \dots, x_n) \mapsto A(x_1) \otimes \cdots \otimes A(x_n)$. From here, the formula for the extension to $\mathcal{P}(\text{Sym}X) \otimes \mathcal{V}$ follows from [RZ25, Lem. 2.13]. \square

Corollary 2.5. The monoidal structure \otimes on $sSeq_X(\mathcal{V}) \simeq \text{Fun}(X \times \text{Sym}X, \mathcal{V})$ sends $A, B : X \times \text{Sym}X \rightarrow \mathcal{V}$ to

$$A \otimes B(z, \underline{x}) = \oint^{\underline{y} \in \text{Sym}X} \underset{\underline{x}^{(1)} \otimes \cdots \otimes \underline{x}^{(k)} \rightarrow \underline{x}}{\text{colim}} A(y_1; \underline{x}^{(1)}) \otimes \cdots \otimes A(y_k; \underline{x}^{(k)}) \otimes B(z; \underline{y}).$$

If additionally X is a space, this agrees with

$$\bigsqcup_{k \geq 0} \bigsqcup_{I_1 \sqcup \cdots \sqcup I_k = n} \underset{(y_1, \dots, y_k) \in X^{\times k}}{\text{colim}} (A(y_1; \underline{x}|_{I_1}) \otimes \cdots \otimes A(y_k; \underline{x}|_{I_k})) \otimes_{\Sigma_k} B(z; y_1, \dots, y_k)$$

where the Σ_k -action permutes the blocks $\underline{x}|_{I_1}, \dots, \underline{x}|_{I_k}$ partitioning \underline{x} and the entries of \underline{y} . Specifically for $X = *$ we obtain

$$\bigsqcup_{k \geq 0} \bigsqcup_{I_1 \sqcup \cdots \sqcup I_k = n} (A(\#I_1) \otimes \cdots \otimes A(\#I_k)) \otimes_{\Sigma_k} B(k) \simeq \bigsqcup_{k \geq 0} \bigsqcup_{n_1 + \cdots + n_k = n} \text{Ind}_{\Sigma_{n_1} \times \cdots \times \Sigma_{n_k}}^{\Sigma_n} (A(n_1) \otimes \cdots \otimes A(n_k)) \otimes_{\Sigma_k} B(k).$$

Proof. If we denote by \bar{A}, \bar{B} the endofunctors of $\mathcal{P}(\text{Sym}X) \otimes \mathcal{V}$ associated to A and B , then by definition we can write $A \otimes B(z, (x_i)) = \bar{A} \circ \bar{B}(\mathbb{1}_z \otimes 1_{\mathcal{V}})(x_1, \dots, x_n) = \bar{A}(B(z; -))(x_1, \dots, x_n)$ so the first expression follows from Lemma 2.4 as well as the formula [Lur17, Ex. 2.2.6.17] for the Day convolution product.

By [Lur18a, Tag 048H] and [Lur18a, Tag 048L], for a space X we have $\text{Tw}(X) \simeq X$ so coends agree with colimits over X . Further, the functor $B\Sigma_k \rightarrow \mathcal{S}$ encoding the Σ_k -action on $X^{\times k}$ unstraightens into a coCartesian fibration $X_{h\Sigma_k}^{\times k} \rightarrow B\Sigma_k$ with fiber $X^{\times k}$. Hence, $\text{colim}_{X_{h\Sigma_k}^{\times k}} \simeq \text{colim}_{B\Sigma_k} \text{colim}_{X^{\times k}}$, and the colimit over $B\Sigma_k$ turns the tensor product into a relative tensor product \otimes_{Σ_k} .

It remains to unwind the Day convolution product. The forgetful functor $\text{Sym}X \rightarrow \text{Fin}^{\simeq}$ into the category Fin^{\simeq} of finite sets and bijections induces an equivalence

$$((\text{Sym}X)^{\times n}) \times_{\text{Sym}X} (\text{Sym}X)_{/\underline{x}} \simeq (\text{Fin}^{\simeq, \times n}) \times_{\text{Fin}^{\simeq}} (\text{Fin}^{\simeq})_{/\underline{x}}$$

on the indexing category of $\text{colim}_{\underline{x}^{(1)} \otimes \cdots \otimes \underline{x}^{(k)} \rightarrow \underline{x}}$, **TODO: Fill in argument**. Further, the right side (which is a priori a $(1, 1)$ -category) can be checked to be discrete, i.e. the set of partitions of n .

Finally, note that for $X = *$ the colimit over this slice category calculates, on each connected component i.e. for fixed $n_1 + \cdots + n_k = n$, the left Kan extension along $B\Sigma_1 \times \cdots \times B\Sigma_k \rightarrow B\Sigma_n$ which is how the induced representation is defined. \square

Construction 2.6. By Observation A.28 the symmetric algebra functor

$$\text{Sym}^{\otimes \mathcal{V}} : \text{RMod}_{\mathcal{V}}(\mathcal{C}\text{at}^{\text{colim}}) \rightarrow \text{CAlg}(\text{RMod}_{\mathcal{V}}(\mathcal{C}\text{at}^{\text{colim}}))$$

is a 2-functor, so induces a monoidal functor between endomorphism objects

$$\text{Fun}(X \times X, \mathcal{V}) \simeq \text{End}_{\mathcal{V}}^L(\mathcal{P}(X) \otimes \mathcal{V}) \rightarrow \text{End}_{\mathcal{V}}^{L, \otimes}(\mathcal{P}\text{Sym}X \otimes \mathcal{V}) \simeq \text{Fun}(X \times \text{Sym}X, \mathcal{V})$$

explicitly acting by left Kan extension along the full inclusion $X \subseteq \text{Sym}X$. In particular it is fully faithful and preserves colimits, so it admits a lax monoidal right adjoint. We obtain an adjunction on algebra objects

$$\text{Triv}_{\mathcal{V}} : v\mathcal{C}\text{at}_X(\mathcal{V}) \rightleftarrows v\mathcal{O}\text{p}_X(\mathcal{V}) : \text{Col}_{\mathcal{V}},$$

where the fully faithful left adjoint $\text{Triv}_{\mathcal{V}}$ sends a \mathcal{V} -enriched category \mathcal{C} to the *trivial \mathcal{V} -operad* with colors \mathcal{C} , while $\text{Col}_{\mathcal{V}}$ sends a \mathcal{V} -operad to its \mathcal{V} -category of colors.

Construction 2.7. Similarly, the forgetful 2-functor $\text{CAlg}(\mathbb{P}\text{r}_{\mathcal{V}}) \rightarrow \mathbb{P}\text{r}_{\mathcal{V}}$ induces a monoidal functor

$$\text{Fun}(X \times \text{Sym}X, \mathcal{V}) \simeq \text{End}_{\mathcal{V}}^{L, \otimes}(\mathcal{P}\text{Sym}X \otimes \mathcal{V}) \rightarrow \text{End}_{\mathcal{V}}^L(\mathcal{P}\text{Sym}X \otimes \mathcal{V}) \simeq \text{Fun}(\text{Sym}X \times \text{Sym}X, \mathcal{V})$$

explicitly given by extending symmetric monoidally in the first argument. On algebra objects we obtain a functor

$$v\text{Env}_{\mathcal{V}} : v\mathcal{O}\text{p}_X(\mathcal{V}) \rightarrow v\mathcal{C}\text{at}_{\text{Sym}X}(\mathcal{V})$$

which we call the *(valent) envelope*. We will see in Definition 9.3 that this enhances to a functor $v\text{Env} : v\mathcal{O}\text{p}(\mathcal{V}) \rightarrow \text{CAlg}(v\mathcal{C}\text{at}(\mathcal{V}))$.

Construction 2.8. A morphism $f : \mathcal{V} \rightarrow \mathcal{W}$ in $\text{CAlg}(\mathbb{P}\text{r}_{\mathcal{V}})$ induces by Proposition A.31 a 2-functor $\text{CAlg}(\mathbb{P}\text{r}_{\mathcal{V}}) \rightarrow \text{CAlg}(\mathbb{P}\text{r}_{\mathcal{W}})$. As in Construction 2.6, we obtain a *change-of-enrichment* adjunction

$$f_! : v\mathcal{O}\text{p}_X(\mathcal{V}) \rightleftarrows v\mathcal{O}\text{p}_X(\mathcal{W}) : f_!^R$$

that acts on multigraphs by postcomposing $\text{Mul}_{\mathcal{O}} : X \times \text{Sym}X \rightarrow \mathcal{V}$ with f and f^R .

Definition 2.9. Given a \mathcal{V} -operad $\mathcal{O} \in v\mathcal{O}\text{p}_X(\mathcal{V})$, we define its *operadic (enriched) presheaf category* as the Eilenberg-Moore object

$$\mathcal{P}_{\mathcal{V}}^{\otimes}(\mathcal{O}) := \text{LMod}_{\mathcal{O}}(\mathcal{P}\text{Sym}(\text{col}\mathcal{O}) \otimes \mathcal{V}) \in \text{CAlg}(\mathbb{P}\text{r}).$$

It is part of an Eilenberg-Moore adjunction

$$\mathcal{P}\text{Sym}(\text{col}\mathcal{O}) \otimes \mathcal{V} \rightleftarrows \mathcal{P}_{\mathcal{V}}^{\otimes}(\mathcal{O})$$

between free and forgetful functor. We define the *operadic Yoneda functor* $\mathfrak{z}_{\mathcal{O}} : \text{col}\mathcal{O} \rightarrow \mathcal{P}\text{Sym}(\text{col}\mathcal{O}) \otimes \mathcal{V} \rightarrow \mathcal{P}_{\mathcal{V}}^{\otimes}(\mathcal{O})$ of \mathcal{O} by composing the unit of the free-forgetful adjunction $\widehat{\mathcal{C}\text{at}} \rightleftarrows \text{CAlg}(\text{RMod}_{\mathcal{V}}(\mathcal{C}\text{at}^{\text{colim}}))$ with the free module functor.

Remark 2.10. This is usually known as the category of *right modules* over \mathcal{O} , c.f. [Hei24a]. The unfortunate change in direction comes from the fact that our composition product is reverse to the usual convention.

Construction 2.11. Given any $\mathcal{M} \in \text{CAlg}(\mathbb{P}\text{r})$, by Observation A.27 the category $\text{Fun}_{\mathcal{V}}^{L, \otimes}(\mathcal{P}(\text{Sym}X) \otimes \mathcal{V}, \mathcal{M}) \simeq \text{Fun}(X, \mathcal{M})$ admits a \mathcal{V} -linear sifted-colimit-preserving right tensoring by $\text{End}_{\mathcal{V}}^{L, \otimes}(\mathcal{P}(\text{Sym}X) \otimes \mathcal{V}) = \text{sSeq}_X(\mathcal{V})$ via precomposition.

Definition 2.12. Given a \mathcal{V} -enriched operad $\mathcal{O} \in v\mathcal{O}\text{p}_X(\mathcal{V})$ and $\mathcal{M} \in \text{CAlg}(\mathbb{P}\text{r})$, we define the presentably symmetric monoidal \mathcal{V} -module category of \mathcal{O} -algebras in \mathcal{M} as

$$\text{Alg}_{\mathcal{O}}(\mathcal{M}) := \text{RMod}_{\mathcal{O}}(\text{Fun}(X, \mathcal{M})) \in \text{CAlg}(\mathbb{P}\text{r}_{\mathcal{V}}).$$

Remark 2.13. More generally for $\mathcal{O} \in v\mathcal{O}p_X(\mathcal{V})$ and $\mathcal{P} \in v\mathcal{O}p_Y(\mathcal{V})$, we can define a category $\text{Alg}_{\mathcal{O}}(\mathcal{P})$ of \mathcal{O} -algebras in \mathcal{P} as the pullback

$$\text{Map}_S(X, Y) \times_{\text{Fun}(X, \mathcal{P}^{\otimes}(\mathcal{P}))} \text{RMod}_{\mathcal{O}}(\text{Fun}(X, \mathcal{P}^{\otimes}(\mathcal{P}))) .$$

We expect that one can enhance this to a \mathcal{V} -operad, obtaining a functor $\text{Alg}_{\mathcal{O}}(-) : v\mathcal{O}p(\mathcal{V}) \rightarrow v\mathcal{O}p(\mathcal{V})$ that is right adjoint to the Boardman-Vogt product $- \otimes_{\text{BV}} \mathcal{O}$ we define in Proposition 6.2.

3. \otimes -ATOMIC OBJECTS

We now study adjoint 1-morphisms in the 2-category $\text{CAlg}(\mathbb{P}\mathcal{V})$, allowing us to define \otimes -atomic objects and \otimes -atomically generated categories. While this nomenclature suggests a comparison to atomic objects and atomically generated categories in the world of $\mathbb{P}\mathcal{V}$, as studied in [Ram24] or [RZ25, §3], the symmetric monoidal world is more subtle as many statements are no longer true or require further assumptions.

Proposition 3.1. A 1-morphism $F : \mathcal{M} \rightarrow \mathcal{N}$ in the 2-category $\text{CAlg}(\mathbb{P}\mathcal{V})$ is internally left adjoint if its right adjoint functor F^R preserves colimits, and the canonical lax symmetric monoidal lax \mathcal{V} -linear structure on F^R is strong symmetric monoidal and strong \mathcal{V} -linear.

Proof. In Observation A.30 we have exhibited $\text{CAlg}(\mathbb{P}\mathcal{V})$ as a full sub-2-category of $\text{Fun}(\text{Fin}_*, \mathbb{P}\mathcal{V})$; and adjunctions a functor 2-category are given by pointwise adjunctions satisfying a Beck-Chevalley condition, see for instance [Hei17, Cor. 5.15]: For any morphism $\alpha : \underline{n}_+ \rightarrow \underline{m}_+$ in Fin_* the diagram

$$\begin{array}{ccc} \mathcal{M}^{\times n} & \xrightarrow{F^{\times n}} & \mathcal{N}^{\times n} \\ \downarrow \alpha_! & & \downarrow \alpha_! \\ \mathcal{M}^{\times m} & \xrightarrow{F^{\times n}} & \mathcal{N}^{\times m} \end{array}$$

must be horizontally right adjointable, yielding the strong symmetric monoidality condition for F^R . It suffices to check the pointwise adjointness condition in $\mathbb{P}\mathcal{V}$ on the component $F^{\times 1} : \mathcal{M}^{\times 1} \rightarrow \mathcal{N}^{\times 1}$, where it unwinds into strong \mathcal{V} -linearity and cocontinuity of F^R by a similar argument. Compare [BM24, § 4]. \square

Definition 3.2. For $\mathcal{M} \in \text{CAlg}(\mathbb{P}\mathcal{V})$, an object $m \in \mathcal{M}$ is called \otimes -atomic if the unique map $\text{Fun}(\bigsqcup_{k \geq 0} B\Sigma_k, \mathcal{V}) \simeq \mathcal{PSym}(\ast) \otimes \mathcal{V} \rightarrow \mathcal{M}$ sending $1_{\mathcal{V}} \mapsto m$ is internally left adjoint. In other words, the *internal multi-hom* functor

$$\underline{\text{Hom}}_{\mathcal{M}}^{\otimes}(m, -) : \mathcal{M} \rightarrow \prod_{k \geq 0} \text{Fun}(B\Sigma_k, \mathcal{V})$$

right adjoint to the above map preserves colimits, and its canonical lax \mathcal{O} -monoidal lax \mathcal{V} -linear structure is strong. Denote by $\mathcal{M}^{\otimes \text{at}} \subseteq \mathcal{M}$ the full subcategory on the \otimes -atomic objects.

More generally given a small category C , a functor $C \rightarrow \mathcal{M}$ is called a \otimes -atomic marking if its unique extension $\mathcal{PSym}C \rightarrow \mathcal{M}$ to $\text{CAlg}(\mathbb{P}\mathcal{V})$ is internally left adjoint, and specifically a sequence of objects $(m_1, \dots, m_n) \in \mathcal{M}$ is called \otimes -atomic sequence if the functor $\{1, \dots, n\} \rightarrow \mathcal{M}$ marking them is a \otimes -atomic marking.

Remark 3.3. This naming is chosen to resemble the case of $\mathcal{M} \in \mathbb{P}\mathcal{V}$, where an object $m \in \mathcal{M}$ is called \mathcal{V} -atomic or simply atomic if the 1-morphism $\mathcal{P}(\ast) \otimes \mathcal{V} \simeq \mathcal{V} \rightarrow \mathcal{M}$ in $\mathbb{P}\mathcal{V}$ sending $\ast \mapsto m$ is internally left adjoint. Compare [BM24], [Ram24], [RZ25, Def. 3.20].

Observation 3.4. Internally left adjoint functors in $\text{CAlg}(\text{Pr}_V)$ are closed under composition; in particular they preserve \otimes -atomic markings and \otimes -atomic objects. We will prove partial converses in Proposition 3.25 and Corollary 7.24 respectively.

Observation 3.5. Let us work out explicitly what it means for an object $m \in \mathcal{M}$ to be \otimes -atomic in $\mathcal{M} \in \text{CAlg}(\text{Pr}_V)$. The induced functor

$$\mathcal{P}\text{Sym}(*) \otimes \mathcal{V} \simeq \prod_{k \geq 0} \text{Fun}(B\Sigma_k, \mathcal{V}) \rightarrow \mathcal{M}$$

sends a tuple (v_0, v_1, v_2, \dots) of objects $v_k \in \mathcal{V}$ with Σ_k -action to

$$\bigsqcup_{k \geq 0} m^{\otimes k} \otimes_{\Sigma_k} v_k \in \mathcal{M}$$

where we set $m^{\otimes 0} := 1_{\mathcal{V}}$, and Σ_k acts on $m^{\otimes k}$ by permuting the components. So its right adjoint $\underline{\text{Hom}}_{\mathcal{M}}^{\otimes}(m, -) : \mathcal{M} \rightarrow \prod_{k \geq 0} \text{Fun}(B\Sigma_k, \mathcal{V})$ sends $m' \in \mathcal{M}$ to the tuple

$$(\underline{\text{Hom}}_{\mathcal{M}}(m^{\otimes k}, m'))_{k \geq 0} \in \prod_{k \geq 0} \text{Fun}(B\Sigma_k, \mathcal{V})$$

with Σ_k -action permuting the factors of m . This means that $m \in \mathcal{M}$ is \otimes -atomic iff for any $n \in \mathbb{N}_0$,

- the functor $\underline{\text{Hom}}_{\mathcal{M}}(m^{\otimes n}, -)$ preserves colimits and \mathcal{V} -tensoring; in other words $m^{\otimes n}$ is \mathcal{V} -atomic,
- $\underline{\text{Hom}}_{\mathcal{M}}(m^{\otimes n}, 1_{\mathcal{M}}) \simeq \emptyset_{\mathcal{V}}$ unless $n = 0$, where $\underline{\text{Hom}}_{\mathcal{M}}(1_{\mathcal{M}}, 1_{\mathcal{M}}) \simeq 1_{\mathcal{V}}$,
- for any $m_1, m_2 \in \mathcal{M}$, the multiplication map

$$\bigsqcup_{n=S \sqcup T} \underline{\text{Hom}}_{\mathcal{M}}(m^{\otimes \#S}, m_1) \otimes \underline{\text{Hom}}_{\mathcal{M}}(m^{\otimes \#T}, m_2) \xrightarrow{\otimes} \underline{\text{Hom}}_{\mathcal{M}}(m^{\otimes n}, m_1 \otimes m_2)$$

is an isomorphism.

Observation 3.6. A similar discussion shows that a marking $y : C \rightarrow \mathcal{M}$ is \otimes -atomic if for any finite sequence of objects $c_0, \dots, c_n \in C$ where $n \geq 0$,

- The product $yc_1 \otimes \dots \otimes yc_n$ is atomic,
- $\underline{\text{Hom}}_{\mathcal{M}}(yc_1 \otimes \dots \otimes yc_n, 1_{\mathcal{M}}) \simeq \emptyset_{\mathcal{V}}$ unless $n = 0$, in which case $\underline{\text{Hom}}_{\mathcal{M}}(1_{\mathcal{M}}, 1_{\mathcal{M}}) \simeq 1_{\mathcal{V}}$,
- for any $m_1, m_2 \in \mathcal{M}$, the multiplication map

$$\bigsqcup_{n=S \sqcup T} \underline{\text{Hom}}_{\mathcal{M}}\left(\bigotimes_{s \in S} yc_s, m_1\right) \otimes \underline{\text{Hom}}_{\mathcal{M}}\left(\bigotimes_{t \in T} yc_t, m_2\right) \xrightarrow{\otimes} \underline{\text{Hom}}_{\mathcal{M}}\left(\bigotimes_{k=1}^n yc_k, m_1 \otimes m_2\right)$$

is an isomorphism. This is known as the *hereditary condition*, c.f. [HK24, Prop. 2.4.6, Rem. 2.4.7].

Observation 3.7. We learn that for any \otimes -atomic objects or \otimes -atomic marking to exist in $\mathcal{M} \in \text{CAlg}(\text{Pr}_V)$, the unit $1_{\mathcal{M}} \in \mathcal{M}$ must be \mathcal{V} -atomic and the lax symmetric monoidal structure on the forgetful functor $\underline{\text{Hom}}_{\mathcal{M}}(1_{\mathcal{M}}, -) : \mathcal{M} \rightarrow \mathcal{V}$ must be strong.

Remark 3.8. Let $m_1, m_2 \in \mathcal{M}$. If the product $m_1 \otimes m_2$ is \otimes -atomic, then in particular

$$\text{Map}_{\mathcal{M}}(m_1 \otimes m_2, m_1) \otimes \text{Map}_{\mathcal{M}}(1, m_2) \sqcup \text{Map}_{\mathcal{M}}(1, m_1) \otimes \text{Map}_{\mathcal{M}}(m_1 \otimes m_2, m_2) \rightarrow \text{Map}_{\mathcal{M}}(m_1 \otimes m_2, m_1 \otimes m_2)$$

so the identity $\text{id}_{m_1 \otimes m_2}$ factors either through $\text{Map}_{\mathcal{M}}(m_1 \otimes m_2, m_1) \otimes \text{Map}_{\mathcal{M}}(1, m_2)$ or the other summand. This means there exist $i : m_1 \otimes m_2 \rightarrow m_1$ and $r : 1 \rightarrow m_2$ such that

$$\text{id}_{m_1 \otimes m_2} \simeq r \otimes i \simeq (m_1 \otimes m_2 \xrightarrow{i} m_1 \simeq m_1 \otimes 1 \xrightarrow{m_1 \otimes r} m_1 \otimes m_2)$$

exhibiting $m_1 \otimes m_2$ as a retract of m_1 .³ Informally, it is rare for the tensor product of \otimes -atomic objects to remain \otimes -atomic; they should be imagined as singletts or indecomposables. We will formalize this in Section 9.

Lemma 3.9. Given any functor $C \rightarrow D$, the induced map $\mathcal{PSym}(C) \otimes \mathcal{V} \rightarrow \mathcal{PSym}(D) \otimes \mathcal{V}$ in $\mathbf{CAlg}(\mathbf{Pr}_{\mathcal{V}})$ is internally left adjoint.

Proof. We apply Sym^{\otimes} and $-\otimes\mathcal{V}$, which are 2-functors by Observation A.28, to $\mathcal{P}(C) \rightarrow \mathcal{P}(D)$ which is internally left adjoint in \mathbf{Pr} . \square

Observation 3.10. If $y : C \rightarrow \mathcal{M}$ is a \otimes -atomic marking, then for any $c \in C$ the object $y(c) \in \mathcal{M}$ is \otimes -atomic, since the functor $\mathcal{PSym}(\ast) \otimes \mathcal{V} \rightarrow \mathcal{PSym}(C) \otimes \mathcal{V} \rightarrow \mathcal{M}$ marking $y(c)$ is a composition of internally left adjoint functors by Lemma 3.9.

Warning 3.11. The converse is wrong: The Cartesian (which agrees with the coCartesian) symmetric monoidal structure on \mathbf{Pr} induces a pointwise symmetric monoidal structure \times on $\mathbf{CAlg}(\mathbf{Pr})$, in particular $\mathcal{PSym}(\ast)^{\times 2} \in \mathbf{CAlg}(\mathbf{Pr})$. Both inclusions into and projections out of it are maps in $\mathbf{CAlg}(\mathbf{Pr})$ by Lemma 3.9. The objects $(\ast, 1), (1, \ast) \in \mathcal{PSym}(\ast)^{\times 2}$ are both \otimes -atomic, e.g.

$$\underline{\text{Hom}}^{\otimes}((\ast, 1), -) \simeq \text{pr}_1 : \mathcal{PSym}(\ast)^{\times 2} \rightarrow \mathcal{PSym}(\ast)$$

preserves colimits and symmetric monoidal structure. However they do not form a \otimes -atomic pair, since otherwise their product $(\ast, \ast) \in \mathcal{PSym}(\ast)^{\times 2} \simeq \mathcal{P}(\text{Sym}(\ast) \sqcup \text{Sym}(\ast))$ would be \mathcal{S} -atomic and thereby representable as $\text{Sym}(\ast) \sqcup \text{Sym}(\ast)$ is a groupoid, which it evidently is not.

Remark 3.12. We will however see in Proposition 3.24 that to check that $y : C \rightarrow \mathcal{M}$ is a \otimes -atomic marking, it is sufficient to verify that the restriction $\{c_1, \dots, c_n\} \rightarrow \mathcal{M}$ is a \otimes -marking for any finite set of objects c_1, \dots, c_n in C . Also if we already suppose that \mathcal{M} is \otimes -atomically generated, then we prove in Corollary 7.24 that the converse is in fact true, i.e. $y : C \rightarrow \mathcal{M}$ is a \otimes -atomic marking iff it factors through the atomics.

Observation 3.13. By definition of the internal multihom, we have

$$\text{Map}_{\text{Fun}(B\Sigma, \mathcal{V})}(1_{\mathcal{V}}, \underline{\text{Hom}}_{\mathcal{M}}^{\otimes}(m, -)) \simeq \text{Map}_{\mathcal{M}}(m \otimes 1_{\mathcal{V}}, -) \simeq \text{Map}_{\mathcal{M}}(m, -).$$

This enhances to $\underline{\text{Hom}}_{\text{Fun}(B\Sigma, \mathcal{V})}(1_{\mathcal{V}}, \underline{\text{Hom}}_{\mathcal{M}}^{\otimes}(m, -)) \simeq \underline{\text{Hom}}_{\mathcal{M}}(m, -)$ since

$$\text{Map}_{\mathcal{V}}(v, \underline{\text{Hom}}_{\text{Fun}(B\Sigma, \mathcal{V})}(1_{\mathcal{V}}, \underline{\text{Hom}}_{\mathcal{M}}^{\otimes}(m, -))) \simeq \text{Map}_{\text{Fun}(B\Sigma, \mathcal{V})}(1_{\mathcal{V}} \otimes v, \underline{\text{Hom}}_{\mathcal{M}}^{\otimes}(m, -)) \simeq \text{Map}_{\mathcal{M}}(m \otimes v, -).$$

Proposition 3.14. If κ is a regular cardinal such that the unit $1_{\mathcal{V}} \in \mathcal{V}$ is κ -compact, then every \otimes -atomic object in $\mathcal{M} \in \mathbf{CAlg}(\mathbf{Pr}_{\mathcal{V}})$ is also κ -compact. In particular, the full subcategory $\mathcal{M}^{\otimes\text{at}} \subseteq \mathcal{M}$ on the \otimes -atomic objects is always small.

Proof. By Observation 3.5, \otimes -atomic objects are in particular \mathcal{V} -atomic, so this follows from [BM24, Prop. 5.9], [RZ25, Prop. 3.25]. \square

Definition 3.15. For C a small category and $\mathcal{M} \in \mathbf{CAlg}(\mathbf{Pr}_{\mathcal{V}})$, a functor $C \rightarrow \mathcal{M}$ is called a \otimes -atomically generating marking if it is a \otimes -atomic marking, and the smallest full subcategory of \mathcal{M} containing its image, that is closed under symmetric monoidal structure, \mathcal{V} -tensoring and colimits, is \mathcal{M} itself. A full subcategory $\mathcal{M}_0 \subseteq \mathcal{M}$ is called a system of \otimes -atomic

³Conversely retracts of \otimes -atomic objects are always \otimes -atomic, since colimit-preserving \mathcal{V} -linear symmetric monoidal functors are closed under retracts in lax \mathcal{V} -linear lax symmetric monoidal functors (compare Example 7.21).

generators if its inclusion is a \otimes -atomically generating marking. We call \mathcal{M} \otimes -atomically generated if it admits a \otimes -atomically generating marking, or equivalently (taking its image) a system of \otimes -atomic generators.

Warning 3.16. While a system of \otimes -atomic generators $\mathcal{M}_0 \subseteq \mathcal{M}$ always consists of \otimes -atomic objects by Observation 3.10, this is not enough to ensure that its inclusion is a \otimes -atomic marking. For instance, the category $\text{PSym}(\ast)^{\times 2}$ from Warning 3.11 turns out not to be \otimes -atomically generated.

Definition 3.17. We call $\mathcal{M} \in \text{CAlg}(\text{Pr}_{\mathcal{V}})$ Cauchy- \otimes -atomically generated if its full subcategory $\mathcal{M}^{\otimes\text{at}} \subseteq \mathcal{M}$ is a system of \otimes -atomic generators.

Observation 3.18. Clearly, a Cauchy- \otimes -atomically generated is \otimes -atomically generated. However the converse is not clear, since the extension $\text{PSym}(\mathcal{M}^{\otimes\text{at}}) \otimes \mathcal{V} \rightarrow \mathcal{M}$ might not be internally left adjoint, because its right adjoint might not be strong monoidal. We will prove this converse in Corollary 7.23, with quite some effort.

Notation 3.19. Given a functor $F : \mathbf{C} \rightarrow \mathbf{D}$ where \mathbf{D} is cocomplete, its *colimit-closed image* $\text{CIm}(F) \subseteq \mathbf{D}$ is the smallest full subcategory of \mathbf{D} containing the image of F that is closed under colimits in \mathbf{D} .

Lemma 3.20. Let $F : \mathcal{M} \rightarrow \mathcal{N}$ be a morphism in $\text{CAlg}(\text{Pr}_{\mathcal{V}})$. Then its colimit-closed image $\text{CIm}(F) \subseteq \mathcal{N}$ is closed under \mathcal{V} -tensoring and the symmetric monoidal structure.

Proof. Let \mathcal{M}_1 denote the full subcategory of \mathcal{M} on those m such that $m \otimes m_0 \in \text{CIm}(F)$ for all m_0 in the actual image of F . This contains the image of F and is closed under colimits, hence it must agree with $\text{CIm}(F)$. Now, let \mathcal{M}_2 be the full subcategory on those $m \in \mathcal{M}$ such that $m \otimes v \in \text{CIm}(F)$ for all $v \in \mathcal{V}$, and $m \otimes m' \in \text{CIm}(F)$ for all $m' \in \text{CIm}(F)$. By the previous argument this contains the image of F , also it is closed under colimits, so \mathcal{M}_2 agrees with $\text{CIm}(F)$ and we are done. \square

Lemma 3.21. Let \mathbf{C} be a small category, $\mathcal{M} \in \text{CAlg}(\text{Pr}_{\mathcal{V}})$ and $y : \mathbf{C} \rightarrow \mathcal{M}$ a functor. Then the following are equivalent:

- (1) The image of y generates \mathcal{M} under colimits, \mathcal{V} -tensoring and the symmetric monoidal structure,
- (2) The unique extension $Y : \text{PSym}(\mathbf{C}) \otimes \mathcal{V} \rightarrow \mathcal{M}$ to a morphism in $\text{CAlg}(\text{Pr}_{\mathcal{V}})$ is colimit-dominant,
- (3) The right adjoint $Y^R : \mathcal{M} \rightarrow \text{PSym}(\mathbf{C}) \otimes \mathcal{V}$, which sends m to $((c_1, \dots, c_k) \mapsto \underline{\text{Hom}}_{\mathcal{M}}(c_1 \otimes \dots \otimes c_k, m)) \in \text{Fun}(\text{Sym}(\mathbf{C})^{\text{op}}, \mathcal{V})$, is conservative.

Proof. The equivalence (2) \Leftrightarrow (3) follows from [RZ25, Cor. 3.13]. Also (2) \Rightarrow (1) since the image of $\mathbf{C} \rightarrow \text{PSym}(\mathbf{C}) \otimes \mathcal{V}$ clearly generates under colimit, \mathcal{V} -tensoring and symmetric monoidal structure. Finally, (1) \Rightarrow (2) follows since the colimit-closed image of Y contains the image of y and is closed under colimits, \mathcal{V} -tensoring and symmetric monoidal structure by Lemma 3.20. \square

Lemma 3.22. Let $\mathcal{M}, \mathcal{N}, \mathcal{P} \in \text{CAlg}(\text{Pr}_{\mathcal{V}})$ together with functors

$$\begin{array}{ccc} \mathcal{M} & \xrightarrow{F} & \mathcal{P} \\ I \swarrow & & \searrow G \\ \text{iL, cdom} & & \mathcal{N} \\ & \nearrow \text{iL} & \end{array}$$

in $\text{CAlg}(\text{Pr}_{\mathcal{V}})$ where I is internally left adjoint and colimit-dominant, and G is internally left adjoint. Then F is internally left adjoint.

Proof. Consider the full subcategory $\tilde{\mathcal{M}} \subseteq \mathcal{M}$ on those $m \in \mathcal{M}$ such that for all diagrams $I \rightarrow \mathcal{P}$, and all objects $p, p' \in \mathcal{P}$ and $v \in \mathcal{V}$ the morphisms

$$\begin{aligned} \text{Map}_{\mathcal{M}}(m, \operatorname{colim}_i F^R p_i) &\rightarrow \text{Map}_{\mathcal{M}}(m, F^R \operatorname{colim}_i p_i) \\ \text{Map}_{\mathcal{M}}(m, F^R p \otimes v) &\rightarrow \text{Map}_{\mathcal{M}}(m, F^R(p \otimes v)) \\ \text{Map}_{\mathcal{M}}(m, F^R p \otimes F^R p') &\rightarrow \text{Map}_{\mathcal{M}}(m, F^R(p \otimes p')) \end{aligned}$$

are isomorphisms. By assumption $\tilde{\mathcal{M}}$ contains the full image of I , since $\text{Map}_{\mathcal{M}}(I(n), -) \simeq \text{Map}_{\mathcal{M}}(n, I^R -)$ and both I^R and $I^R F^R$ belong to $\text{CAlg}(\text{Pr}_{\mathcal{V}})$. Moreover, $\tilde{\mathcal{M}}$ is closed under colimits since we can pull them out as limits, so by colimit-dominance we deduce $\tilde{\mathcal{M}} = \mathcal{M}$. By Yoneda, implies that F^R preserves colimits, symmetric monoidal structure and tensoring and thus F were internally left adjoint. \square

Corollary 3.23. Let $y : C \rightarrow \mathcal{M}$ be a functor with $\mathcal{M} \in \text{CAlg}(\text{Pr}_{\mathcal{V}})$, and $f : C' \rightarrow C$ a surjective functor. Then y is a \otimes -atomically generating marking iff the composition $y \circ f : C' \rightarrow \mathcal{M}$ is a \otimes -atomically generating marking.

In particular, $y : C \rightarrow \mathcal{M}$ is a \otimes -atomically generating marking iff the fully faithful inclusion $\text{Im}(y) \hookrightarrow \mathcal{M}$ is, iff the subcategory inclusion $\text{Im}(y)^\simeq \hookrightarrow \mathcal{M}$ is.

Proof. Since $f : C \rightarrow C'$ is surjective, the induced $\text{PSym}(C) \rightarrow \text{PSym}(C')$ is colimit-dominant since it hits all representables, and internally left adjoint by Lemma 3.9. Now the result follows by applying Lemma 3.22, together with composition and cancellation properties of colimit-dominant and internally left adjoint functors. \square

Proposition 3.24. A functor $y : C \rightarrow \mathcal{M}$ into $\mathcal{M} \in \text{CAlg}(\text{Pr}_{\mathcal{V}})$ is a \otimes -atomic marking iff for any tuple (c_1, \dots, c_n) of objects in C , the images $(y(c_1), \dots, y(c_n))$ form a \otimes -atomic sequence in \mathcal{M} .

Proof. Let $Y : \text{PSym}(C) \otimes \mathcal{V} \rightarrow \mathcal{M}$ be the unique extension of y , and consider the full subcategory $\tilde{\mathcal{C}} \subseteq \text{PSym}(C) \otimes \mathcal{V}$ on those c such that for all diagrams $I \rightarrow \mathcal{P}$, and all objects $p, p' \in \mathcal{P}$ and $v \in \mathcal{V}$ the morphisms

$$\begin{aligned} \text{Map}_{\text{PSym}(C) \otimes \mathcal{V}}(c, \operatorname{colim}_i Y^R p_i) &\rightarrow \text{Map}_{\text{PSym}(C) \otimes \mathcal{V}}(c, Y^R \operatorname{colim}_i p_i) \\ \text{Map}_{\text{PSym}(C) \otimes \mathcal{V}}(c, Y^R p \otimes v) &\rightarrow \text{Map}_{\text{PSym}(C) \otimes \mathcal{V}}(c, Y^R(p \otimes v)) \\ \text{Map}_{\text{PSym}(C) \otimes \mathcal{V}}(c, Y^R p \otimes Y^R p') &\rightarrow \text{Map}_{\text{PSym}(C) \otimes \mathcal{V}}(c, Y^R(p \otimes p')) \end{aligned}$$

are isomorphisms. We now show it contains the image of $\text{Sym}C \subseteq \text{PSym}(C) \rightarrow \text{PSym}(C) \otimes \mathcal{V}$. Then since it is closed under colimits and \mathcal{V} -tensoring, we are done. So let us choose $c_1, \dots, c_n \in C$ and denote $Z : \text{PSym}\{1, \dots, n\} \rightarrow \text{PSym}(C)$ the induced functor; then for instance the last map agrees with

$$\text{Map}_{\text{PSym}(C) \otimes \mathcal{V}}(Z(c_1 \otimes \cdots \otimes c_n), Y^R p \otimes Y^R p') \simeq \text{Map}_{\text{PSym}\{1, \dots, n\} \otimes \mathcal{V}}(c_1 \otimes \cdots \otimes c_n, (Y \circ Z)^R p \otimes (Y \circ Z)^R p')$$

which is an isomorphism as $Y \circ Z$ is internally left adjoint by assumption. \square

Proposition 3.25. Let $F : \mathcal{M} \rightarrow \mathcal{N}$ be a morphism in $\text{CAlg}(\text{Pr}_{\mathcal{V}})$, and $C \rightarrow \mathcal{M}$ any \otimes -atomically generating marking. Then, F is internally left adjoint iff the composition $C \rightarrow \mathcal{M} \rightarrow \mathcal{N}$ is a \otimes -atomic marking.

Proof. Consider the composition of the unique extension:

$$\mathbb{P}\text{Sym}(C) \otimes \mathcal{V} \rightarrow \mathcal{M} \rightarrow \mathcal{N}$$

Internally left adjoint functors compose, so the *if* direction is immediate. For the only if direction, apply Lemma 3.22 to this composition. \square

Lemma 3.26. Let $y : C \rightarrow \mathcal{M}$ be \otimes -atomically generating. An internally left adjoint morphism $F : \mathcal{M} \rightarrow \mathcal{N}$ in $\text{CAlg}(\text{Pr}_{\mathcal{V}})$ is fully faithful if and only if for all $c_1, \dots, c_n, c' \in C$, the induced morphism

$$F : \underline{\text{Hom}}_{\mathcal{M}}(yc_1 \otimes \cdots \otimes yc_n, yc') \rightarrow \underline{\text{Hom}}_{\mathcal{N}}(F(yc_1) \otimes \cdots \otimes F(yc_n), F(yc'_m))$$

is an isomorphism in \mathcal{V} .

Proof. Let $Y : \mathbb{P}\text{Sym}C \otimes \mathcal{V} \rightarrow \mathcal{M}$ be the unique extension of y to a morphism in $\text{CAlg}(\text{Pr}_{\mathcal{V}})$, then the above comparison map is obtained by evaluating the transformation $Y^R(yc') \rightarrow (F \circ Y)^R(Fyc')$ induced by the unit $\text{id} \rightarrow F^R F$ at the tuple (c_1, \dots, c_n) . Since both Y and F are internally left adjoint by assumption, the full subcategory of $m' \in \mathcal{M}$ where $Y^R(m') \rightarrow Y^R F^R F(m')$ is an isomorphism is closed under colimits, \mathcal{V} -tensoring and symmetric monoidal structure, so since it contains the image of y it agrees with \mathcal{M} .

Conversely for fixed $m' \in \mathcal{M}$, the full subcategory on those $m \in \mathcal{M}$ such that $\underline{\text{Hom}}_{\mathcal{M}}(m, m') \rightarrow \underline{\text{Hom}}_{\mathcal{M}}(Fm, Fm')$ is an isomorphism contains the image of the symmetric monoidal extension $\text{Sym}C \rightarrow \mathcal{M}$ by assumption, and is closed under colimits and \mathcal{V} -tensoring since we can pull them out. Hence it contains the colimit-closed image of $\mathbb{P}\text{Sym}(C) \otimes \mathcal{V}$ which is all of \mathcal{M} . \square

Proposition 3.27. The subcategory $\text{CAlg}(\text{Pr}_{\mathcal{V}})^{\text{IL}} \hookrightarrow \text{CAlg}(\text{Pr}_{\mathcal{V}})$ is closed under sifted colimits.

Proof. Since the forgetful functor $\text{CAlg}(\text{Pr}_{\mathcal{V}}) \rightarrow \text{Pr}_{\mathcal{V}}$ preserves sifted colimits by [Lur17, Cor. 3.2.3.2], this is analogous to [Ram24, Corollary 1.32]. \square

Warning 3.28. The subcategory $\text{CAlg}(\text{Pr}_{\mathcal{V}})^{\text{IL}} \hookrightarrow \text{CAlg}(\text{Pr}_{\mathcal{V}})$ is not closed under coproducts: By [Lur17, Prop. 3.2.4.7] the coproduct is the pointwise tensor product $\otimes_{\mathcal{V}}$ in $\text{Pr}_{\mathcal{V}}$. Consider $\mathbb{P}\text{Sym}(\ast) \otimes \mathcal{V}$, then internally left adjoint maps from it into $\mathcal{M} \in \text{CAlg}(\text{Pr}_{\mathcal{V}})$ correspond to \otimes -objects, while internally left adjoint maps from $(\mathbb{P}\text{Sym}(\ast) \otimes \mathcal{V}) \otimes_{\mathcal{V}} (\mathbb{P}\text{Sym}(\ast) \otimes \mathcal{V}) \simeq \mathbb{P}\text{Sym}(\ast \sqcup \ast) \otimes \mathcal{V}$ correspond to \otimes -atomic pairs, so compare Warning 3.11. We can fix this by restricting to \otimes -atomically generated categories, see Proposition 7.25.

The extensive list of conditions in Observation 3.5 indicates that checking explicitly whether a given object or pair is \otimes -atomic can be difficult. However the following discussion ensures a steady supply of internally left adjoint functors and \otimes -atomic objects:

Notation 3.29. Given a functor $F : C \rightarrow D$ and $d \in D$, we write $C_{/d}$ for the pullback $C \times_D D_{/d}$.

Definition 3.30 (compare [BS22, Def. 3.2.14]). A symmetric monoidal functor $F : C \rightarrow D$ is \otimes -*disjunctive* if for any $a, b \in D$ the induced functor

$$\otimes : C_{/a} \times C_{/b} \rightarrow C_{/a \otimes b}$$

is an equivalence. More generally F is called *weakly \otimes -disjunctive* if this induced functor is colimit-cofinal for all $a, b \in D$.

Observation 3.31. Inductively, note that F is (weakly) \otimes -disjunctive iff for any $n \in \mathbb{N}_0$ and $d_1, \dots, d_n \in D$ the functor

$$\otimes : C_{/d_1} \times \cdots \times C_{/d_n} \rightarrow C_{/d_1 \otimes \cdots \otimes d_n}$$

induced by the symmetric monoidal structure is an equivalence (colimit-cofinal).

Observation 3.32. This generalizes the notion of \otimes -disjunctive symmetric monoidal categories from [BS22, Def. 3.2.14], in the sense that C is \otimes -disjunctive iff the identity functor id_C is. It follows from [BS22, Cor. 3.2.16] that the envelope $\text{Env}(O)$ of any operad O is \otimes -disjunctive, i.e. for tuples $\underline{o}, \underline{o}' \in \text{Env}(O)$ we have

$$\text{Env}(O)_{/\underline{o}} \times \text{Env}(O)_{/\underline{o}'} \xrightarrow{\cong} \text{Env}(O)_{/\underline{o} \otimes \underline{o}'}$$

where $\underline{o} \otimes \underline{o}'$ is the concatenation of tuples. This extends to map of operads, generalizing ??:

Proposition 3.33. Let $f : O \rightarrow P$ be a map of Lurie-operads. Then the induced symmetric monoidal functor $\text{Env}(f) : \text{Env}(O) \rightarrow \text{Env}(P)$ is \otimes -disjunctive.

Proof. Fill in proof. □

Remark 3.34. We will see in Corollary 9.11 that in fact, a symmetric monoidal functor $F : \text{Env}(O) \rightarrow \text{Env}(P)$ is of the form $\text{Env}(f)$ for some map of operads $f : O \rightarrow P$ iff it is \otimes -disjunctive iff it is weakly \otimes -disjunctive.

Observation 3.35. For $F : C \rightarrow D$ a symmetric monoidal functor, since $\mathcal{P} : \mathcal{Cat} \rightarrow \mathcal{Pr}$ is symmetric monoidal by [Lur17, Rem. 4.8.1.8] the induced $F_! : \mathcal{P}(C) \rightarrow \mathcal{P}(D)$ is symmetric monoidal with respect to the Day convolution product. Thus its right adjoint precomposition functor $F^* : \mathcal{P}(D) \rightarrow \mathcal{P}(C)$ inherits a canonical lax symmetric monoidal structure.

We thank Jan Steinebrunner for communicating to us the following statement:

Theorem 3.36. Let $F : C \rightarrow D$ be a symmetric monoidal functor, then the lax symmetric monoidal structure on $F^* : \mathcal{P}(D) \rightarrow \mathcal{P}(C)$ from Observation 3.35 is strong symmetric monoidal if and only if F is weakly \otimes -disjunctive.

Proof. To show that the lax symmetric monoidal functor F^* is monoidal, it suffices to prove that for any active morphism $\alpha : \underline{n}_+ \rightarrow \underline{m}_+$ and $w_1, \dots, w_n \in \mathcal{P}(D)$ the commutative (by symmetric monoidality of $F_!$) diagram

$$\begin{array}{ccc} \mathcal{P}(C^{\times n}) & \xrightarrow{F_!} & \mathcal{P}(D^{\times n}) \\ \downarrow \otimes_\alpha & & \downarrow \otimes_\alpha \\ \mathcal{P}(C^{\times m}) & \xrightarrow{F_!} & \mathcal{P}(D^{\times m}) \end{array}$$

is horizontally right adjointable. But by the definition of a Lurie-operad, the operation $\otimes_\alpha : \mathcal{P}(D^{\times n}) \rightarrow \mathcal{P}(D^{\times m})$ splits into a product of m operations $\otimes_{\alpha_i} : \mathcal{P}(D^{\times f^{-1}(\{i\})}) \rightarrow \mathcal{P}(D^{\times \{i\}})$, so it suffices to consider the case where $m = 1$ and $\alpha : \underline{n}_+ \rightarrow \underline{1}_+$ is the unique active map. Horizontal right adjointability of the diagram

$$\begin{array}{ccc} \mathcal{P}(C^{\times n}) & \longrightarrow & \mathcal{P}(D^{\times n}) \\ \downarrow & & \downarrow \\ \mathcal{P}(C) & \longrightarrow & \mathcal{P}(D) \end{array}$$

can be checked on representable presheaves $\mathbb{X}_{(d_1, d_2)} \in \mathcal{P}(D \times D)$, since all of the involved functors (including the horizontal right adjoints) preserve colimits. This presheaf is represented by the right fibration $(D^{\times n})_{/(d_1, \dots, d_n)} \rightarrow D^{\times n}$, and its image $\otimes_! \mathbb{X}_{(d_1, d_2)} \simeq \mathbb{X}_{d_1 \otimes d_2}$ by the right fibration $D_{/d_1 \otimes d_2} \rightarrow D$. They fit into a commutative diagram

$$\begin{array}{ccccc}
& & (C \times C)_{/(d_1, d_2)} & \xrightarrow{\otimes} & C_{/d_1 \otimes d_2} \\
& \swarrow F \times F & \downarrow \otimes & & \downarrow F \\
(D \times D)_{/(d_1, d_2)} & \xrightarrow{\quad \otimes \quad} & D_{/d_1 \otimes d_2} & \swarrow F & \\
\downarrow & & \downarrow & & \downarrow \\
& C \times C & \xrightarrow{\otimes} & D & C \\
& \swarrow F \times F & \otimes & \downarrow & \swarrow F \\
D \times D & \xrightarrow{\quad \otimes \quad} & D & &
\end{array}$$

where the vertical morphisms are right fibrations, and the left and right squares are pullbacks. Recall that for a presheaf $W \in \mathcal{P}(B)$ represented by a right fibration $E \rightarrow B$ and a functor $g : B \rightarrow B'$, if we factor the composite map $E \rightarrow B'$ into a cofinal map $E \rightarrow E'$ and a right fibration $E' \rightarrow B'$ using that those classes form a factorization system, then $E' \rightarrow B'$ represents the left Kan extension $F_! W \in \mathcal{P}(B')$: This follows from the composing the adjunction $g \circ - : \mathcal{C}\mathcal{A}\mathcal{T}_{/B} \rightarrow \mathcal{C}\mathcal{A}\mathcal{T}_{/B'} : g^*$ and the reflection of $\mathbf{RFib}_{/B'} \subseteq \mathcal{C}\mathcal{A}\mathcal{T}_{/B'}$ by factoring through a right fibration. In other words, to show that the Beck-Chevalley map is an isomorphism it suffices to check that the horizontal map $(C \times C)_{/(d_1, d_2)} \rightarrow C_{/d_1 \otimes d_2}$ is colimit-cofinal, thereby exhibiting the presheaf $F^* \mathbb{X}_{/d_1 \otimes d_2}$ as $\otimes_! F^* \mathbb{X}_{(d_1, d_2)}$. But this is precisely the condition of weak \otimes -disjunctivity. \square

Corollary 3.37. If $f : O \rightarrow P$ is a map of Lurie-operads, then the induced functor $\mathcal{P}\text{Env}(f) \otimes \mathcal{V} : \mathcal{P}\text{Env}(O) \otimes \mathcal{V} \rightarrow \mathcal{P}\text{Env}(P) \otimes \mathcal{V}$ is internally left adjoint in $\mathbf{CAlg}(\mathbf{Pr}_V)$.

Proof. Since the free module functor $- \otimes \mathcal{V} : \mathbf{CAlg}(\mathbf{Pr}) \rightarrow \mathbf{CAlg}(\mathbf{Pr}_V)$ is a 2-functor by Observation A.28, and thus preserves internal left adjoints, it suffices to consider the case $\mathcal{V} = \mathcal{S}$, which is part of Theorem 3.36. \square

Corollary 3.38. If O is a Lurie-operad, then $\mathcal{P}\text{Env } O \otimes \mathcal{V} \in \mathbf{CAlg}(\mathbf{Pr}_V)$ is \otimes -atomically generated by the colors $\text{col}(O)^\simeq$ via the Yoneda functor $\text{col } O \hookrightarrow \text{Env}(O) \subseteq \mathcal{P}\text{Env}(O)$.

Corollary 3.39. For $\mathcal{O} \in v\mathcal{O}\mathcal{O}_X(\mathcal{V})$ any \mathcal{V} -operad, its category $\mathcal{P}_V^\otimes(\mathcal{O}) = \mathbf{LMod}_{\mathcal{O}}(\mathcal{P}\text{Sym} X \otimes \mathcal{V}) \in \mathbf{CAlg}(\mathbf{Pr}_V)$ of operadic presheaves is \otimes -atomically generated by X via the Yoneda functor $\mathbb{X}_{\mathcal{O}} : X \rightarrow \mathcal{P}\text{Sym} X \otimes \mathcal{V} \rightarrow \mathcal{P}_V^\otimes(\mathcal{O})$.

Proof. We know from Corollary 3.38 that the category $\mathcal{P}\text{Sym} X \otimes \mathcal{V} \simeq \mathcal{P}\text{Env } \text{Triv}_X \otimes \mathcal{V}$ is \otimes -atomically generated by X . The free functor $\mathcal{P}\text{Sym} X \otimes \mathcal{V} \rightarrow \mathbf{LMod}_{\mathcal{O}}(\mathcal{P}\text{Sym} X \otimes \mathcal{V})$ is internally left adjoint as well. We are done since any module is a geometric realization of free modules. \square

4. MARKED ALGEBRAS

We have defined enriched operads as certain monads in $\mathbf{CAlg}(\mathbf{Pr}_V)$. Next, we give a description and characterization of the associated monadic 1-morphisms, leading to the notion of marked algebras.

Proposition 4.1. An adjunction $F : \mathcal{M} \leftrightarrows \mathcal{N} : G$ internal to $\mathbf{CAlg}(\mathbf{Pr}_V)$ is monadic iff it satisfies either of the following equivalent conditions:

- The underlying adjunction in $\mathbb{P}\mathbf{r}_V$ is monadic,
- The underlying adjunction in $\mathbb{P}\mathbf{r}$ is monadic,
- The underlying adjunction in $\widehat{\mathbb{C}\mathbf{at}}$ is monadic,
- F is colimit-dominant,
- G is conservative.

Proof. The forgetful 2-functors $\mathbf{CAlg}(\mathbb{P}\mathbf{r}_V) \rightarrow \mathbb{P}\mathbf{r}_V \rightarrow \mathbb{P}\mathbf{r} \rightarrow \widehat{\mathbb{C}\mathbf{at}}$ create Eilenberg-Moore objects by Proposition A.35, in particular they create the associated colimit cones, which involve monadic 1-morphisms. In $\widehat{\mathbb{C}\mathbf{at}}$ we may apply Barr-Beck-Lurie [Lur17, Thm. 4.7.3.5], where the colimit conditions are automatically satisfied so only conservativity of G remains. This is equivalent to colimit-dominance of F by [RZ25, Cor. 3.15]. \square

Given a monad T on an object c in a 2-category \mathbb{C} , we should always be able to recover T from the associated monadic adjunction

$$\text{free} : c \leftrightarrows \mathbf{LMod}_T(c) : \text{fgt}$$

as the composition $\text{fgt} \circ \text{free} : c \rightarrow c$, assuming the Eilenberg-Moore object $\mathbf{LMod}_T(c)$ exists. We can make this precise as follows:

Proposition 4.2 ([Hei17, Hau20, Sto25]). Let \mathbb{C} be a 2-category that admits Eilenberg-Moore objects, with underlying 1-category $\mathbb{C}^{\leq 1}$ and $c \in \mathbb{C}$. Then there exists a fully faithful left adjoint functor

$$\mathcal{EM} : \mathbf{Alg}(\mathbf{End}_{\mathbb{C}}(c)) \hookrightarrow (\mathbb{C}^{\leq 1})_{c/}$$

sending a monad T on c to its Eilenberg-Moore object $\mathbf{LMod}_T(c) \in \mathbb{C}$, equipped with the left adjoint $c \rightarrow \mathbf{LMod}_T(c)$ in the corresponding monadic adjunction.

Notation 4.3. For $X \in \mathbb{C}\mathbf{at}$, let $\mathbf{CAlg}(\mathbb{P}\mathbf{r}_V)_X/$ denote the pullback $\mathbf{CAlg}(\mathbb{P}\mathbf{r}_V) \times_{\widehat{\mathbb{C}\mathbf{at}}} \widehat{\mathbb{C}\mathbf{at}}_X/$. By the same argument as in [RZ25, Lem. 5.4] this is equivalent to $\mathbf{CAlg}(\mathbb{P}\mathbf{r}_V)_{\mathcal{P}\mathbf{Sym}X \otimes V/}$.

Corollary 4.4. The assignment $\mathcal{O} \mapsto (X \rightarrow \mathcal{P}_V^\otimes(\mathcal{O}))$ induces a fully faithful embedding

$$v\mathcal{O}p_X(V) = \mathbf{Alg}(\mathbf{End}_V^{L,\otimes}((\mathcal{P}(\mathbf{Sym}X) \otimes V))) \hookrightarrow \mathbf{CAlg}(\mathbb{P}\mathbf{r}_V)_X/$$

whose image consists those functors $\mathcal{Y} : X \rightarrow \mathcal{M}$ with $\mathcal{M} \in \mathbf{CAlg}(\mathbf{RMod}_V(\mathbf{Pr}))$ such that:

- The unique extension $Y : \mathcal{P}\mathbf{Sym}(X) \otimes V \rightarrow \mathcal{M}$ is an internally left adjoint 1-morphism in $\mathbf{CAlg}(\mathbf{RMod}_V(\mathbf{Pr}))$,
- The image of \mathcal{Y} generates \mathcal{M} under colimits, symmetric monoidal structure and V -tensoring.

Proof. Immediate from Proposition 4.2 if we can show the a morphism $F : \mathcal{P}(\mathbf{Sym}X) \otimes V \rightarrow \mathcal{M}$ in $\mathbf{CAlg}(\mathbb{P}\mathbf{r}_V)$ is a monadic left adjoint iff the associated functor $\mathcal{Y} : X \rightarrow \mathcal{M}$ by Notation 4.3 satisfies the given conditions. Using the characterization Proposition 4.1 it suffices to show that the second is equivalent to colimit-dominance of F . Evidently $\mathcal{P}(\mathbf{Sym}X) \otimes V$ is generated under colimits, V -tensoring and symmetric monoidal structure by the image of X , so this follows from the cancellation property of colimit-dominant morphisms. \square

Definition 4.5. We refer to objects $(X \rightarrow \mathcal{M}) \in \mathbf{CAlg}(\mathbb{P}\mathbf{r}_V)_X/$ in the image of the Eilenberg-Moore functor in ?? as *marked V -algebras*.

Definition 4.6. The *category of valent V -enriched operads* is defined as the pullback

$$v\mathcal{O}p(V) := \mathcal{S} \times_{\mathbf{CAlg}(\mathbb{P}\mathbf{r}_V)} \mathbf{Arr}^{\text{IL}, \text{cdom}}(\mathbf{CAlg}(\mathbb{P}\mathbf{r}_V))$$

of the source projection along the free functor $\mathcal{PSym}(-) \otimes \mathcal{V} : \mathcal{S} \rightarrow \mathbf{CAlg}(\mathbf{Pr}_{\mathcal{V}})$. We refer to its morphisms as *maps of \mathcal{V} -enriched operads*.

Denote by $col : v\mathcal{O}p(\mathcal{V}) \rightarrow \mathcal{S}$ the projection to the first component, and call $col(\mathcal{O})$ the *space of colors* of \mathcal{O} . Similarly, denote the target projection by $\mathcal{P}_{\mathcal{V}}^{\otimes} : v\mathcal{O}p(\mathcal{V}) \rightarrow \mathbf{CAlg}(\mathbf{Pr}_{\mathcal{V}})$ as it sends \mathcal{O} to its operadic enriched presheaf category.

Proposition 4.7. The space-of-colors functor $col : v\mathcal{O}p(\mathcal{V}) \rightarrow \mathcal{S}$ is a Cartesian and co-Cartesian fibration, where a map of \mathcal{V} -operads $F : \mathcal{O} \rightarrow \mathcal{P}$ encoded by a commutative square

$$\begin{array}{ccc} \mathcal{PSym}(col\mathcal{O}) \otimes \mathcal{V} & \longrightarrow & \mathcal{PSym}(col\mathcal{P}) \otimes \mathcal{V} \\ \downarrow & & \downarrow \\ \mathcal{P}_{\mathcal{V}}^{\otimes}(\mathcal{O}) & \longrightarrow & \mathcal{P}_{\mathcal{V}}^{\otimes}(\mathcal{P}) \end{array}$$

- is a *col*-Cartesian morphism iff $\mathcal{P}_{\mathcal{V}}^{\otimes}(\mathcal{O}) \rightarrow \mathcal{P}_{\mathcal{V}}^{\otimes}(\mathcal{P})$ is fully faithful,
- is a *col*-coCartesian morphism iff this is a pushout square.

The category $v\mathcal{O}p(\mathcal{V})$ of valent \mathcal{V} -operads admits limits and colimits, and col preserves them. Its fiber over a space X is equivalent to the category $v\mathcal{O}p_X(\mathcal{V}) := \mathbf{Alg}(\mathbf{sSeq}_X(\mathcal{V}))$ defined in Definition 2.1.

Proof. Completely analogous to [RZ25, Cor. 6.6], [RZ25, Obs. 6.8] and [RZ25, Cor. 6.9]. \square

Construction 4.8. Given a morphism $f : \mathcal{V} \rightarrow \mathcal{W}$ in $\mathbf{CAlg}(\mathbf{Pr})$, we define the *change-of-enrichment* functor

$$f_! : v\mathcal{O}p(\mathcal{V}) \simeq \mathcal{S} \times_{\mathbf{CAlg}(\mathbf{Pr}_{\mathcal{V}})} \mathbf{Arr}^{iL, cdom}(\mathbf{CAlg}(\mathbf{Pr}_{\mathcal{V}})) \rightarrow \mathcal{S} \times_{\mathbf{CAlg}(\mathbf{Pr}_{\mathcal{V}})} \mathbf{Arr}^{iL, cdom}(\mathbf{CAlg}(\mathbf{Pr}_{\mathcal{V}})) \simeq v\mathcal{O}p(\mathcal{W})$$

using the identity on \mathcal{S} , and the extension-of-scalars functor $f_{\text{ext}} : \mathbf{CAlg}(\mathbf{Pr}_{\mathcal{V}}) \rightarrow \mathbf{CAlg}(\mathbf{Pr}_{\mathcal{W}})$. Note that it preserves colimit-dominant functors by [RZ25, Cor. 3.18]⁴, and internal left adjoints as it is a 2-functor by Proposition A.31.

As a left adjoint 2-functor f_{ext} even preserves Eilenberg-Moore objects, so we learn that fiberwise it agrees with the construction of Construction 2.8. Further, one can show analogously to [RZ25, Cor. 6.19] that $f_!$ preserves colimits, so it admits a right adjoint $f_!^R$.

5. COMPARISON AND UNIVALENCE

Our next task will be to investigate how the above notion of \mathcal{S} -enriched operads compares to Lurie's category $\mathcal{O}p$ of ∞ -operads, defined as a subcategory of $\mathcal{C}\mathbf{at}_{/\mathbf{Fin}_*}$ (for distinction, we will refer to them as Lurie-operads). We prove that $v\mathcal{O}p(\mathcal{S})$ is equivalent to the category of *flagged operads*, and we will introduce a notion of univalence to obtain an equivalence with $\mathcal{O}p$.

Reminder 5.1. Both the inclusion $\mathbf{CAlg}(\mathcal{C}\mathbf{at}) \hookrightarrow \mathcal{O}p$ and the functor $(-) : \mathcal{O}p \rightarrow \mathcal{C}\mathbf{at}$ sending $P \mapsto P_{1+}^{\otimes}$ admit left adjoints, namely the symmetric monoidal envelope $\mathbf{Env} : \mathcal{O}p \rightarrow \mathbf{CAlg}(\mathcal{C}\mathbf{at})$ from [Lur17, Prop. 2.2.4.9] and the trivial operad $\mathbf{Triv}_{(-)} : \mathcal{C}\mathbf{at} \rightarrow \mathcal{O}p$ on a given category by [Lur17, Prop. 2.1.4.11]. Composition of left adjoints implies that $\mathbf{Sym} \simeq \mathbf{Env} \circ \mathbf{Triv}_{(-)}$.

Definition 5.2. A map of Lurie-operads $f : \mathcal{O} \rightarrow \mathcal{P}$ is called *surjective* if the underlying functor $f : \mathcal{O}_{1+} \rightarrow \mathcal{P}_{1+}$ on categories of colors is surjective. We denote by $\mathbf{Arr}^{\text{surj}}(\mathcal{O}p) \subseteq \mathbf{Arr}(\mathcal{O}p)$ the full subcategory on surjective maps of Lurie-operads.

⁴Alternatively, as a 2-functor that locally preserves geometric realizations it preserves monadic morphisms by Proposition A.35.

A map of Lurie-operads $f : O \rightarrow P$ is called *fully faithful* if it induces isomorphisms on multimorphism spaces, i.e. for any $n \in \mathbb{N}$ and $o_1, \dots, o_n, o \in O$ the induced map $\text{Mul}_O(o_1, \dots, o_n; o) \rightarrow \text{Mul}_P(f(o_1), \dots, f(o_n); f(o))$ is an isomorphism.

Observation 5.3. The classes of surjective and fully faithful maps of operads form a factorization system on \mathcal{Op} .

Lemma 5.4. If $f : O \rightarrow P$ in \mathcal{Op} is surjective, then the induced symmetric monoidal functor $\text{Env}(f) : \text{Env}(O) \rightarrow \text{Env}(P)$ is surjective, and $\mathcal{P}\text{Env}(f) \otimes \mathcal{V} : \mathcal{P}\text{Env}(O) \otimes \mathcal{V} \rightarrow \mathcal{P}\text{Env}(P) \otimes \mathcal{V}$ in $\text{CAlg}(\text{Pr}_{\mathcal{V}})$ is colimit-dominant.

Proof. The first claim is clear, since the image of $O \hookrightarrow \text{Env } O$ generates $\text{Env } O$ under the symmetric monoidal structure, which is preserved by $\text{Env}(f)$. Then $\mathcal{P}\text{Env}(f)$ is colimit-dominant since it hits all representables, and so is $\mathcal{P}\text{Env}(f) \otimes \mathcal{V}$ by [RZ25, Lem. 3.9]. \square

Definition 5.5. A *flagged operad* consists of a Lurie-operad O , a space X and a surjective map $X \rightarrow O_{1+}$ into the colors of O . We will also shortly denote it as $X \rightarrow O$.

The category \mathcal{FOp} of flagged operads is the full subcategory of the pullback $\text{Arr}(\mathcal{Cat}) \times_{\mathcal{Cat}} \mathcal{Op}$ along the target projection and $(-)_{1+}$, on those pairs $(X \rightarrow O_{1+}, O)$ where X is a space and the functor is surjective. The adjunction $\mathcal{Cat} \leftrightarrows \mathcal{Op}$ exhibits this as equivalent to the pullback $S \times_{\mathcal{Op}} \text{Arr}^{\text{surj}}(\mathcal{Op})$, c.f. [RZ25, Lem. A.7].

Construction 5.6. The *associated marked S -algebra* of a flagged operad $X \rightarrow O$ is the marked algebra $X \rightarrow O \rightarrow \mathcal{P}(\text{Env } O)$. Note that the image of this functor consists of \otimes -atomic objects by Corollary 3.38, and generates under colimits by Lemma 5.4. This construction assembles into a functor $\mathcal{FOp} \rightarrow v\mathcal{Op}(S)$ via the following map of pullback squares:

$$\begin{array}{ccccc}
 & v\mathcal{Op}(S) & \xrightarrow{\quad} & \text{Arr}^{\text{iL,cdom}}(\text{CAlg}(\text{Pr})) & \\
 \mathcal{FOp} \xrightarrow{\quad} & \downarrow & \nearrow \mathcal{P}\text{Env} & \downarrow \text{src} & \\
 & \text{Arr}^{\text{surj}}(\mathcal{Op}) & \xrightarrow{\quad} & & \\
 \downarrow & \downarrow & \downarrow \text{src} & \downarrow & \\
 S & \xrightarrow{\quad} & \text{CAlg}(\text{Pr}) & \xrightarrow{\quad} & \\
 \downarrow & \searrow \mathcal{P}\text{Env} & & & \\
 S & \xrightarrow{\quad} & \mathcal{Op} & \xrightarrow{\quad} &
 \end{array}$$

Definition 5.7. The *underlying flagged operad* of a marked \mathcal{V} -algebra $(\text{col}\mathcal{O} \rightarrow \mathcal{P}_{\mathcal{V}}^{\otimes}(\mathcal{O})) \in v\mathcal{Op}(\mathcal{V})$ is the surjective functor $\text{col}\mathcal{O} \rightarrow \text{Im}(\text{col}\mathcal{O} \rightarrow \mathcal{P}_{\mathcal{V}}^{\otimes}(\mathcal{O})) \in \mathcal{FOp}$, where we view the full image as an operad by virtue of it being a full subcategory of the symmetric monoidal category $\mathcal{P}_{\mathcal{V}}^{\otimes}(\mathcal{O})$.

Proposition 5.8. Let $\mathcal{V} \in \text{Alg}(\text{Pr})$ and let $\iota : S \rightarrow \mathcal{V}$ in $\text{Alg}(\text{Pr})$ denote its unit. The composite

$$\mathcal{FOp} \rightarrow v\mathcal{Op}(S) \xrightarrow{\iota!} v\mathcal{Op}(\mathcal{V})$$

admits a right adjoint, which sends a valent \mathcal{V} -enriched operad \mathcal{O} to its underlying flagged operad $\text{col}\mathcal{O} \rightarrow \text{Im}(\mathfrak{J}_{\mathcal{O}} : \text{col}\mathcal{O} \rightarrow \mathcal{P}_{\mathcal{V}}^{\otimes}(\mathcal{O}))$.

Proof. Recall from Construction 4.8 that the change-of-enrichment functor $\iota_! : v\mathcal{Op}(S) \rightarrow v\mathcal{Op}(\mathcal{V})$ sends a marked \mathcal{V} -algebra $X \rightarrow \mathcal{M}$ to $X \rightarrow \mathcal{M} \otimes_S \mathcal{V} \simeq \mathcal{M} \otimes \mathcal{V}$. For $X \rightarrow O$ a flagged

operad and $\wp : Y \rightarrow \mathcal{M}$ a marked \mathcal{V} -algebra, consider the following diagram:

$$\begin{array}{ccccc} \text{Map}_{\mathcal{F}\mathcal{O}p} \left(\begin{smallmatrix} X & Y \\ \downarrow & \downarrow \\ O & \text{Im}(\wp) \end{smallmatrix} \right) & \longrightarrow & \text{Map}_{\widehat{\mathcal{O}p}}(O, \text{Im}(\wp)) & \longrightarrow & \text{Map}_{\widehat{\mathcal{O}p}}(O, \mathcal{M}) \\ \downarrow & & \downarrow & & \downarrow \\ \text{Map}_{\mathcal{S}}(X, Y) & \longrightarrow & \text{Map}_{\widehat{\mathcal{O}p}}(X, \text{Im}(\wp)) & \longrightarrow & \text{Map}_{\widehat{\mathcal{O}p}}(X, \mathcal{M}) \end{array}$$

The left square is a pullback by definition of the mapping spaces of $\mathcal{F}\mathcal{C}\mathcal{A}\mathcal{T}$. Orthogonality of surjective and fully faithful maps of operads shows that the right square is a pullback, since $X \rightarrow O$ is surjective and $\text{Im}(\wp) \rightarrow \mathcal{M}$ fully faithful. Thus, the total square is a pullback and

$$\begin{aligned} \text{Map}_{\mathcal{F}\mathcal{O}p} \left(\begin{smallmatrix} X & Y \\ \downarrow & \downarrow \\ O & \text{Im}(\wp) \end{smallmatrix} \right) &\simeq \text{Map}_{\mathcal{S}}(X, Y) \times_{\text{Map}_{\widehat{\mathcal{O}p}}(X, \mathcal{M})} \text{Map}_{\widehat{\mathcal{O}p}}(O, \mathcal{M}) \simeq \\ &\simeq \text{Map}_{\mathcal{S}}(X, Y) \times_{\text{Map}_{\text{CAlg}(\text{Pr}_{\mathcal{V}})}(\mathcal{P}\text{Sym}X \otimes \mathcal{V}, \mathcal{M})} \text{Map}_{\text{CAlg}(\text{Pr}_{\mathcal{V}})}(\mathcal{P}\text{Env } O \otimes \mathcal{V}, \mathcal{M}) =: \text{Map}_{v\mathcal{O}p(\mathcal{V})} \left(\begin{smallmatrix} X & Y \\ \mathcal{P}\text{Env } O \otimes \mathcal{V} & \mathcal{M} \end{smallmatrix} \right). \end{aligned} \quad \square$$

Inspecting the unit and counit, we conclude that for $\mathcal{V} = \mathcal{S}$, this adjunction is in fact an equivalence:

Theorem 5.9. The associated-marked- \mathcal{S} -module functor $\mathcal{F}\mathcal{O}p \rightarrow v\mathcal{O}p(\mathcal{S})$ from Construction 5.6 is an equivalence.

Proof. Let $(X \rightarrow O) \in \mathcal{F}\mathcal{O}p$; our goal is to prove that both unit and counit of the adjunction from Proposition 5.8 are isomorphisms. The unit is the map of flagged operads $(X \rightarrow O) \rightarrow (X \rightarrow \text{Im}(\wp : O \rightarrow \mathcal{P}\text{Env } O))$. Since $O \rightarrow \text{Env}(O) \rightarrow \mathcal{P}\text{Env}(O)$ is fully faithful, this is an isomorphism.

Conversely, for $(\wp : Y \rightarrow \mathcal{M}) \in v\mathcal{O}p(\mathcal{S})$, the counit is the map of marked \mathcal{S} -algebras $(Y \rightarrow \text{Im}(\wp) \rightarrow \mathcal{P}\text{Env}(\text{Im}(\wp))) \rightarrow (Y \rightarrow \mathcal{M})$. Since $\text{Im}(\wp) \subseteq \mathcal{M}$ is a full suboperad, their multimorphism spaces agree, meaning the full inclusion $\text{Env}(\text{Im}(\wp)) \rightarrow \mathcal{M}$ is fully faithful. We deduce from Lemma 3.26 that the functor $\mathcal{P}\text{Env}(\text{Im}(\wp))$ is fully faithful. Also its image contains all representable presheaves, i.e. a set of \otimes -atomic generators, so since it is closed under tensor products, \mathcal{V} -tensoring and colimits it must agree with \mathcal{M} . \square

Definition 5.10. A \mathcal{V} -operad $\mathcal{O} \in v\mathcal{O}p(\mathcal{V})$, with associated marked \mathcal{V} -algebra $(\wp : \text{col}\mathcal{O} \rightarrow \mathcal{P}_{\mathcal{V}}^{\otimes}(\mathcal{O}))$, is called *univalent* if the functor \wp is a subcategory inclusion. In other words, it exhibits $\text{col}\mathcal{O} \simeq \text{Im}(\wp)^{\simeq}$. Denote by $\mathcal{O}p(\mathcal{V}) \subseteq v\mathcal{O}p(\mathcal{V})$ the full subcategory on univalent flagged categories.

Definition 5.11. The target projection $\text{trg} : \mathcal{F}\mathcal{O}p \rightarrow \mathcal{O}p$ admits a fully faithful right adjoint $O \mapsto (\underline{O}^{\simeq} \rightarrow O)$. We call a flagged operad $(X \rightarrow O)$ *univalent* if it lies in the image of this right adjoint, i.e. the induced map $X \rightarrow \underline{O}^{\simeq}$ is an isomorphism, or equivalently $X \rightarrow \underline{O}$ is a subcategory inclusion.

Corollary 5.12. The equivalence from Theorem 5.9 restricts to an equivalence $\mathcal{O}p(\mathcal{S}) \simeq \mathcal{O}p$, where we embed $\mathcal{O}p \subseteq \mathcal{F}\mathcal{O}p$ as in Definition 5.11.

Proof. Clearly if a marked algebra $(\wp : X \rightarrow \mathcal{M})$ is univalent, then so is its associated flagged operad $(X \rightarrow \text{Im}(\wp))$. Conversely, given a flagged operad $(X \rightarrow O)$ such that $X \rightarrow \underline{O}$ is a subcategory inclusion, then so is the composition $X \rightarrow \underline{O} \subseteq \text{Env}(O) \subseteq \mathcal{P}\text{Env}(O)$. \square

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