

GLOBAL FUKAYA CATEGORY AND QUANTUM NOVIKOV CONJECTURE I

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ABSTRACT. Using Floer-Fukaya theory for a monotone (M, ω) we construct a natural group homomorphism

$$\pi_{i-1} Ham(M, \omega) \rightarrow HH_{geom}^{2-i}(Fuk(M)),$$

where $HH_{geom}^*(C)$ is a certain geometric analogue of Hochschild cohomology groups associated to an A_∞ category C , which is defined here, using the theory of ∞ -categories of Joyal and Lurie, and the A_∞ -nerve. In part II the above map is shown to be non trivial by an explicit calculation. More fundamentally, using the recent theory of A_∞ -nerve for an A_∞ category, we associate to a Hamiltonian fibration $M \hookrightarrow P \rightarrow X$, a natural classifying map $cl(P) : X \rightarrow \mathcal{S}$, with the latter denoting the “space” of ∞ -categories, in the component of the A_∞ -nerve $NFuk(M)$ of the Fukaya category of the fiber. This gives in particular a new “quantum” invariant of a smooth manifold, and a “quantum” Novikov conjecture.

CONTENTS

1. Introduction	2
1.1. A functor from the category of smooth simplices of X	2
1.2. Hochschild and geometric Hochschild cohomology and homotopy groups of $Ham(M, \omega)$	3
1.3. Towards new invariants and quantum Novikov conjecture	4
1.4. Acknowledgements	5
2. Notations and conventions and large categories	5
3. Preliminaries	6
3.1. The category $Simp(X)$	6
3.2. Preliminaries on Riemann surfaces	6
4. A system of natural maps from the universal curve to Δ^n	9
4.1. Auxiliary data \mathcal{D}	15
5. The functor F	20
5.1. F on a point	20
5.2. F on higher dimensional simplices	22
5.3. Unital replacement of F	23
5.4. Naturality	24
5.5. Concordance classes of functors $F : Simp(X) \rightarrow A_\infty - Cat$	24
5.6. Remark	25
6. Global Fukaya category	25
6.1. The A_∞ -nerve	25
6.2. Global Fukaya category	26
6.3. Universal construction	26

6.4. Global Fukaya category and unital replacement	27
7. Algebraic considerations	27
7.1. Extending F to degenerate simplices	27
7.2. Colimit of F	28
Appendix A. Quasi-categories and Joyal model structure	30
A.1. Categorical equivalences, morphisms and equivalences	31
A.2. Inner fibrations	31
A.3. (co)-Cartesian fibrations	31
A.4. Semi-locality	32
A.5. A_∞ -nerve	33
References	35

1. INTRODUCTION

Smooth fibrations over a Lorentz 4-manifold with fiber a Calabi-Yau 6-fold are a model for the physical background in string theory. This suggests that there may be some string theory linked mathematical invariants of such a fibration. Indeed when the structure group of $M \hookrightarrow P \rightarrow X$ can be reduced to the group of Hamiltonian symplectomorphisms of M , in which case P is called a Hamiltonian fibration, there are a couple of basic invariants of such a fibration based on Floer-Gromov-Witten theory. For example the Seidel representation [15], and the related quantum characteristic classes of the author [14], related invariants are also proposed by Hutchings [5]. Even earlier there is work on parametric Gromov-Witten invariants of Hamiltonian fibrations by Le-Ono [6]. At the same time, Costello's theorem [1] on reconstruction of topological conformal field theories from Calabi-Yau A_∞ categories suggested that the above invariants must have a similar reconstruction principle.

For a given a Hamiltonian fibration P as above, the A_∞ Fukaya categories of the fibers, fit into a “family”, then our basic idea is that associated to a Hamiltonian fibration there should be a classifying map from X into an appropriate “classifying” space of A_∞ categories, from which the other invariants can be reconstructed, via a version of Toen's derived Morita theory, [18]. We say more on this in Section 1.2.

This note will be mostly self contained, as we will explain many (especially algebraic) concepts used.

1.1. A functor from the category of smooth simplices of X . Given P as above, and a choice of analytic perturbation data, to each smooth simplex $\Sigma : \Delta^n \rightarrow X$, we associate an A_∞ category $F(\Sigma)$. The principal step in this is the construction of natural maps, satisfying various axioms, from the universal curves over $\{\overline{\mathcal{R}}_d\}$, into the standard topological simplices Δ^n , where $\overline{\mathcal{R}}_d$ is the moduli spaces of Riemann surfaces which are topologically disks with $d + 1$ punctures on the boundary. The use and indeed discovery of these maps, appears to be new. This is then extended to functor

$$F : \text{Simp}(X) \rightarrow A_\infty - \text{Cat}^{\text{unit}},$$

from the category of smooth non-degenerate simplices of X into the category of small unital \mathbb{Z}_2 -graded A_∞ categories over \mathbb{Q} , with morphisms strict embeddings, which are moreover quasi-equivalences. Let X_\bullet denotes the smooth singular set of

X . We shall see that F canonically extends as

$$F : \Delta/X_{\bullet} \rightarrow A_{\infty} - \text{Cat}^{unit},$$

with Δ/X_{\bullet} the category of all smooth simplices of X .

We then use the above and the A_{∞} nerve functor

$$N : A_{\infty} - \text{Cat} \rightarrow s\text{Set}$$

to obtain:

Theorem 1.1. *After a choice of auxiliary perturbation data \mathcal{D} , there is a natural ∞ -category $Fuk_{\infty}(P, \mathcal{D}) = \text{colim}_{\Delta/X_{\bullet}} NF$, and a (co)-Cartesian fibration*

$$NFuk(M) \hookrightarrow Fuk_{\infty}(P, \mathcal{D}) \rightarrow X_{\bullet},$$

whose equivalence class depends only on the Hamiltonian isomorphism class of P .

The functor N is an analogue for A_{∞} categories of the classical nerve construction, and is originally due to Lurie [8]. It was then clarified in the A_{∞} context by Tanaka [7] and Faonte [3]. Using this we get using Lurie's straightening theorem for such fibrations:

Theorem 1.2. *For (M, ω) a monotone symplectic manifold, a Hamiltonian fibration $M \hookrightarrow P \rightarrow X$ together with some choice of auxiliary perturbation data \mathcal{D} induces a classifying map*

$$cl(P) : X \rightarrow (\mathcal{S}, NFuk(M)),$$

where $(\mathcal{S}, NFuk(M))$ denotes the space of ∞ -categories, in the component of $NFuk(M)$. (See Section A.1) The homotopy class of $cl(P)$ is independent of the choice of \mathcal{D} .

1.2. Hochschild and geometric Hochschild cohomology and homotopy groups of $Ham(M, \omega)$. For an A_{∞} category C we define

$$HH_{geom}^{2-i}(C) = \pi_i(\mathcal{S}, NC).$$

We will justify the name a bit further below. Using the construction above for the universal bundle over $BHam(M, \omega)$, we shall show:

Theorem 1.3. *For (M, ω) monotone, there is a natural group homomorphism*

$$(1.1) \quad \pi_{i-1} Ham(M, \omega) \rightarrow HH_{geom}^{2-i}(Fuk(M)).$$

$HH^*(Fuk(M))$ is known to be isomorphic to $QH^*(M)$ for a wide class of cases, and so the above, when $i > 2$ has the same formal form as the author's quantum characteristic classes [14], provided there is a connection between $HH^*(Fuk(M))$ and $HH_{geom}^*(Fuk(M))$. This would be the most basic form of the "reconstruction" that was mentioned before. Such a connection is described further below.

Remark 1.4. *Note that the case of $i = 2$ which "corresponds to" the Seidel homomorphism [15], is a bit special since the correspondence in Theorem 1.6 works differently.*

In Part II we calculate with Hamiltonian S^2 fibrations over S^4 to get:

Theorem 1.5. *The map*

$$\mathbb{Z} \rightarrow HH_{geom}^{-2}(Fuk(S^2)),$$

determined by (1.1) is an injection.

1.2.1. *Geometric Hochschild cohomology and Toen's derived Morita theory.* A small disclaimer. $HH_{geom}^*(C)$ is just a name for an object whose construction is immediate from work of Joyal and Lurie, and might possibly appear elsewhere. We claim no originality for its construction. What may however be interesting is the connection to symplectic geometry that we discover in these papers, and perhaps $HH_{geom}^*(C)$ deserves a more careful study on its own.

Let us then describe the connection of $HH_{geom}^*(C)$ with Hochschild cohomology via Toen's derived Morita theory. Our goal is not to be detailed, as this is only of background interest at the moment. First we recall:

Theorem 1.6. [18, Corollary 8.4] *For a small dg-category C , (with cohomological grading conventions) there are natural isomorphisms*

$$(1.2) \quad \pi_i(|dg - Cat, C|) \simeq HH^{2-i}(C), i > 2,$$

$$(1.3) \quad \pi_2(|dg - Cat, C|) \simeq HH^0(C)^*,$$

with $HH^0(C)^*$ denoting the multiplicative group of invertible elements, $(dg - Cat, C)$ denoting the C component of the subcategory of $dg - Cat$ with morphisms quasi-equivalences, and with $|\cdot|$ the geometric realization or the classical nerve functor.

On the other hand the nerve functor N naturally induces a homomorphism,

$$N_* : \pi_i(|dg - Cat, C|) \rightarrow \pi_i(|\infty - Cat, NC|) \simeq \pi_i(\mathcal{S}, NC),$$

when C is \mathbb{Z} -graded rational and (pre)-triangulated there are folklore theorems of Lurie (personal communication) to the effect that this is an isomorphism. Thus in this case, for $i > 2$

$$HH^{2-i}(C) = \pi_i(\mathcal{S}, NC) = HH_{geom}^{2-i}(C),$$

by our definition. This should extend without issues to \mathbb{Z} -graded rational (pre)-triangulated A_∞ categories. Beyond that it seems nothing is known.

1.3. Towards new invariants and quantum Novikov conjecture. By the above discussion we automatically obtain a new invariant of a Hamiltonian fibration $M \hookrightarrow P \rightarrow X$ as the homotopy class of its classifying map to \mathcal{S} .

It may difficult to get intrinsic motivation for Hamiltonian fibrations for a reader outside of symplectic geometry, as a start one may read [4]. However as one particular case we can take the projectivization of the complexified tangent bundle of a smooth manifold, which in particular has the structure of a smooth Hamiltonian fibration. In this way we also get a new invariant of a general smooth manifold X , given by the homotopy class of the classifying map

$$cl(X^r) : X \rightarrow (\mathcal{S}, NFuk(\mathbb{CP}^{r-1}))$$

of its projectivized complexified tangent bundle. It should be remarked that a priori the homotopy class of $cl(X)$ depends not just on the tangent bundle but also on the smooth structure of the tangent bundle. However it readily follows from the universal construction in Section 6.3, (Theorem 6.3) that only the topological type of the tangent bundle is detected by the homotopy class of $[cl(X)]$. Recall that Pontryagin classes of a smooth manifold are defined as Chern classes of its complexified tangent bundle. Novikov has shown that rational Pontryagin classes are topologically invariant. We may then ask the following:

Question 1.7. *Suppose that $f : X \rightarrow Y$ is a homeomorphism of smooth manifolds. Is $cl(X)$ homotopic to $cl(Y) \circ f$? What if f is a homotopy equivalence? This latter question maybe considered to be “quantum analogue” of the Novikov conjecture.*

Why may one expect the answer of yes? One substantial reason is that like the rational Pontryagin classes of X the invariant $[cl(X)]$ is based on a rational algebraic theory, (we passed through rational Fukaya categories). But of course the answer of “no” to any part of the above question is also very interesting. As will likely be apparent our construction should be highly amenable to combinatorial methods, in particular we plan give in the future a combinatorial construction of the classifying map $cl(X)$ for a combinatorial manifold, which would immediately give combinatorial invariance of $[cl(X)]$.

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2. NOTATIONS AND CONVENTIONS AND LARGE CATEGORIES

We shall use terms ∞ -category and quasi-category interchangeably, usually the term quasi-category will be used when we want to do something concrete.

We use diagrammatic order for composition of morphisms in the Fukaya category, and quasi-categories so $f \circ g$ means

$$\cdot \xrightarrow{f} \cdot \xrightarrow{g} \cdot,$$

as reversing order for composition there becomes rather confusing at least to the author, since morphisms are identified with edges of simplices. Elsewhere we use the opposite Leibnitz notation, although this is somewhat contradictory in practice things should be clear from context. By simplex and notation Δ^n we will interchangeably mean the topological n -simplex and the standard representable n -simplex as a simplicial set, for the latter we will also write Δ_\bullet^n , for clarity, when both objects may appers at once.

Given a category C the over-category of an object $c \in C$ is denoted by C/c . We say that a morphism in C is *over* c exactly if it is a morphism in the over-category of c .

Given an A_∞ category by the nerve we always mean the A_∞ nerve.

Some of our quasi-categories are “large” with proper classes of simplices instead of sets. The standard formal treatment of this is to work with Grothendieck universes. We shall not make this explicit, as this not a real obstruction for any particular argument that we make. For reference one paper that does make this kind of thing explicit is [18] also previously cited.

3. PRELIMINARIES

3.1. The category $Simp(X)$. Although it will be a long while before we have to really get into simplicial sets, as they will play such a big role let us introduce them early. A simplicial set S_\bullet is a functor $S_\bullet : \Delta^{op} \rightarrow Set$, where Δ^{op} denotes the opposite category to Δ : the category of combinatorial simplices, whose objects are non negative integers and morphisms non-strictly increasing maps

$$\{0 < 1 < \dots < n\} \rightarrow \{0 < 1 < \dots < m\}.$$

We will denote the objects of Δ^{op} by $[n]$. Later on it will convenient to think of objects $[n]$ as totally ordered finite sets and so talk about membership.

If Δ_\bullet^n denotes the standard n -simplex: $\Delta_\bullet^n = hom_\Delta(\cdot, [n])$, we have the category of simplices over S_\bullet , Δ/S_\bullet whose set of objects is the set of natural transformations $Nat(\Delta_\bullet^n, S_\bullet)$ and morphisms commutative diagrams,

$$\begin{array}{ccc} \Delta_\bullet^n & \longrightarrow & \Delta_\bullet^m \\ & \searrow & \downarrow \\ & & S_\bullet \end{array}$$

with natural transformation $\Delta_\bullet^n \rightarrow \Delta_\bullet^m$ induced by maps $[n] \rightarrow [m]$.

Let X be a smooth manifold, and let Δ^n denote the standard topological n -simplex. Denote by X_\bullet the total smooth singular set of X . In other words this is the simplicial set defined by: $X_\bullet([n]) = C^\infty(\Delta^n, X)$: the set of all smooth maps $\Delta^n \rightarrow X$. Consider the category of simplices over X_\bullet , Δ/X_\bullet . This is clearly the same as the category with objects smooth maps $\Delta^n \rightarrow X$, and morphisms commutative diagrams,

$$\begin{array}{ccc} \Delta^n & \longrightarrow & \Delta^m \\ & \searrow & \downarrow \\ & & X \end{array}$$

with Δ^n denoting the standard topological n -simplex and top horizontal arrow a simplicial map. We say that $\Sigma : \Delta^n \rightarrow X$ is *non-degenerate* if it does not fit into a commutative diagram

$$\begin{array}{ccc} \Delta^n & \longrightarrow & \Delta^m \\ & \searrow \Sigma & \downarrow \\ & & X \end{array}$$

with $m < n$. To simplify notation we will denote by $Simp(X)$ the subcategory of Δ/X_\bullet , obtained from Δ/X_\bullet by restricting to non-degenerate objects and to monomorphisms in Δ/X_\bullet for morphisms.

3.2. Preliminaries on Riemann surfaces. Let S be a nodal Riemann surface, with $d + 1$ cyclically ordered punctures in other words specific kind of ends $\{e_i\}_{i \in I}$ corresponding to the removed marked points on the boundary, and nodal points $\{n_j\}_{j \in J}$, each of which (smooth) components $S_{j,\pm}$ having the n_j node in common, are topologically disks with punctures

$$\{e_i\}_{i \in I_{j,\pm}} \subset \{e_i\}_{i \in I},$$



FIGURE 1.

on the boundary. If we remove the nodes from S , then $S_{j,\pm}^\circ = S_{j,\pm} - n_j$ have an additional puncture $n_{j,\pm}$ called the node ends. We distinguish one puncture of S as the root, and use the cyclic ordering to order the punctures, $0, \dots, d$ going clockwise, starting from the root.

It is sometimes convenient to depict such Riemann surfaces as stable, rooted semi-infinite trees, embedded in the plane, where stable means the valency of each vertex is at least 3. We do this by assigning a vertex to each smooth component as above, a half infinite edge to each marked point, and an edge to each nodal point, as depicted in figure 1.

There is also a linear ordering on the smooth components of S , or vertices by order of composition. The component with the root semi-infinite edge e_0 will be called the root vertex denoted by ω . In terms of the associated tree for the surface, we have a pre-order on vertices given by the distance to the root vertex, (by giving each edge length 1). Arranging the tree in the plane while preserving the cyclic ordering so that the root semi-infinite edge 0 is pointing downward, we first ask that all the vertices that are equidistant to the root vertex, are on horizontal lines in the plane. And then order vertices equidistant to root vertex from left to right, which then induces an order on all vertices. We shall denote by α the furthestmost component from ω , by β the next furthestmost component, etc. (Pretending that we can't run out of letters.) For $d \geq 2$ let $\bar{S}_d \rightarrow \bar{\mathcal{R}}_d$ denote the universal family of the Riemann surfaces S , as above. (Note that Seidel [16] calls our $\bar{\mathcal{R}}_d$ by $\bar{\mathcal{R}}_{d+1}$.) We shall also denote by $\bar{S}_d^\circ \rightarrow \bar{\mathcal{R}}_d$, this universal family where the nodal points of the surfaces have been removed.

Notation 3.1. We denote by $S_{d,r}$ and sometimes just by S_r the fiber over $r \in \bar{\mathcal{R}}_d$.

As part of the data at the e_i end, $i \neq 0$, we shall ask for a holomorphic diffeomorphism (having the name of the removed point or the end)

$$e_i : [0, 1] \times (0, \infty) \rightarrow S,$$

we shall call this *positive strip chart*. And at the e_0 end a holomorphic diffeomorphism

$$e_0 : [0, 1] \times (-\infty, 0) \rightarrow S,$$

called *negative strip chart*. Let e_i^t denote the restriction of e_i to $[0, 1] \times [t, \infty)$, or to $[0, 1] \times (-\infty, t]$ if $i = 0$.

Let $S_{j,\pm}^\circ, S_{j,\pm}$ be as above. We further specify the \pm distinction so that $S_{j,-} > S_{j,+}$ with respect to the linear order above. And we ask for a similar pair of holomorphic diffeomorphisms

$$(3.1) \quad e_{j,-} : [0, 1] \times (-\infty, 0) \rightarrow S_{j,-}^\circ,$$

$$(3.2) \quad e_{j,+} : [0, 1] \times (0, \infty) \rightarrow S_{j,+}^\circ$$

at the $n_{j,\pm}$ ends. Likewise $e_{j,\pm}^t$ will denote the restrictions of the above diffeomorphisms to $[0, 1] \times [t, \infty)$, respectively to $[0, 1] \times (-\infty, t]$. The data of such a diffeomorphism shall be called *strip end structure*, and the particular diffeomorphisms *strip charts*, or *strip coordinates*.

Choose r -smooth families $\{e_{i,r}\}$, $\{e_{j,\pm,r}\}$ of strip charts, for the entire universal family $\overline{\mathcal{S}}_d \rightarrow \overline{\mathcal{R}}_d$, (note that further on r is suppressed). These choices have to be consistent with gluing in the natural sense as explained in [16, Section 9g]. We shall keep track of this choice of strip charts only implicitly.

Although we won't use the following in any truly essential way, for instructional purposes it will be helpful to remind the reader of the following metric characterization of the moduli space $\overline{\mathcal{R}}_d$. The family $\{\mathcal{S}_{d,r}\}$, determines (in a suitable sense universal) family $\{\text{Met}_r\}$ of constant curvature -1 metrics on the disk with $d+1$ marked points, (in the Gromov-Hausdorff compactification of the space of such metrics). The complex structure on \mathcal{S}_r is just the conformal structure induced by Met_r . This is of course classical, to see all this use Schwartz reflection to "double" each \mathcal{S}_r to a possibly nodal Riemann surface without boundary \mathcal{D}_r with $d+1$ punctures. This determines an embedding of $\overline{\mathcal{R}}_d$ into the Grothendieck-Knudsen moduli space $\overline{\mathcal{M}}_{0,d+1}$ of Riemann surfaces which are topologically S^2 with $d+1$ points removed. As $d > 2$, for r in the interior of $\overline{\mathcal{R}}_d$, by uniformization theorem \mathcal{D}_r is a quotient of the disk by a subgroup of $PSL(2, \mathbb{R})$, which must also preserve the hyperbolic metric. Therefore \mathcal{S}_r inherits a hyperbolic metric.

The metric point of view gives an illuminating description of the compactification $\overline{\mathcal{M}}_{0,d+1}$, for $d \geq 2$: starting with some \mathcal{D}_r and taking r to a boundary stratum some fixed collection of embedded, closed, disjoint geodesics on \mathcal{D}_r will have their length shrunk to zero. Each boundary stratum is completely determined by such a collection of geodesics.

The reverse of this degeneration process is the so called gluing construction, (see for example [16]), which takes a surface in $\overline{\mathcal{R}}_d$ and produces a surface with one less node. This gluing is determined by gluing parameters which we parametrize by $[0, 1)$, assigned to each node. For us 0 means don't glue, and 1 is meant to correspond to "sufficiently small" value of gluing parameter used in actual gluing, so this is a reparametrizations of parameters used in actual gluing. We shall write $d_{\alpha,\beta}$ for the parameter used in the gluing of components α, β , and likewise with other components.

The gluing map for parameters in $[0, 1)$ determines an open neighborhood of the boundary we call the gluing normal neighborhood and "sufficiently small" means that if two gluing neighborhoods of a codimension l face of \mathcal{R}_d intersect then the intersection is contained in the gluing normal neighborhood of some codimension $l+1$ face.

The gluing construction also induces a kind of thick thin decomposition of the surface, with thin parts conformally identified with $[0, 1] \times [0, l]$ for l determined by the corresponding gluing parameter, or in case of ends with $[0, 1] \times [0, \mathbb{R}]$. This decomposition is not intrinsic, as it depends in particular on the choice of the family of strip charts. However, instructively these gluing parameters can be thought of as lengths of geodesic segments, for example m_α, m_β in figure 2, and the thin parts are in principle closely related to thin parts of thick-thin decomposition in hyperbolic geometry.

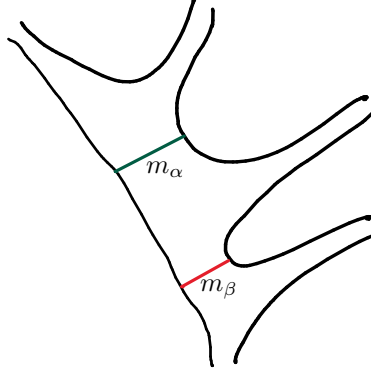


FIGURE 2. This diagram is only schematic. The embedding into the plane is not mean to be holomorphic or isometric for the natural hyperbolic structure on the surface.

4. A SYSTEM OF NATURAL MAPS FROM THE UNIVERSAL CURVE TO Δ^n

We explain here a remarkable connection between the universal curve over $\overline{\mathcal{R}}_d$ and the standard topological simplex Δ^n , which will be used in our construction, but may be of independent interest.

Let $\Pi(\Delta^n)$ be the category whose objects are vertices of Δ^n and morphisms simplicial maps $m : [0, 1] \rightarrow \Delta^n$ (possibly constant). As there is a unique edge between a pair of vertices, the composition maps in $\Pi(\Delta^n)$ are obvious. We say that (m_1, \dots, m_d) is a *composable chain* of morphisms $m_i \in \text{hom}(\Pi(\Delta^n))$ if $t(m_{i-1}) = s(m_i)$, for $s(m)$ the source object and $t(m)$ the target object. For future use let $m_{i-1,i}$ denote the unique morphism from the $i-1$ vertex to the i vertex in Δ^n .

We now construct a “natural” system of maps $u(m_1, \dots, m_d, n) : \overline{\mathcal{S}}_d^\circ \rightarrow \Delta^n$, $d \geq 2$ for each composable chain (m_1, \dots, m_d) which in particular will satisfy the following properties.

- Let $u(m_1, \dots, m_d, n, r)$ denote the restriction of $u(m_1, \dots, m_d, n)$ to \mathcal{S}_r , and let m_0 denote the composition $m_1 \cdot \dots \cdot m_d$, in $\Pi(\Delta^n)$ then in the strip coordinates $e_k^1 : [0, 1] \times [1, \infty] \rightarrow \mathcal{S}_r$ at the k 'th end $u(m_1, \dots, m_d, n, r)$ has the form of the projection to $[0, 1]$ composed with m_k .
- For $1 \leq k \leq d$, the component of the boundary of the surface between e_{k-1}, e_k ends is mapped to $s(m_k)$, and the component of the boundary of the surface between e_d and e_0 is mapped by $u(m_1, \dots, m_d, n, r)$ to $t(m_d)$ for each $r \in \overline{\mathcal{R}}_d$.

Let us explain naturality. First denote by $\mathcal{T}(m_1, \dots, m_d, n)$ the space of maps satisfying the pair of properties above. We have the natural gluing map

$$(4.1) \quad St_i : \overline{\mathcal{R}}_{s_1} \times \overline{\mathcal{R}}_{s_2} \times [0, 1) \rightarrow \overline{\mathcal{R}}_{s_1+s_2-1},$$

whose value on (r, r', τ) is given by gluing the surface \mathcal{S}_r at the root and $\mathcal{S}_{r'}$ at its i 'th marked point, with gluing parameter $\tau \in [0, 1)$, and then following with the classifying map to $\overline{\mathcal{R}}_{s_1+s_2-1}$. (When value of the gluing parameter is 0, this is the composition map in the Stasheff topological A_∞ operad).

Given an element $u \in \mathcal{T}(m_1, \dots, m_{s_1}, n)$ and an element

$$u' \in \mathcal{T}(m'_1, \dots, m'_{i-1}, m_1 \cdot \dots \cdot m_{s_1}, m'_{i+1}, \dots, m'_{s_2}),$$

the gluing construction naturally induces a map

$$u \star u'_0 : \bar{\mathcal{S}}_{s_1, s_2, 0}^\circ \rightarrow \Delta^n,$$

where

$$\bar{\mathcal{S}}_{s_1, s_2, 0}^\circ \rightarrow \bar{\mathcal{R}}_{s_1} \times \bar{\mathcal{R}}_{s_2} \times \{0\}$$

is the pullback of the family $\bar{\mathcal{S}}_d^\circ$ by St_i .

We can extend $u \star u'_0$ to a map

$$u \star u'_\epsilon : \bar{\mathcal{S}}_{s_1, s_2, \epsilon}^\circ \rightarrow \Delta^n,$$

with $\bar{\mathcal{S}}_{s_1, s_2, \epsilon}^\circ$ being the pullback of the family by St_i restricted over $\bar{\mathcal{R}}_{s_1} \times \bar{\mathcal{R}}_{s_2} \times [0, \epsilon]$. To do this we specify $u \star u'_\epsilon|_{\mathcal{S}_{r, r'}}$, for $\mathcal{S}_{r, r'}$ the fiber over $(r, r', t) \in \bar{\mathcal{R}}_{s_1} \times \bar{\mathcal{R}}_{s_2} \times [0, \epsilon]$, $t \neq 0$. Recall that the surface $\mathcal{S}_{r, r'}$ glued from $\mathcal{S}_r, \mathcal{S}_{r'}$ has a sub-domain denoted *thin* which has a determined conformal identification with a strip of the form $[0, 1] \times [-\tau, \tau]$, for some τ (dependent on t). $\mathcal{S}_{r, r'} - \text{thin}$ has 2 components, which can be holomorphically identified with regions $Reg_r \subset \mathcal{S}_r, Reg_{r'} \subset \mathcal{S}_{r'}$, so that Reg_r is identified with the complement of $[0, 1] \times [1, \infty)$ in \mathcal{S}_r , for the strip coordinates on the root end. And likewise, so that $Reg_{r'}$ is identified with the complement of $[0, 1] \times [1, \infty)$ in $\mathcal{S}_{r'}$, for the strip coordinates on the i 'th end. We then define $u \star u'_\epsilon$ to coincide with u, u' on Reg_r respectively $Reg_{r'}$, while on *thin* in the coordinates $[0, 1] \times [-\tau, \tau]$ $u \star u'_\epsilon$ is the map given by the projection $[0, 1] \times [-\tau, \tau] \rightarrow [0, 1]$ followed by the map m_i .

Let $C_s(\Delta^n)$ denote the set of composable chains (m_1, \dots, m_s) of length s , in $\Pi(\Delta^n)$. A system of maps: \mathcal{U} , is an element of:

$$(4.2) \quad \prod_{n \in \mathbb{N}_{\geq 0}} \prod_{s \in \mathbb{N}_{> 2}} \prod_{(m_1, \dots, m_s) \in C_s(\Delta^n)} \mathcal{T}(m_1, \dots, m_s, n).$$

Given a system \mathcal{U} its projection onto $(n, s, (m_1, \dots, m_s))$ component will be denoted by $u(m_1, \dots, m_s, n)$.

Definition 4.1. We say that \mathcal{U} is **natural** if it satisfies the following axioms:

(1) For all s_1, s_2 the map

$$(4.3) \quad u(m_1, \dots, m_{s_1}, n) \star u(m'_1, \dots, m'_{i-1}, m_1 \cdot \dots \cdot m_{s_1}, m'_{i+1}, \dots, m'_{s_2}, n)_\epsilon,$$

coincides with the composition

$$(4.4) \quad \bar{\mathcal{S}}_{s_1, s_2, \epsilon} \xrightarrow{St_i} \bar{\mathcal{S}}_{s_1 + s_2 - 1} \xrightarrow{u(m'_1, \dots, m'_{i-1}, m_1, \dots, m_{s_1}, m'_{i+1}, \dots, m'_{s_2}, n)} \Delta^n,$$

for a sufficiently small $\epsilon > 0$.

(2) Given a face map $f : \Delta^{n-1} \rightarrow \Delta^n$,

$$f \circ u(m_1, \dots, m_s, n-1) = u(f(m_1), \dots, f(m_s), n).$$

(3) The final axiom actually follows by the previous axioms, we leave this as an exercise to the reader, and just postulate it as an axiom. Let N denote a normal ϵ -neighborhood of the boundary $\partial \bar{\mathcal{R}}_d$, and $S_0^{d-3} \subset N$ be an embedded sphere, homotopic to the boundary $\partial \bar{\mathcal{R}}_d$ but not intersecting it. And let R_0^{d-2} be the region in $\bar{\mathcal{R}}_d$ bounded by S_0^{d-3} . Let $\mathcal{S}_r - \text{ends}$ denote the compact Riemann surface with boundary obtained from \mathcal{S}_r by removing

the ends, that is images of the charts $e_i|_{[0,1] \times (0,\infty)}$. For $r \notin \partial \overline{\mathcal{R}}_d$ we may identify $\mathcal{S}_r - \text{ends} / \partial(\mathcal{S}_r - \text{ends})$ with S^2 in a homotopy natural in r way. For $\{m_i\} \in \Pi(\Delta^n)$ let $D(m_1, \dots, m_s)$ denote the minimal dimension of a subsimplex of Δ^n which contains the edges corresponding to the $\{m_i\}$. Suppose that $D(m_1, \dots, m_d) = d$ then $u(m_1, \dots, m_d, d)$ induces a map

$$(4.5) \quad \tilde{u}^\epsilon : (R_0^{d-2} / S_0^{d-3} \simeq S^{d-2}) \times S^2 \rightarrow \Delta^d / \partial \Delta^d \simeq S^d,$$

which by previous axioms factors through $S^{d-2} \wedge S^2 \simeq S^d$, and we ask that \tilde{u}^ϵ is a homological degree 1 map for all sufficiently small ϵ .

Proposition 4.2. *A natural system \mathcal{U} exists, and is unique up to homotopy (through natural systems).*

For the sake of exposition and to build the reader's intuition, we shall give an explicit construction of the maps that would satisfy the axioms, in the case of $\overline{\mathcal{R}}_4$ and Δ^4 , and which can then be extended without issues (but at the cost of much complexity) to the general case. We then give a not explicitly constructive topological proof in complete generality. As the explicit construction is not used by us, the reader may also skip ahead.

Fix a geometric model for $\overline{\mathcal{R}}_d$, for example as the Stasheff associahedra. When $d = 4$ this is a pentagon. Recall that to each corner of $\overline{\mathcal{R}}_4$ we have a uniquely associated nodal Riemann surface, with 3 components, and 5 marked points, one of which is called the root. Recall that we label the root component by ω , the next component by β and the component furthest from root by α . (With respect to the linear ordering described earlier.) Denote by M_α the collection of marked points, different from the root e_0 , on α , likewise with β, ω . This determines a subcomposable sequence $\text{mor}(S_\alpha)$ of a composable sequence (m_1, \dots, m_4) , and likewise with β, ω , (note that M_ω, M_β could be empty).

Let r be in the normal gluing neighborhood of some corner, corresponding to parameters non-zero parameters $d_{\alpha,\beta}, d_{\beta,\omega}$. We now construct a map

$$f_r = f_r(m_1, \dots, m_4) : [0, 4] \times [0, 1] \rightarrow \Delta^4$$

In what follows by *concatenation* of a collection of paths we mean their product in the Moore path category of Δ^4 , the notation for composition will be assumed to be diagrammatic. That is the category with objects points, and morphisms from x_0 to x_1 continuous paths $[0, T] \rightarrow \Delta^4$, $T > 0$, between x_0, x_1 , with composition the natural concatenation of paths. For a morphism m in $\Pi(\Delta^4)$, let $s(m)$, and $t(m)$ denote the source respectively target of m . Let $H^m : \Delta^4 \times [0, 1] \rightarrow \Delta^4$ denote the natural deformation retraction of Δ^4 onto the edge determined by $s(m), t(m)$, with time 1 map the orthogonal linear projection onto this edge (for the standard metric on Δ^n). Set $H_\tau^m = H^m|_{\Delta^n \times \{\tau\}}$. Next for a general piece-wise linear path $p : [0, T] \rightarrow \Delta^4$, with end points $s(m), t(m)$ set $D(p, \tau)$, $\tau \in [0, 1]$ to be the concatenation of the homotopy $H_\tau^m \circ p$, $\tau \in [0, 1]$ from p to a path $\tilde{p} : [0, T] \rightarrow \Delta^4$, with image in the edge determined by m , with the homotopy G_τ of paths with fixed end points, from \tilde{p} to the map $\tilde{m} : [0, T] \rightarrow \Delta^4$ linearly parametrizing the edge determined by m . This second homotopy G_τ , $\tau \in [0, 1]$ can be chosen in a way that depends only on \tilde{p} . This can be done explicitly, using piece-wise linearity of p .

The map f_τ^t from the $y = t$ slice $[0, 4] \times \{t\}$, is constructed as follows. Set $I_\alpha = (1 - d_{\alpha,\beta})/2$, set $f_{\alpha,r}$ to be the concatenation of the morphisms in $\text{mor}(M_\alpha)$, that is if $M_\alpha = (m_1^\alpha, \dots, m_k^\alpha)$ then $f_{\alpha,r} = m_1^\alpha \cdot \dots \cdot m_k^\alpha$. Then for $t \in [0, I_\alpha]$, set

$f_{\alpha,r}^t = D(f_{\alpha,r}, 2t)$. Then set f_r^t to be the concatenation of morphisms in $\text{mor}(M_\beta)$, $\text{mor}(M_\gamma)$ and of $f_{\alpha,r}^t$, in that order, although note that the order of the morphisms in the concatenation is uniquely determined by the end point conditions, this holds further on as well.

Next set $I_\beta = I_\alpha + (1 - I_\alpha)(1 - d_\beta)/2$. If α and β components have a nodal point in common we set $f_{\beta,r} : [0, 4] \times \{t\} \rightarrow \Delta^4$ to be the concatenation of $f_{\alpha,r}^{I_\alpha}$ with morphisms in $\text{mor}(M_\beta)$, and for $t \in [I_\alpha, I_\beta]$ we set

$$f_{\beta,r}^t = D(f_{\beta,r}, \frac{2(t - I_\alpha)}{1 - I_\alpha}).$$

And then for $t \in [I_\alpha, I_\beta]$ set f_r^t to be the concatenation of morphisms in $\text{mor}(M_\omega)$ and of $f_{\beta,r}^t$.

Finally set $f_{\omega,r}$ to be the concatenation of $f_{\beta,r}^{I_\beta}$ with morphisms in $\text{mor}(M_\omega)$, and for $t \in [I_\beta, 1]$ set

$$f_r^t = D(f_{\omega,r}, \frac{2(t - I_\beta)}{1 - I_\beta}).$$

When α has a nodal point in common with the ω component, set $f_{\beta,r}$ to be the concatenation of morphisms in $\text{mor}(M_\beta)$, and for $t \in [I_\alpha, I_\beta]$ set

$$f_{\beta,r}^t = D(f_{\beta,r}, \frac{2(t - I_\alpha)}{1 - I_\alpha}).$$

Then for $t \in [I_\alpha, I_\beta]$ set f_r^t to be the concatenation of morphisms $f_r^{I_\alpha}$ and $f_{\beta,r}^t$, and $\text{mor}(M_\omega)$ (although $\text{mor}(M_\omega)$ in this particular case is empty, we add this so that the degenerate case $M_\alpha = \emptyset$, $M_\beta = \emptyset$ makes sense, see the discussion below). Finally for $t \in [I_\beta, 1]$ set $f_r^t = D(f_r^{I_\beta}, \frac{2(t - I_\beta)}{1 - I_\beta})$.

When $r \in \overline{\mathcal{R}}_4$ is in the gluing neighborhood of a face but not of a corner the construction of $f_r : [0, 4] \times [0, 1] \rightarrow \Delta^4$ is similar, in fact we can think of it as a special case of the above by setting $d_\beta = 1$, $M_\beta = \emptyset$. When $r \in \overline{\mathcal{R}}_4$ is not in the gluing neighborhood of the boundary, we can also think of this as a special case of the above with $M_\alpha = \emptyset$, $M_\beta = \emptyset$, $d_\alpha = 1$, $d_\beta = 1$ in the above construction.

4.0.1. Flattening $\{f_r\}$. We now slightly rig our family of maps. Fix an embedding $i : \overline{\mathcal{R}}_4 \rightarrow \overline{\mathcal{R}}'_4 \simeq \overline{\mathcal{R}}_4$, so that the boundary of embedded domain is contained in the ϵ -normal neighborhood of the boundary of target $\overline{\mathcal{R}}'_4$, where $0 < \epsilon < 1$, and set $g : \overline{\mathcal{R}}'_4 \rightarrow \overline{\mathcal{R}}'_4$ to be the smooth retraction onto $i(\overline{\mathcal{R}}_4)$. The family of maps $\{f_r\}$, $r \in \overline{\mathcal{R}}_4$ then gives us a family $\{f_{i^{-1}g(r)}\}$, $r \in \overline{\mathcal{R}}'_4$. Let us identify $\overline{\mathcal{R}}'_4$ back with $\overline{\mathcal{R}}_4$ and rename $\{f_{i^{-1}g(r)}\}$ by $\{f_r\}$. This procedure is just meant to flatten out the family of maps $\{f_r\}$ near the boundary of $\overline{\mathcal{R}}_4$, so that axiom (1) will be satisfied.

4.0.2. Retracting \mathcal{S}_r onto $[0, 4] \times [0, 1]$. We now construct a smooth r -family of maps $\text{ret}_r : \mathcal{S}_r \rightarrow [0, 4] \times [0, 1]$, $r \in \mathcal{R}_4$, suitably compatible with the maps $f_r : [0, 4] \times [0, 1] \rightarrow \Delta^4$. In figure 3 (a), (b), (c) represent cases where (c): r is not within gluing normal neighborhood of boundary, (b): r is in a gluing neighborhood of a side but not a corner, and (a): r is within gluing neighborhood of a corner, (we picked a particular corner and side for these diagrams). The color shading will be explained in a moment. In each case (a), (b), (c) we first color shade $[0, 4] \times [0, 1]$ as in figure 4, the green region is the domain of $f_{\alpha,r}^t$ contained in $[0, 4] \times [0, I_\alpha]$, in the blue regions the map f_r is vertically constant, the red region is the domain of $f_{\beta,r}^t$

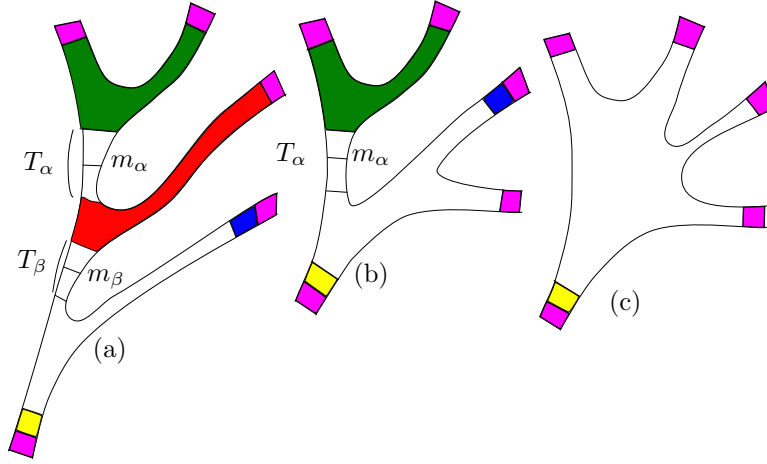


FIGURE 3. The uncolored enclosed regions labeled T_α , T_β surrounding segments m_α , m_β are “thin”.

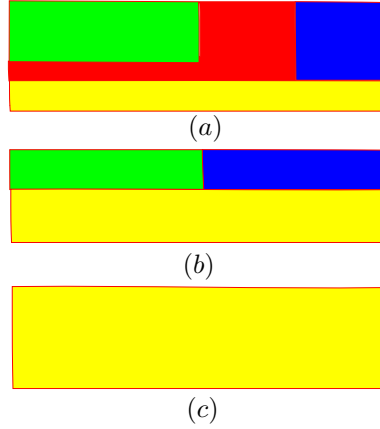


FIGURE 4. Diagram for S_d . Solid black border is boundary, while dashed red lines are open ends. The connection $\mathcal{A}(r, \{L_i\})$ preserves Lagrangians L_i over boundary components labeled L_i .

contained in $[0, 4] \times [I_\alpha, I_\beta]$ and yellow region is the rest of the domain of f_r . The maps $ret_r : \mathcal{S}_r \rightarrow [0, 4] \times [0, 1]$ are defined for each r by taking color shaded areas to color shaded areas, so that the following holds.

- (1) The ends e_0, e_1, \dots, e_4 of \mathcal{S}_r , colored in purple, are identified in strip coordinate charts as $[1, \infty] \times [0, 1]$ and in these coordinates ret_r is the composition of the projection $[1, \infty] \times [0, 1] \rightarrow [0, 1]$ with the map to the boundary of $[0, 4] \times [0, 1]$, so that composition with f_r parametrizes the morphism $m_0 = m_1 \cdot \dots \cdot m_4, m_1, \dots, m_4$ in $\Pi(\Delta^4)$ respectively.
- (2) The boundary of \mathcal{S}_r goes either to the boundary of $[0, 4] \times [0, 1]$ or to the vertical boundary lines between colored regions.

- (3) The unshaded “thin” regions labeled T_α, T_β come from the gluing construction and are identified with $[0, 1] \times [0, l_\alpha]$, respectively $[0, 1] \times [0, l_\beta]$. In these coordinates ret_r on T_α, T_β is the projection to $[0, 1]$ composed with a diffeomorphism onto the lower edge of green, respectively red region, (linear in respective natural coordinates).
- (4) The unshaded part of S_r is collapsed onto the horizontal line bounding yellow region of $[0, 4] \times [0, 1]$.
- (5) Blue shaded regions are identified in strip charts $[0, \infty] \times [0, 1] \rightarrow \Sigma_r$, as $[0, 1] \times [0, 1]$, and are mapped to the corresponding blue regions in $[0, 4] \times [0, 1]$.

(The above prescription naturally extends to the boundary $\overline{\mathcal{R}}_4$.)

Proof of 4.2. To construct our maps $u(m_1, \dots, m_s, n)$, we will proceed by induction. When $n = 0$, there is nothing to do, as we have unique maps for all $s \geq 2$. Now suppose we have chosen maps $u(m_1, \dots, m_s, n)$, for all $s \geq 2$ and all $n \leq N$ and every composable chain (m_1, \dots, m_s) , so that naturality axioms are satisfied. We need to construct maps $u(m_1, \dots, m_s, n)$ for all $s \geq 2$, $n \leq N+1$ and all composable chains (m_1, \dots, m_s) so that naturality is satisfied.

Let $D(m_1, \dots, m_s)$ denote the least dimension of a subsimplex of Δ^{N+1} , which contains the edges corresponding to $\{m_i\}$. Note that the Axiom 2 and the maps $\{u(m_1, \dots, m_s, n)\}_{n \leq N, s \geq 2}$ uniquely determine

$$(4.6) \quad u(m_1, \dots, m_s, N+1),$$

for all $(s, (m_1, \dots, m_s))$, with $D(m_1, \dots, m_s) \leq N$. We need an extension in the case $D(m_1, \dots, m_s) = N+1$, and in this case s is at least $N+1$. Suppose first that $s > N+1$. In this case, gluing and the maps (4.6), naturally determine maps

$$(4.7) \quad u(m_1, \dots, m_s, N+1) : Sub_s \rightarrow \Delta^{N+1},$$

where Sub_s is a subfibration of $\overline{\mathcal{S}}_s^\circ \rightarrow \overline{\mathcal{R}}_s$, over a part of the boundary of $\overline{\mathcal{R}}_s$. Specifically, for some (not all) $r \in \partial \overline{\mathcal{R}}_s$ the corresponding fiber \mathcal{S}_r is a nodal surface with ends e_0, \dots, e_s , with smooth components \mathcal{S}_r^j having non-nodal ends a subsequence of $\{e_{s_k}\}$ of e_0, \dots, e_s s.t. the corresponding subsequence $\{m_{s_k}\}$ is contained in $\Pi(\Delta^N)$. Then Sub_s is the restriction over the subspace of $\partial \overline{\mathcal{R}}_s$ corresponding to such r 's. Since we have a constraint only over part of the boundary of $\overline{\mathcal{R}}_s$, there are no topological obstructions, and we can extend $u(m_1, \dots, m_s, N+1)$ arbitrarily over all of $\overline{\mathcal{S}}_s^\circ$, so that $u(m_1, \dots, m_s, N+1) \in \mathcal{T}(m_1, \dots, m_s, N+1)$ and so that naturality is satisfied.

The next and interesting case is when $s = N+1$, and we assume $N+1 > 3$ as the cases $N+1 = 2, 3$ are special and follow upon simple reflection. In this case, gluing and the maps from the induction hypothesis, naturally determine a map

$$(4.8) \quad u = u(m_1, \dots, m_{N+1}, N+1) : \overline{\mathcal{S}}_{N+1}^\circ|_{\partial \overline{\mathcal{R}}_{N+1}} \rightarrow \Delta^{N+1},$$

that is we are now determined over the entire boundary, which by the condition $N+1 > 3$ is connected. Extend u to a normal ϵ -neighborhood U of the boundary $\overline{\mathcal{R}}_{N+1}$, so that Axiom (1) of naturality is satisfied. We need an extension over $\overline{\mathcal{R}}_{N+1}$ so that the final axiom of naturality is satisfied. Let $S_0^{N-2} \subset U$, be an embedded sphere in U not intersecting $\overline{\mathcal{R}}_{N+1}$. Then u induces a map of a pair

$$(4.9) \quad B : (S_0^{N-2} \times D^2, S_0^{N-2} \times \partial D^2) \rightarrow (\partial \Delta^{N+1} \simeq S^N, loop),$$

where $loop$ is a topologically embedded S^1 in $\partial\Delta^{N+1}$, which is the image of the loop $(m_1 \cdot \dots \cdot m_{N+1} \cdot m_{s(m_1), t(m_{N+1})}^{-1})$, where \cdot is concatenation of paths and the order of composition is diagrammatic. This is constructed analogously to the map (4.5).

Lemma 4.3. *The map B is homological degree 1.*

Proof. Note first that since $loop$ has codimension higher than 1, the meaning of homological degree is unambiguous as the pair $(S^N, loop)$ has a well defined fundamental class, by the homology long exact sequence for a pair. Moreover approximating B by a smooth map we may compute the homological degree via the smooth degree, (denote the approximation still by B). That is let f be a N -face of Δ^{N+1} , and $p \in f$ a regular image point of B in the interior. The homological degree of B is then the count of elements of $B^{-1}(p)$ with signs given by whether dB_k , $k \in B^{-1}(p)$ is orientation preserving or reversing. Suppose without loss of generality that the vertices of f are $0, \dots, N$. Then the face f is covered by the image of

$$(4.10) \quad u(m_1, \dots, m_N, N+1) \star u(m_1 \cdot \dots \cdot m_N, m_{N+1}, N+1)_\epsilon|_{\widetilde{face}},$$

where ϵ is as in the first naturality axiom, m_i are the unique morphisms from the vertex i to $i+1$, and where

$$\widetilde{face} = \overline{\mathcal{S}}_{N+1}^\circ|_{face}$$

while $face$ is the image of

$$St_2 : (R_0^{N-2} \subset \overline{\mathcal{R}}_N) \times \mathcal{R}_2 \times \{\epsilon'\} \rightarrow \mathcal{R}_{N+1},$$

for R_0^{N-2} as in the naturality axioms, and $0 < \epsilon' < \epsilon$. As the degree of B is clearly independent of the choice of S_0^{N-2} we may assume that St_2 above is an embedding into S_0^{N-2} . Moreover we may assume that S_0^{N-2} is covered by embeddings St_2 as above, corresponding to the various faces of Δ^{N+1} , except for a region $R \subset S_0^{N-2}$, so that B maps $R \times D^2$ into the union of $N-1$ faces of Δ^{N+1} .

By construction the smooth degree of $B|_{face \times D^2}$ is the smooth degree of (4.10). But by the naturality axioms for the maps

$$u(m_1, \dots, m_{s'}, n)_{n \leq N, s' \geq 2}$$

(especially the last one) (4.10) is smooth degree one. And again by naturality and the assumption on the form of S_0^{N-2} above nothing else in $S_0^{N-2} \times D^2$ can hit p by the map B . It follows that B is smooth degree one and so is homological degree one. \square

Consequently we may find an extension of u over the whole $\overline{\mathcal{S}}_{N+1}^\circ$ so that,

$$u \in \mathcal{T}(m_1, \dots, m_{N+1}, N+1)$$

and so that the last and consequently all naturality axioms are satisfied. To prove uniqueness up to homotopy we may use an analogous induction argument as above. Let us leave this to the reader. \square

4.1. Auxiliary data \mathcal{D} . Let

$$M \hookrightarrow P \xrightarrow{\pi} X$$

be a Hamiltonian fiber bundle with model fiber (M^{2n}, ω) , which we shall assume here to be a closed, monotone:

$$\omega = \text{const} \cdot 2c_1(TM),$$

$const \geq 0$, symplectic manifold. The data \mathcal{D} consists of the following.

We say that a Lagrangian submanifold $L \subset M$ is *monotone* if the homomorphisms given by symplectic area and Maslov class

$$[\omega] : H_2(M, L) \rightarrow \mathbb{R}, \quad \mu : H_2(M, L) \rightarrow \mathbb{Z}$$

are proportional:

$$[\omega] = const \cdot \mu.$$

Let L be a spin, monotone Lagrangian submanifold L in $P_x = x^*P \simeq M$ with minimal Maslov number at least 2, so that the inclusion map $\pi_1(L) \rightarrow \pi_1(M)$ vanishes. For an almost complex structure j compactible with ω , let $\mathcal{M}(L, j)$ denote the moduli space of Maslov number 2 j -holomorphic discs, with one marked point on the boundary, with boundary of the disk going to L . It is well known, c.f. [17] that for a generic such j , $\mathcal{M}(L, j)$ is regular, that is transversely cut out n -dimensional manifold, and is compact. Then we have an evaluation map at the marked point:

$$ev : \mathcal{M}(L, j) \rightarrow L,$$

and we define $\omega(L) \in \mathbb{Z}$ as the degree of ev .

For an $x : pt \rightarrow X$ by an *object* we shall mean a spin monotone Lagrangian submanifold L in $P_x = x^*P \simeq M$ with minimal Maslov number at least 2, so that the inclusion map $\pi_1(L) \rightarrow \pi_1(M)$ vanishes. Given a non-degenerate simplex $\Sigma : \Delta^n \rightarrow X$, let $m : [0, 1] \rightarrow \Delta^n$ be the edge between i, j corners of Δ^n and set $\bar{m} = \Sigma \circ m$. The data \mathcal{D} gives for every pair of objects $L_0 \subset P_{x_i}, L_1 \subset P_{x_j}$, (including $i = j$) with $\omega(L_0) = \omega(L_1)$ a Hamiltonian connection $\mathcal{A}(L_0, L_1) = \mathcal{A}(L_0, L_1, \bar{m})$ on \bar{m}^*P . Denote by $\mathcal{A}(L_0, L_1)(L_0)$ the image in P_{x_j} of the $\mathcal{A}(L_0, L_1)$ -parallel transport of L_0 . Then we require that $\mathcal{A}(L_0, L_1)(L_0)$ is transverse to L_1 . We also fix for every L_0, L_1 and m as above a family $\{j_t\} = \{j_t(L_0, L_1, \bar{m})\}$ of fiber-wise almost complex structures on \bar{m}^*P so that:

- For each t , Chern number 1 j_t holomorphic spheres in $P_{\bar{m}(t)} \subset \bar{m}^*P$ do not intersect any of the elements of $S(L_0, L_1) \simeq L_i$, which denotes the space of $\mathcal{A}(L_0, L_1)$ -flat sections, with boundary on L_0, L_1 . Here $P_{\bar{m}(t)}$ denotes the fiber of \bar{m}^*P over $\bar{m}(t)$.
- The moduli spaces $\mathcal{M}(L_0, j_0), \mathcal{M}(L_1, j_1)$ are regular, and the evaluation map

$$ev_0 : \mathcal{M}(L_0, j_0) \rightarrow L,$$

does not intersect the set of starting positions of elements of $S(L_0, L_1)$. Likewise the evaluation map

$$ev_1 : \mathcal{M}(L_1, j_1) \rightarrow L,$$

does not intersect the set of ending positions of elements of $S(L_0, L_1)$.

Such a family $\{j_t\}$ is easily seen to exist, cf [17]. Let us call such a $\{j_t(L_0, L_1, \bar{m})\}$ *admissible with respect to $\mathcal{A}(L_0, L_1)$* . Next \mathcal{D} makes a choice of a natural system \mathcal{U} as previously described. Finally \mathcal{D} specifies a certain natural system of Hamiltonian connections, and a system of complex structures, which we now describe. This is a bit notationally complicated but ultimately trivial, given the main geometric input of the system \mathcal{U} . It is just a system of compatible perturbations in the sense of Seidel, but relative to \mathcal{U} .

Given a composable chain (m_1, \dots, m_d) and a map

$$u(m_1, \dots, m_d, n) : \bar{\mathcal{S}}_d^\circ \rightarrow \Delta^n, \text{ which is part of a natural system } \mathcal{U},$$

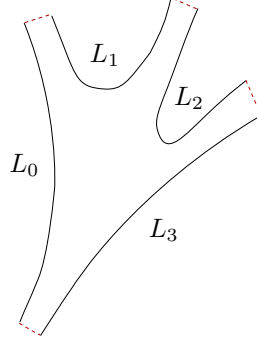


FIGURE 5. The connection \mathcal{A} preserves Lagrangians L_i over boundary components labeled L_i .

we have an induced fibration

$$M \hookrightarrow \tilde{S}(m_1, \dots, m_d, \Sigma^n) \rightarrow \bar{S}_d^\circ$$

by pulling back $M \hookrightarrow P \rightarrow X$ first by $\Sigma^n : \Delta^n \rightarrow X$ and then by $u(m_1, \dots, m_d, n)$. Denote the iterated fiber of $\tilde{S}(m_1, \dots, m_d, \Sigma^n)$ over $r \in \bar{\mathcal{R}}_d$ by $\tilde{S}(m_1, \dots, m_d, \Sigma^n, r)$, or simply by \tilde{S}_r where there can be no confusion (this is an M fibration, smooth over components of \mathcal{S}_r). Suppose now that we have chosen labels by objects L_i for the sides between punctures $i, i+1$, $0 \leq i \leq d-1$ and L_d for the side between $d, 0$ of \mathcal{S}_r , $r \in \bar{\mathcal{R}}_d$, where $L_i \in \text{Fuk}(P_{s(m_{i+1})})$ for $0 \leq i \leq d-1$, and $L_d \in \text{Fuk}(P_{t(m_d)})$, such that $\omega(L_i) = \omega(L_d)$ for all i . Extend the labeling naturally to $\bar{\mathcal{R}}_d$, so as to be compatible with gluing.

Definition 4.4. We say that a Hamiltonian connection \mathcal{A} on $\tilde{S}(m_1, \dots, m_d, \Sigma^n, r) \rightarrow \mathcal{S}_r$ is **admissible** with respect to L_0, \dots, L_d if:

- Parallel transport by \mathcal{A} over the boundary component labeled L_i preserves Lagrangian L_i . This condition is unambiguous as by construction over this boundary component $\tilde{S}(m_1, \dots, m_d, n, r)$ is identified with $P_{s(m_{i+1})}$, $0 \leq i \leq d-1$, or $P_{t(m_d)}$ in case of L_d .
- At the i 'th end of \mathcal{S}_r , in strip chart $e_i^1 : [0, 1] \times [1, \infty] \rightarrow \mathcal{S}_r$, \mathcal{A} has the form of the canonical, flat, \mathbb{R} -translation invariant extension of the connection $\mathcal{A}(L_{i-1}, L_i, \bar{m}_i)$.

Note that the above determines a Lagrangian sub-fibration of

$$\tilde{S}(m_1, \dots, m_d, \Sigma^n, r) \rightarrow \mathcal{S}_r$$

over the boundary of \mathcal{S}_r , whose fiber over an element of the boundary component labeled L_i is L_i . As we mention above this is unambiguous. We name this sub-fibration by

$$(4.11) \quad \mathcal{L}(\mathcal{U}, L_0, \dots, L_d, r).$$

Denote by $\mathcal{T}(L_0, \dots, L_s, \Sigma^n, r)$ the space of Hamiltonian connections on

$$\tilde{S}(m_1, \dots, m_s, \Sigma^n, r)$$

admissible with respect to L_0, \dots, L_s . Given an element \mathcal{A} in $\mathcal{T}(L_0, \dots, L_{s_1}, \Sigma^n, r)$ and an element

$$\mathcal{A}' \in \mathcal{T}(L'_0, \dots, L'_{i-2}, L_0, L_{s_1}, L'_{i+2}, \dots, L'_{s_2}, \Sigma^n, r'),$$

we have an induced element:

$$St_i(\mathcal{A}, \mathcal{A}', \epsilon) \in \mathcal{T}(L'_0, \dots, L'_{i-2}, L_0, \dots, L_{s_1}, L'_{i+2}, \dots, L'_{s_2}, \Sigma^n, St_i(r, r', \epsilon)).$$

Such a pair $\mathcal{A}, \mathcal{A}'$ will be called *composable*.

Definition 4.5. We say that a family $\{j_z\}$ of fiber-wise, $\{\omega_z\}$ -compatible, almost complex structures on $\tilde{\mathcal{S}}(m_1, \dots, m_d, \Sigma^n, r) \rightarrow \mathcal{S}_r$ is **admissible** with respect to L_0, \dots, L_d if:

- At the i 'th end of \mathcal{S}_r , in the coordinate chart $[0, 1] \times [1, \infty] \times \overline{m}^*P \rightarrow \tilde{\mathcal{S}}(m_1, \dots, m_d, \Sigma^n, r)$, induced by the strip chart e_i^1 , the family $\{j_z\}$ coincides with the canonical \mathbb{R} -translation invariant extension of the family $\{j_t(L_{i-1}, L_i, \overline{m}_i)\}$.

Denote by $\mathcal{J}(L_0, \dots, L_s, \Sigma^n, r)$ the space of families of fiberwise almost complex structures $\{j_z\}$ on

$$\tilde{\mathcal{S}}(m_1, \dots, m_s, \Sigma^n, r)$$

admissible with respect to L_0, \dots, L_s . Given an element $\{j_z\}$ in $\mathcal{J}(L_0, \dots, L_{s_1}, \Sigma^n, r)$ and an element

$$\{j'_z\} \in \mathcal{J}(L'_0, \dots, L'_{i-2}, L_0, L_{s_1}, L'_{i+2}, \dots, L'_{s_2}, \Sigma^n, r'),$$

we have an induced element:

$$St_i(\{j_z\}, \{j'_z\}, \epsilon) \in \mathcal{J}(L'_0, \dots, L'_{i-2}, L_0, \dots, L_{s_1}, L'_{i+2}, \dots, L'_{s_2}, \Sigma^n, St_i(r, r', \epsilon)).$$

Such a pair $\{j_z\}, \{j'_z\}$ will be called *composable*.

Definition 4.6. A **system** \mathcal{F} : of connections, and almost complex structures compatible with a system of maps \mathcal{U} is an element of

$$\prod_{r \in \overline{\mathcal{R}}_s} \prod_{\{(L_0, \dots, L_s) | L_i \in F(\Sigma^n)\}} \prod_{s \geq 2} \prod_{\Sigma} \mathcal{T}(L_0, \dots, L_s, \Sigma, r) \times \mathcal{J}(L_0, \dots, L_s, \Sigma, r)$$

The projection of \mathcal{F} onto the $(r, (L_0, \dots, L_s), \Sigma^n, s)$ component will be denoted by $\mathcal{F}(L_0, \dots, L_s, \Sigma^n, r)$. And for shorthand we say that a Hamiltonian connection $\mathcal{A} \in \mathcal{F}$ if it is of the form $pr_1 \mathcal{F}(L_0, \dots, L_s, \Sigma^n, r)$, for pr_i , $i = 1, 2$ the pair of projections of $\mathcal{F}(L_0, \dots, L_s, \Sigma^n, r)$ onto the component of $\mathcal{T}(L_0, \dots, L_s, \Sigma^n, r)$, respectively $\mathcal{J}(L_0, \dots, L_s, \Sigma, r)$.

We say that \mathcal{F} is **natural** if:

- For a composable pair $\mathcal{A}, \mathcal{A}' \in \mathcal{F}$ as above the connection $St_i(\mathcal{A}, \mathcal{A}', \epsilon)$ coincides with

$$pr_1 \mathcal{F}(L'_0, \dots, L'_{i-2}, L_0, \dots, L_{s_1}, L'_{i+2}, \dots, L'_{s_2}, \Sigma^n, St_i(r, r', \epsilon)),$$

for $\epsilon = 0$.

- The pair of connections above also agree for a sufficiently small non zero ϵ on the “thin part” of $\mathcal{S}_{St_i(r, r', \epsilon)}$.

- Given a face map $f : \Delta^{n-1} \rightarrow \Delta^n$, by the third naturality property of maps $u(m_1, \dots, m_d, n)$ determined by \mathcal{U} there is bundle map

$$p : \tilde{\mathcal{S}}(m_1, \dots, m_d, \Sigma_f^{n-1} = \Sigma^n \circ f, r) \rightarrow \tilde{\mathcal{S}}(f(m_1), \dots, f(m_d), \Sigma^n, r),$$

and we ask that the pullback map takes $pr_1 \mathcal{F}(p(L_0), \dots, p(L_d), \Sigma^n, r)$ to

$$pr_1 \mathcal{F}(L_0, \dots, L_d, \Sigma_f^{n-1}, r).$$

- There are analogous conditions on the families of almost complex structures $pr_2 \mathcal{F}(L_0, \dots, L_s, \Sigma^n, r)$, which we shall not state to keep things a bit simpler.

Notation 4.7. We shall sometimes write by abuse of notation $\mathcal{F}(\dots)$, for either the connection $pr_1 \mathcal{F}(\dots)$, or the family of almost complex structures $pr_2 \mathcal{F}(\dots)$, since there usually can be no confusion.

Lemma 4.8. A natural system \mathcal{F} compatible with a given \mathcal{U} exists, and is unique up to homotopy.

Proof. When $n = 0$, this is the classical Fukaya category case, and the proof of existence of a natural system is given in [16], in the language of what Seidel calls compatible system of perturbations. Now suppose that we have chosen an element

$$\mathcal{F} \in \prod_{r \in \overline{\mathcal{R}}_s} \prod_{\{(L_0, \dots, L_s) | L_i \in F(\Sigma^n)\}} \prod_{s \geq 2} \prod_{\{\Sigma^n | n \leq N\}} \mathcal{T}(L_0, \dots, L_s, \Sigma^n, r) \times \mathcal{J}(L_0, \dots, L_s, \Sigma^n, r)$$

satisfying naturality. We need to extend this to an element of

$$\prod_{r \in \overline{\mathcal{R}}_s} \prod_{\{(L_0, \dots, L_s) | L_i \in F(\Sigma^n)\}} \prod_{s \geq 2} \prod_{\{\Sigma^n | n \leq N+1\}} \mathcal{T}(L_0, \dots, L_s, \Sigma^n, r) \times \mathcal{J}(L_0, \dots, L_s, \Sigma^n, r),$$

also satisfying naturality.

Denote by $D(L_0, \dots, L_s)$ the least dimension of a subsimplex of Δ^{N+1} , with vertices determined by the $\{L_i\}$. Naturality and \mathcal{F} uniquely determine an element of

$$(4.12) \quad \mathcal{F} \in \prod_{r \in \overline{\mathcal{R}}_s} \prod_{\{(L_0, \dots, L_s) | N \geq D(L_0, \dots, L_s)\}} \prod_{s \geq 2} \prod_{\{\Sigma^n | n \leq N+1\}} \mathcal{T}(L_0, \dots, L_s, \Sigma^n, r) \times \mathcal{J}(L_0, \dots, L_s, \Sigma^n, r).$$

We need to extend to the case $N+1 = D(L_0, \dots, L_s)$, and so that naturality is satisfied. Then for all (L_0, \dots, L_s) with $D(L_0, \dots, L_s) = N+1$, naturality and (4.12) determine

$$\mathcal{F}(L_0, \dots, L_s, \Sigma^{N+1}, r)$$

for r in part or all of the boundary of $\overline{\mathcal{R}}_s$, see the discussion following (4.7). Now $\{\mathcal{T}(L_0, \dots, L_s, \Sigma^n, r) \times \mathcal{J}(L_0, \dots, L_s, \Sigma^n, r)\}$ forms a Serre fibration over $\overline{\mathcal{R}}_s$, with non-empty contractible fibers. Thus, we may simply pick an extension of the family

$$\{\mathcal{F}(L_0, \dots, L_s, \Sigma^{N+1}, r)\}$$

for all $r \in \overline{\mathcal{R}}_s$, such that the second naturality condition is satisfied. The other naturality conditions then follow by construction. Uniqueness up to homotopy is obvious from the argument above. \square

5. THE FUNCTOR F

Let $A_\infty\text{-Cat}$ denote the category of small \mathbb{Z}_2 graded A_∞ categories over \mathbb{Q} , with morphisms fully-faithful embeddings as defined below, which are in addition quasi-equivalences. Note that we can work in principle over a completely general ring, but this can give no extra information in our setting (without additional geometric input) as in the construction of the Fukaya categories any torsion is annihilated.

Definition 5.1. *We say that an A_∞ functor F is a **fully-faithful embedding**, if F has vanishing higher order components, is injective on objects and the first component map on hom spaces is an isomorphism of chain complexes. In other words F above is just an identification map of a full A_∞ sub-category.*

We now describe construction of the functor

$$F_{P,\mathcal{D}} : \text{Simp}(X) \rightarrow A_\infty\text{-Cat},$$

associated to a Hamiltonian fibration P , and the chosen auxiliary data \mathcal{D} , described in the previous section. In what follows we usually drop \mathcal{D} and P from notation.

5.1. F on a point. For $x : pt \rightarrow X$, $F(x)$ is defined to be the Fukaya A_∞ category $\text{Fuk}(x^*P)$, whose objects are the objects as described in Section 4.1. For a pair L_0, L_1 of objects, with $\omega(L_0) \neq \omega(L_1)$ we set $\text{hom}(L_0, L_1) = 0$, (to avoid dealing with curved A_∞ categories), otherwise we set

$$\text{hom}(L_0, L_1) = CF(L_0, L_1, \mathcal{D}),$$

where the latter is a \mathbb{Z}_2 graded Floer chain complex over \mathbb{Q} , which is defined as follows.

Let $\mathcal{A}(L_0, L_1)$ be the Hamiltonian connection on $P_x \times [0, 1]$, determined by the chosen data \mathcal{D} , and likewise let $j(L_0, L_1)$ be the family of almost complex structures determined by \mathcal{D} . Then $CF(L_0, L_1, \mathcal{D})$ is generated over \mathbb{Q} by $\mathcal{A}(L_0, L_1)$ -flat sections γ of $P_x \times [0, 1]$, with boundary on the pair of Lagrangians $L_0 \subset P_x \times \{0\}$, $L_1 \subset P_x \times \{1\}$. The \mathbb{Z}_2 grading is given by the sign of the corresponding intersection of $\mathcal{A}(L_0, L_1)(L_0)$ with L_1 .

5.1.1. Differential on $CF(L_0, L_1, \mathcal{D})$. For γ_0, γ_1 geometric generators of

$$CF(L_0, L_1, \mathcal{D}),$$

let $\overline{\mathcal{M}}(\gamma_0; \gamma_1)$ denote the natural Floer compactification of the quotient by the translation \mathbb{R} action of the space of holomorphic sections of $P_x \times ([0, 1] \times \mathbb{R})$, with boundary on the Lagrangian sub-bundles $L_0 \times \mathbb{R}, L_1 \times \mathbb{R}$, and asymptotic to γ_i , at the ∞ , respectively $-\infty$ ends.

Terminology 5.2. *Here and elsewhere the term **holomorphic section** of various Hamiltonian fibrations over 2-d Riemann surfaces will mean the following. Our Hamiltonian fibrations \tilde{S} always come with choices of a Hamiltonian connection \mathcal{A} , and a family of fiber-wise almost complex structures $\{j_z\}$, determined by the perturbation data \mathcal{D} . This gives an induced almost complex structure $J(\mathcal{A}, \{j_z\})$ on \tilde{S} restricting to $\{j_z\}$ on the fibers, having a holomorphic projection map to the base, and preserving the horizontal distribution of \mathcal{A} . Holomorphic then means that the section has $J(\mathcal{A}, \{j_z\})$ -complex linear differential.*

In the above case, “holomorphic” is with respect to the almost complex structure induced by the flat, \mathbb{R} -translation invariant extension of $\mathcal{A}(L_0, L_1)$ to $P_x \times [0, 1] \times \mathbb{R}$, and likewise by the translation invariant extension of $j(L_0, L_1)$ to $P_x \times [0, 1] \times \mathbb{R}$.

For a generic pair $\mathcal{A}(L_0, L_1), j(L_0, L_1)$, all the moduli spaces $\overline{\mathcal{M}}(\gamma_0; \gamma_1)$ are transversely cut out for all γ_i . The differential $\mu^1 : CF(L_0, L_1, \mathcal{D}) \rightarrow CF(L_0, L_1, \mathcal{D})$ is defined as usual by

$$\mu^1(\gamma_j) = \sum_i \# \mathcal{M}(\gamma_i; \gamma_j) \gamma_j,$$

for $\{\gamma_i\}$ a basis of geometric generators for $CF(L_0, L_1, \mathcal{D})$, when $\mathcal{M}(\gamma_i; \gamma_j)$ has dimension 0, and hence is compact in the monotone case as index bounds give energy bounds.

5.1.2. *Higher multiplication maps.* The multiplication maps

$$(5.1) \quad \begin{aligned} \mu^d : \text{hom}(L_0, L_1) \otimes \text{hom}(L_1, L_2) \otimes \dots \\ \otimes \text{hom}(L_{d-1}, L_d) \rightarrow \text{hom}(L_0, L_d), \end{aligned}$$

$d > 1$ are defined as follows.

Let \mathcal{U}, \mathcal{F} be the natural systems determined by \mathcal{D} . Then we may define the moduli space

$$(5.2) \quad \mathcal{M}(\{\gamma^i\}; \gamma_0, x, \mathcal{F}, A),$$

whose elements are class A $\mathcal{F}(\{L_i\}, x, r)$ -holomorphic sections (σ, r) , $r \in \overline{\mathcal{R}}_d$ of

$$P_x \times \mathcal{S}_r.$$

s.t.

- The boundary of (σ, r) is in the subfibration $\mathcal{L}(\mathcal{U}, L_0, \dots, L_d, r)$, see (4.11), of $P_x \times \mathcal{S}_r$ over the boundary of \mathcal{S}_r .
- By assumptions, at the e_i end, of \mathcal{S}_r , in the strip charts $e_i^1 : [0, 1] \times [1, \infty] \rightarrow \mathcal{S}_r$, the data $\mathcal{F}(\{L_i\}, x, r)$ is \mathbb{R} -translation invariant, and when $i \neq 0$ we ask that σ is asymptotic to γ^i , a geometric generator of $\text{hom}_{F(x)}(L_{i-1}, L_i)$, or at the e_0 asymptotic to γ_0 a geometric generator of $\text{hom}_{F(x)}(L_0, L_d)$.

Given basis of geometric generators $\{\gamma_j^i\}$ for $\text{hom}_{F(x)}(L_{i-1}, L_i)$, $i \neq 0$, and $\{\gamma_j^0\}$ for $\text{hom}_{F(x)}(L_0, L_d)$, $i = 0$. For $d \geq 2$, and assuming that $\mathcal{F}(\{L_i\}, x, r)$ is regular we define

$$(5.3) \quad \langle \mu^d(\gamma_{j_1}^1, \dots, \gamma_{j_d}^d), \gamma_{j_0}^0 \rangle = \sum_A \# \mathcal{M}(\gamma_{j_1}^1, \dots, \gamma_{j_d}^d; \gamma_{j_0}^0, x, \mathcal{F}, A),$$

when the above moduli spaces have dimension 0, for \langle, \rangle the natural pairing induced by our choice of basis. The sum is finite by monotonicity.

5.1.3. *Compactification regularity, and associativity.* The moduli spaces

$$\mathcal{M}(\{\gamma^i\}; \gamma_0, x, \mathcal{F}, A)$$

are identical to the moduli spaces in Sheridan [17] with respect to a system of Hamiltonian perturbations, and a domain dependent family of almost complex structures on (in this case) trivial bundles, determined by \mathcal{F} . To be more explicit, a Hamiltonian connection on a trivial M bundle over a surface S is the same as the data of a 1-form on S with values in $C_0^\infty(M)$: mean 0 smooth functions, which is the data of a Hamiltonian perturbation. So in our case we just have a language change, the reason for which will be obvious when we shall construct the value of

F on higher dimensional simplices of X . Consequently the compactification and regularity story is word for word identical to Sheridan [17].

5.1.4. A_∞ associativity. The maps $\mu_{F(\Sigma)}^d$ satisfy the A_∞ -associativity equations (stated over \mathbb{F}_2 for simplicity)

$$(5.4) \quad \sum_{n,m} \mu_\Sigma^{d-m+1}(\gamma_1, \dots, \gamma_n, \mu_\Sigma^m(\gamma_{n+1}, \dots, \gamma_{m+n}), \gamma_{n+m+1}, \dots, \gamma_d) = 0,$$

This is shown as usual by considering boundary of the one dimensional moduli spaces, $\overline{\mathcal{M}}(\{\gamma^i\}; \gamma_0, x, \mathcal{F}, A)$.

5.2. F on higher dimensional simplices. We will consider for the moment the case of non-degenerate simplices $\Sigma : \Delta^n \rightarrow X$. The category $F(\Sigma)$, has objects $\bigsqcup_i \text{obj } F(x_i)$, where $x_i : pt \rightarrow X$ is the composition of the vertex inclusion $\Delta^0 \rightarrow \Delta^n$ corresponding to the i 'th corner, with Σ . Abusing notation we may also write x_i for the image of x_i in X .

Let $m : [0, 1] \rightarrow \Delta^n$ be the edge between i, j corners of Δ^n and set $\overline{m} = \Sigma \circ m$. Given a pair of objects $L_0 \subset P_{x_i}, L_1 \subset P_{x_j}$, (including $i = j$) and the Hamiltonian connection $\mathcal{A}(L_0, L_1) = \mathcal{A}(L_0, L_1, \overline{m})$ on \overline{m}^*P , determined by \mathcal{D} , we define as before $\text{hom}_{F(\Sigma)}(L_0, L_1)$ to be the \mathbb{Z}_2 graded chain complex over \mathbb{Q} generated by flat sections of $(\overline{m}^*P, \mathcal{A}(L_0, L_1))$, with boundary on the Lagrangian submanifolds $L_0 \in \overline{m}^*P|_0, L_1 \in \overline{m}^*P|_1$. The differential μ^1 is defined identically to the differential on morphism spaces of categories $\text{Fuk}(P_x)$. The only difference is that \overline{m}^*P may no longer be naturally trivialized.

This completely describes all objects and morphisms of $F(\Sigma)$. We now need to describe the A_∞ structure. Given $\{L_{\rho(k)} \in F(x_{\rho(k)})\}_{k=0}^d$,

$$\rho : \{0, \dots, d\} \rightarrow \{x_i\}_{i=0}^n,$$

with $\omega(L_{\rho(k)}) = n \in \mathbb{Z}$, we define the higher composition maps

$$(5.5) \quad \mu_\Sigma^d : \text{hom}(L_{\rho(0)}, L_{\rho(1)}) \otimes \dots \otimes \text{hom}(L_{\rho(d-1)}, L_{\rho(d)}) \rightarrow \text{hom}(L_{\rho(0)}, L_{\rho(d)}).$$

Note that by construction to each morphism of $F(\Sigma)$ naturally corresponds either an edge or a vertex of Δ^n , in either case we may naturally associate to these a morphism in the category $\Pi(\Delta^n)$. The collection $\{x_{\rho(k)}\}$ then clearly determines a composable chain (m_1, \dots, m_d) of morphisms in $\Pi(\Delta^n)$. Given the map

$$u(m_1, \dots, m_d, n) : \overline{\mathcal{S}}_d^\circ \rightarrow \Delta^n, \text{ which is part of a natural system } \mathcal{U},$$

and the system \mathcal{F} determined by \mathcal{D} , we define the moduli space $\mathcal{M}(\{\gamma^i\}; \gamma_0, \Sigma^n, \mathcal{F}, A)$ analogously to (5.2). Explicitly, its elements are class A $\mathcal{F}(\{L_i\}, \Sigma, r)$ -holomorphic sections (σ, r) , $r \in \overline{\mathcal{R}}_d$ of

$$\tilde{S}_r = \tilde{S}(m_1, \dots, m_d, \Sigma, r),$$

satisfying:

- The boundary of (σ, r) is in the sub-fibration $\mathcal{L}(\mathcal{U}, L_0, \dots, L_d, r)$, see (4.11), of \tilde{S}_r over the boundary of \mathcal{S}_r .
- By assumptions, at the i 'th end of \mathcal{S}_r , in the strip chart $e_i^1 : [0, 1] \times [1, \infty] \rightarrow \mathcal{S}_r$, the data $\mathcal{F}(\{L_i\}, \Sigma, r)$ is \mathbb{R} -translation invariant and when $i \neq 0$ we ask that σ is asymptotic to γ^i a geometric generator of $\text{hom}_{F(\Sigma)}(L_{i-1}, L_i)$, or when $i = 0$ asymptotic in forward time to γ_0 a geometric generator of $\text{hom}_{F(\Sigma)}(L_0, L_d)$.

5.2.1. *Compactness and regularity.* We do not need to reinvent the wheel proving compactness and regularity results for the above moduli spaces. (Although it obviously works the same way.) Instead pick a Hamiltonian trivialization of $M \times \Delta^n \xrightarrow{tr} \Sigma^* P$, then we may pullback the systems of connections $\mathcal{F}(\{L_i\}, \Sigma, r)$, and the systems of almost complex structures $\mathcal{J}(\{L_i\}, \Sigma)$ to $M \times \Delta^n$. Then in the coordinates of $M \times \Delta^n$, these systems of connections and complex structures are essentially equivalent to systems of compatible perturbations, in the sense of Seidel [16], for the Lagrangian boundary conditions given by $\{\pi \circ tr^{-1}(L_i)\}$ for $\pi : M \times \Delta^n \rightarrow M$ the projection. (Only “essentially” because we have extra copies of the same object.) Consequently compactness and regularity works the same way as described in Section 5.1.3.

5.2.2. *Composition maps.* Then as before given a basis of geometric generators $\{\gamma_j^i\}$ for $\text{hom}_{F(x)}(L_{i-1}, L_i)$, $i \neq 0$, and $\{\gamma_j^0\}$ for $\text{hom}_{F(x)}(L_0, L_d)$, $i = 0$. For $d \geq 2$, and assuming that $\mathcal{F}(\{L_i\}, \Sigma, r)$ is regular we define

$$(5.6) \quad \langle \mu_{F(\Sigma)}^d(\gamma_{j_1}^1, \dots, \gamma_{j_d}^d), \gamma_{j_0}^0 \rangle = \sum_A \# \mathcal{M}(\gamma_{j_1}^1, \dots, \gamma_{j_d}^d; \gamma_{j_0}^0, \Sigma, \mathcal{F}, A),$$

when the above moduli spaces are of dimension 0, for \langle, \rangle as before.

5.2.3. *Associativity.* This works as before.

Lemma 5.3. *The assignment $\Sigma \mapsto F(\Sigma)$ extends to a natural functor*

$$F : \text{Simp}(X) \rightarrow A_\infty - \text{Cat}.$$

Proof. Given a face map $f : \Delta^{n-1} \rightarrow \Delta^n$, and $\Sigma^n : \Delta^n \rightarrow X$, by the third naturality property of our connections there is a canonical functor $F(\Sigma^n \circ f) \rightarrow F(\Sigma^n)$, which is by construction a fully-faithful embedding. It follows via iteration, that a morphism $m : \Sigma^k \rightarrow \Sigma^l$, with $\Sigma^k, \Sigma^l \in \text{Simp}(X)$, $k < l$ induces a fully-faithful embedding:

$$F(m) : F(\Sigma^k) \rightarrow F(\Sigma^l),$$

and this assignment is clearly functorial. Note that $F(m)$ is essentially surjective on the cohomological level, which follows by a classical continuation argument, cf. [16, Section 10a], and so $F(m)$ is a quasi-equivalence. \square

Let us call the functor $F_{P,D} : \text{Simp}(X) \rightarrow A_\infty - \text{Cat}$ as constructed geometrically in this section a *geometric functor* to emphasize the origin, (as we may have lots of other such functors which do not arise geometrically).

5.3. **Unital replacement of F .** Let $A_\infty - \text{Cat}^{\text{unit}}$ denote the subcategory of $A_\infty - \text{Cat}$ consisting of unital A_∞ categories and unital functors. By *unital replacement* for $F : \text{Simp}(X) \rightarrow A_\infty - \text{Cat}$ we mean a functor $F^{\text{unit}} : \text{Simp}(X) \rightarrow A_\infty - \text{Cat}^{\text{unit}}$, together with a natural transformation $N : F \rightarrow F^{\text{unit}}$, which is object-wise quasi-equivalence.

Lemma 5.4. *Any functor $F : \text{Simp}(X) \rightarrow A_\infty - \text{Cat}$ has a unital replacement.*

Proof. To obtain this we proceed inductively: for each 0-simplex $x \in \text{Simp}(X)$, since each $F(x)$ is c-unital we may fix a formal diffeomorphism $\Phi_x : F(x) \rightarrow F(x)$, with first component maps Φ_x^1 the identity maps, such that induced A_∞ -structure $F^{\text{unit}}(x) = \Phi_{x*}(F(x))$ is strictly unital, [16, Lemma 2.1]. Let $N_x : F(x) \rightarrow F^{\text{unit}}(x)$ denote the induced A_∞ functor. Let F_k denote the restriction F to $\text{Simp}^{\leq k}(X)$

with $\text{Simp}^{\leq k}(X)$ denoting the sub-category of $\text{Simp}(X)$, consisting of simplices whose degree is at most k . And suppose that the maps N_x can be extended to a natural transformation N_k of functors

$$\begin{aligned} F_k &: \text{Simp}^{\leq k}(X) \rightarrow A_\infty - \text{Cat}, \\ F_k^{\text{unit}} &: \text{Simp}^{\leq k}(X) \rightarrow A_\infty - \text{Cat}^{\text{unit}}, \end{aligned}$$

where for each Σ $N_k(\Sigma) : F(\Sigma) \rightarrow F^{\text{unit}}(\Sigma)$ is induced by a formal diffeomorphism $\Phi_\Sigma : F(\Sigma) \rightarrow F(\Sigma)$, whose first component maps are the identity maps.

We construct an extension N_{k+1} . Since for each given $\Sigma^{k+1} : \Delta^{k+1} \rightarrow X$, and $i : \Sigma^k \rightarrow \Sigma^{k+1}$ a morphism in $\text{Simp}(X)$, $F(i)$ is a fully-faithful embedding by assumption, and identifying $F(\Sigma^k)$ with a full subcategory of $F(\Sigma^{k+1})$, we may clearly construct as in the proof of [16, Lemma 2.1] a formal diffeomorphism

$$\Phi_{\Sigma^{k+1}} : F(\Sigma^{k+1}) \rightarrow F(\Sigma^{k+1}),$$

with $\Phi_{\Sigma^{k+1}}^*(\Sigma^{k+1})$ unital, so that its restriction to $F(\Sigma^k)$ coincides with the formal diffeomorphisms $\{\Phi_{\Sigma^{k+1} \circ i}\}$, for each $i : \Sigma^k \rightarrow \Sigma^{k+1}$. The result then follows. \square

Let us write F^{unit} for the particular unital replacement of F as constructed in the proof of the lemma above.

5.4. Naturality. Given a smooth embedding $f : Y \rightarrow X$ and $M \hookrightarrow P \rightarrow X$ a Hamiltonian bundle as before, there is an induced functor $\text{Simp}(Y) \rightarrow \text{Simp}(X)$ and consequently the pullback functor $f^*F_{P,\mathcal{D}} : \text{Simp}(Y) \rightarrow A_\infty - \text{Cat}$, where $F_{P,\mathcal{D}} : \text{Simp}(X) \rightarrow A_\infty - \text{Cat}$ is the functor constructed above for the perturbation data \mathcal{D} . On the other hand we may pullback by f the bundle as well as the perturbation data \mathcal{D} , to get another functor $F_{f^*P, f^*\mathcal{D}} : \text{Simp}(Y) \rightarrow A_\infty - \text{Cat}$. The following is immediate from construction.

Lemma 5.5. $F_{f^*P, f^*\mathcal{D}} = f^*F_{P,\mathcal{D}}$.

5.5. Concordance classes of functors $F : \text{Simp}(X) \rightarrow A_\infty - \text{Cat}$. We say that a pair of functors $F_0, F_1 : \text{Simp}(X) \rightarrow A_\infty - \text{Cat}$ are *concordant* if there is a functor

$$T : \text{Simp}(X \times I) \rightarrow A_\infty - \text{Cat},$$

restricting to F_0, F_1 over $\text{Simp}(X \times \{0\})$, respectively over $\text{Simp}(X \times \{1\})$. Note that by the proof of Lemma 5.4 if F_1, F_2 are concordant then so are $F_1^{\text{unit}}, F_2^{\text{unit}}$.

Theorem 5.6. *For a given pair of data $\mathcal{D}_1, \mathcal{D}_2$, the functors*

$$\begin{aligned} F_{P,\mathcal{D}_1} &: \text{Simp}(X) \rightarrow A_\infty - \text{Cat}, \\ F_{P,\mathcal{D}_2} &: \text{Simp}(X) \rightarrow A_\infty - \text{Cat} \end{aligned}$$

are concordant.

Proof. A given pair of choices $\mathcal{D}_1, \mathcal{D}_2$ of auxiliary data, are homotopic in the natural sense through perturbation data $\{\mathcal{D}_t\} = (\{\mathcal{U}_t\}, \{\mathcal{F}_t\})$, $t \in I = [0, 1]$, by Proposition 4.2. Let $\tilde{P} \rightarrow X \times I$ be the Hamiltonian fibration given by pull-back of P by the projection map $X \times I \rightarrow X$. Then for any

$$\Sigma : \Delta^n \rightarrow X \times \{t\} \subset X \times I$$

we may define $T(\Sigma) = F_{P,\mathcal{D}_t}(\Sigma)$. Then extend the perturbation data $\{\mathcal{D}_t\}$ in any way to all $\text{Simp}(X \times I)$, call this data \mathcal{H} . Consequently we may define the functor T giving a concordance between $F_{P,\mathcal{D}_1}, F_{P,\mathcal{D}_2}$ to be the geometric functor

$F_{\bar{P}, \mathcal{H}} : \text{Simp}(X \times I) \rightarrow A_\infty - \text{Cat}$. The extension \mathcal{H} clearly exists once one has an extension for the natural system of maps $\{\mathcal{U}_t\}$, since there are no obstructions at all for extending $\{\mathcal{F}_t\}$. On the other hand extension of $\{\mathcal{U}_t\}$ exists by the same kind of inductive argument as in the construction of a natural system \mathcal{U} . \square

5.6. Remark. We will not show it here as it requires substantial algebra (some of which is possibly new), but concordance relation is an equivalence relation (in the special case above). The concordance class of the functor $F_{P, \mathcal{D}}$ is then the most fundamental invariant that is constructed in this paper, however calculating with it may be very difficult.

6. GLOBAL FUKAYA CATEGORY

Concordance “classes” of functors $F_{P, \mathcal{D}}$ constructed as above, have a wealth of information, but we shall cut down on this information by assigning a more geometric object to it. We shall assign to the concordance classes above, equivalence classes of certain simplicial fibrations over X_\bullet , which are certain analogues of Serre fibrations in the topological category.

The first necessary ingredient for this story is the notion of a quasi-category, which is a simplicial set with an additional property, relaxing the notion of Kan complex. The latter are fibrant objects in the Quillen model structure on the category $s\text{Set}$ of simplicial sets, and play the same role in the category of simplicial sets as CW complexes play in the category of topological spaces: they are the fibrant objects in the corresponding Quillen equivalent model categories. Quasi-categories or alternatively called ∞ -categories, are in turn the fibrant objects for a different non Quillen equivalent model structure on $s\text{Set}$ called the Joyal model structure, which will play a background role in this paper. For reader’s convenience we will review some of this theory of simplicial sets in the Appendix.

6.1. The A_∞ -nerve. The A_∞ -nerve is an analogue for A_∞ categories of the classical nerve functor from the category of small categories to the category of simplicial sets, (in-fact quasi-categories). From now A_∞ -nerve will be just “nerve”: N , where there can be no confusion. This construction is due to Lurie [8, Construction 1.3.1.6], and the output is an ∞ -category, or in the more specific model in this paper a quasi-category. Thus N is a functor from the category of all (strictly-unital) A_∞ categories, with morphisms A_∞ unital functors to the category of quasi-categories $\infty - \text{Cat}$. More precisely Lurie discusses the case of dg-categories, and only indicates the case of A_∞ categories. A complete description of the nerve construction for A_∞ categories is contained in the thesis of Tanaka, [7], where it plays a central role, and is also carefully worked out in Faonte [3]. We will reproduce it here for the reader’s convenience, a bit further on.

It should be noted that in the Lagrangian cobordism approach to Fukaya category in Nadler-Tanaka [12] a stable quasi-category \mathcal{Z} is constructed directly. The category \mathcal{Z} is expected to be closely related to the nerve of the triangulated envelope of the Fukaya category.

6.1.1. Outline of the (A_∞) -nerve construction. The first step in the construction of N is as follows. Let C be a strictly unital A_∞ category. The 2-skeleton of the nerve $N(C)$, has objects of C as 0-simplices, morphisms of C as 1-simplices and

the 2-simplices consist of a triple of objects X, Y, Z , a triple of morphisms

$$f \in \text{hom}_C(X), g \in \text{hom}_C(Y, Z), h \in \text{hom}_C(X, Z),$$

a morphism $e \in \text{hom}_C(X, Z)_1$, with $de = h - f \circ g$. We will describe the full nerve construction in the Appendix A following Tanaka [7].

6.2. Global Fukaya category. Suppose we are given a geometric functor $F^{unit} = F_{P, \mathcal{D}}^{unit} : \text{Simp}(X) \rightarrow A_\infty\text{-Cat}^{unit}$. We shall see in Section 7 that there is a canonical extension of F to a functor $F^{unit} : \Delta/X_\bullet \rightarrow A_\infty\text{-Cat}^{unit}$, that is to the entire category of simplices of X_\bullet .

Definition 6.1. *And we define:*

$$\text{Fuk}_\infty(P, \mathcal{D}) \equiv \text{colim}_{\Delta/X_\bullet} N \circ F^{unit} \in s\text{Set}.$$

An explicit construction of the colimit is given in Lemma 7.2. In principle the above definition could be very impractical since general objects in $s\text{Set}$ are difficult to deal with, while taking fibrant replacements for the Joyal model category structure could obfuscate all original geometry contained in the Fukaya category. Thankfully none of this is necessary as we have a couple of miracles coming from the underlying geometry to save us. The proof of the following will be given in Section 7.

Theorem 6.2. *As defined $\text{Fuk}_\infty(P, \mathcal{D}) \in \infty\text{-Cat}$, i.e. is a quasi-category, moreover there is a natural (co)-Cartesian fibration*

$$N(\text{Fuk}(M)) \hookrightarrow \text{Fuk}_\infty(P, \mathcal{D}) \rightarrow X_\bullet,$$

whose equivalence class in the over category $s\text{Set}/X_\bullet$ is independent of the choice of \mathcal{D} .

6.3. Universal construction. Let $P_U \rightarrow B\text{Ham}(M, \omega)$ be the associated Hamiltonian M -bundle to the universal principal $\text{Ham}(M, \omega)$ bundle. $B\text{Ham}(M, \omega)$ or the classifying space of any smooth Lie group, based on Milnor's construction [11] admits a well defined notion of smooth maps into it from smooth manifolds. To be precise it has a natural diffeology [10]. In particular the category of smooth simplices in $B\text{Ham}(M, \omega)$ makes good sense and the construction of $\text{Fuk}_\infty(P_U)$, proceeds the same way.

Proof of Theorem 1.3. By the above, Theorem 6.2 and Lurie's straightening Corollary A.5 give a homotopy class of a “classifying” map

$$cl = cl(\text{Fuk}_\infty(P_U)) : B\text{Ham}(M, \omega)_\bullet \rightarrow \infty\text{-Cat}.$$

And so a group homomorphism

$$cl_* : \pi_i B\text{Ham}(M, \omega) \rightarrow \pi_i(\infty\text{-Cat}, N\text{Fuk}(M)).$$

□

The following theorem shows only the topological type of the Hamiltonian fibration is detected by the associated (co)-Cartesian fibration.

Theorem 6.3. *Let $M \hookrightarrow P_1 \rightarrow X$, $M \hookrightarrow P_2 \rightarrow X$ be as before. Suppose that there is a topological Hamiltonian bundle map $P_1 \rightarrow P_2$. Then*

$$[cl(P_1)] = [cl(P_2)].$$

Proof. We may approximate the classifying maps $f_i : X \rightarrow BHam(M, \omega)$ for P_i by diffeological embeddings, it then follows by Lemma 5.5, that $Fuk_\infty(P_i)$ are equivalent to pull-backs by f_i of $Fuk_\infty(P_U)$. But f_i are homotopic, so the conclusion follows. \square

6.4. Global Fukaya category and unital replacement. In the construction of $Fuk_\infty(P)$ we had to take a unital replacement for the functor $F : Simp(X) \rightarrow A_\infty - Cat$, one may worry then that this algebraic step will obfuscate the “geometry” of simplices of $Fuk_\infty(P)$. This is not really the case. First the A_∞ nerve NC of a non-unital A_∞ category C still exists as a semi-simplicial set, that is as a co-functor $\Delta^{inj} \rightarrow Set$, with Δ^{inj} the subcategory of Δ consisting of injective morphisms. For a unital replacement equivalence $C \rightarrow C^{unit}$ of C , constructed as in Section 5.3. We have an induced morphism of semi-simplicial sets $NC \rightarrow NC^{unit}$, which by construction induces a bijection $NC([n]) \rightarrow NC^{unit}([n])$, for each $[n]$. So we may think without loss of geometric information, of simplices of NC^{unit} in terms of simplices of NC . (The former just have an extra formal algebraic structure.)

7. ALGEBRAIC CONSIDERATIONS

In this section by equivalence of quasi-categories we always mean categorical equivalence. This and other categorical preliminaries needed for this section are discussed in the Appendix A.

We will prove here Theorem 6.2.

7.1. Extending F to degenerate simplices. Let

$$F : Simp(X_\bullet) \rightarrow A_\infty - Cat^{unit}$$

be a functor. We extend this to a functor with the same name:

$$(7.1) \quad F : \Delta/X_\bullet \rightarrow A_\infty - Cat^{unit}.$$

We need to say what to do with degenerate simplices. Suppose we are given a diagram

$$\begin{array}{ccccc} \Delta^0 & \xrightarrow{j+1} & \Delta^{n+1} & \xrightarrow{pr_j} & \Delta^n \\ & \searrow j_* & \downarrow s_j(\Sigma) & \swarrow \Sigma & \\ & & X & & \end{array}$$

where

$$pr_j : \Delta^{n+1} \rightarrow \Delta^n, \quad j \in [n]$$

is induced by the unique surjection $[n+1] \rightarrow [n]$, hitting j twice. Here $j_* = \Sigma \circ j$, and j also denotes the map $pt \rightarrow \Delta^n$ corresponding to this vertex.

Then

$$(7.2) \quad F(s_j(\Sigma))$$

is defined to be the A_∞ category with objects

$$\text{obj } F(\Sigma)) \sqcup \text{obj } F(j_*).$$

Note that there are then two embeddings $\text{obj } F(j_*) \rightarrow \text{obj } F(s_j(\Sigma))$, one given by

$$F(inc_j) : \text{obj } F(j_*) \rightarrow \text{obj } F(\Sigma),$$

$inc_j : j_* \rightarrow \Sigma$ the map in $Simp(X)$ corresponding to the vertex inclusion map of j , and the other just being the tautological map τ to the summand $\text{obj } F(j_*)$.

The hom sets are defined so that there are tautological strict embeddings of A_∞ categories

$$F(\Sigma) \rightarrow F(s_j(\Sigma)), \quad F(j) \rightarrow F(s_j(\Sigma))$$

and so that

$$hom_{F(s_j(\Sigma))}(L', \tau(L)) \equiv hom_{F(\Sigma)}(L', F(inc_j)(L)),$$

for

$$L' \in \text{obj } F(\Sigma),$$

and

$$L \in \text{obj } F(j).$$

The composition operations $\mu_{F(s_j(\Sigma))}^d$ are defined naturally so that the tautological projection

$$F(d_j) : F(s_j(\Sigma)) \rightarrow F(\Sigma)$$

is a strict, fully-faithful A_∞ functor, for $d_j : s_j \Sigma \rightarrow \Sigma$ the morphism induced by pr_j .

7.2. Colimit of F . For F as above, let

$$Fuk_\infty(F) = \text{colim}_{\Delta/X_\bullet} NF.$$

Proposition 7.1. *There is a natural projection of simplicial sets $p : Fuk_\infty(F) \rightarrow X_\bullet$, and this is a (co)-Cartesian fibration.*

Proof. Recall that a given $\Sigma : \Delta^n \rightarrow X$, could equally be thought of as an element of $X_\bullet([n])$, or of Δ/X_\bullet that is as a natural transformation $\Delta_\bullet^n \rightarrow X_\bullet$. Let us first give a more easily conceptualized presentation of $Fuk_\infty(F)$. Define a partial order $<$ on the set of pairs (f, Σ) , $f \in F(\Sigma)$, $\Sigma \in \Delta/X_\bullet$ by $(f, \Sigma) < (f', \Sigma')$ if there is a morphism $i : \Sigma \rightarrow \Sigma'$ induced by $[n] \rightarrow [m]$ with $n \leq m$, i.e. a *face morphism*, s.t. $F(i)(f) = f'$. Clearly for every (f, Σ) there is a unique least pair $(f_{\min}, \Sigma_{\min}) < (f, \Sigma)$. Let \tilde{L} be the set of minimal pairs. Define an equivalence relation on \tilde{L} by $(f, \Sigma) \sim (f', \Sigma')$ if there exists a morphism $d : \Sigma \rightarrow \Sigma'$ induced by $[m] \rightarrow [n]$ with $m > n$, (i.e. it is a degeneracy morphism) with $F(d)(f) = f'$. Denote the equivalence class of (f, Σ) by $[f, \Sigma]$. Then $L = \tilde{L} / \sim$ is naturally a simplicial set, with

$$L([k]) = \{[f, \Sigma] \in L \mid f \in NF(\Sigma)([k])\}.$$

For example $L([0])$ is just

$$\bigsqcup_{x \in X} \text{Obj } F(x).$$

Lemma 7.2. $L = Fuk_\infty(F)$.

Proof. Note first that L is a co-cone on the diagram NF . Indeed for each Σ , define $\phi_\Sigma : NF(\Sigma) \rightarrow L$ by

$$\phi_\Sigma(f) = [f_{\min}, \Sigma_{\min}].$$

It is easy to see that for a face morphism $i : \Sigma \rightarrow \Sigma'$ we have that the composition

$$NF(\Sigma) \xrightarrow{NF(i)} NF(\Sigma') \xrightarrow{\phi_{\Sigma'}} L,$$

coincides with ϕ_Σ . Likewise for a degeneracy morphism $d : \Sigma \rightarrow \Sigma'$ we have that the composition

$$NF(\Sigma) \xrightarrow{NF(d)} NF(\Sigma') \xrightarrow{\phi_{\Sigma'}} L,$$

coincides with ϕ_Σ , because of the equivalence relation \sim .

The universal property is also easy to verify, for given another co-cone L' with maps $\rho_\Sigma : NF(\Sigma) \rightarrow L'$, $\Sigma \in \text{Simp}(X)$ we can naturally define $U : L \rightarrow L'$ by

$$U([f, \Sigma]) = \rho_\Sigma(f).$$

Then U is clearly well defined, as L' is by assumption a co-cone, and for a given $f \in NF(\Sigma)$, we have

$$U\phi_\Sigma(f) = \rho_{\Sigma_{\min}}(f_{\min}) = \rho_\Sigma f,$$

where the last equality holds since $L', \{\rho_\Sigma\}$ is a co-cone, and since by construction there is a morphism $i : NF(\Sigma_{\min}) \rightarrow NF(\Sigma)$, with $F(i)f_{\min} = f$. \square

For Σ as above, we have a natural simplicial map

$$p_\Sigma : NF(\Sigma) \rightarrow \Sigma_*(\Delta_\bullet^n) \subset X_\bullet,$$

defined as follows. On the vertices of $NF(\Sigma)$, p_Σ is just the obvious projection. Now a k -simplex f in $NF(\Sigma)$ by definition determines a composable chain (f_1, \dots, f_k) in $NF(\Sigma)$, and hence determines a sequence of vertices e_0, \dots, e_k s.t. the source/target of f_i is e_{i-1} respectively e_i . This in turn determines a sequence of vertices $\{p_\Sigma(e_i)\}$, and we set $p_\Sigma(f)$ to be the unique (degenerate) k -simplex of $\Sigma_*(\Delta_\bullet^n)$ with these vertices. We shall omit the verification that p_Σ is simplicial. The simplicial projection

$$p : L \rightarrow X_\bullet$$

is then: send $[f, \Sigma]$ to $p_\Sigma f$, which is readily seen to be well defined.

It is immediate from definitions that p is an inner-fibration if and only if the pre-image of every simplex $\Sigma : \Delta_\bullet^n \rightarrow X_\bullet$ by p is a quasi-category, where “pre-image” $p^{-1}(\Sigma)$ is the preimage by p of the simplicial subset $\Sigma(\Delta_\bullet^n)$. In our case this follows by construction as the preimage of Σ is clearly identified $NF(\Sigma)$. Let m be an edge in X_\bullet from x_0 to x_1 and let $L_m = p^{-1}m$ and let $L_i = p^{-1}x_i$, see definition of pre-image above. To show that p is a (co)-Cartesian fibration, by [9, Proposition 2.4.1.5] it is enough to show that for every such m and $a \in L_1$ there is an equivalence $e_a \in L_m$ with target a , with $p(e_a) = m$.

Lemma 7.3. *The functor $N : A_\infty - \text{Cat}^{\text{unit}} \rightarrow \text{Cat} - \infty$, takes quasi-equivalences to weak equivalences in the Joyal model structure, i.e. categorical equivalences.*

Proof. The proof of this is contained in the proof of proposition 1.3.1.20, Lurie [8]. We can also prove this directly by first recalling that quasi-equivalences of A_∞ -categories A, B are invertible, up to homotopy, and then via the nerve construction translate this to a categorical equivalence of $N(A), N(B)$. \square

Then by construction of L the inclusion of L_i into L_m are equivalences of quasi-categories, and so e_a as above must exist. \square

Proof of Theorem 6.2, 1.1. By the discussion above we have a (co)-Cartesian fibration

$$\text{Fuk}_\infty(P, \mathcal{D}) \rightarrow X_\bullet.$$

The first part of the theorem follows by the following general fact: for an inner fibration of simplicial sets $p : P_\bullet \rightarrow X_\bullet$, if X_\bullet is a quasi-category then P_\bullet is a quasi-category. Let us prove this elementary point. Suppose we are given $\rho : \Lambda_k^n \rightarrow P_\bullet$, for $0 < k < n$. As X_\bullet is a quasi-category there a simplex $\tilde{\rho} : \Delta_\bullet^n \rightarrow X_\bullet$ extending

$p \circ \rho$. But then ρ maps into the quasi-category $p^{-1}(\tilde{\rho})$, consequently there is an extension of ρ , c.f. Proposition A.3.

The final part of the theorem follows by the following.

Lemma 7.4. *For the geometric functor $F_{P, \mathcal{D}}$, the equivalence class of the fibration $p : \text{Fuk}_\infty(P, \mathcal{D}) \rightarrow X_\bullet$, in the over category $s\text{Set}/X_\bullet$ is independent of the choice of \mathcal{D} .*

Proof. By Theorem 5.6 and previous discussion for any pair \mathcal{D}_i of perturbation data there exists a (co)-Cartesian fibration:

$$\mathcal{T} \rightarrow X_\bullet \times I_\bullet,$$

whose restriction over $X_\bullet \times \partial I_\bullet$ coincides with

$$\text{Fuk}_\infty(P, \mathcal{D}_1) \sqcup \text{Fuk}_\infty(P, \mathcal{D}_2),$$

The lemma then follows by Lurie’s straightening theorem A.4, or more simply by Corollary A.5. (Strictly speaking by its proof, as we need the straightening functor for \mathcal{T} to restrict to straightening functor for $\text{Fuk}_\infty(P, \mathcal{D}_1) \sqcup \text{Fuk}_\infty(P, \mathcal{D}_2)$ over $\partial X_\bullet \times I_\bullet$.) \square

\square

APPENDIX A. QUASI-CATEGORIES AND JOYAL MODEL STRUCTURE

A very good concise reference for much of this material is Riehl [13], which we will mostly follow. The material on co-Cartesian fibrations is taken from Lurie [9, Section 2.4]. First let us recall the notion of a Kan complex, which maybe thought of as formalizing the property of a simplicial set to be like the singular set of a topological space.

Let Δ^n be the standard representable n -simplex: $\Delta([i]) = \Delta([i], [n])$. Previously we denoted this by Δ_\bullet^n but as there are no topological simplices in this section we simplify the notation, which is also consistent with above references. Let $\Lambda_k^n \subset \Delta^n$ denote the sub-simplicial set corresponding to the “boundary” of Δ^n with the k ’th face removed, $0 \leq k \leq n$. By k ’th face we mean the face opposite to k ’th vertex.

A simplicial set S_\bullet is said to be a *Kan complex* if given a diagram with solid arrows

$$\begin{array}{ccc} \Lambda_k^n & \xrightarrow{\quad} & S_\bullet \\ \downarrow & \nearrow \text{---} & \\ \Delta^n & & \end{array},$$

there is a dashed arrow making the diagram commute.

A *quasi-category* is a simplicial set S_\bullet for which the above extension property is only required to hold for inner horns Λ_k^n , i.e. those horns with $0 < k < n$. A morphism between quasi-categories is just a simplicial map. We will denote quasi-categories by calligraphic letters e.g. \mathcal{B} . The full-subcategory of $s\text{Set}$ with objects quasi-categories will be denoted by $\infty\text{-Cat}$.

A.1. Categorical equivalences, morphisms and equivalences. We have a natural functor $\tau : sSet \rightarrow Cat$, $\tau(S_\bullet)$ is the category with objects 0-simplices of S_\bullet , 1-simplices as morphisms, degenerate 1-simplices as identities and freely generated composition subject to the relation $g = f \circ h$ if there is a 2-simplex e with 0-face h , 2-face f and 1-face g . (Remembering our diagrammatic order for composition.) We then have a functor $\tau_0 : sSet \rightarrow Set$ by sending A_\bullet to the set of isomorphism classes of objects in τA_\bullet . If $S_\bullet = \mathcal{X}$ is a quasi-category an edge $e \in \mathcal{X}$ is said to be an *equivalence* if it is an isomorphism in $\tau \mathcal{X}$. The *maximal Kan subcomplex* of a quasi-category \mathcal{X} is the sub-complex obtained by removing edges which are not equivalences.

Notation A.1. *The category $\infty-Cat$ naturally has a structure of a quasi-category itself see [9, Chapter 3], we shall denote its maximal Kan subcomplex by \mathcal{S} .*

We define $sSet^{\tau_0}$ to be the category with the same objects as $sSet$ but with the morphisms given by $sSet^{\tau_0}(A_\bullet, B_\bullet) = \tau^0(B_\bullet^{A_\bullet})$. A map of simplicial sets $u : A_\bullet \rightarrow B_\bullet$ is said to be a *categorical equivalence* if the induced map in $sSet^{\tau_0}$ is an equivalence. It is said to be a *weak equivalence* if the pull-back map

$$sSet^{\tau_0}(B_\bullet, X_\bullet) \rightarrow sSet^{\tau_0}(A_\bullet, X_\bullet)$$

induced by u is an equivalence for all X_\bullet . A categorical equivalence is necessarily a weak categorical equivalence. Conversely a weak categorical equivalence between quasi-categories is necessarily a categorical equivalence. We will say that a pair of quasi-categories are *equivalent* if there is categorical equivalence between them.

As we are following Riehl [13], we refer the reader there for the following:

Theorem A.2 (Joyal, Lurie, Riehl). *There is a model structure on $sSet$, with weak equivalences weak categorical equivalences and cofibrations monomorphisms. Moreover the fibrant objects are quasi-categories.*

A.2. Inner fibrations. A map $p : \mathcal{A} \rightarrow \mathcal{B}$ is said to be an *inner fibration* if it has the lifting property with respect to all inner horn inclusions. More specifically if for $0 < k < n$ whenever we are given a commutative diagram with solid arrows,

$$(A.1) \quad \begin{array}{ccc} \Lambda_k^n & \xrightarrow{\quad} & \mathcal{A} \\ \downarrow & \nearrow & \downarrow p \\ \Delta^n & \xrightarrow{\quad} & \mathcal{B} \end{array},$$

there exists a dashed arrow as in the diagram. For reference p is said to be an *Kan fibration* if the above extension property holds for all horns. A Kan fibration is an analogue in the simplicial world of Serre fibrations of topological spaces. The following is immediate from definitions.

Proposition A.3. *A map $p : A_\bullet \rightarrow B_\bullet$ is an inner fibration, if and only if the pre-image of every simplex of B_\bullet is a quasi-category.*

A.3. (co)-Cartesian fibrations. These are the analogue in the quasi-categories world of Grothendieck fibrations. We will explain the co-Cartesian version, as the other is just dual to it.

Given $p : A_\bullet \rightarrow B_\bullet$, an edge $f : \Delta^1 \rightarrow A_\bullet$ is said to be *co-Cartesian* if whenever we are given a diagram with solid arrows:

$$(A.2) \quad \begin{array}{ccc} \Delta_{0,1}^n & & \\ \downarrow & \searrow f & \\ \Lambda_0^n & \longrightarrow & A_\bullet \\ \downarrow & \nearrow & \downarrow p \\ \Delta^n & \longrightarrow & B_\bullet \end{array},$$

there is a dashed arrow making the diagram commutative. Here $\Delta_{0,1}^n$ denotes the “edge” (sub-simplicial complex) joining the vertexes 0, 1.

The map p is said to be a *co-Cartesian fibration*, if it is an inner fibration and if for every edge $e : \Delta^1 \rightarrow B_\bullet$, with co-domain b , and every \tilde{b} lifting b there is a co-Cartesian lift $\tilde{e} : \Delta^1 \rightarrow A_\bullet$, with co-domain \tilde{b} .

Denote by $coCFib(\mathcal{B})$ the quasi-category of (co)-Cartesian fibrations over \mathcal{B} , which by definition is the full-subcategory of the over-category Cat_∞/\mathcal{B} , with objects (co)-Cartesian fibrations.

Theorem A.4. [9, Theorem 3.2.01] ***Straightening theorem.** There is equivalence of quasi-categories $Fun(\mathcal{B}, Cat_\infty) \simeq coCFib(\mathcal{B})$.*

Stated more properly this combines [9, Theorem 3.2.01] and [9, Proposition 3.1.5.3], both of which are statements on the level of model categories. When \mathcal{B} is a Kan complex, the notions of Cartesian and co-Cartesian fibrations over \mathcal{B} coincide and the model category presenting $coCFib(\mathcal{B})$ is just the over category $sSet/\mathcal{B}$ with the induced Joyal model structure, the fibrant objects in this model structure are the (co)-Cartesian fibrations over \mathcal{B} . The term “presents” here means that the underlying quasi-category is the simplicial nerve of the Dwyer-Kan [2] simplicial localization of the model category. Thus we simplify the above as follows for our needs in this paper. We say that a pair of co-Cartesian fibrations $\mathcal{P}_1 \rightarrow \mathcal{B}$, $\mathcal{P}_2 \rightarrow \mathcal{B}$ are *equivalent* if there is an (categorical) equivalence of quasi-categories $\mathcal{P}_1 \rightarrow \mathcal{P}_2$ over \mathcal{B} . The set of such equivalence classes is formally $\tau_0 CFib(\mathcal{B})$.

Corollary A.5. *For a Kan complex X_\bullet , the set $\tau_0 CFib(X_\bullet)$ is naturally identified with the set of homotopy classes of maps $X_\bullet \rightarrow \infty - Cat$.*

A.4. Semi-locality. Suppose that $S_\bullet \subset X_\bullet$ is a Kan sub-complex, whose inclusion map is a weak equivalence.

Lemma A.6. *The restriction functor*

$$\tau CFib(X_\bullet) \rightarrow \tau CFib(S_\bullet),$$

is an isomorphism, and so the restriction map

$$\tau_0 CFib(X_\bullet) \rightarrow \tau_0 CFib(S_\bullet),$$

is a set-isomorphism.

Proof. By Lurie’s straightening theorem A.4, this is equivalent to the restriction functor

$$(A.3) \quad \tau Func(X_\bullet, \infty - Cat) \rightarrow \tau Func(S_\bullet, \infty - Cat),$$

being an isomorphism. But X_\bullet and S_\bullet are Kan complexes and so

$$\tau \text{Func}(X_\bullet, \infty - \text{Cat}) \simeq \tau \text{Func}(X_\bullet, \mathcal{S}) \simeq \text{hoTop}(|X_\bullet|, |\mathcal{S}|),$$

with \mathcal{S} denoting the maximal Kan subcomplex of the quasi-category $\infty - \text{Cat}$, where $|\cdot|$ denotes geometric realization functor and where hoTop denotes the homotopy category of topological spaces. The last equivalence is due to the following. $\text{Func}(X_\bullet, \mathcal{S})$ is a Kan complex as it is the mapping space of Kan complexes, then observe that for Kan complexes τ_0 is just the functor of connected components, next use that the geometric realization $|\cdot|$, and singular set functors induce a derived Quillen equivalence between hoTop and hoSet .

Similarly

$$\tau \text{Func}(S_\bullet, \infty - \text{Cat}) \simeq \tau \text{Func}(S_\bullet, \mathcal{S}) \simeq \text{hoTop}(|S_\bullet|, |\mathcal{S}|),$$

The inclusion $|S_\bullet| \rightarrow |X_\bullet| \simeq X$ is a homotopy equivalence, as the inclusion $S_\bullet \subset X_\bullet$ is a weak equivalence by assumption and since geometric realization has image in CW complexes. It follows that (A.3) is an isomorphism. \square

Using this we may compute the class of global Fukaya category of $M \hookrightarrow P \rightarrow X$ in $\tau_0 \text{CFib}(X_\bullet)$, by restricting F to a sub-category Δ/S_\bullet , with $S_\bullet \subset X_\bullet$ minimal Kan sub-complex generated by the sub-simplicial set of X_\bullet corresponding to some smooth triangulation of X . This is in principle finite local data if X is compact, and in general locally finite. This plays a role in the calculation in part II.

A.5. A_∞ -nerve. This is a natural analogue for A_∞ categories of the dg-nerve construction of Lurie, [8], which is a functor

$$N : dg - \text{Cat} \rightarrow \infty - \text{Cat}.$$

This section follows Tanaka [7, 2.3], except that for us everything will be ungraded, and for simplicity with \mathbb{F}_2 -coefficients.

For $[n] \in \Delta$, a *length s wedge decomposition* of $[n]$, is a collection of monomorphisms in Δ

$$j_i : [n_i] \rightarrow [n], \quad i = 1, \dots, s, \quad |n_i + 1| \geq 2,$$

such that the fiber product

$$[n_i] \times_{[n]} [n_{i+1}] \simeq [0]$$

and the canonical projection

$$[n_i] \times_{[n]} [n_{i+1}] \rightarrow [n_i],$$

is the map $[0] \rightarrow [n_i]$ sending $\{0\}$ to $\{n_i\} \subset [n_i]$. Here we are thinking of $[n]$ as the totally ordered finite set $\{0, \dots, n\}$. We denote the set of all decompositions of $[n]$ by $D[n]$.

Definition A.7. For A a small unital A_∞ category its nerve $N(A)$ is a simplicial set with the set of vertices the set of objects of A . A n -simplex f of $N(A)$ consists of the following data:

- A map $[n] \rightarrow \text{Ob}A$. We denote the corresponding objects X_0, \dots, X_n .

- For each mono-morphism $j : [n_j] \rightarrow [n]$ with $|n_j| \geq 2$ an element

$$f_j \in \text{hom}_A(X_{j(0)}, X_{j(n_j)}).$$

We may completely characterize each such j by its image set, and will sometimes write j for the corresponding set and vice versa, thus $f_{[n]}$ corresponds to the identity $j : [n] \rightarrow [n]$.

- For a given $j : [n_j] \rightarrow \Delta^n$, denote by $j - \{i\} : [n_j - 1] \rightarrow [n]$ the morphism with image set $j - \{i\}$. Then the collection of these f_j is required to satisfy the following equation:

$$(A.4) \quad \mu^1(f_j) = \sum_{0 < i < n_j} f_{j - \{i\}} + \sum_s \sum_{\text{decomp}_s \in D[n_j]} \mu^s(f_{j_1}, \dots, f_{j_s}),$$

with $\text{decomp}_s \in D[n_j]$ denoting a length s decomposition and $\{f_{j_i}\}$ its elements.

The simplicial maps are as follows. Given an injection $k : [m] \rightarrow [n]$, an n -simplex f , for $j : [l] \rightarrow [m]$ an injection, define an m -simplex f' by $\{f'_j = f_{k \circ j}\}$.

On the other hand given $s_i : [n+1] \rightarrow [n]$, $s_i(i+1) = s_i(i)$, and an n -simplex f , define an $(n+1)$ -simplex f' by setting

$$f_j = \begin{cases} e_{X_i} & \text{if } j = \{i, i+1\}; \\ f_{s_i \circ j} & \text{if } s_i|_j \text{ is injective.} \\ 0 & \text{otherwise,} \end{cases}$$

for $j : [l] \rightarrow [n+1]$ an injection. It is straightforward but tedious to verify that the latter is indeed a face and that simplicial relations are satisfied.

Proposition A.8. [7, 2.3.2], [3] *For A a unital A_∞ category its nerve $\mathcal{A} = N(A)$ is a quasi-category.*

For the reader's convenience we outline the proof here.

Proof. Suppose we have an inner horn $\rho_k : \Lambda_k^n \rightarrow \mathcal{A}$, in particular this determines morphisms in A : f_j , for all j except $j = [n] - \{k\}$ as part of the structure of the face simplices. Set $f_{[n]} = 0$, and set

$$f_{[n] - \{k\}} = \sum_{0 < i < n; i \neq k} f_{[n] - \{i\}} + \sum_s \sum_{\text{decomp}_s \in D[n]} \mu^s(f_{j_1}, \dots, f_{j_s}),$$

then by construction (A.4) is satisfied for the collection of maps $\{f_j\}$. Only thing left to check is that as defined $f_{[n] - \{k\}}$ actually determines the k 'th face of our simplex. A direct calculation for this is long but straightforward, using the A_∞ associativity equations. For $n = 2$ this is automatic and for $n = 3$ this can be checked in a few lines. \square

For $F : A \rightarrow B$ an A_∞ functor we define $NF : NA \rightarrow NB$ via the assignment:

$$f_j \mapsto \sum_{\text{decomp}_s \in D[n_j]} F^s(f_{j_1}, \dots, f_{j_s}).$$

Lemma A.9. [7], [3] *The assignment $A \mapsto NA$, and $F \mapsto NF$ as above, determines a functor*

$$N : A_\infty - \text{Cat}^{\text{unit}} \rightarrow \infty - \text{Cat}.$$

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