Higher algebra of A_∞-algebras in Morse theory

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The results presented in this talk are taken from my two recent papers : *Higher algebra of A_∞ and ΩBAs-algebras in Morse theory I* (arXiv:2102.06654) and *Higher algebra of A_∞ and ΩBAs-algebras in Morse theory II* (arxiv:2102.08996).

The talk will be divided in two parts. First I will define the notion of *higher morphisms between A_∞-algebras*, or *$n - A_\infty$-morphisms*, and explain how they are encoded by new families of polytopes called the *n-multiplihedra*. Then I will show how these higher morphisms can be realized in Morse theory, by counting moduli spaces of perturbed Morse gradient trees.

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   - Higher morphisms between A_∞-algebras
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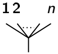
Definition

Let A be a cochain complex with differential m_1. An A_∞-algebra structure on A is the data of a collection of maps of degree $2-n$

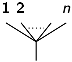
$$m_n : A^{\otimes n} \longrightarrow A \ , \ \ n \geqslant 1,$$

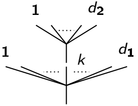
extending m_1 and which satisfy

$$[m_1, m_n] = \sum_{\substack{i_1+i_2+i_3=n \\ 2 \leqslant i_2 \leqslant n-1}} \pm m_{i_1+1+i_3}(\mathrm{id}^{\otimes i_1} \otimes m_{i_2} \otimes \mathrm{id}^{\otimes i_3}).$$

Representing m_n as 

, these equations can be written as

$[m_1,$ 

$] = \sum_{\substack{h+k=n+1 \\ 2\leqslant h\leqslant n-1 \\ 1\leqslant i\leqslant k}} \pm$ 

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These equations are called the A_∞-equations.

In particular,

$$[m_1, m_2] = 0 \ ,$$
$$[m_1, m_3] = m_2(\mathrm{id} \otimes m_2 - m_2 \otimes \mathrm{id}) \ ,$$

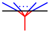
implying that m_2 descends to an associative product on $H^*(A)$. An A_∞-algebra is thus simply a correct notion of a dg-algebra whose product is associative up to homotopy.

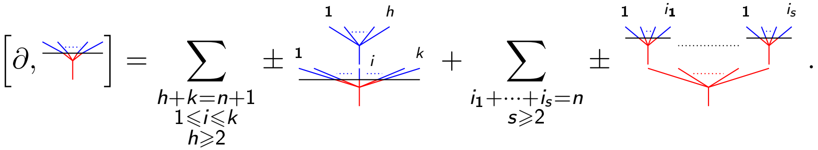
The operations m_n are the higher coherent homotopies which keep track of the fact that the product is associative up to homotopy.

Definition

An A_∞-*morphism* between two A_∞-algebras A and B is a family of maps $f_n : A^{\otimes n} \to B$ of degree $1-n$ satisfying

$$[m_1, f_n] = \sum_{\substack{i_1+i_2+i_3=n \\ i_2 \geqslant 2}} \pm f_{i_1+1+i_3}(\mathrm{id}^{\otimes i_1} \otimes m_{i_2} \otimes \mathrm{id}^{\otimes i_3}) + \sum_{\substack{i_1+\cdots+i_s=n \\ s \geqslant 2}} \pm m_s(f_{i_1} \otimes \cdots \otimes f_{i_s}) \ .$$

Representing the operations f_n as , the operations m_n^A in red and the operations m_n^B in blue, these equations read as



We check that

$$[m_1, f_1] = 0 \ ,$$
$$[m_1, f_2] = f_1 m_2^A - m_2^B(f_1 \otimes f_1) \ .$$

An A_∞-morphism between A_∞-algebras induces a morphism of associative algebras on the level of cohomology, and is a correct notion of morphism which preserves the product up to homotopy.

Given two A_∞-morphisms $F : A \to B$ and $G : B \to C$, we define the composition $G \circ F : A \to C$ as the family of morphisms

$$(G \circ F)_n := \sum_{i_1+\cdots+i_s=n} \pm g_s(f_{i_1} \otimes \cdots \otimes f_{i_s}) \ .$$

This composition is in fact associative. Hence, A_∞-algebras together with A_∞-morphisms form a category, denoted $\mathtt{A}_\infty - \mathtt{alg}$.

The category $\mathtt{A}_\infty - \mathtt{alg}$ provides a framework that behaves well with respect to homotopy-theoretic constructions, when studying homotopy theory of associative algebras. See for instance [Val20] and [LH02].

We illustrate this fact with two fundamental theorems.

Theorem (Homotopy transfer theorem [Kad80])

Let (A, ∂_A) and (H, ∂_H) be two cochain complexes. Suppose that H is a deformation retract of A, that is that they fit into a diagram

$$h \circlearrowright (A, \partial_A) \underset{i}{\overset{p}{\rightleftarrows}} (H, \partial_H) \ ,$$

where $\mathrm{id}_A - ip = [\partial, h]$ and $pi = \mathrm{id}_H$. Then if (A, ∂_A) is endowed with an associative algebra structure, H can be made into an A_∞-algebra such that i and p extend to A_∞-morphisms, that are then A_∞-quasi-isomorphisms.

Theorem (Fundamental theorem of A_∞-quasi-isomorphisms [LH02])

For every A_∞-quasi-isomorphism $f : A \to B$ there exists an A_∞-quasi-isomorphism $B \to A$ which inverts f on the level of cohomology.

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Our goal now : study the *higher algebra of A_∞-algebras*.

Higher algebra is a general term standing for all problems that involve defining coherent sets of *higher homotopies* (also called *n-morphisms*) when starting from a basic homotopy setting.

Considering two A_∞-morphisms F, G, we would like first to determine a notion giving a satisfactory meaning to the sentence "F and G are homotopic". Then, A_∞-homotopies being defined, what is now a good notion of a homotopy between homotopies ? And of a homotopy between two homotopies between homotopies ? And so on.

Definition

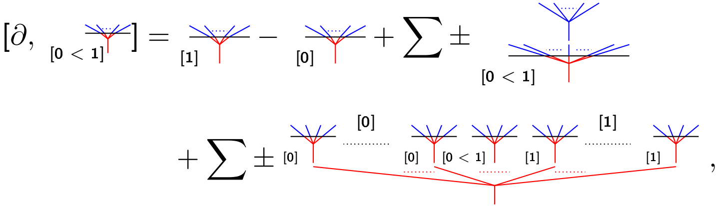
An A_∞-*homotopy* between two A_∞-morphisms $(f_n)_{n\geqslant 1}$ and $(g_n)_{n\geqslant 1}$ is a collection of maps

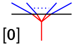
$$h_n : A^{\otimes n} \longrightarrow B \ ,$$

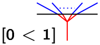
of degree $-n$, satisfying

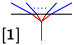
$$[\partial, h_n] = g_n - f_n + \sum_{\substack{i_1+i_2+i_3=m \\ i_2\geqslant 2}} \pm h_{i_1+1+i_3}(\mathrm{id}^{\otimes i_1} \otimes m_{i_2} \otimes \mathrm{id}^{\otimes i_3}) + \sum_{\substack{i_1+\cdots+i_s+l \\ +j_1+\cdots+j_t=n \\ s+1+t\geqslant 2}} \pm m_{s+1+t}(f_{i_1} \otimes \cdots \otimes f_{i_s} \otimes h_l \otimes g_{j_1} \otimes \cdots \otimes g_{j_t}) \ .$$

In symbolic formalism,



where we denote 

, 

and 

respectively for the f_n, the h_n and the g_n.

The relation *being A_∞-homotopic* on the class of A_∞-morphisms is an equivalence relation. It is moreover stable under composition. These results cannot all be proven using naive algebraic tools, some of them require considerations of model categories.

Definition ([MS03])

Let I be a face of Δ^n. An *overlapping partition* of I is a sequence of faces $(I_l)_{1\leqslant \ell \leqslant s}$ of I such that

(i) the union of this sequence of faces is I, i.e. $\cup_{1\leqslant \ell \leqslant s} I_l = I$;

(ii) for all $1 \leqslant \ell < s$, $\max(I_\ell) = \min(I_{\ell+1})$.

An overlapping 6-partition for $[0 < 1 < 2]$ is for instance

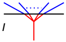
$$[0 < 1 < 2] = [0] \cup [0] \cup [0 < 1] \cup [1] \cup [1 < 2] \cup [2] \ .$$

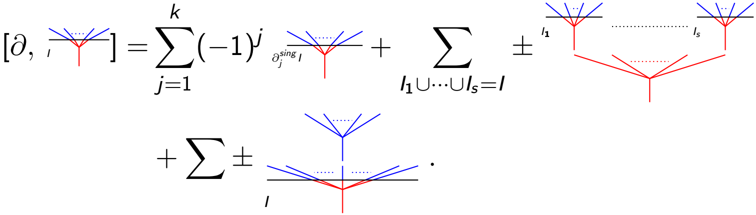
Definition ([Maz21b])

A *n-morphism* from A to B is defined to be a collection of maps $f_I^{(m)} : A^{\otimes m} \longrightarrow B$ of degree $1 - m + |I|$ for $I \subset \Delta^n$ and $m \geqslant 1$, that satisfy

$$\left[\partial, f_I^{(m)}\right] = \sum_{j=0}^{\dim(I)} (-1)^j f_{\partial_j I}^{(m)} + \sum_{\substack{i_1+\cdots+i_s=m \\ I_1\cup\cdots\cup I_s=I \\ s\geqslant 2}} \pm m_s(f_{I_1}^{(i_1)} \otimes \cdots \otimes f_{I_s}^{(i_s)})$$
$$+ (-1)^{|I|} \sum_{\substack{i_1+i_2+i_3=m \\ i_2\geqslant 2}} \pm f_I^{(i_1+1+i_3)}(\mathrm{id}^{\otimes i_1} \otimes m_{i_2} \otimes \mathrm{id}^{\otimes i_3}) .$$

Here we have set $|I| := -\dim(I)$.

Equivalently and more visually, a collection of maps  satisfying



We check that 0-morphisms then correspond to A_∞-morphisms and 1-morphisms correspond to A_∞-homotopies.

We mention that the correct way to define higher morphisms between A_∞-algebras is by using the suspended bar construction $\overline{T}(sA)$. We have the following one-to-one correspondences :

$$\left\{ \begin{array}{c} \text{collections of morphisms of degree } 2-n \\ m_n : A^{\otimes n} \to A \ , \ \ n \geqslant 1, \\ \text{satisfying the } A_\infty\text{-equations} \end{array} \right\}$$
$$\updownarrow$$
$$\left\{ \begin{array}{c} \text{coderivations } D \text{ of degree } +1 \text{ of } \overline{T}(sA) \\ \text{such that } D^2 = 0 \end{array} \right\} ,$$

$$\left\{ \begin{array}{c} \text{collections of morphisms of degree } 1-n \\ f_n : A^{\otimes n} \to B \ , \ n \geqslant 1, \\ \text{satisfying the } A_\infty\text{-equations} \end{array} \right\} \\ \updownarrow \\ \left\{ \begin{array}{c} \text{morphisms of dg-coalgebras} \\ F : \overline{T}(sA) \to \overline{T}(sB) \end{array} \right\} ,$$

$$\left\{ \begin{array}{c} \text{collections of morphisms of degree } 1-m+|I| \\ f_I^{(m)} : A^{\otimes m} \to B \ , \ m \geqslant 1, I \subset \Delta^n, \\ \text{satisfying the } A_\infty\text{-equations} \end{array} \right\} .$$

$$\updownarrow$$

$$\left\{ \begin{array}{c} \text{morphisms of dg-coalgebras} \\ F : \mathbf{\Delta}^n \otimes \overline{T}(sA) \to \overline{T}(sB) \end{array} \right\}$$

where $\mathbf{\Delta}^n$ denotes the cellular chains coalgebra $C_{-*}^{cell}(\Delta^n)$ with coproduct the Alexander-Whitney coproduct.

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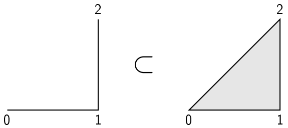
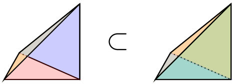
The sets $\mathrm{HOM}_{\mathrm{A}_\infty-\mathrm{alg}}(A,B)_n$ of n-morphisms between two A_∞-algebras A and B fit into a simplicial set $\mathrm{HOM}_{\mathrm{A}_\infty-\mathrm{alg}}(A,B)_\bullet$. It provides a satisfactory framework to study the higher algebra of A_∞-algebras.

Theorem ([Maz21b])

For A and B two A_∞-algebras, the simplicial set $\mathrm{HOM}_{A_\infty}(A,B)_\bullet$ is an ∞-groupoid.

Write Δ^n the simplicial set realizing the standard n-simplex Δ^n, and Λ_n^k the simplicial set realizing the simplicial subcomplex obtained from Δ^n by removing the faces $[0 < \cdots < n]$ and $[0 < \cdots < \widehat{k} < \cdots < n]$. The simplicial set Λ_n^k is called a *horn*, and if $0 < k < n$ it is called an *inner horn*.





The inner horns $\Lambda_2^1 \subset \Delta^2$ and $\Lambda_3^2 \subset \Delta^3$

An ∞-*groupoid* is a simplicial set X which has the left-lifting property with respect to all horn inclusions $\Lambda_n^k \to \Delta^n$.

$$\begin{array}{ccc} \Lambda_n^k & \xrightarrow{u} & X \\ \big\downarrow & \overset{\exists\, \overline{u}}{\nearrow} & \\ \Delta^n & & \end{array}$$

If X has the left-lifting property with respect to all inner horn inclusions one speaks about an ∞-*category*. The vertices of X are then to be seen as objects, and its edges correspond to morphisms. If X is an ∞-groupoid, these morphisms are to be thought as being all invertible up to homotopy.

Theorem ([Maz21b])

For A and B two A_∞-algebras, the simplicial set $\mathrm{HOM}_{A_\infty}(A,B)_\bullet$ is an ∞-groupoid.

Beware that the points of these ∞-groupoids are the A_∞-morphisms, and the arrows between them are the A_∞-homotopies. This can be misleading at first sight, but *the points are the morphisms and NOT the algebras* and *the arrows are the homotopies and NOT the morphisms*.

We point out that the simplicial set $\mathrm{HOM}_{A_\infty}(A,B)_\bullet$ being an ∞-groupoid, it comes in particular with *simplicial homotopy groups* (which are exactly the standard homotopy groups of its geometric realization). The simplicial homotopy groups of $\mathrm{HOM}_{A_\infty}(A,B)_\bullet$ are in fact easily computable and admit a nice combinatorial description.

Moreover, I can explicitly describe all the fillers for any inner horn $\Lambda_n^k \to \mathrm{HOM}_{A_\infty}(A,B)_\bullet$, $0 < k < n$. Beware this is not true for outer horns. This makes in particular $\mathrm{HOM}_{A_\infty}(A,B)_\bullet$ into an *algebraic ∞-category*.

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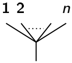
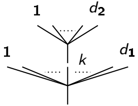
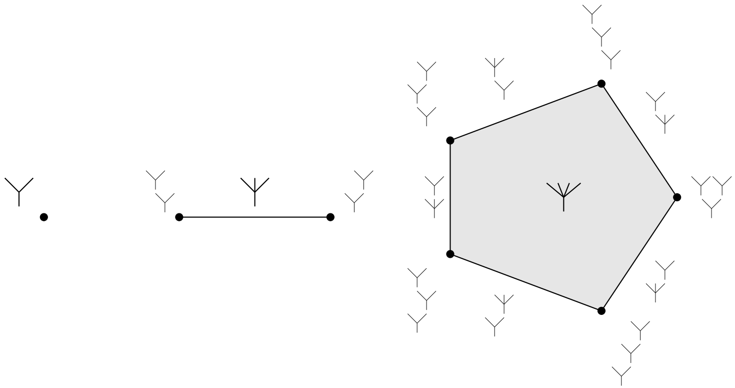
Recall that the A_∞-equations for A_∞-algebras read as

$$[m_1 ,$$  $$] = \sum_{\substack{h+k=n+1 \\ 2 \leqslant h \leqslant n-1 \\ 1 \leqslant i \leqslant k}} \pm$$  .

These equations are encoded by a collection of polytopes, called the *associahedra* and denoted K_n. In particular, the boundary of K_n is given by

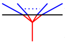
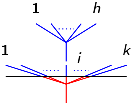
$$\partial K_n = \bigcup_{\substack{h+k=n+1 \\ 2 \leqslant h \leqslant n-1}} \bigcup_{1 \leqslant i \leqslant k} K_k \times_i K_h \ .$$

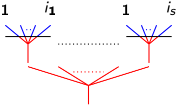
We point out that A_∞-algebras are in fact encoded by an *operad*, called the operad A_∞. The collection of associahedra $\{K_n\}$ are then in fact endowed with a structure of operad in the category `Poly` whose image under the functor C_{-*}^{cell} yields the operad A_∞.



The associahedra K_2, K_3 and K_4, with cells labeled by the operations they define in A_∞

The A_∞-equations for A_∞-morphisms read as

$\partial($  $) = \sum_{\substack{h+k=n+1 \\ 1 \leqslant i \leqslant k \\ h \geqslant 2}} \pm$ 

$+ \sum_{\substack{i_1+\cdots+i_s=n \\ s \geqslant 2}} \pm$ 

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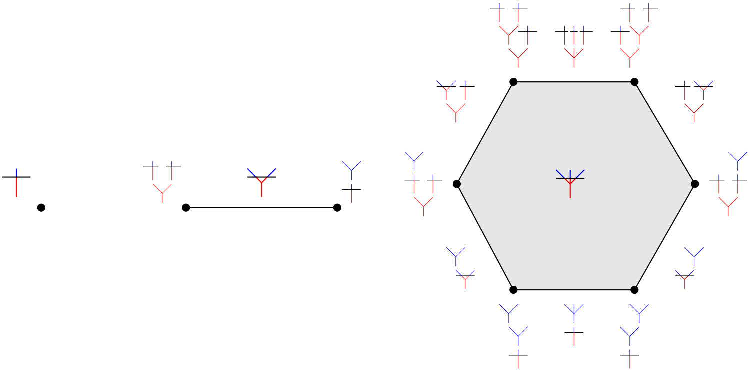
These equations are again encoded by a collection of polytopes, called the *multiplihedra* and denoted J_n. In particular the boundary of J_n is given by

$$\partial J_n = \bigcup_{\substack{h+k=n+1 \\ h \geqslant 2}} \bigcup_{1 \leqslant i \leqslant k} J_k \times_i K_h \cup \bigcup_{\substack{i_1+\cdots+i_s=n \\ s \geqslant 2}} K_s \times J_{i_1} \times \cdots \times J_{i_s} .$$



The multiplihedra J_1, J_2 and J_3 with cells labeled by the operations they define in $A_\infty - \mathrm{Morph}$

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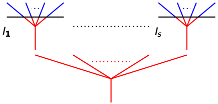
We would like to define a family of polytopes encoding n-morphisms between A_∞-algebras. These polytopes will then be called *n-multiplihedra*.

We have seen that A_∞-morphisms $\overline{T}(sA) \to \overline{T}(sB)$ are encoded by the multiplihedra. n-morphisms being defined as the set of morphisms $\mathbf{\Delta}^n \otimes \overline{T}(sA) \to \overline{T}(sB)$, a natural candidate would thus be $\{\Delta^n \times J_m\}_{m \geqslant 1}$.

However, $\Delta^n \times J_m$ does not fulfill that property as it is. Faces correspond to the data of a face of $I \subset \Delta^n$, and of a broken two-colored tree labeling a face of J_m. This labeling is too coarse, as it does not contain the trees



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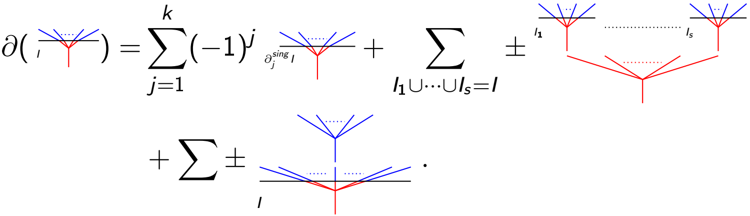
that appear in the A_∞-equations for n-morphisms.

We thus want to lift the combinatorics of overlapping partitions to the level of the n-simplices Δ^n.

Recall that the $n - A_\infty$-equations read as



Proposition ([Maz21b])

There exists a polytopal subdivision of $n - J_m := \Delta^n \times J_m$ such that the boundary of the inner cell $[n - J_m]$ is given by

$$\partial^{sing}[n - J_m] \cup \bigcup_{\substack{h+k=m+1 \\ 1 \leqslant i \leqslant k \\ h \geqslant 2}} [n - J_k] \times_i [K_h] \cup \bigcup_{\substack{i_1+\cdots+i_s=m \\ I_1\cup\cdots\cup I_s=\Delta^n \\ s\geqslant 2}} [K_s] \times [\dim(I_1) - J_{i_1}] \times \cdots \times [\dim(I_s) - J_{i_s}] \ ,$$

where $I_1 \cup \cdots \cup I_s = \Delta^n$ is an overlapping partition of Δ^n.

Definition ([Maz21b])

The *n-multiplihedra* are defined to be the polytopes $\Delta^n \times J_m$ endowed with the previous polytopal subdivision. We denote them $n - J_m$.

In other words, the n-multiplihedra are the polytopes encoding n-morphisms between A_∞-algebras.

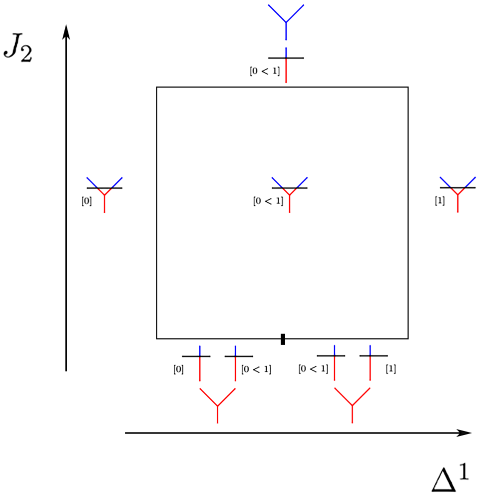


Figure: The 1-multiplihedron $\Delta^1 \times J_2$

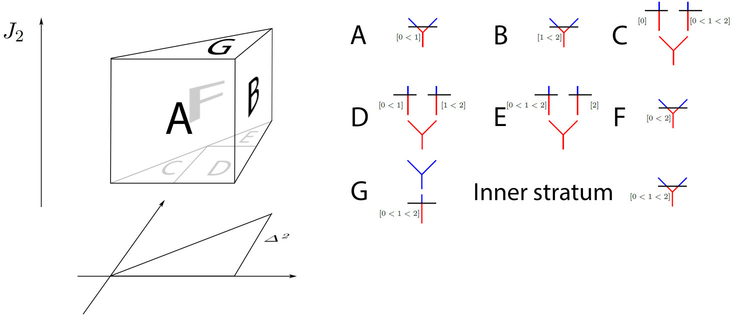


Figure: The 2-multiplihedron $\Delta^2 \times J_2$

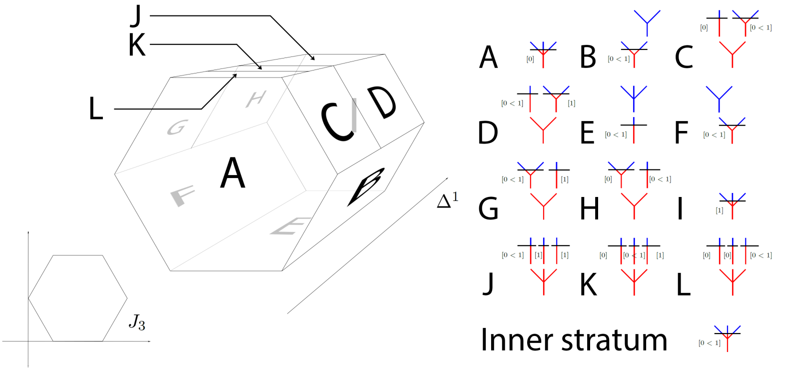


Figure: The 1-multiplihedron $\Delta^1 \times J_3$

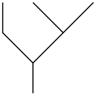
Let M be an oriented closed Riemannian manifold endowed with a Morse function f together with a Morse-Smale metric. The Morse cochains $C^*(f)$ form a deformation retract of the singular cochains $C^*_{sing}(M)$ as shown in [Hut08].

$$h \circlearrowright (C^*_{sing}, \partial_{sing}) \underset{i}{\overset{p}{\rightleftarrows}} (C^*(f), \partial_{Morse}) \ .$$

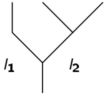
The cup product naturally endows the singular cochains $C^*_{sing}(M)$ with a dg-algebra structure. The homotopy transfer theorem ensures that it can be transferred to an A_∞-algebra structure on the Morse cochains $C^*(f)$.

The differential on the Morse cochains is defined by a count of moduli spaces of gradient trajectories. Is it then possible to define higher multiplications m_n on $C^*(f)$ by a count of moduli spaces such that they fit in a structure of A_∞-algebra ?

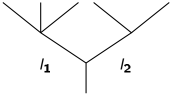
Question solved for the first time by Abouzaid in [Abo11], drawing from earlier works by Fukaya ([Fuk97] for instance). See also [Mes18] and [AL18]. In [Maz21a] I prove that this A_∞-algebra structure actually stems from an ΩBAs-algebra structure, but I will not dwell on that notion today.



A ribbon tree



A metric ribbon tree



A stable metric ribbon tree

Definition

Define $\mathcal{T}_n$ to be *moduli space of stable metric ribbon trees with n incoming edges*. For each stable ribbon tree type t, we define moreover $\mathcal{T}_n(t) \subset \mathcal{T}_n$ to be the moduli space

$$\mathcal{T}_n(t) := \{\text{stable metric ribbon trees of type } t\} \ .$$

We then have that

$$\mathcal{T}_n = \bigcup_{t \in SRT_n} \mathcal{T}_n(t) \ .$$

Allowing lengths of internal edges to go to $+\infty$, this moduli space can be compactified into a $(n-2)$-dimensional CW-complex $\overline{\mathcal{T}}_n$, where $\mathcal{T}_n$ is seen as its unique $(n-2)$-dimensional stratum.

Theorem

The compactified moduli space $\overline{\mathcal{T}}_n$ is isomorphic as a CW-complex to the associahedron K_n.

This was first noticed in section 1.4. of Boardman-Vogt [BV73].

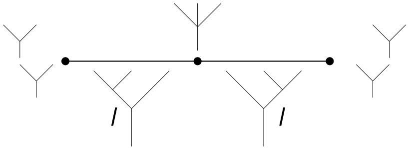


Figure: The compactified moduli space $\overline{\mathcal{T}}_3$

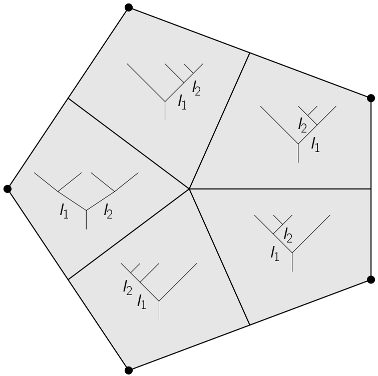
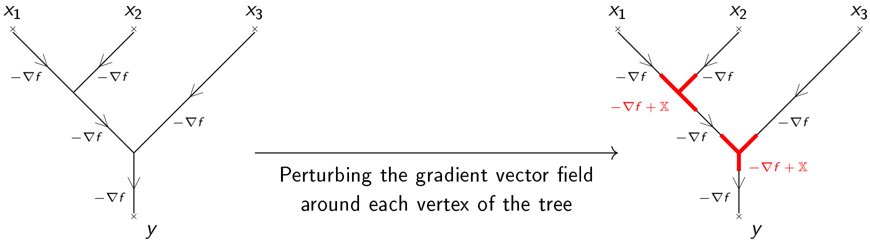


Figure: The compactified moduli space $\overline{\mathcal{T}}_4$

The goal is now to realize these moduli spaces of stable metric ribbon trees in Morse theory.



Definition

$T := (t, \{l_e\}_{e \in E(t)})$ where $\{l_e\}_{e \in E(t)}$ are the lengths of its internal edges of the tree t. *Choice of perturbation data* on T consists of the following data :

(i) a vector field $[0, l_e] \times M \underset{\mathbb{X}_e}{\longrightarrow} TM$, that vanishes on $[1, l_e - 1]$, for every internal edge e of t ;

(ii) a vector field $[0, +\infty[\times M \underset{\mathbb{X}_{e_0}}{\longrightarrow} TM$, that vanishes away from $[0, 1]$, for the outgoing edge e_0 of t ;

(iii) a vector field $]-\infty, 0] \times M \underset{\mathbb{X}_{e_i}}{\longrightarrow} TM$, that vanishes away from $[-1, 0]$, for every incoming edge e_i $(1 \leqslant i \leqslant n)$ of t.

We will write D_e for all segments $[0, l_e]$ as well as for all semi-infinite segments $]-\infty, 0]$ and $[0, +\infty[$ in the rest of the talk.

Definition ([Abo11])

A *perturbed Morse gradient tree* T^{Morse} associated to $(T, \mathbb{X})$ is the data for each edge e of t of a smooth map $\gamma_e : D_e \to M$ such that γ_e is a trajectory of the perturbed negative gradient $-\nabla f + \mathbb{X}_e$, i.e.

$$\dot{\gamma}_e(s) = -\nabla f(\gamma_e(s)) + \mathbb{X}_e(s, \gamma_e(s)) \ ,$$

and such that the endpoints of these trajectories coincide as prescribed by the edges of the tree T.

Definition

Let $\mathbb{X}_n$ be a smooth choice of perturbation data on $\mathcal{T}_n$. For critical points y and $x_1, \dots, x_n$, we define the moduli space

$$\mathcal{T}_n^{\mathbb{X}_n}(y; x_1, \dots, x_n) := \left\{ \begin{array}{c} \text{perturbed Morse gradient trees associated to } (T, \mathbb{X}_T) \\ \text{and connecting } x_1, \dots, x_n \text{ to } y, \text{ for } T \in \mathcal{T}_n \end{array} \right\}.$$

Proposition

Given a generic choice of perturbation data $\mathbb{X}_n$, the moduli space $\mathcal{T}_n^{\mathbb{X}_n}(y; x_1, \dots, x_n)$ is an orientable manifold of dimension

$$\dim\left(\mathcal{T}_n(y; x_1, \dots, x_n)\right) = n - 2 + |y| - \sum_{i=1}^{n} |x_i| \ .$$

Choose perturbation data $\mathbb{X}_n$ on each moduli space $\mathcal{T}_n$ for $n \geqslant 2$. By assuming some gluing-compatibility conditions on $(\mathbb{X}_n)_{n\geqslant 2}$, the 1-dimensional moduli spaces $\mathcal{T}_n(y; x_1, \dots, x_n)$ can be compactified to manifolds with boundary whose boundary is given by the spaces

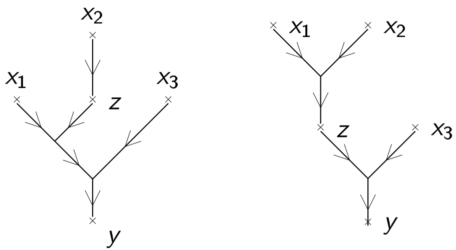
(i) corresponding to an internal edge breaking :

$$\mathcal{T}_{i_1+1+i_3}^{\mathbb{X}_{i_1+1+i_3}}(y; x_1, \dots, x_{i_1}, z, x_{i_1+i_2+1}, \dots, x_n) \times \mathcal{T}_{i_2}^{\mathbb{X}_{i_2}}(z; x_{i_1+1}, \dots, x_{i_1+i_2}),$$

where$i_1 + i_2 + i_3 = n$ and the trees of arity i_2 are seen to lie above the $i_1 + 1$-incoming edge of the trees of arity $i_1 + 1 + i_3$;

(ii) corresponding to an external edge breaking :

$$\mathcal{T}(y; z) \times \mathcal{T}_n^{\mathbb{X}_n}(z; x_1, \dots, x_n) \text{ and } \mathcal{T}_n^{\mathbb{X}_n}(y; x_1, \dots, z, \dots, x_n) \times \mathcal{T}(z; x_i)$$



Two examples of perturbed Morse gradient trees breaking at a critical point

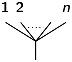
Theorem ([Abo11])

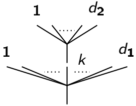
For an admissible choice of perturbation data $\mathbb{X} := (\mathbb{X}_n)_{n \geqslant 2}$, defining for every n the operation m_n as

$$\begin{aligned} m_n : C^*(f) \otimes \cdots \otimes C^*(f) &\longrightarrow C^*(f) \\ x_1 \otimes \cdots \otimes x_n &\longmapsto \sum_{|y| = \sum_{i=1}^n |x_i| + 2 - n} \# \mathcal{T}_n^{\mathbb{X}}(y; x_1, \cdots, x_n) \cdot y \ , \end{aligned}$$

they endow the Morse cochains $C^*(f)$ with an A_∞-algebra structure.

Indeed, the boundary of the previous compactification is modeled on the A_∞-equations for A_∞-algebras :

$[\partial_{Morse},$ 

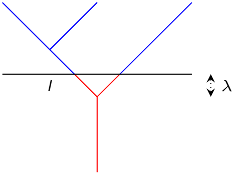
$] = \sum_{\substack{h+k=n+1 \\ 2 \leqslant h \leqslant n-1 \\ 1 \leqslant i \leqslant k}} \pm$ 

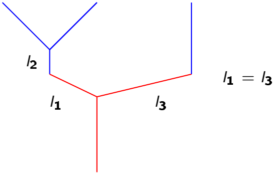
.

Consider an additional Morse function g on the manifold M. Our goal is now to construct an A_∞-morphism from the Morse cochains $C^*(f)$ to the Morse cochains $C^*(g)$, through a count of moduli spaces of perturbed Morse trees. While we considered stable metric ribbon trees to construct and A_∞-algebra structure, we will this time consider stable two-colored metric ribbon trees to define our A_∞-morphism.

Definition

A *stable two-colored metric ribbon tree* or *stable gauged metric ribbon tree* is defined to be a stable metric ribbon tree together with a length $\lambda \in \mathbb{R}$. This length is to be thought of as a gauge drawn over the metric tree, at distance λ from its root, where the positive direction is pointing down.





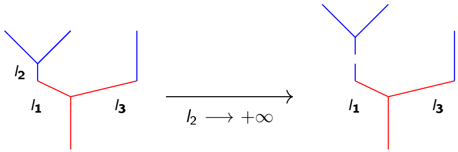
Definition

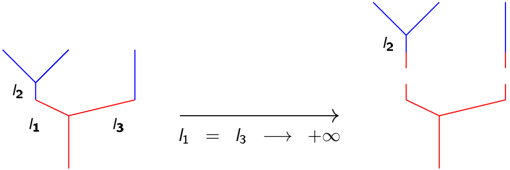
For $n \geqslant 2$, we define $\mathcal{CT}_n$ to be the *moduli space of stable two-colored metric ribbon trees*. It has a cell decomposition by stable two-colored ribbon tree type,

$$\mathcal{CT}_n = \bigcup_{t_c \in SCRT_n} \mathcal{CT}_n(t_c) \ .$$

We also denote $\mathcal{CT}_1 :=$ {  } the space whose only element is the unique two-colored ribbon tree of arity 1.

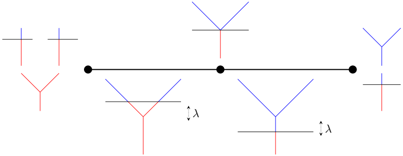
Allowing again internal edges of metric trees to go to $+\infty$, this moduli space $\mathcal{CT}_n$ can be compactified into a $(n-1)$-dimensional CW-complex $\overline{\mathcal{CT}}_n$.



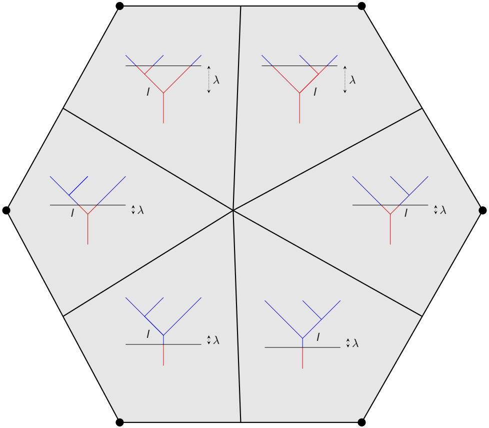


Theorem ([MW10])

The compactified moduli space $\overline{\mathcal{CT}}_n$ is isomorphic as a CW-complex to the multiplihedron J_n.



The compactified moduli space $\overline{\mathcal{CT}}_2$ with its cell decomposition by stable two-colored ribbon tree type



The compactified moduli space $\overline{\mathcal{CT}}_3$ with its cell decomposition by stable two-colored ribbon tree type

Definition

A *two-colored perturbed Morse gradient tree* T_g^{Morse} associated to a pair two-colored metric ribbon tree and perturbation data $(T_g, \mathbb{Y})$ is the data

(i) for each edge f_c of t_c which is above the gauge, of a smooth map

$$D_{f_c} \xrightarrow[\gamma_{f_c}]{} M \ ,$$

such that γ_{f_c} is a trajectory of the perturbed negative gradient $-\nabla f + \mathbb{Y}_{f_c}$,

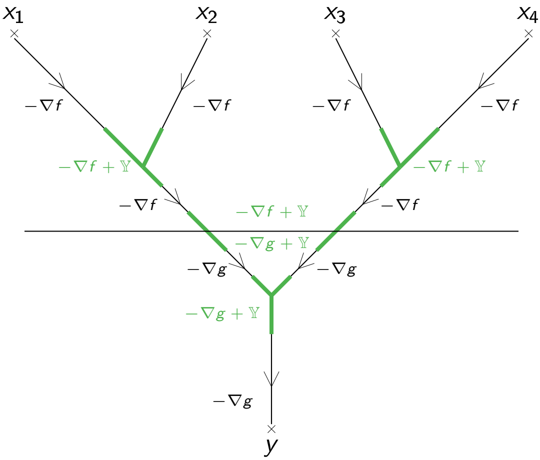
Definition

(ii) for each edge f_c of t_c which is below the gauge, of a smooth map

$$D_{f_c} \xrightarrow[\gamma_{f_c}]{} M ,$$

such that γ_{f_c} is a trajectory of the perturbed negative gradient $-\nabla g + \mathbb{Y}_{f_c}$,

and such that the endpoints of these trajectories coincide as prescribed by the edges of the two-colored tree type.



An example of a perturbed two-colored Morse gradient tree, where the x_i are critical points of f and y is a critical point of g

Definition

Let $\mathbb{Y}_n$ be a smooth choice of perturbation data on the moduli space $\mathcal{CT}_n$. Given $y \in \mathrm{Crit}(g)$ and $x_1, \dots, x_n \in \mathrm{Crit}(f)$, we define the moduli spaces

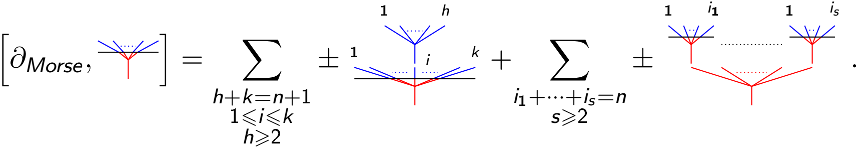
$$\mathcal{CT}_n^{\mathbb{Y}_n}(y; x_1, \dots, x_n) :=$$
$$\left\{ \begin{array}{l} \text{two-colored perturbed Morse gradient trees associated to} \\ (T_g, \mathbb{Y}_{T_g}) \text{ and connecting } x_1, \dots, x_n \text{ to } y \text{ for } T_g \in \mathcal{CT}_n \end{array} \right\} .$$

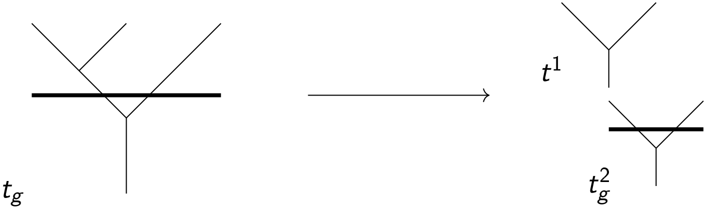
Proposition

Given a generic choice of perturbation data $\mathbb{Y}_n$, the moduli spaces $\mathcal{CT}_n^{\mathbb{Y}_n}(y; x_1, \ldots, x_n)$ are orientable manifolds of dimension

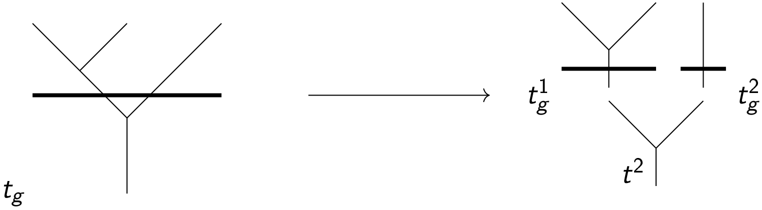
$$\dim\left(\mathcal{CT}_n(y; x_1, \ldots, x_n)\right) = |y| - \sum_{i=1}^{n} |x_i| + n - 1 \ .$$

Given perturbation data $\mathbb{X}^f$ and $\mathbb{X}^g$ for the functions f and g, by assuming some gluing-compatibility conditions for a choice of perturbation data $\mathbb{Y}_n$ for all $n \geqslant 1$, the 1-dimensional moduli spaces $\mathcal{CT}_n^{\mathbb{Y}_n}(y; x_1, \dots, x_n)$ can be compactified into manifolds with boundary whose boundary is modeled on the A_∞-equations for A_∞-morphisms :





(above-break)



(below-break)

Theorem ([Maz21a])

Let $\mathbb{X}^f$, $\mathbb{X}^g$ and $(\mathbb{Y}_n)_{n\geqslant 1}$ be generic choices of perturbation data. Defining for every n the operation μ_n as

$$\mu_n^{\mathbb{Y}} : C^*(f) \otimes \cdots \otimes C^*(f) \longrightarrow C^*(g)$$
$$x_1 \otimes \cdots \otimes x_n \longmapsto \sum_{|y|=\sum_{i=1}^n |x_i|+1-n} \#\mathcal{CT}_n^{\mathbb{Y}}(y; x_1, \cdots, x_n) \cdot y \ .$$

they fit into an A_∞-morphism $\mu^{\mathbb{Y}} : (C^*(f), m_n^{\mathbb{X}^f}) \to (C^*(g), m_n^{\mathbb{X}^g})$.

Again, I prove in [Maz21a] that this A_∞-morphism actually stems from an ΩBAs-morphism between the ΩBAs-algebras $C^*(f)$ and $C^*(g)$.

Endowing the Morse cochains $C^*(f)$ and $C^*(g)$ with their A_∞-algebra structures, we now prove that one can always construct n-A_∞-morphisms between $C^*(f)$ and $C^*(g)$ by counting suitable moduli spaces of perturbed Morse gradient trees.

While the spaces parametrizing the perturbation data were the $\mathcal{T}_m$ (a model for the associahedra K_m) and the $\mathcal{CT}_m$ (a model for the multiplihedra J_m), perturbation data will now be parametrized by the n-multiplihedra $\Delta^n \times \mathcal{CT}_m$.

Definition

A *n-simplex of perturbation data* for a two-colored metric ribbon tree T_g is defined to be a choice of perturbation data $\mathbb{Y}_{\delta,T_g}$ for every $\delta \in \mathring{\Delta}^n$. We will denote it as $\mathbb{Y}_{\Delta^n,T_g} := \{\mathbb{Y}_{\delta,T_g}\}_{\delta\in\mathring{\Delta}^n}$.

Definition

Let $\mathbb{Y}_{\Delta^n,m}$ be a n-simplex of perturbation data on $\mathcal{CT}_m$. Given $y \in \mathrm{Crit}(g)$ and $x_1, \ldots, x_m \in \mathrm{Crit}(f)$, we define the moduli spaces

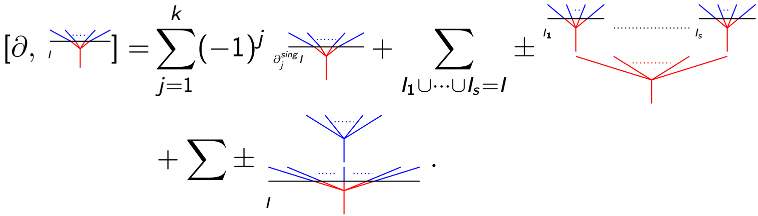
$$\mathcal{CT}_{\Delta^n,m}^{\mathbb{Y}_{\Delta^n,m}}(y; x_1, \ldots, x_m) := \bigcup_{\delta \in \mathring{\Delta}^n} \mathcal{CT}_m^{\mathbb{Y}_{\delta,m}}(y; x_1, \ldots, x_m) .$$

Proposition ([Maz21b])

Under a generic choice of n-simplex of perturbation data $\mathbb{Y}_{\Delta^n,m}$, the moduli space $\mathcal{CT}_{\Delta^n,m}(y; x_1, \ldots, x_m)$ is an orientable manifold of dimension

$$\dim\left(\mathcal{CT}_{\Delta^n,m}(y; x_1, \ldots, x_m)\right) = n + m - 1 + |y| - \sum_{i=1}^{m} |x_i| \ .$$

Choose perturbation data $\mathbb{X}^f$ and $\mathbb{X}^g$ for the functions f and g together with perturbation data $(\mathbb{Y}_{I,m})^{m \geqslant 1}_{I \subset \Delta^n}$. By assuming some gluing-compatibility conditions on $(\mathbb{Y}_{I,m})^{m \geqslant 1}_{I \subset \Delta^n}$ *modeling the combinatorics of overlapping partitions*, the 1-dimensional moduli spaces $\mathcal{CT}^{\mathbb{Y}_{I,m}}_{I,m}(y; x_1, \dots, x_m)$ can be compactified into manifolds with boundary whose boundary is modeled on the A_∞-equations for n-morphisms :



Theorem ([Maz21b])

Let $\mathbb{X}^f$, $\mathbb{X}^g$ and $(\mathbb{Y}_{I,m})_{I \subset \Delta^n}^{m \geqslant 1}$ be generic choices of perturbation data. Defining for every m the operation $\mu_I^{(m)}$ as

$$\begin{aligned} C^*(f) \otimes \cdots \otimes C^*(f) &\xrightarrow{\mu_I^{(m)}} C^*(g) \\ x_1 \otimes \cdots \otimes x_m &\longmapsto \\ &\sum_{|y| = \sum_{i=1}^m |x_i| + 1 - m + |I|} \# \mathcal{CT}_{I,m}^{\mathbb{Y}_{I,m}}(y; x_1, \cdots, x_m) \cdot y , \end{aligned}$$

they fit into a n-morphism $\mu_I^{\mathbb{Y}} : (C^*(f), m_n^{\mathbb{X}^f}) \to (C^*(g), m_n^{\mathbb{X}^g})$, $I \subset \Delta^n$.

Again, I prove in [Maz21b] that this n-A_∞-morphism actually stems from a n-ΩBAs-morphism between the ΩBAs-algebras $C^*(f)$ and $C^*(g)$.

Theorem ([Maz21b])

For every admissible choice of perturbation data $\mathbb{Y}_S$ parametrized by a simplicial subcomplex $S \subset \Delta^n$, there exists an admissible n-simplex of perturbation data $\mathbb{Y}_{\Delta^n}$ extending $\mathbb{Y}_S$.

The simplicial set $\mathrm{HOM}_{A_\infty}(C^*(f), C^*(g))_\bullet$ being an ∞-groupoid, we know that every horn $\Lambda^k_n \to \mathrm{HOM}_{A_\infty}(C^*(f), C^*(g))_\bullet$ admits an *algebraic* filler

$$\begin{array}{ccc} \Lambda^k_n & \xrightarrow{\mu} & \mathrm{HOM}_{A_\infty}(C^*(f), C^*(g))_\bullet \\ \big\downarrow & \overset{\overline{\mu}}{\nearrow} & \\ \Delta^n & & \end{array} .$$

The previous theorem tells us that when μ stems from a choice of perturbation data, this diagram can always be filled *geometrically*, by directly filling the horn of perturbation data.

Corollary ([Maz21b])

Let $\mathbb{Y}$ and $\mathbb{Y}'$ be two admissible choices of perturbation data on the moduli spaces $\mathcal{CT}_m$. The A_∞-morphisms $\mu^{\mathbb{Y}}$ and $\mu^{\mathbb{Y}'}$ are then A_∞-homotopic

$$C^*(f) \underset{\mu^{\mathbb{Y}'}}{\overset{\mu^{\mathbb{Y}}}{\rightrightarrows}} C^*(g) \quad (\Downarrow) \; .$$

Indeed, these two choices of perturbation data correspond to a choice of perturbation data parametrized by the simplicial subcomplex of Δ^1 consisting of its two vertices.

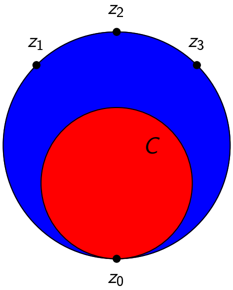
1 Higher algebra of A_∞-algebras ...

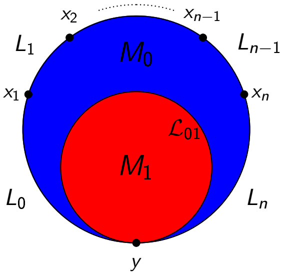
2 ... in Morse theory

3 Further directions

4 References

1. It is quite clear that given two compact symplectic manifolds M and N, one should be able to construct n-morphisms between their Fukaya categories $\mathrm{Fuk}(M)$ and $\mathrm{Fuk}(N)$ through counts of moduli spaces of quilted disks (see [MWW18] for the $n = 0$ case).



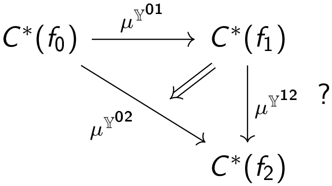


2. Given three Morse functions f_0, f_1, f_2, choices of perturbation data $\mathbb{X}^i$, and choices of perturbation data $\mathbb{Y}^{ij}$ defining morphisms

$$\mu^{\mathbb{Y}^{01}} : (C^*(f_0), m_n^{\mathbb{X}^0}) \longrightarrow (C^*(f_1), m_n^{\mathbb{X}^1}) ,$$
$$\mu^{\mathbb{Y}^{12}} : (C^*(f_1), m_n^{\mathbb{X}^1}) \longrightarrow (C^*(f_2), m_n^{\mathbb{X}^2}) ,$$
$$\mu^{\mathbb{Y}^{02}} : (C^*(f_0), m_n^{\mathbb{X}^0}) \longrightarrow (C^*(f_2), m_n^{\mathbb{X}^2}) ,$$

can we construct an A_∞-homotopy such that $\mu^{\mathbb{Y}^{12}} \circ \mu^{\mathbb{Y}^{01}} \simeq \mu^{\mathbb{Y}^{02}}$ through this homotopy ? (work in progress ; see also [MWW18] for a similar question)

That is, can the following cone be filled in the A_∞ realm



3. Links between the n-multiplihedra and the 2-associahedra of Bottman (see [Bot19a] and [Bot19b] for instance) ? We are currently inspecting this matter with Nate Bottman.

4. We would like to see the simplicial sets $\mathrm{HOM}_{\mathtt{A}_\infty - \mathtt{alg}}(A, B)_\bullet$ as part of a simplicial enrichment of the category $\mathtt{A}_\infty - \mathtt{alg}$. In other words, we would like to define simplicial maps

$$\mathrm{HOM}_{\mathtt{A}_\infty - \mathtt{alg}}(A, B)_n \times \mathrm{HOM}_{\mathtt{A}_\infty - \mathtt{alg}}(B, C)_n \longrightarrow \mathrm{HOM}_{\mathtt{A}_\infty - \mathtt{alg}}(A, C)_n ,$$

lifting the composition on the $\mathrm{HOM}_0 = \mathrm{Hom}$.

This would then endow $\mathtt{A}_\infty - \mathtt{alg}$ with a structure of ∞-category.

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