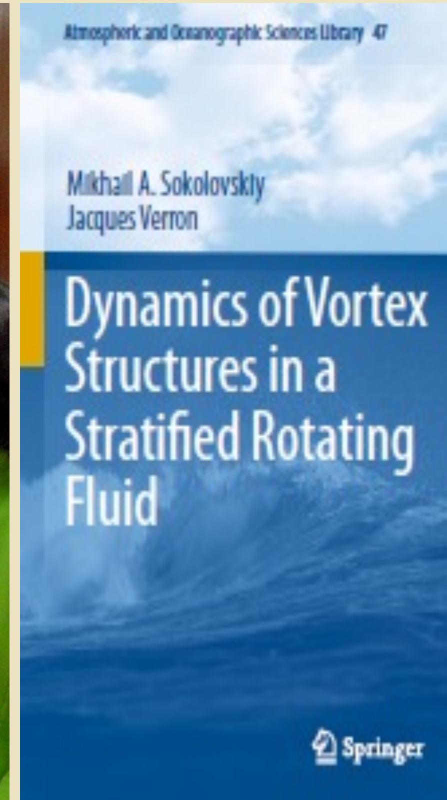
Surface and subsurface dynamics of two vortex patches

M.A. Sokolovskiy[a,b], J. Verron[c], and X. Carton[d]

[a] ***Institute of Water Problems of RAS; Moscow, Russia***
[b] ***P.P. Shirshov Institute of Oceanology of RAS; Moscow, Russia***
[c] ***Laboratoire de Glaciologie et Géophysique de l'Environnement, CNRS/UJF, Grenoble, France***
[d] ***Laboratoire de Physique des Océans, UBO, Brest, France***


М. А. Соколовский, Ж. Веррон
ДИНАМИКА
ВИХРЕВЫХ СТРУКТУР
В СТРАТИФИЦИРОВАННОЙ
ВРАЩАЮЩЕЙСЯ
ЖИДКОСТИ


Atmospheric and Oceanographic Sciences Library 47
Mikhail A. Sokolovskiy
Jacques Verron
Dynamics of Vortex
Structures in a
Stratified Rotating
Fluid
Springer

Dedicated

to the blessed memory of
Professor Vadim Fedorovich Kozlov,
the Founder of Far Eastern School
of Geophysical Fluid Dynamics,
Vladivostok, Russia
(1933–2005)

and

to Emil Hopfinger,
Directeur de Recherche CNRS,
Ex-Director of Laboratoire des Ecoulements
Géophysiques et Industriels,
Grenoble, France

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BOOK REVIEW

Dynamics of Vortex Structures in a Stratified Rotating Fluid, by
Mikhail A. Sokolovskiy and JacquesVerron, Atmospheric and Oceanographic Sciences Library, Springer International Publishing, Switzerland, 2014, XII + 382 pp., £$179.00 (hardback), ISBN 978-3-319-00788-5, (eBook) ISBN 978-3-319-00789-2.

Appendix A
E.J. Hopfinger. Experimental Study of Hetons

This Appendix is a summary of the experiments with hetons, conducted by Griffiths and Hopfinger [309, 310], aimed at illustrating heton generation in the laboratory. These experiments were motivated by the work of Hogg and Stommel [350, 351] who considered discrete, baroclinic geostrophic vortices that have the capacity of transporting heat. Real vortices have a finite core size and it was of interest to compare experiments with the theoretical, idealized point vortex solutions. Numerical solutions of, finite core size geostrophic vortices have followed and are presented in this book.

Griffiths and Hopfinger [309, 310] considered the simplest situation of a rotating, two layer stratified fluid in a tank 100 cm in diameter and 45 cm deep with the fluid layers being of equal depth, $H = 20$ cm. The rotating tank was first filled with fresh water to 20 cm depth and then a sugar solution of desired density was slowly injected through a tube placed near the sidewall at the bottom of the tank. When the lower, denser layer reached 20 cm the system was left to spin-up to solid body rotation. It needs to be mentioned that the two layer system never reached complete solid body rotation. A weak azimuthal drift, generally <3% of the tank rotation, remained that switched from being axisymmetric to non-axisymmetric and reverse. Griffiths and Linden [312] interpreted this drift as being the result of a meridional Eddington-Sweet circulation, driven by the diffusion of solute across the isopycnals. The use of sugar solution instead of salt solution reduced this diffusion, hence the importance of this circulation. Lower diffusion resulted also in a thinner interface thickness, which was close to 2 cm at the time when the heton experiments were stared. The tank rotation was $\Omega = 1.0$ rad s^{-1} ($f = 2s^{-1}$) and the reduced gravity $g' = g\Delta\rho/\rho$ was chosen such that the internal Rossby radius of deformation $\lambda' = (g'H)^{1/2}/f = 5$, 10 and 15 cm. Note that the Rossby radius λ used in this book is defined as $\lambda = [g'h_1h_2/(h_1 + h_2)]^{1/2}/f$, hence, when $h_1 = h_2 = H$, $\lambda = \lambda'/\sqrt{2}$.

The vortices in this two layer stratified, rotating system were generated by sources (anticyclones) and sinks (cyclones) placed at the free surface or the bottom. These vortices have a core radius R' of about 4 cm at which the azimuthal velocity is maximum. The vortex strength is a function of the flow rate. With sinks strong

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Classical problem: interaction of two identical vortices

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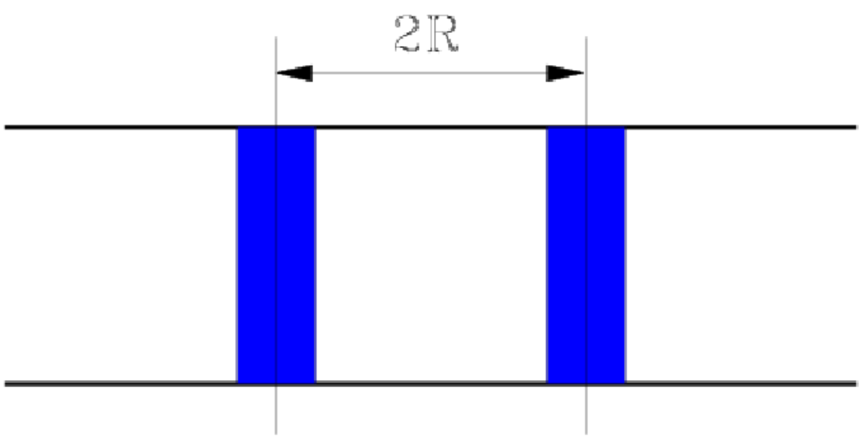
VORTICES IN ROTATING FLUIDS

E.J. Hopfinger

Institut de Mécanique-LEGI, U.J.F. et CNRS, B.P.53, 38041 Grenoble Cédex, France

G.J.F. van Heijst

Department of Technical Physics, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands



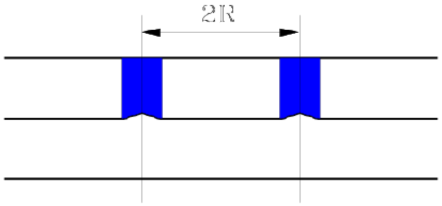
$R_{cr} \approx 1.6$

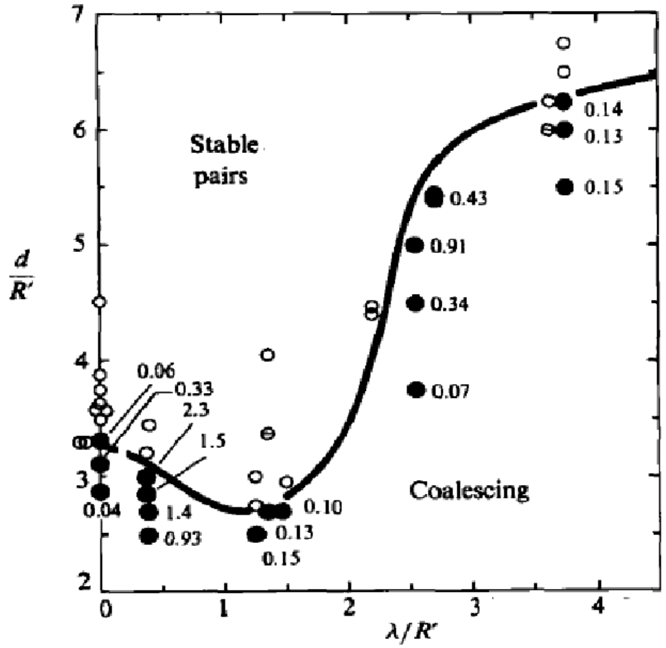
Geophysical problem: interaction of two identical vortices of upper layer in two-layer rotating fluid

J. Fluid Mech. (1987), *vol.* 178, *pp* . 73-97

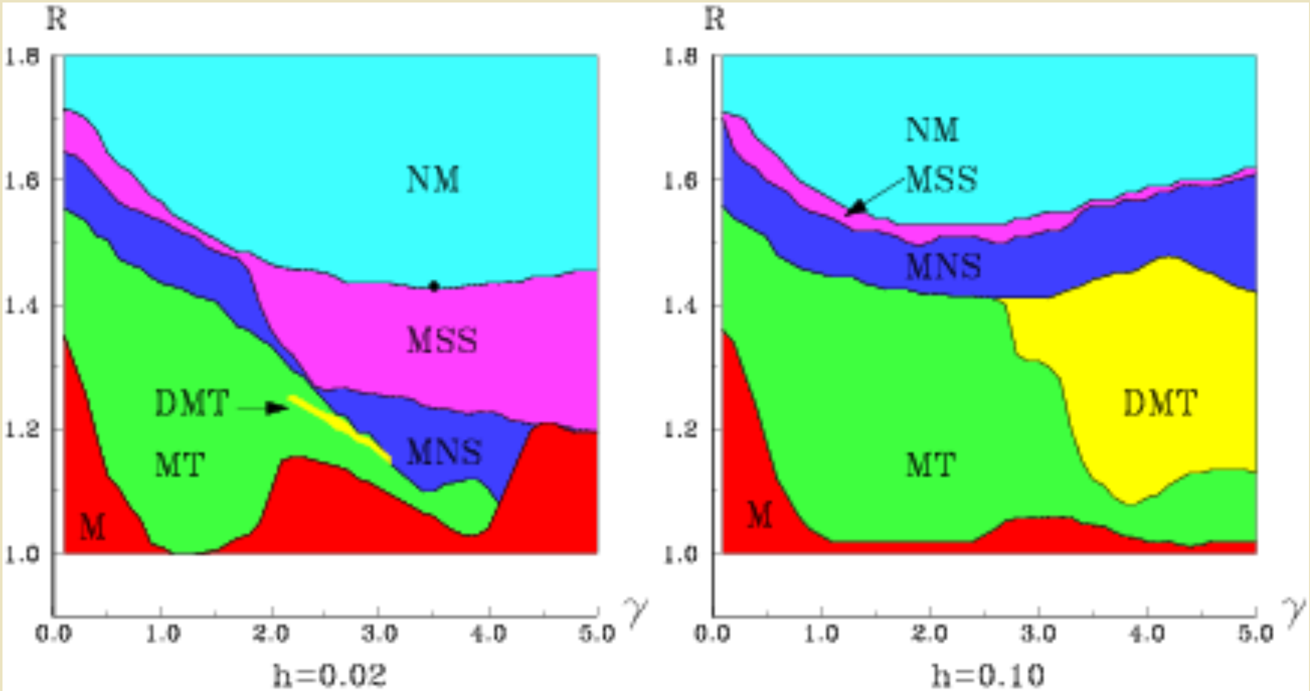
Coalescing of geostrophic vortices

By R. W. GRIFFITHS
Research School of Earth Sciences, Australian National University, GPO Box 4, Canberra, A.C.T. 2001. Australia
and E. J. HOPFINGER
Institut de Mecanique, Laboratoire Associé au C.N.R.S., Université de Grenoble, B.P. 68, 38402 St. Martin d'Heres, France





CDM-modeling of interaction of two cyclones of upper layer in two-layer rotating fluid: diagrams of states



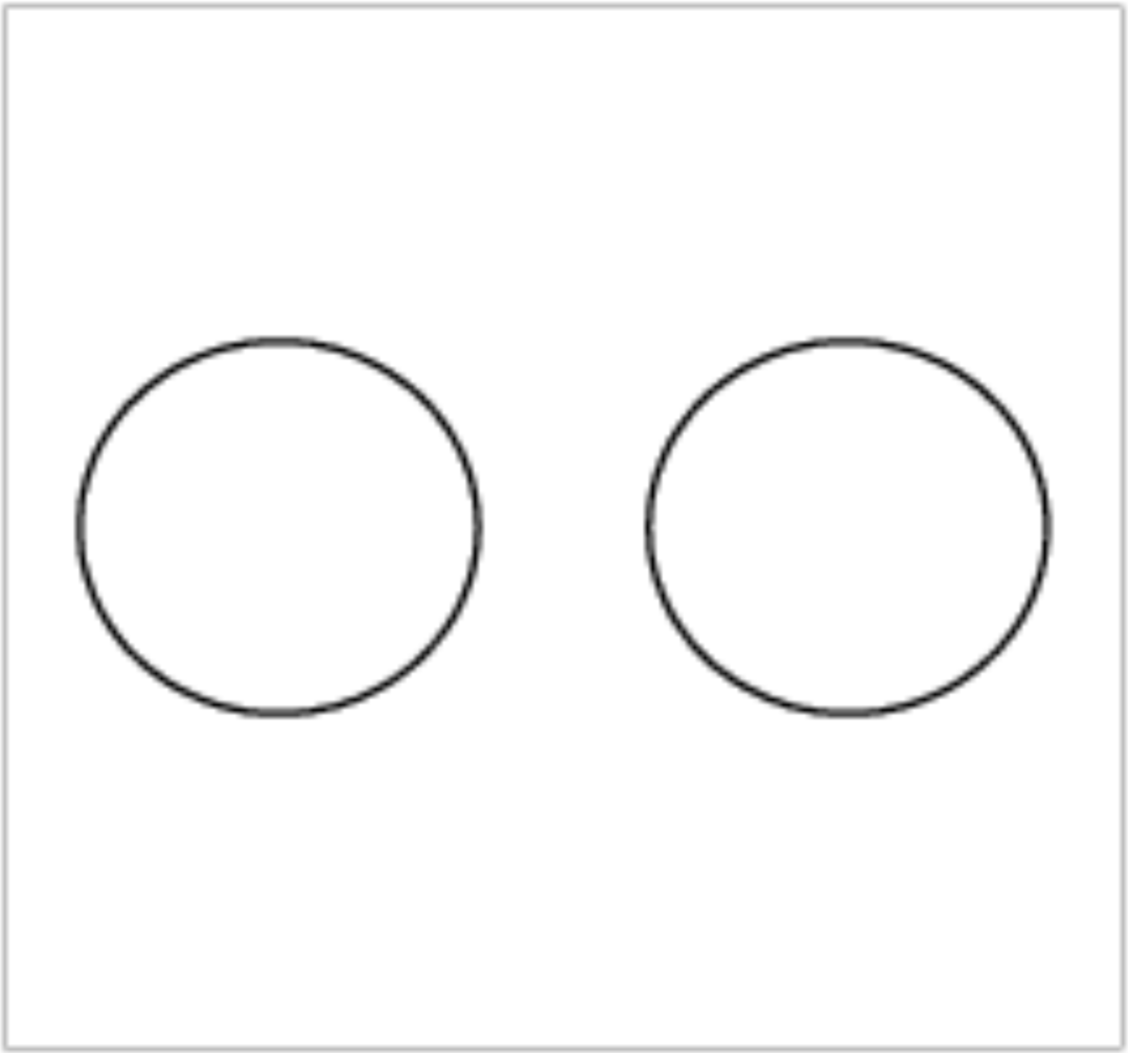
Diagrams in the rectangular domain of plane (γ, R) of possible states of two circular vortices of upper layer with the specified values of the upper-layer thickness: M (merger) - a state, when after the merging of the vortex patches and a short intermediate stage of the thin vortex-line formation, there remains one compact vortex of larger scale. MT (merger/triplet) - merging of vortex patches, and the subsequent formation of a triplet composed of a large central vortex and two peripheral smaller like signed vortices. DMT (double merger/triplet) - the first stage of the evolution is similar to that of MT but later, a new vortex merger occurs leading to the birth of a new triplet. MNS (merger/non-symmetric separation) - a merging, followed by separation into unequal vortex patches. MSS (merger/symmetric separation) - the division is symmetrical, i.e. after a temporary merging, two identical vortex patches are formed again. NM (no merger) - vortex patches, pulsating, rotate around a common center of vorticity without merging.

h_1=0.02

γ=3.5, R=1.43

(NM-type)

t=0



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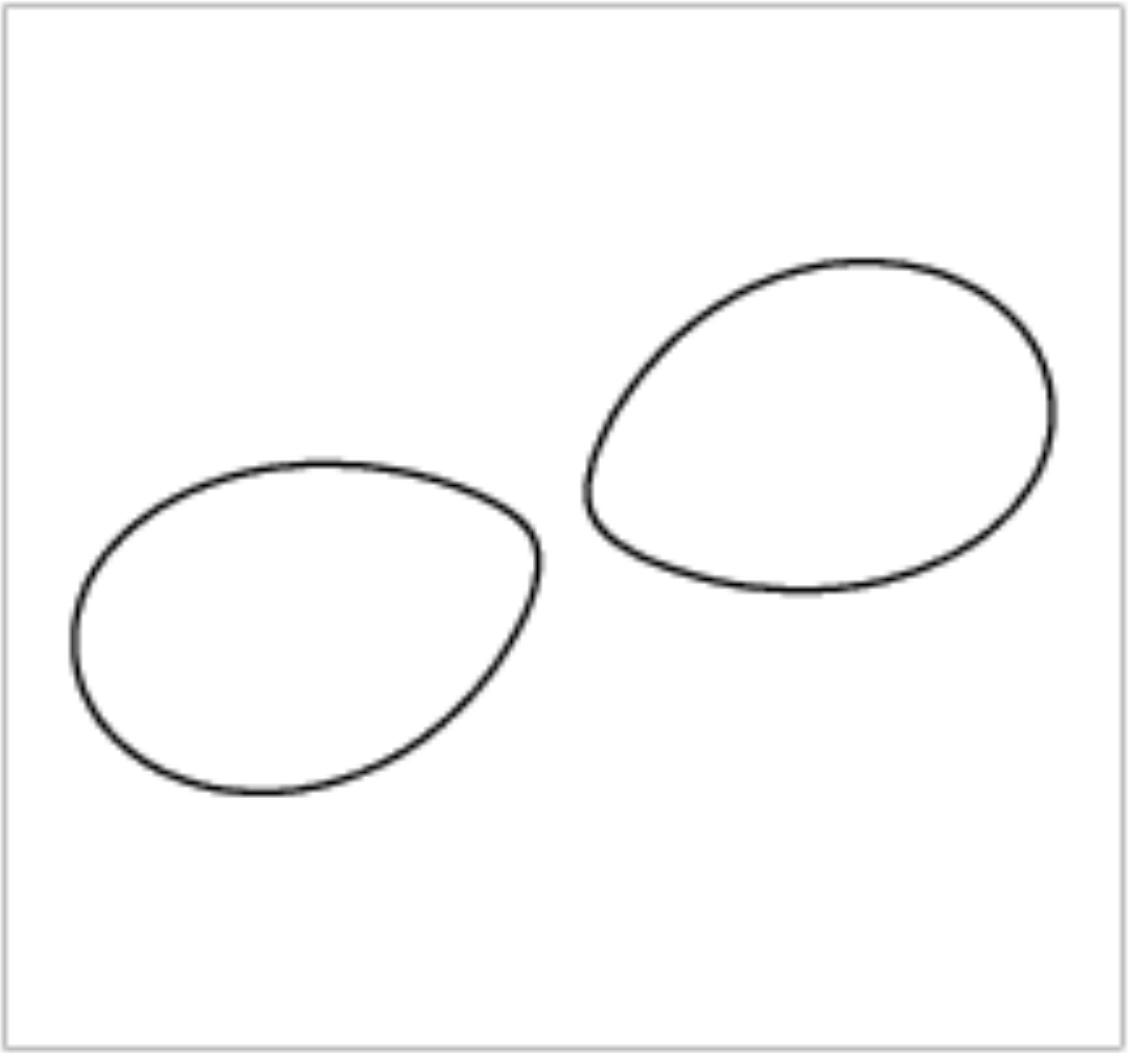

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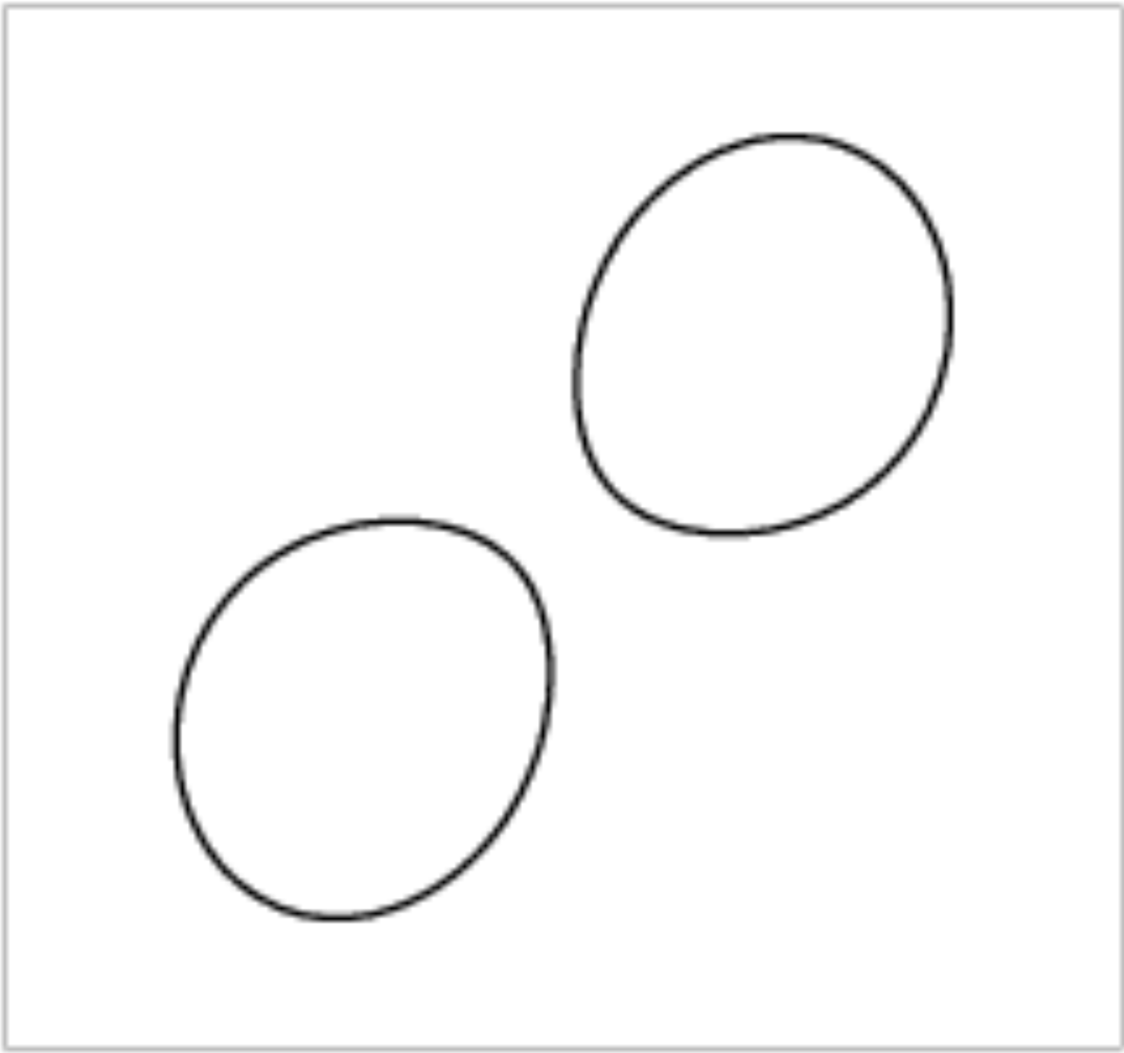

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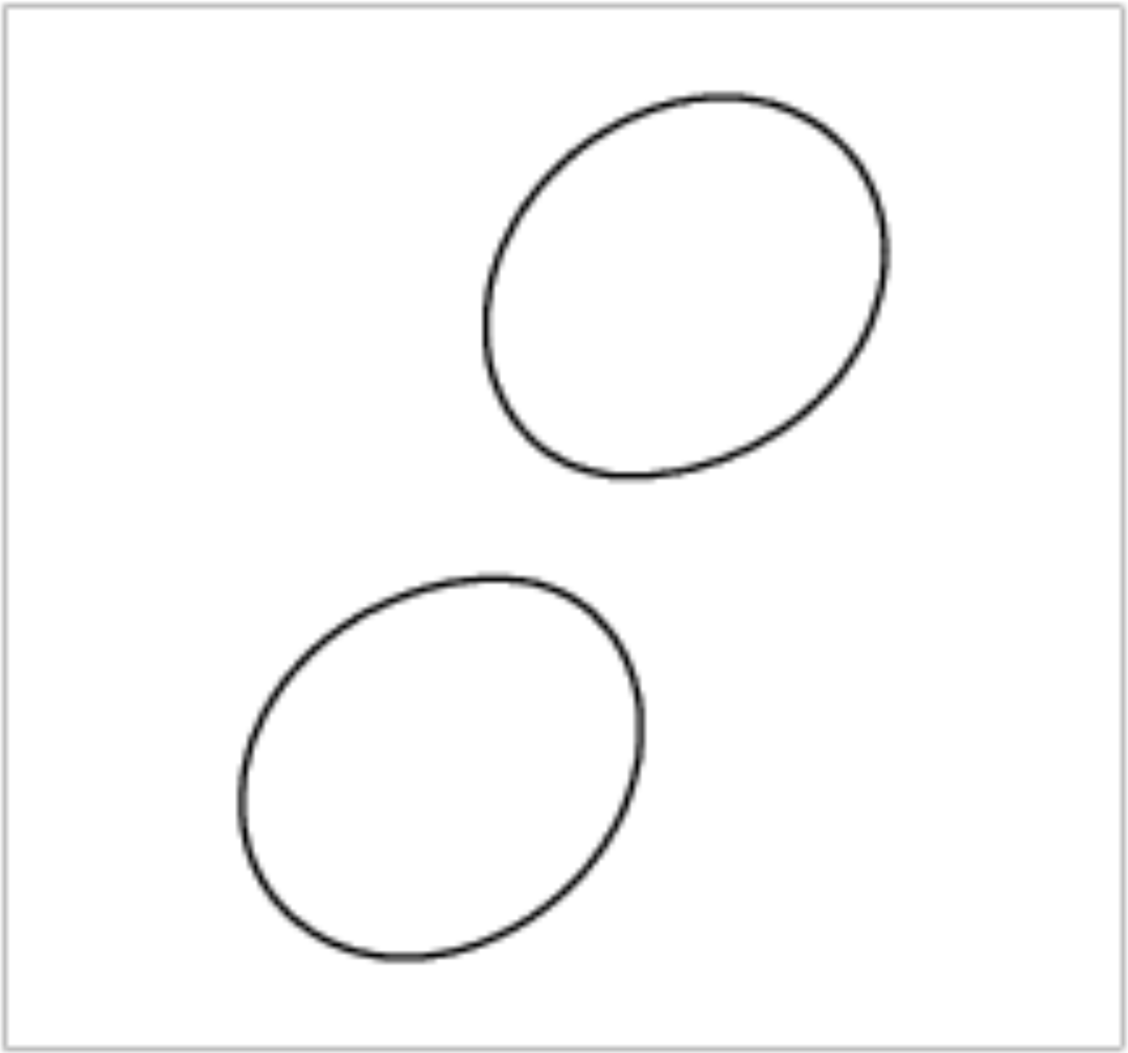

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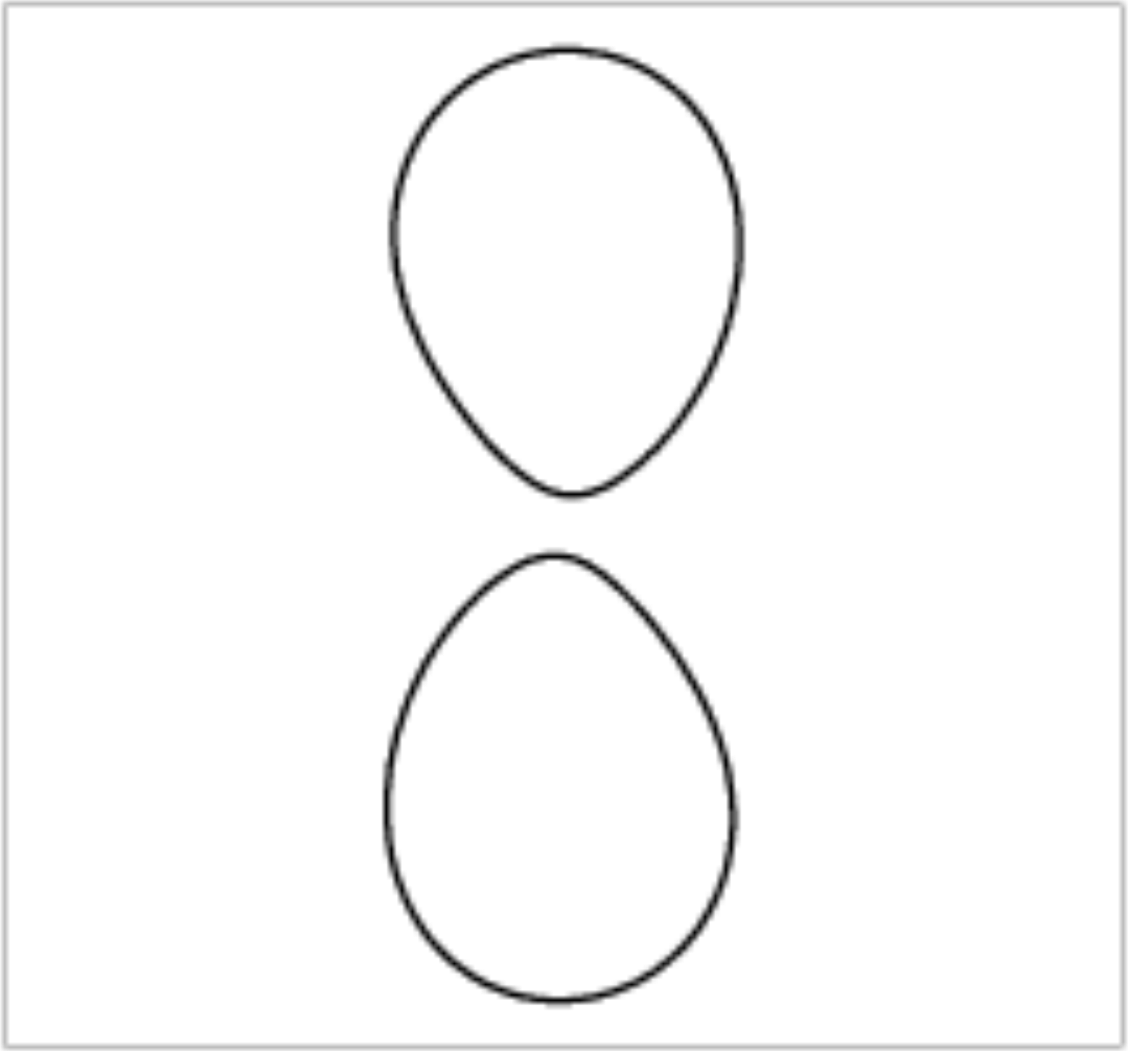

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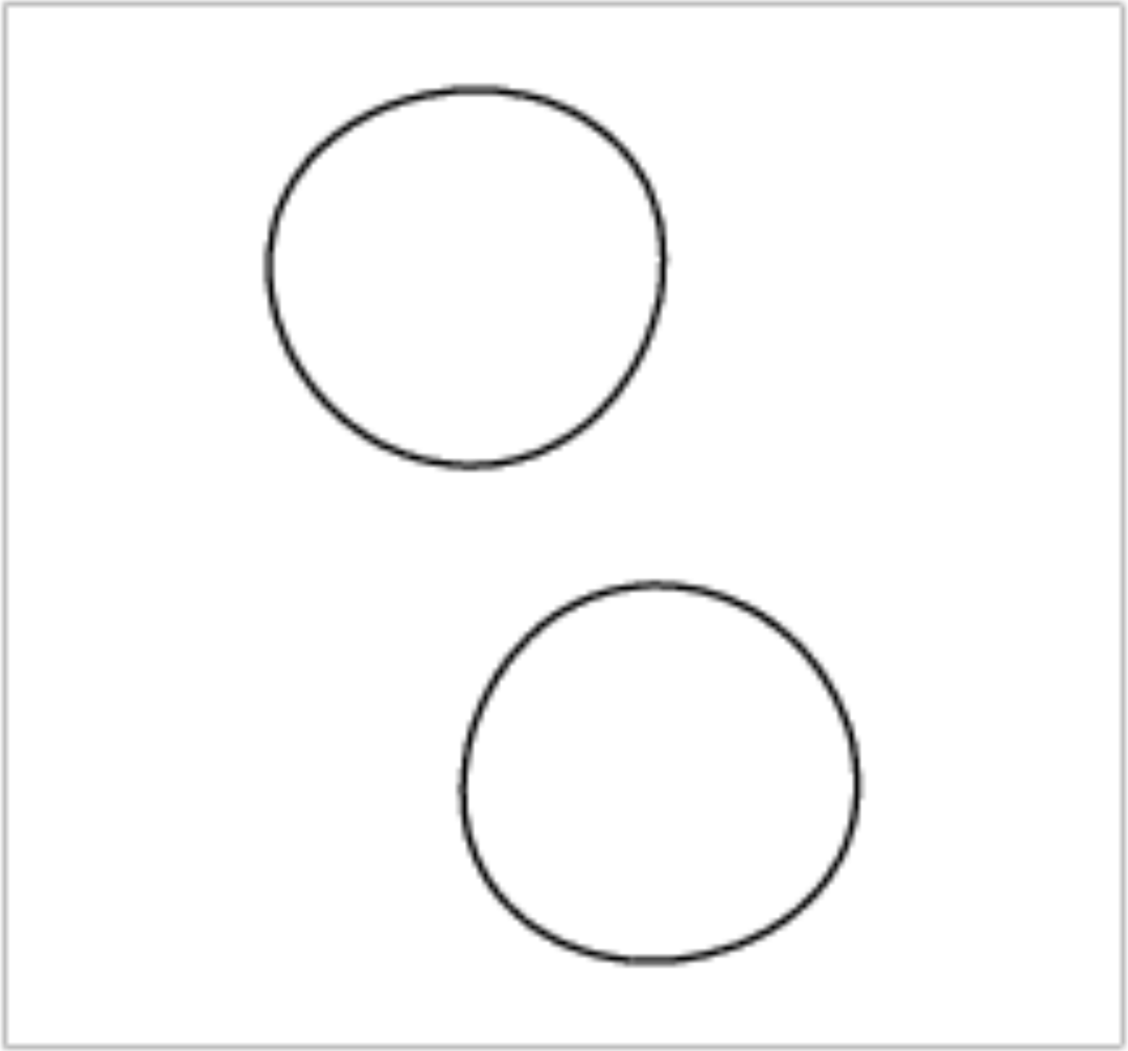

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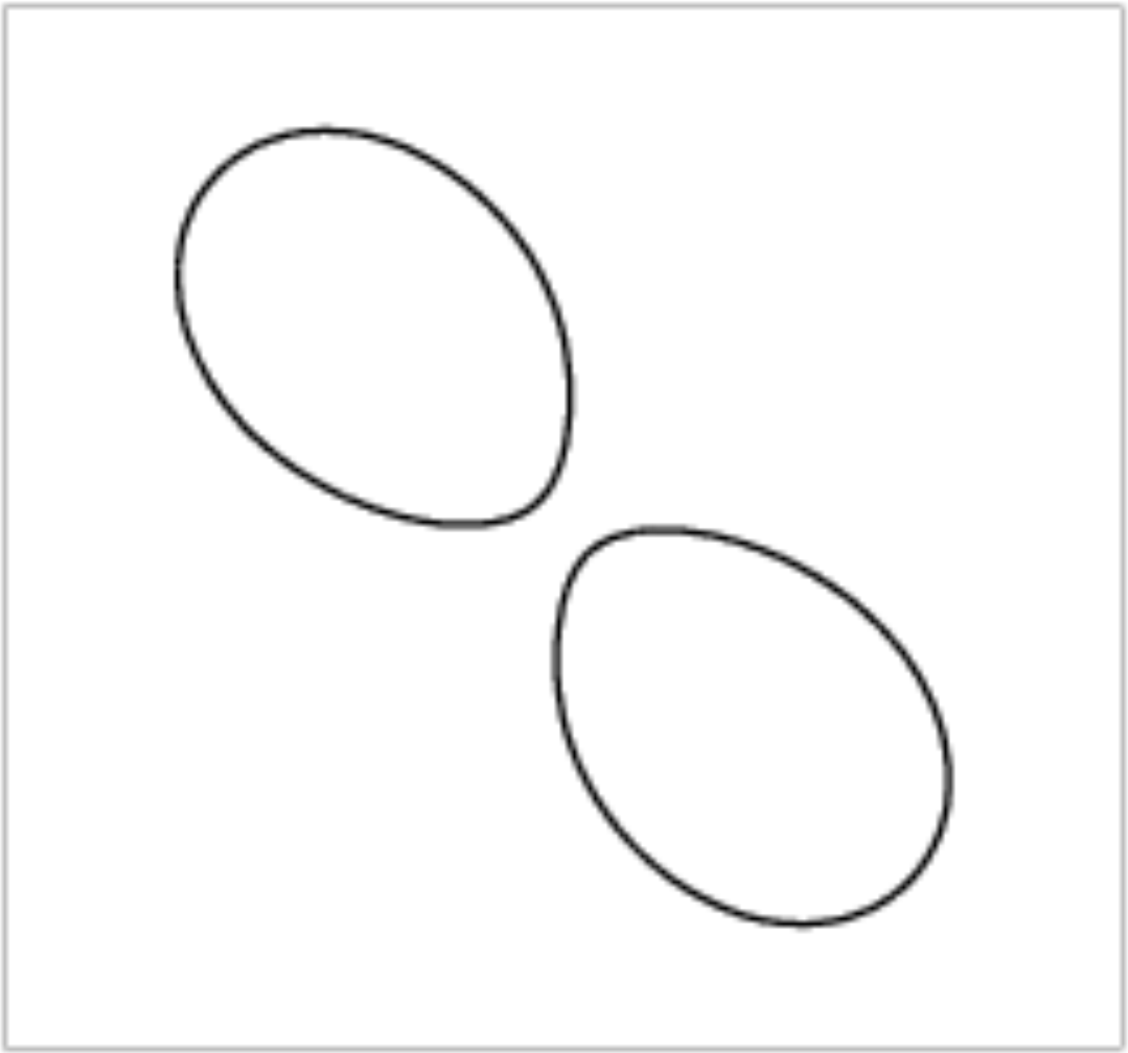

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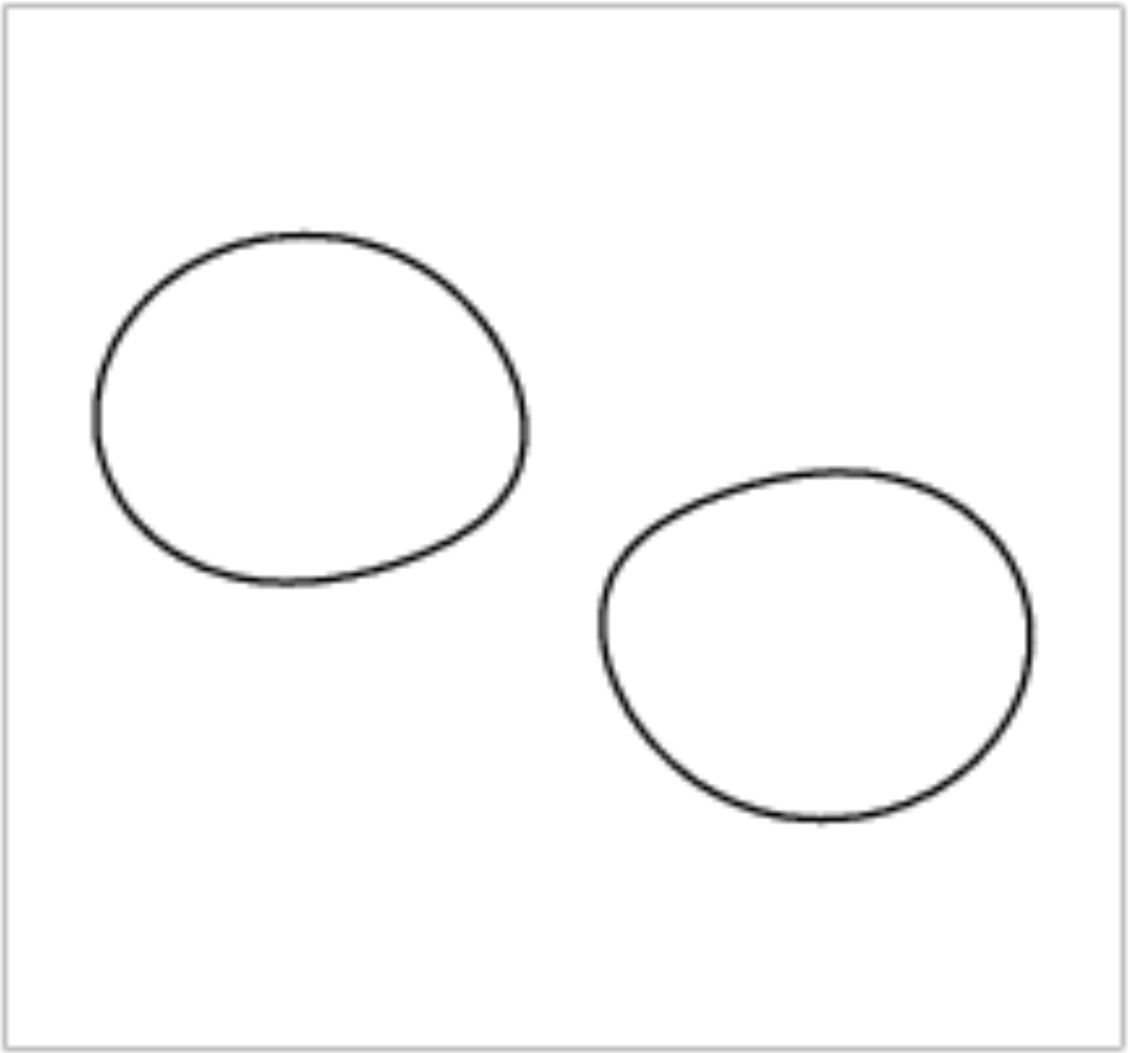

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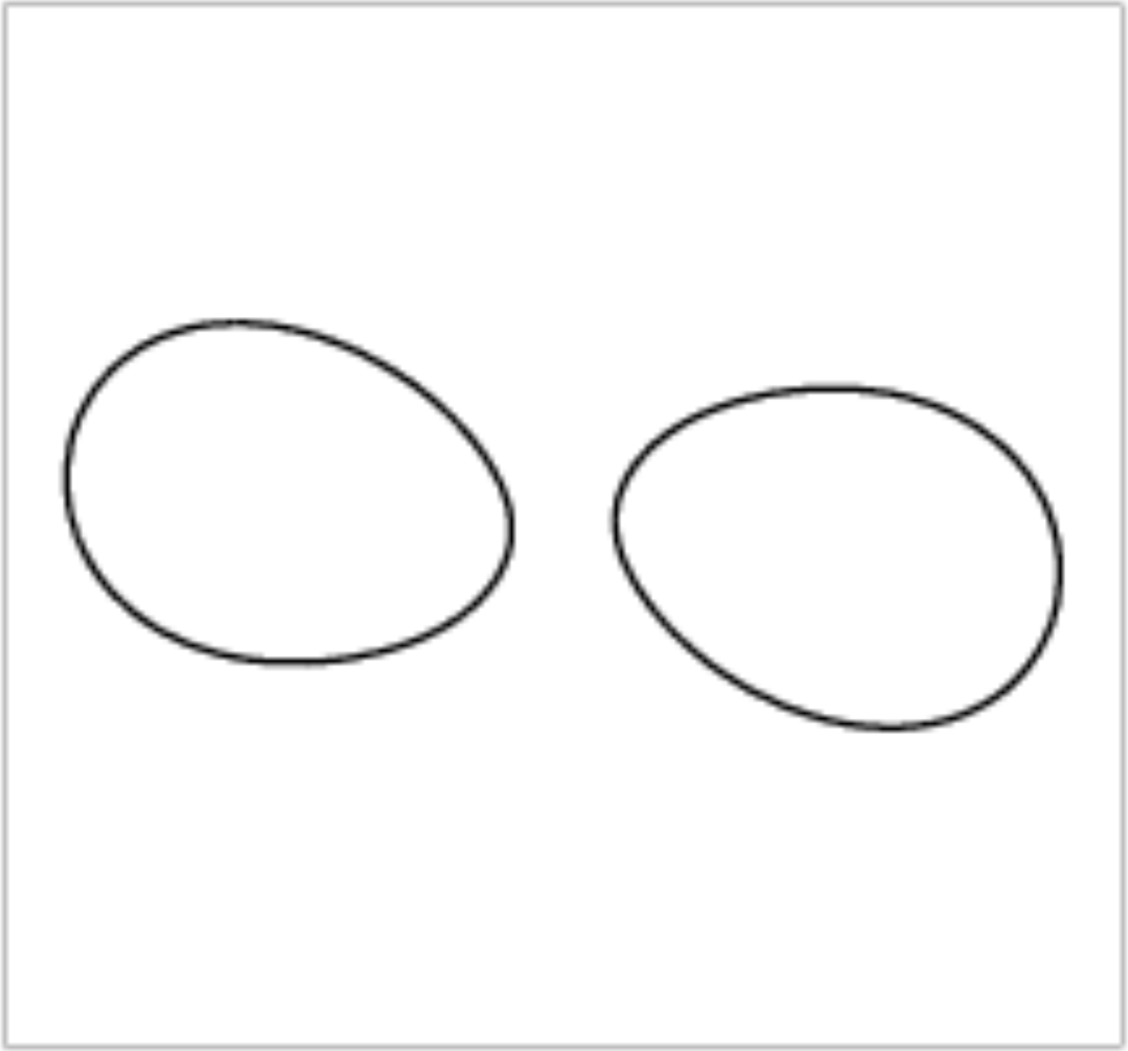

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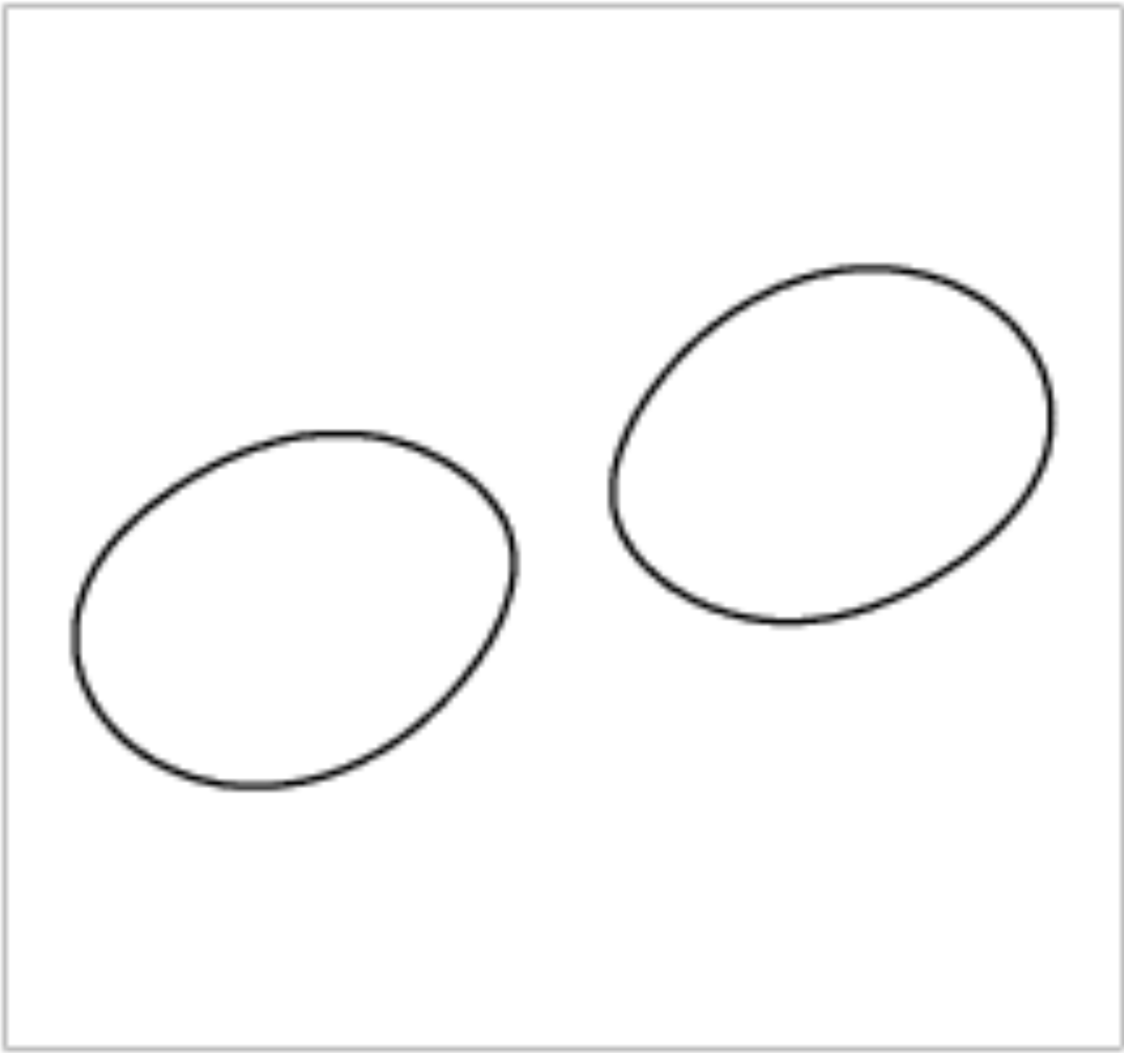

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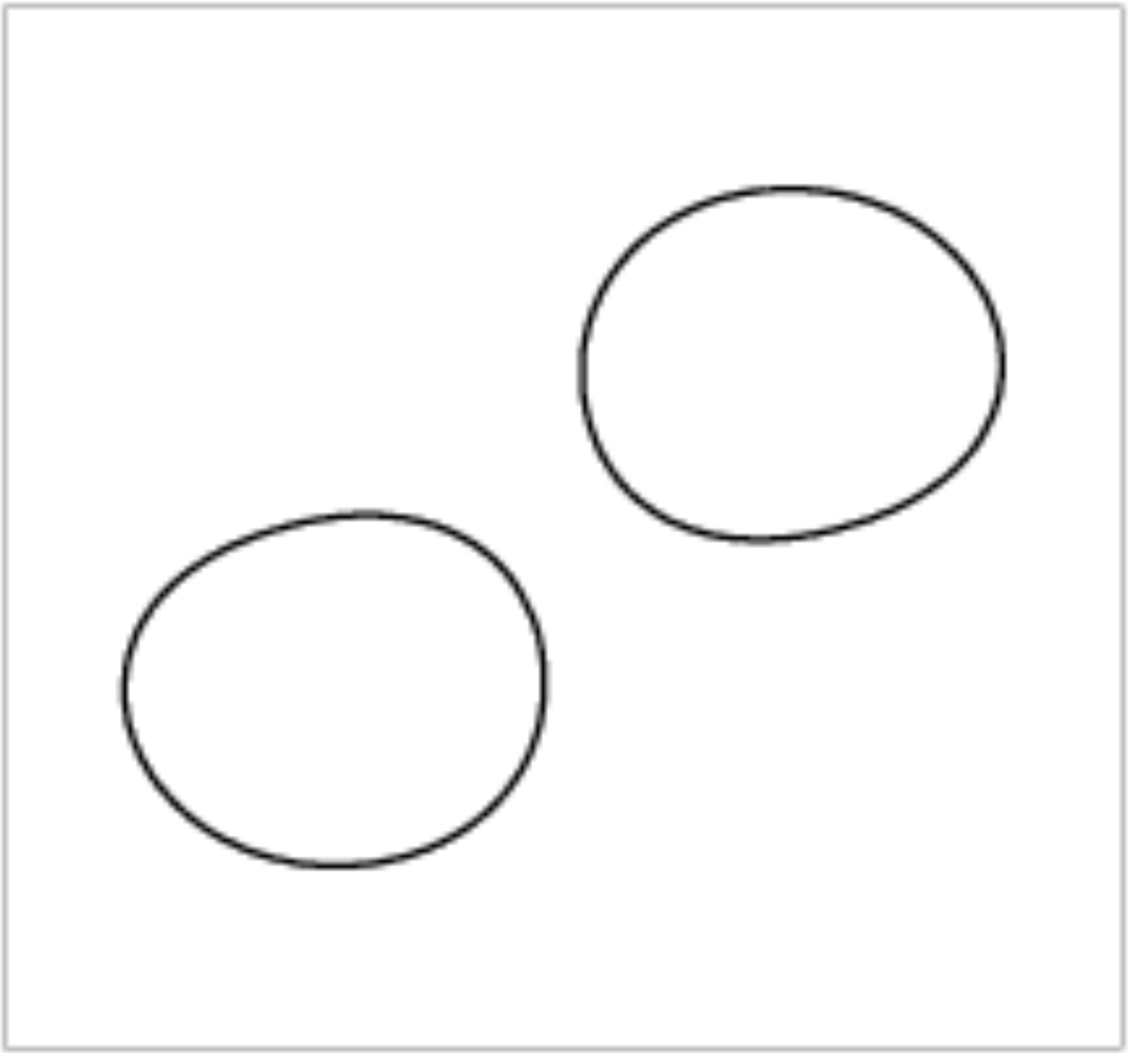

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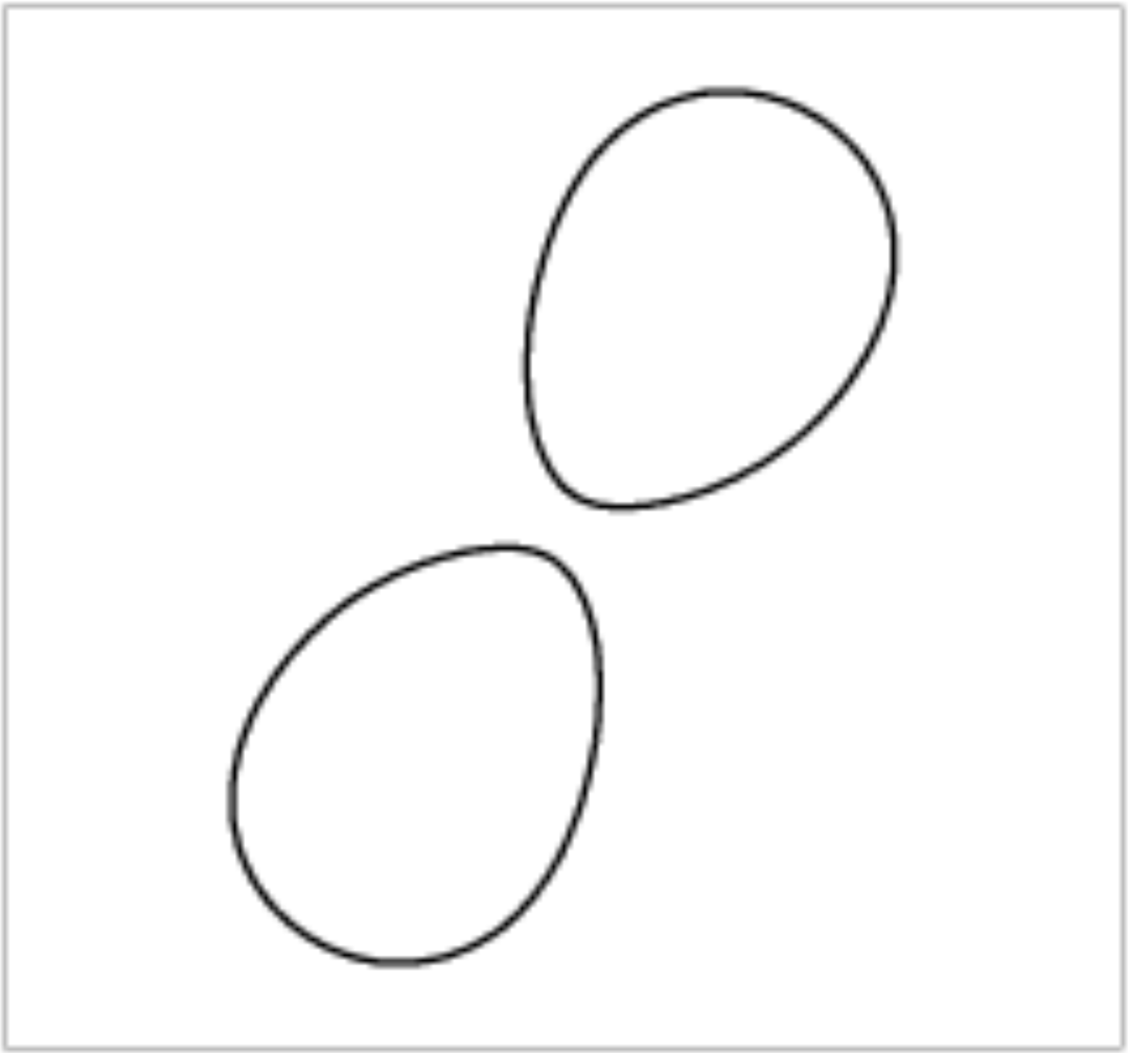

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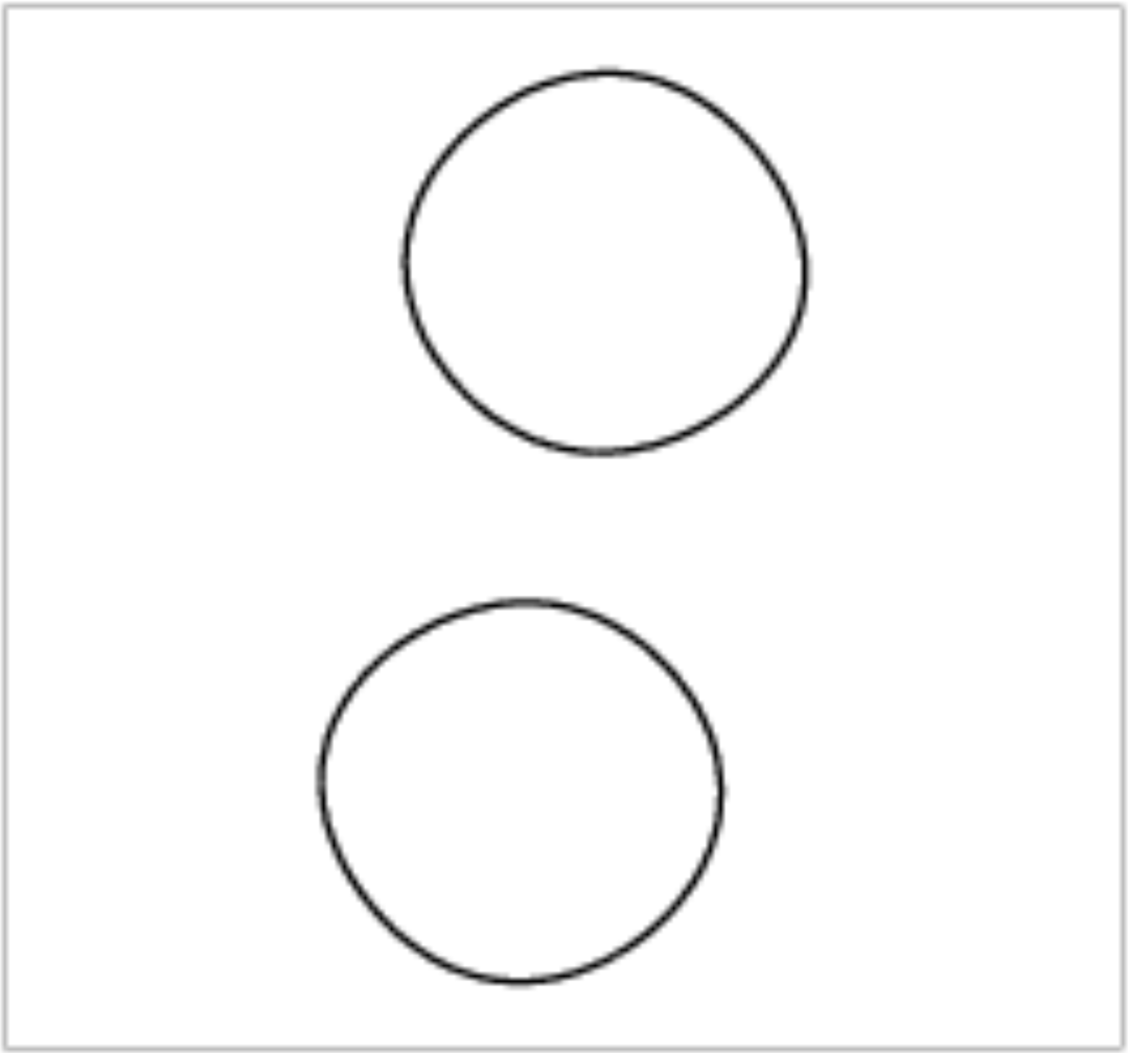

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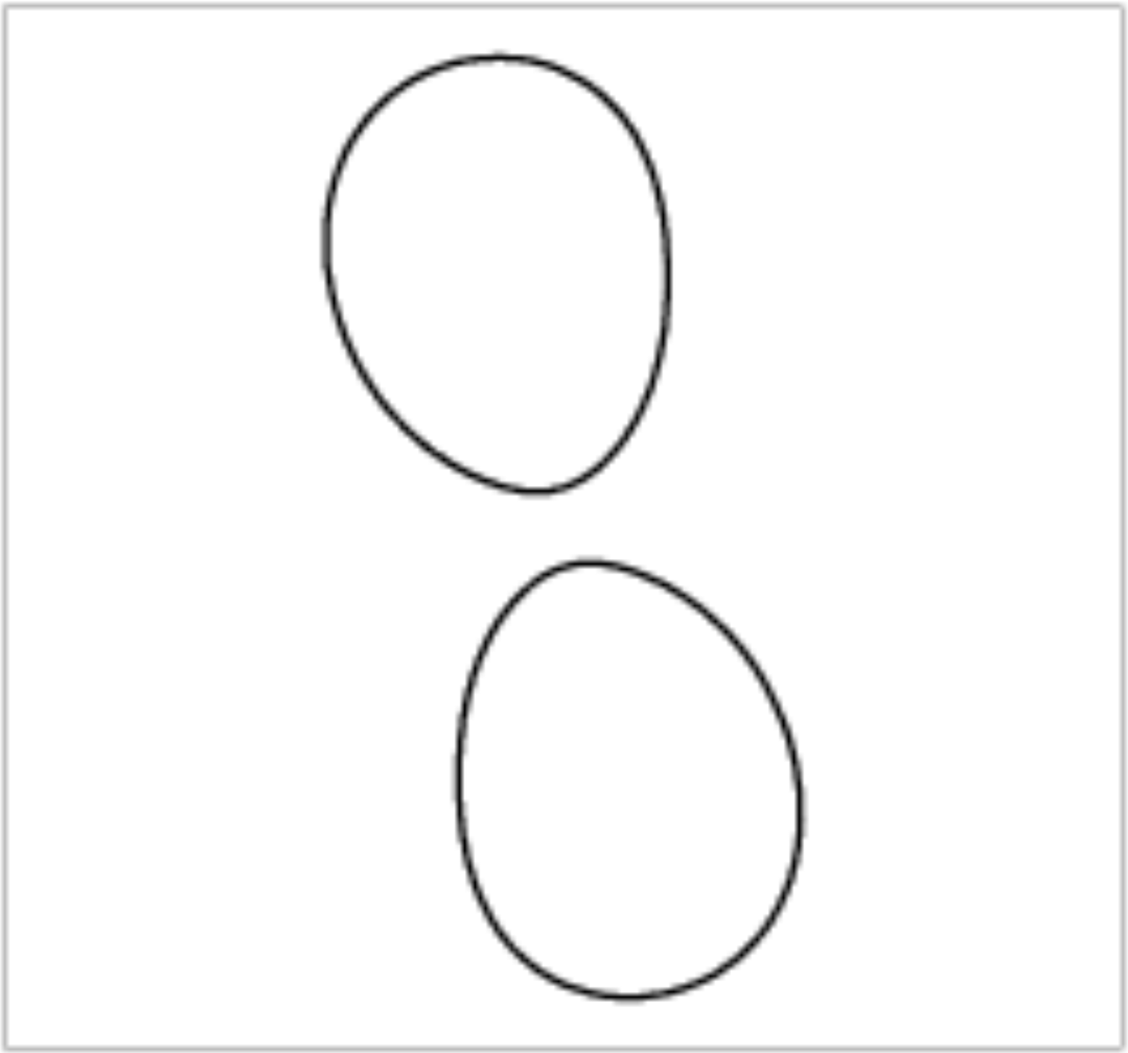

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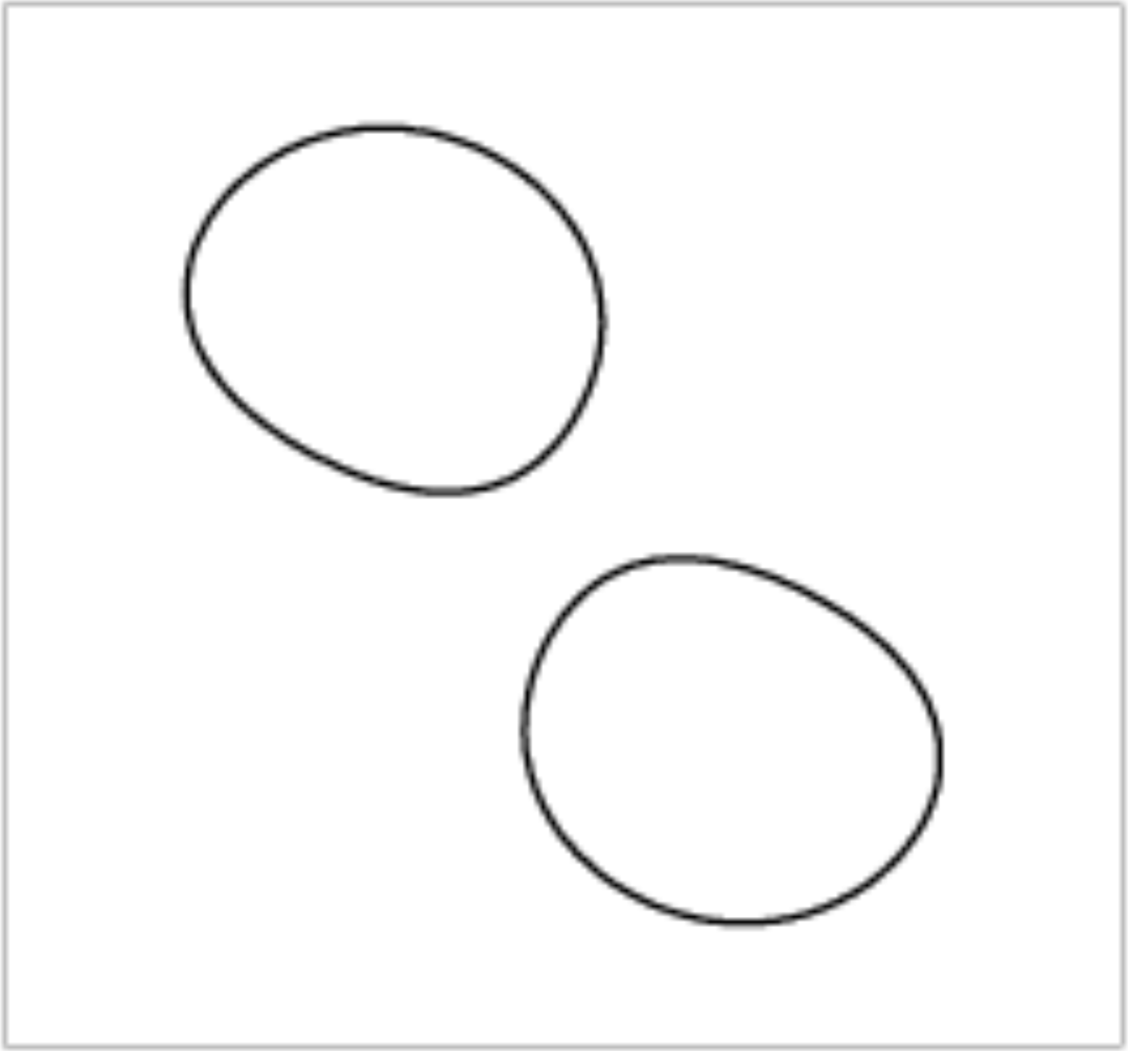

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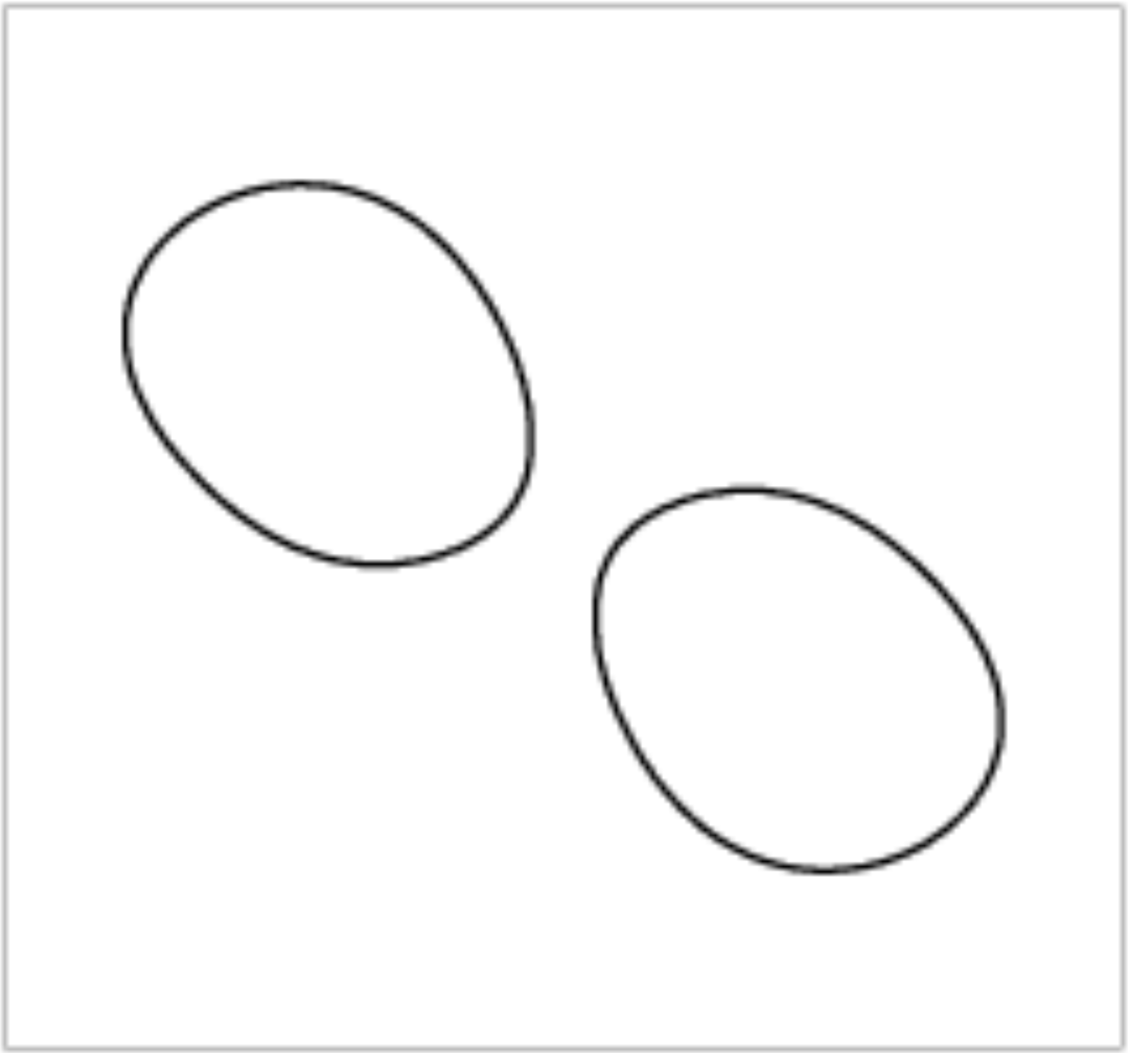

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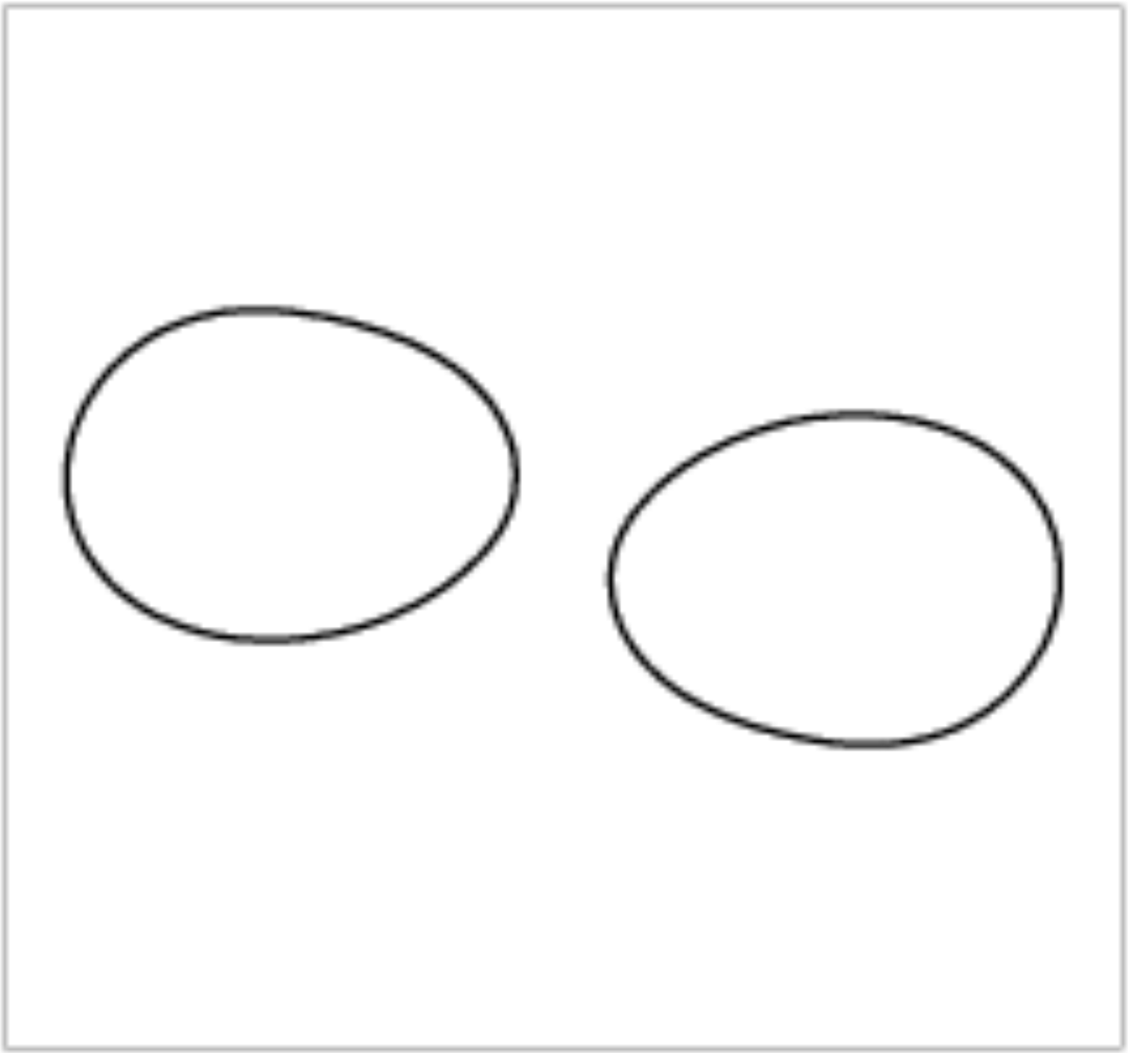

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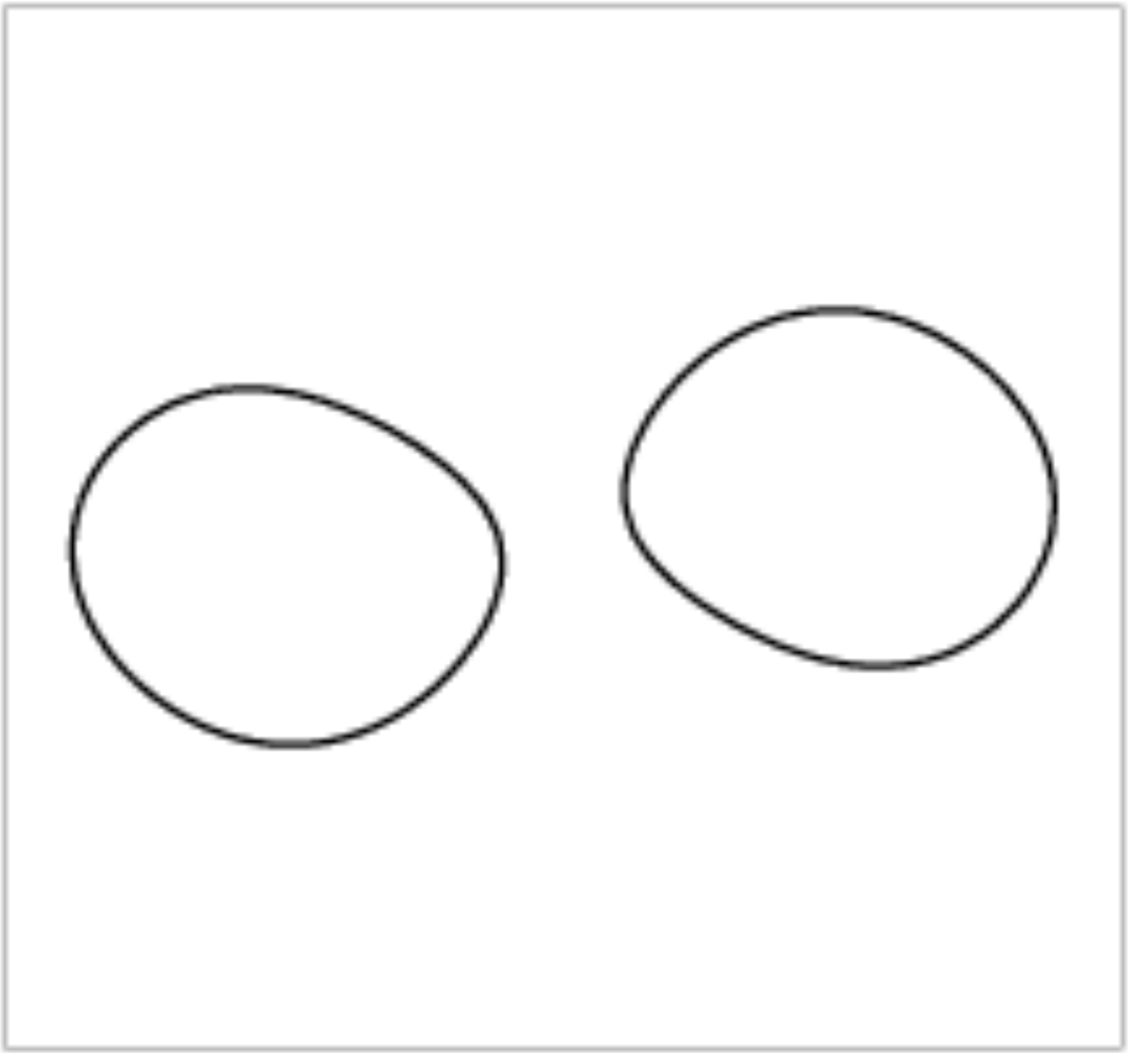
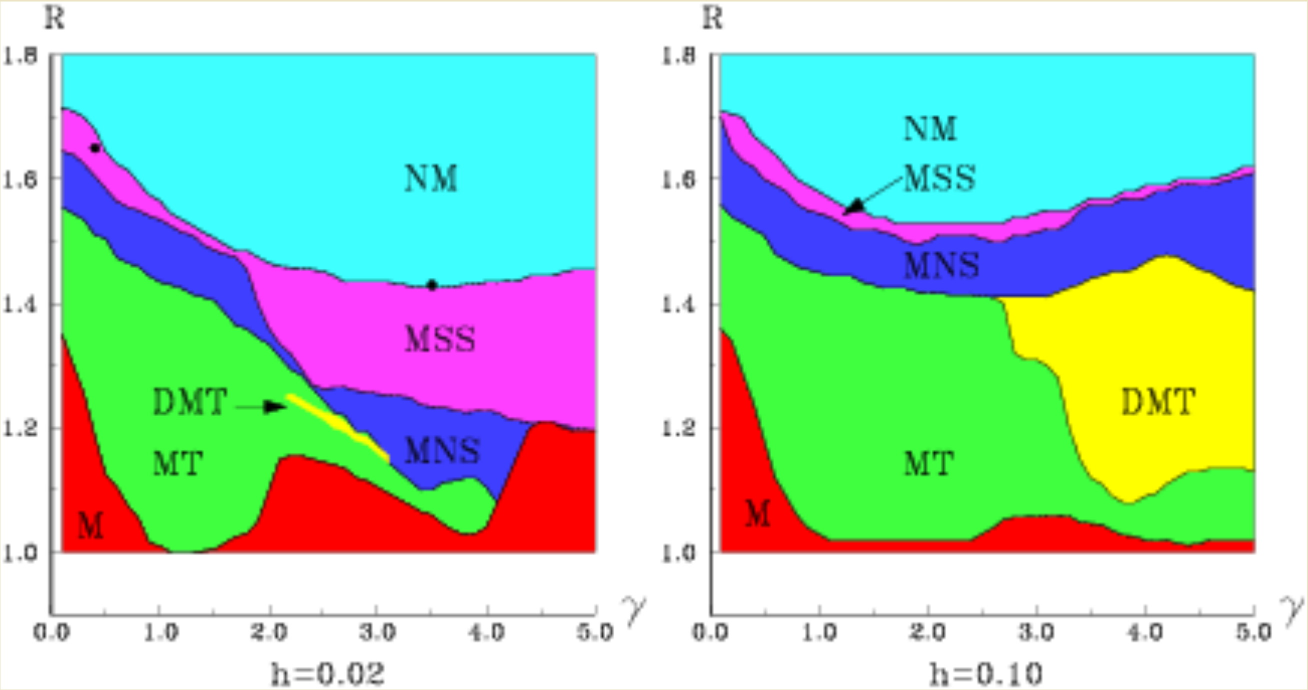


CDM-modeling of interaction of two cyclones of upper layer in two-layer rotating fluid: diagrams of states



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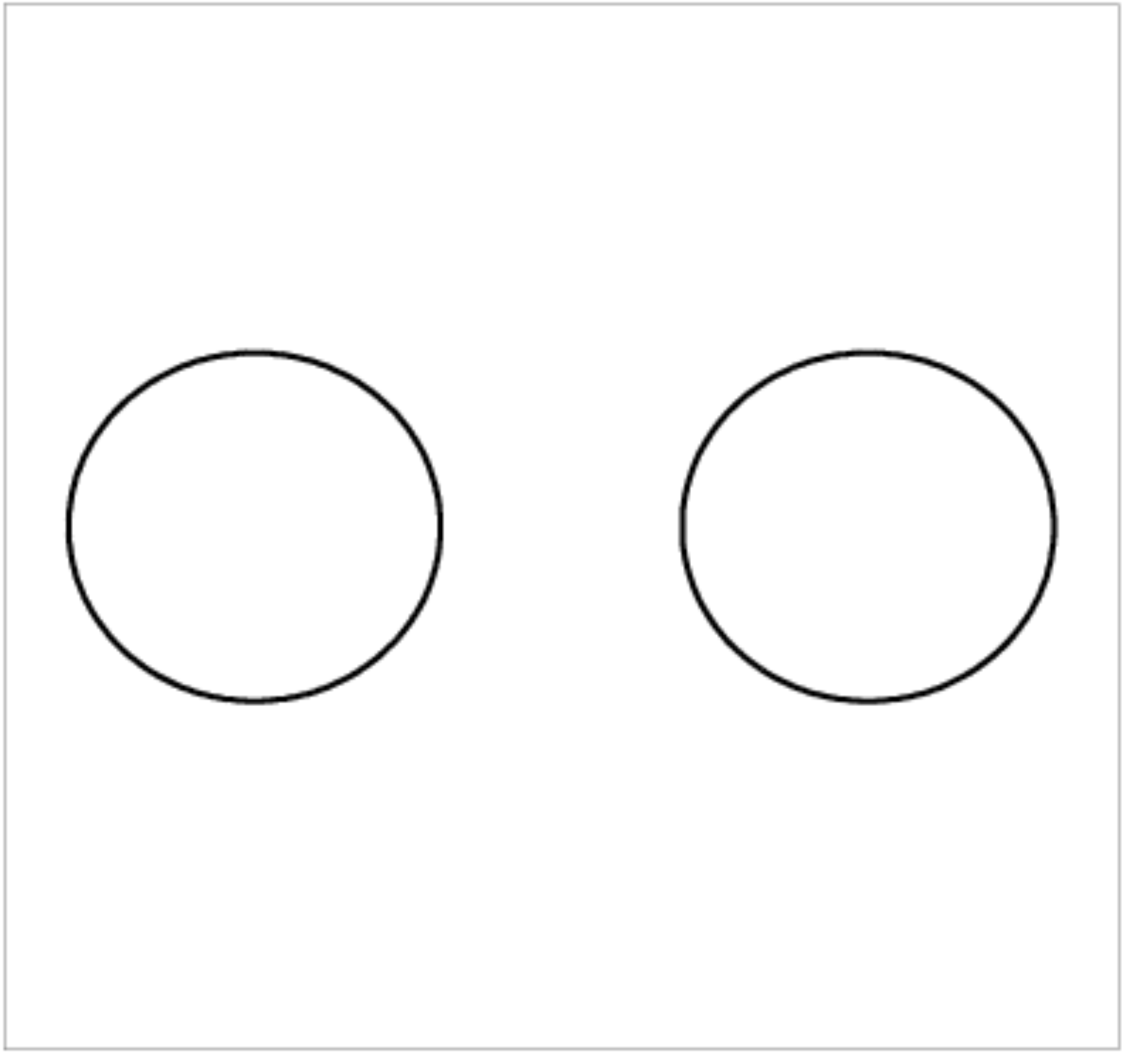
h_1=0.02

γ=0.4, R=1.65

(MSS-type)

t=0



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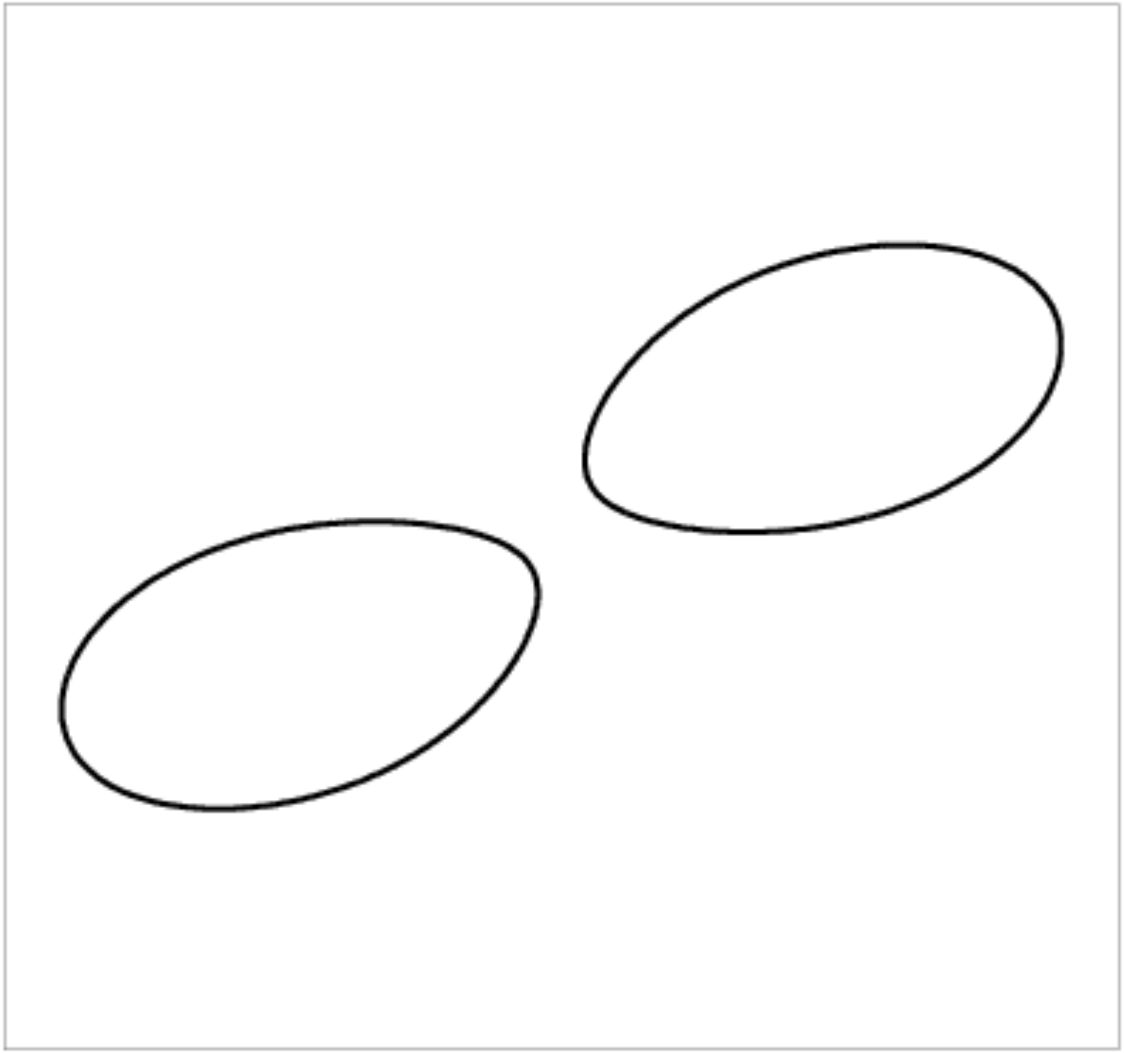

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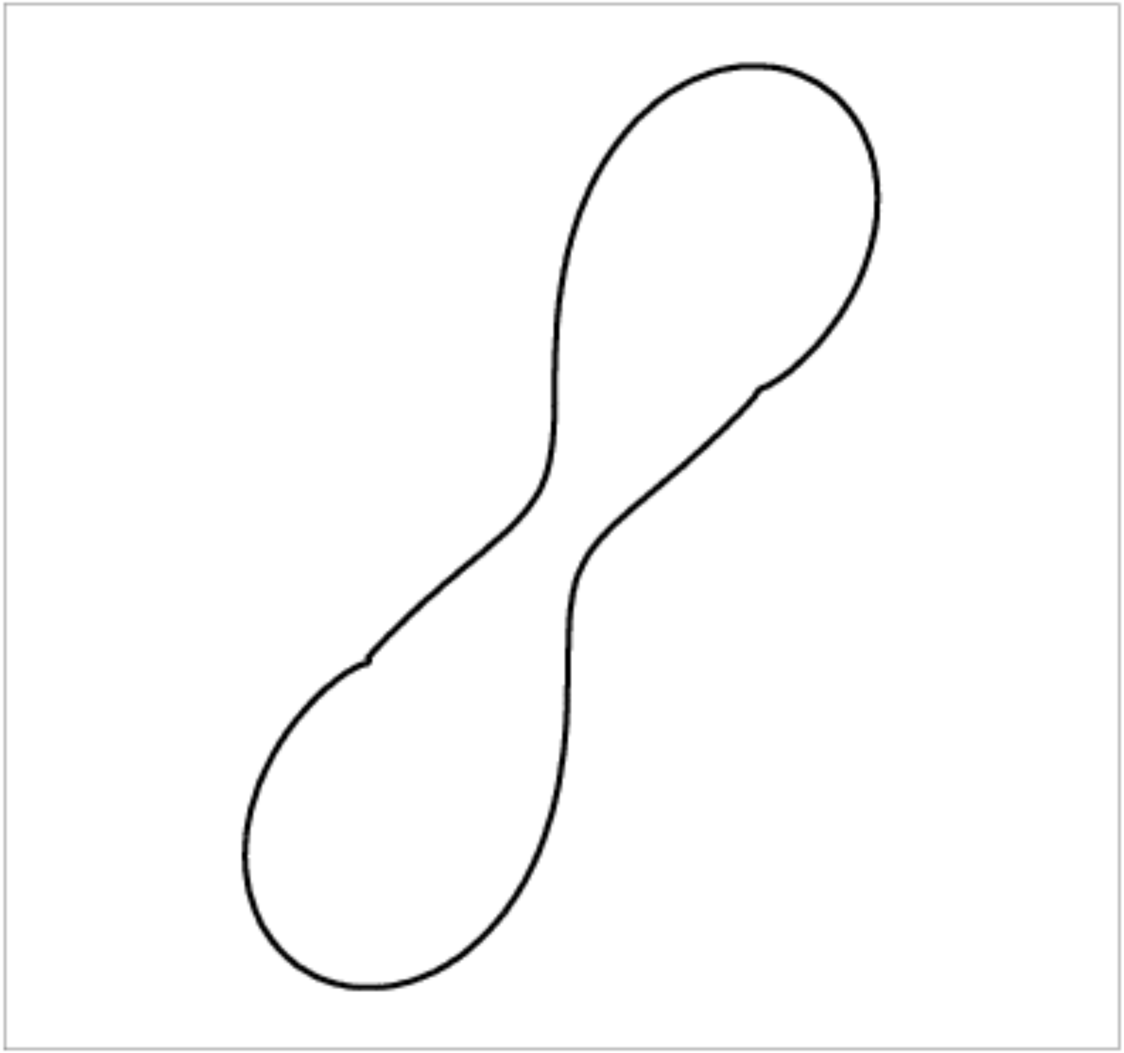

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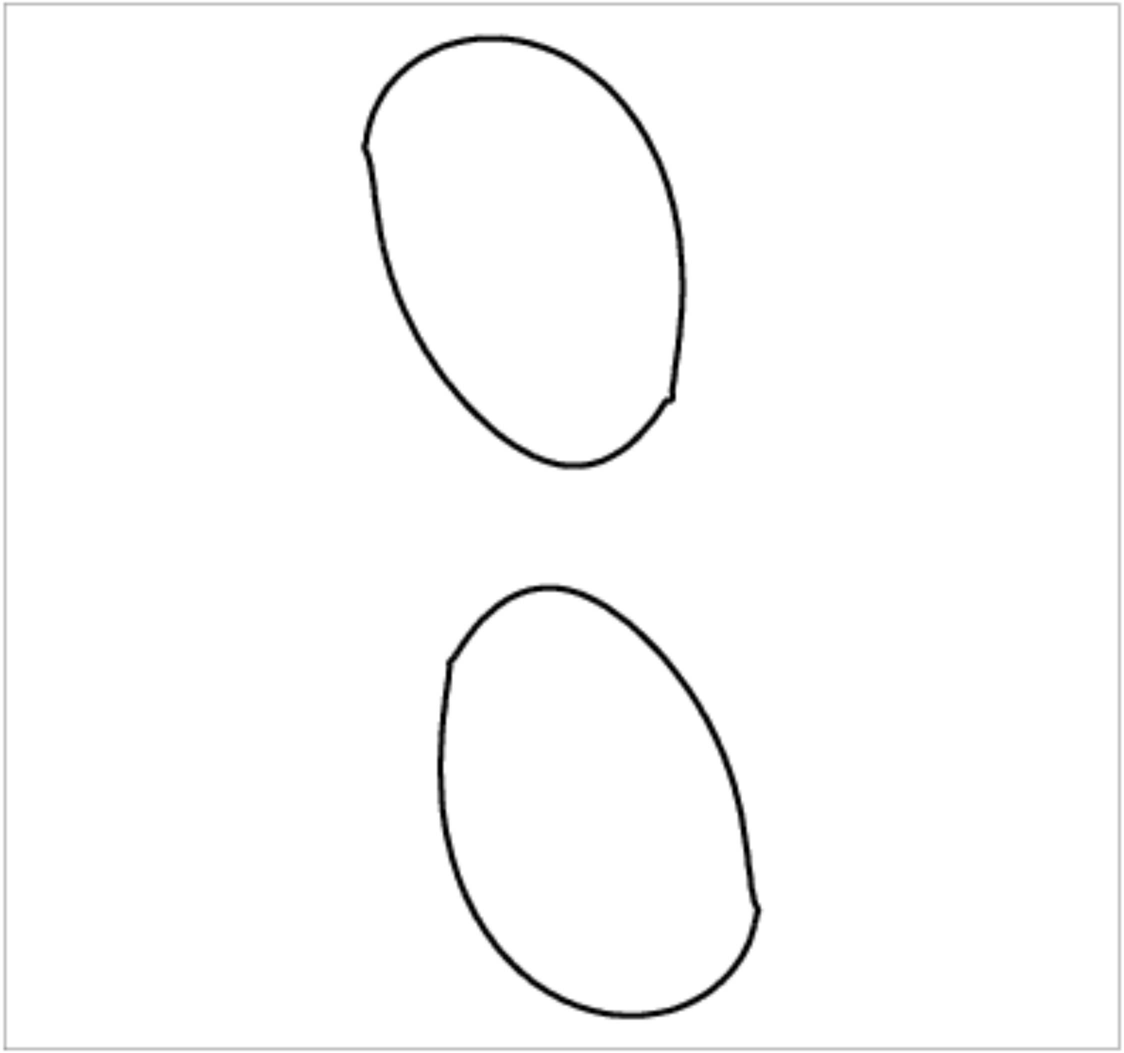

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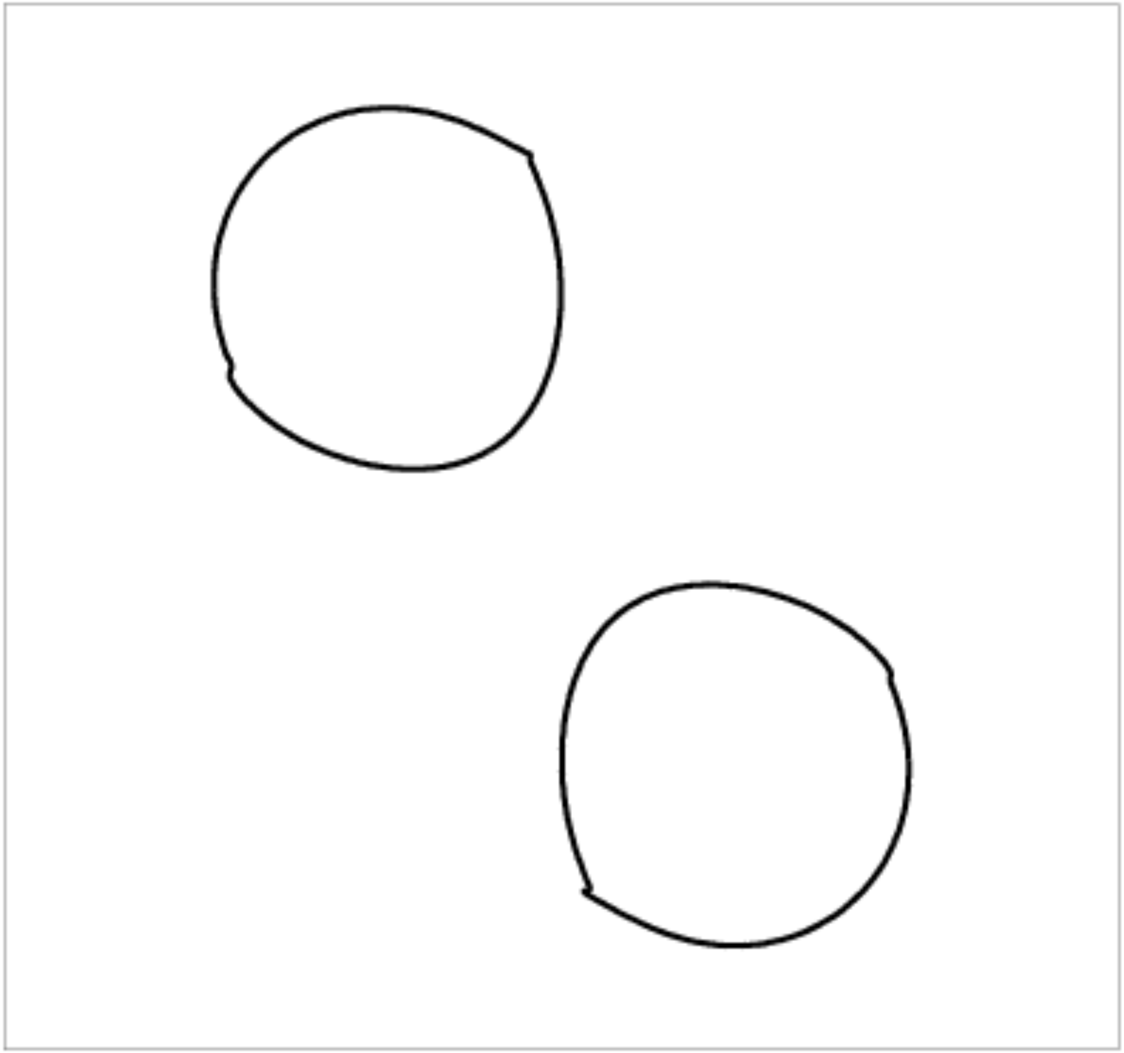

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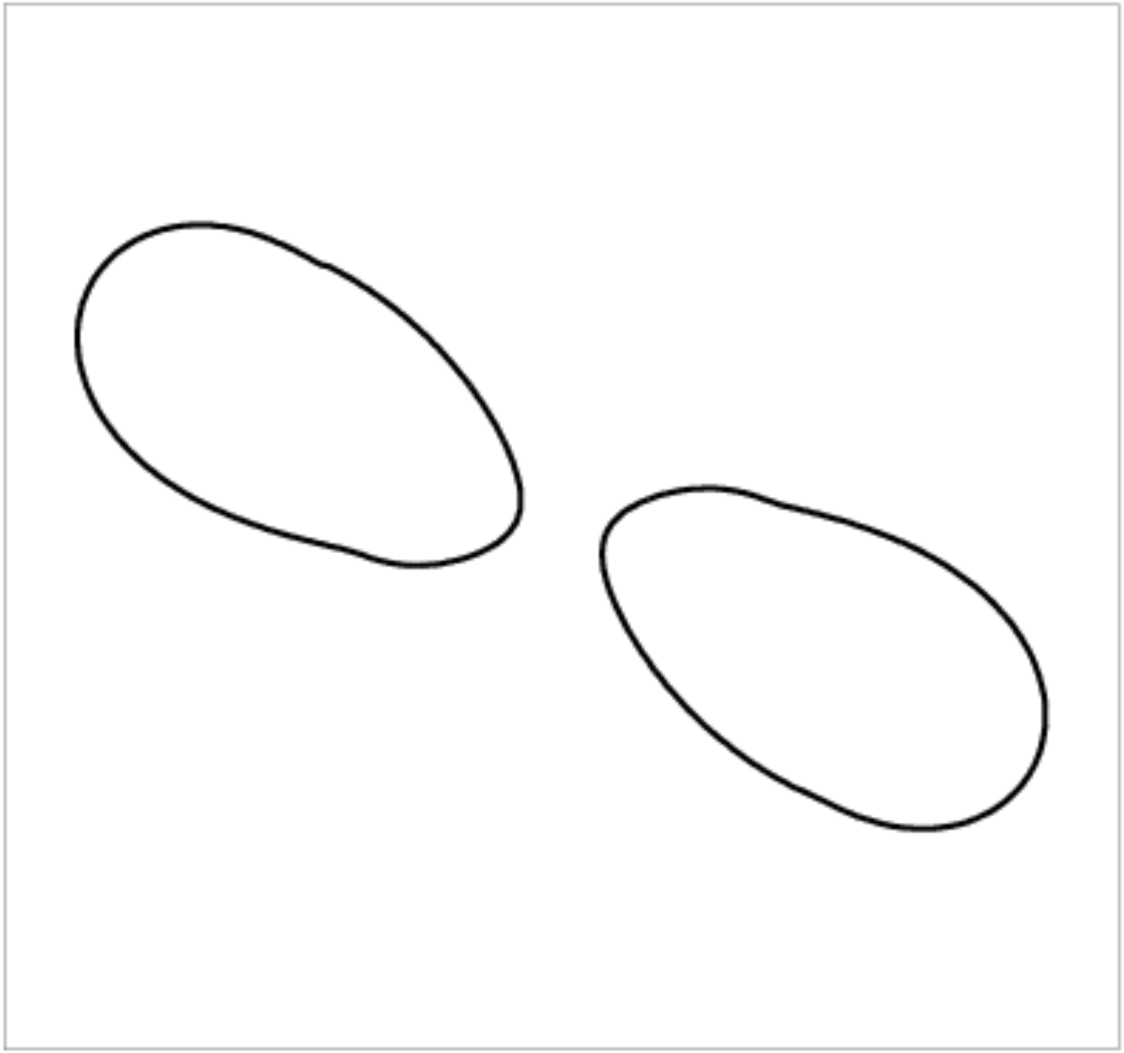

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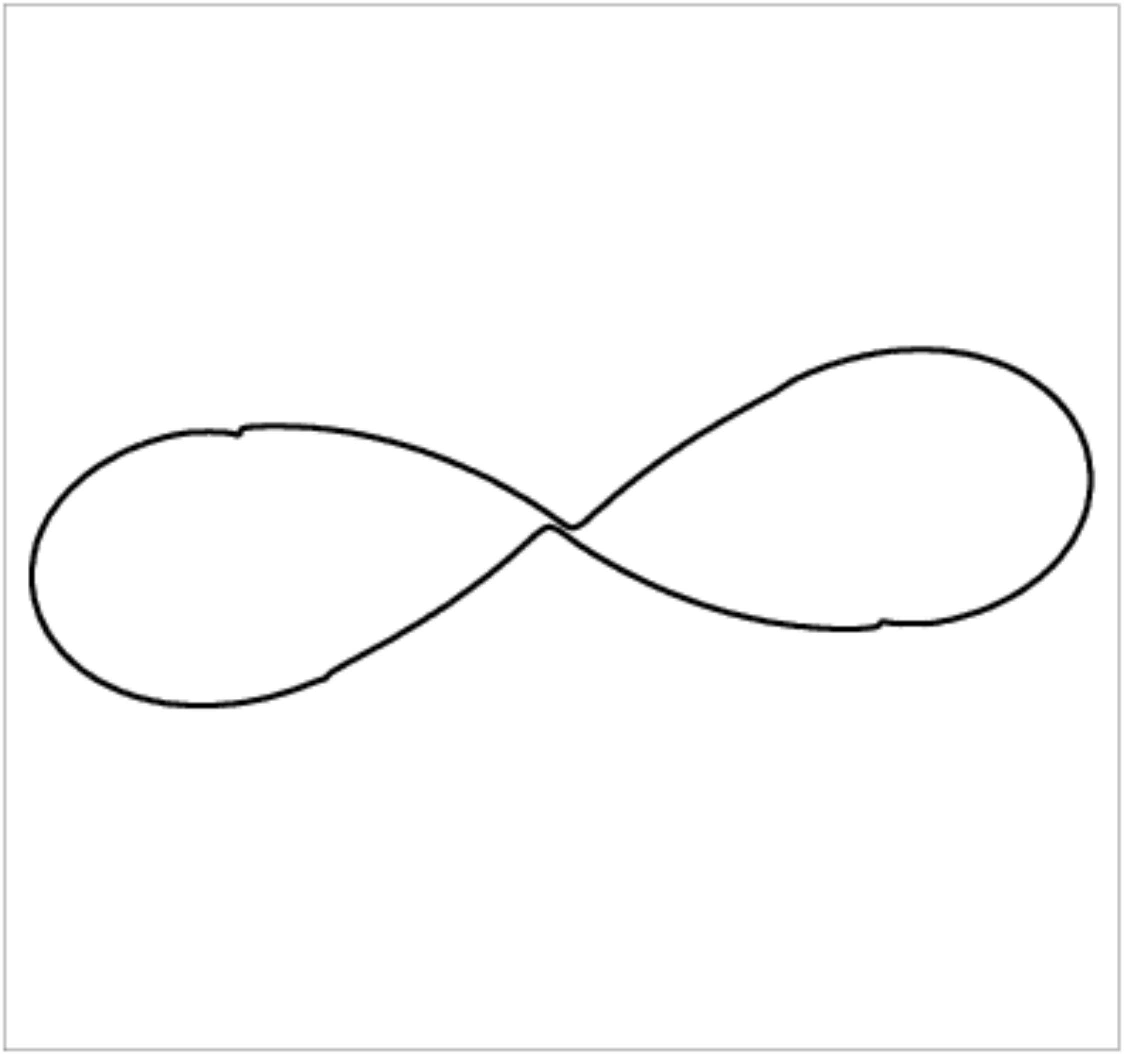

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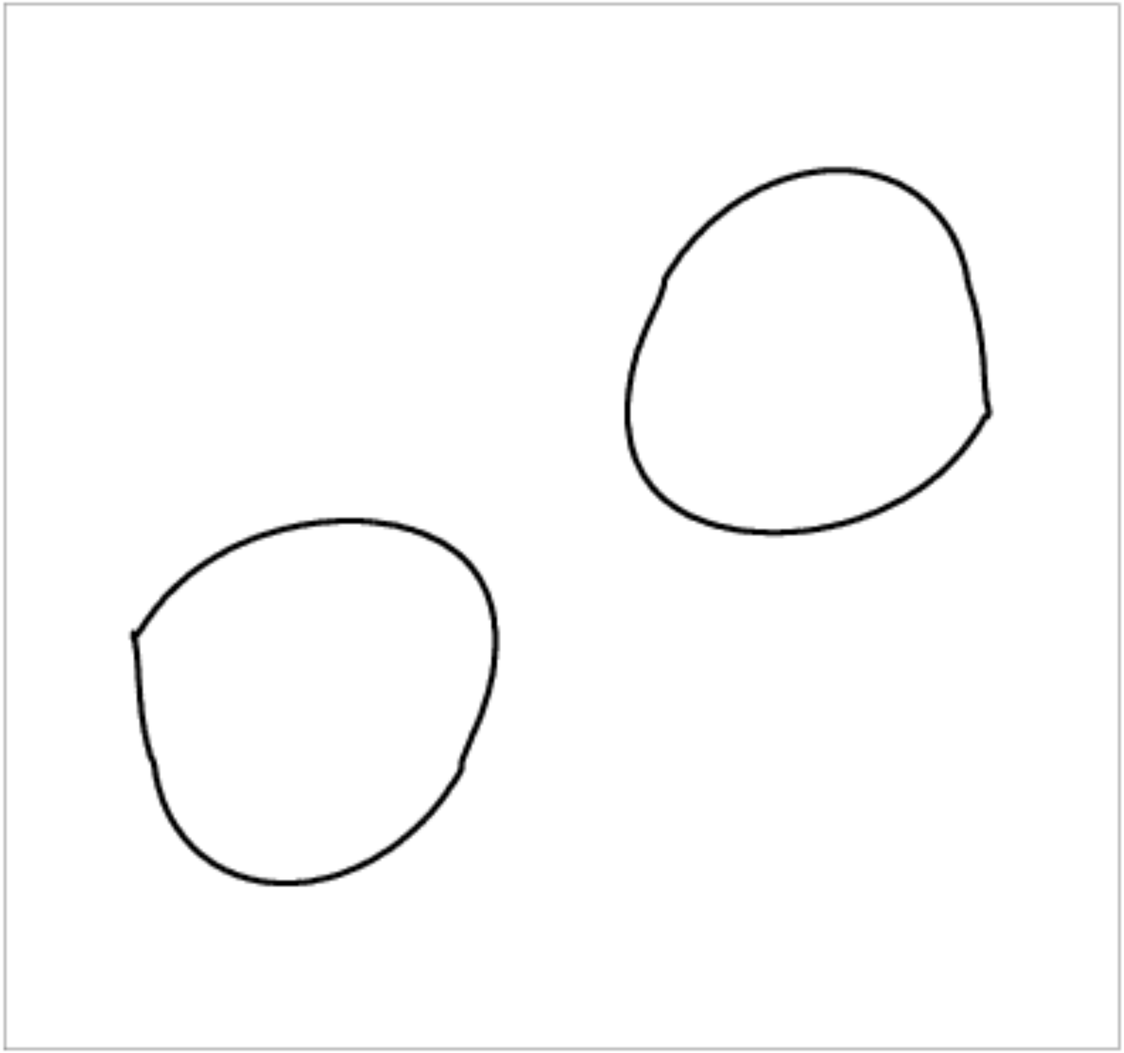

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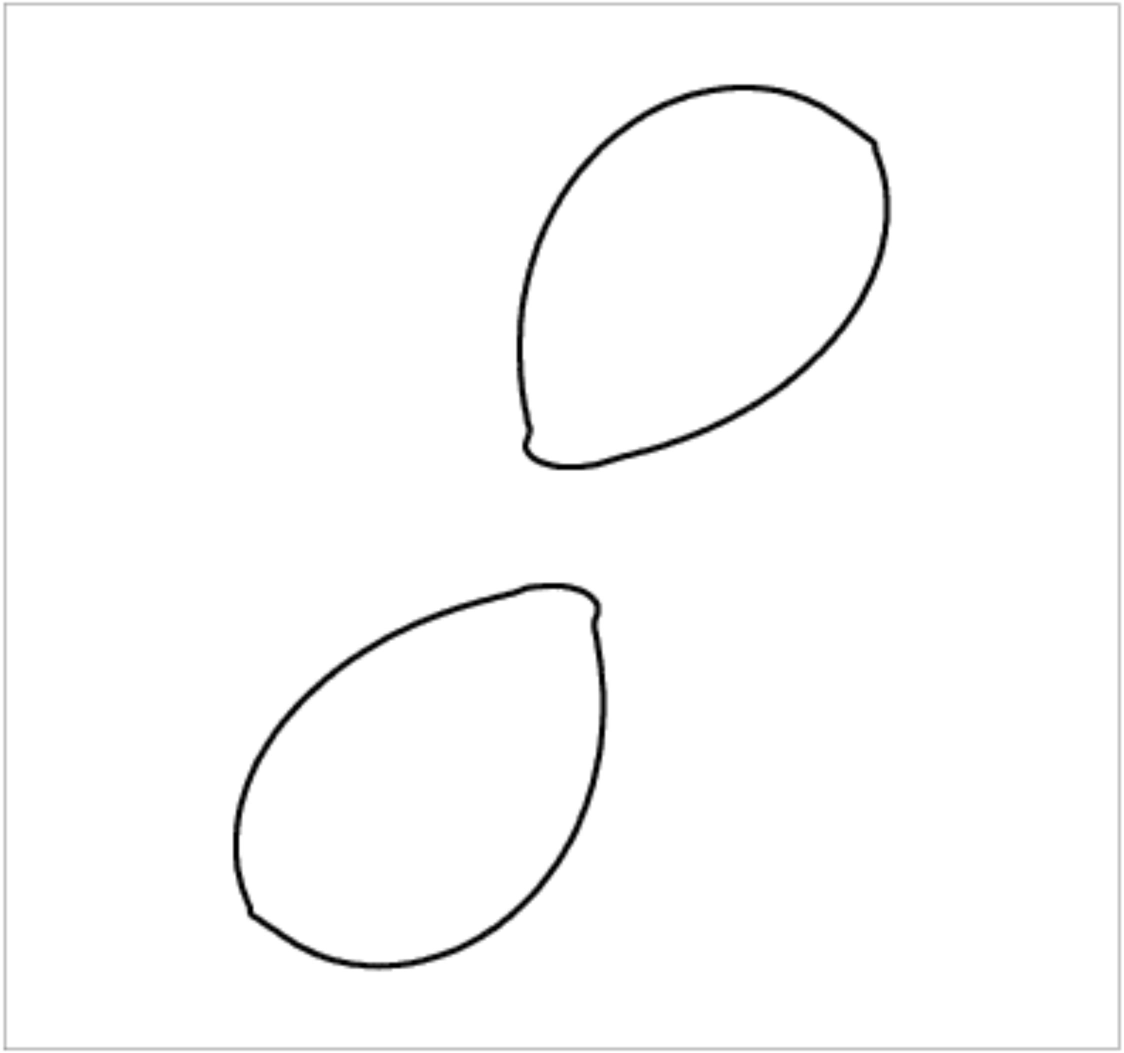

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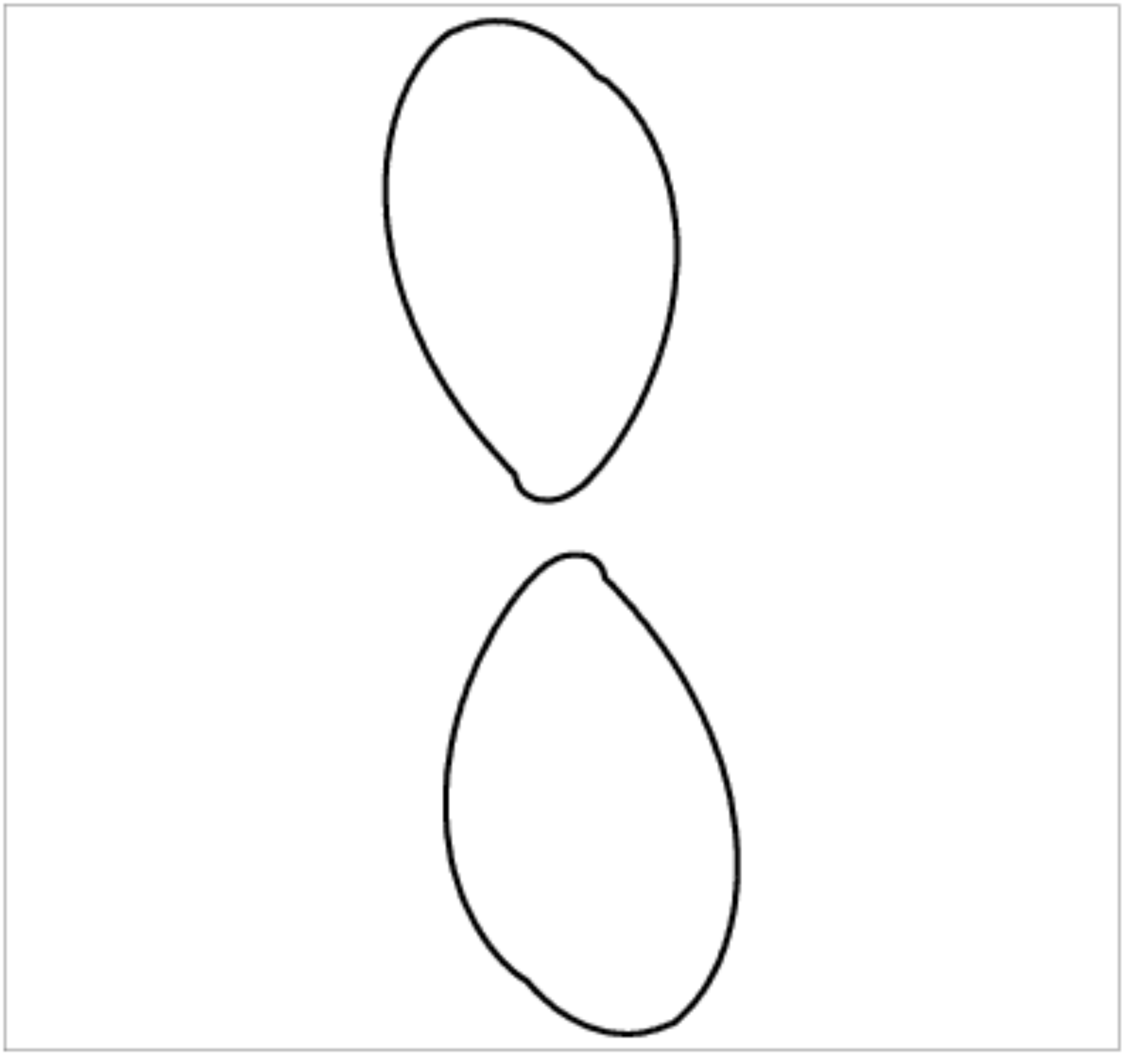

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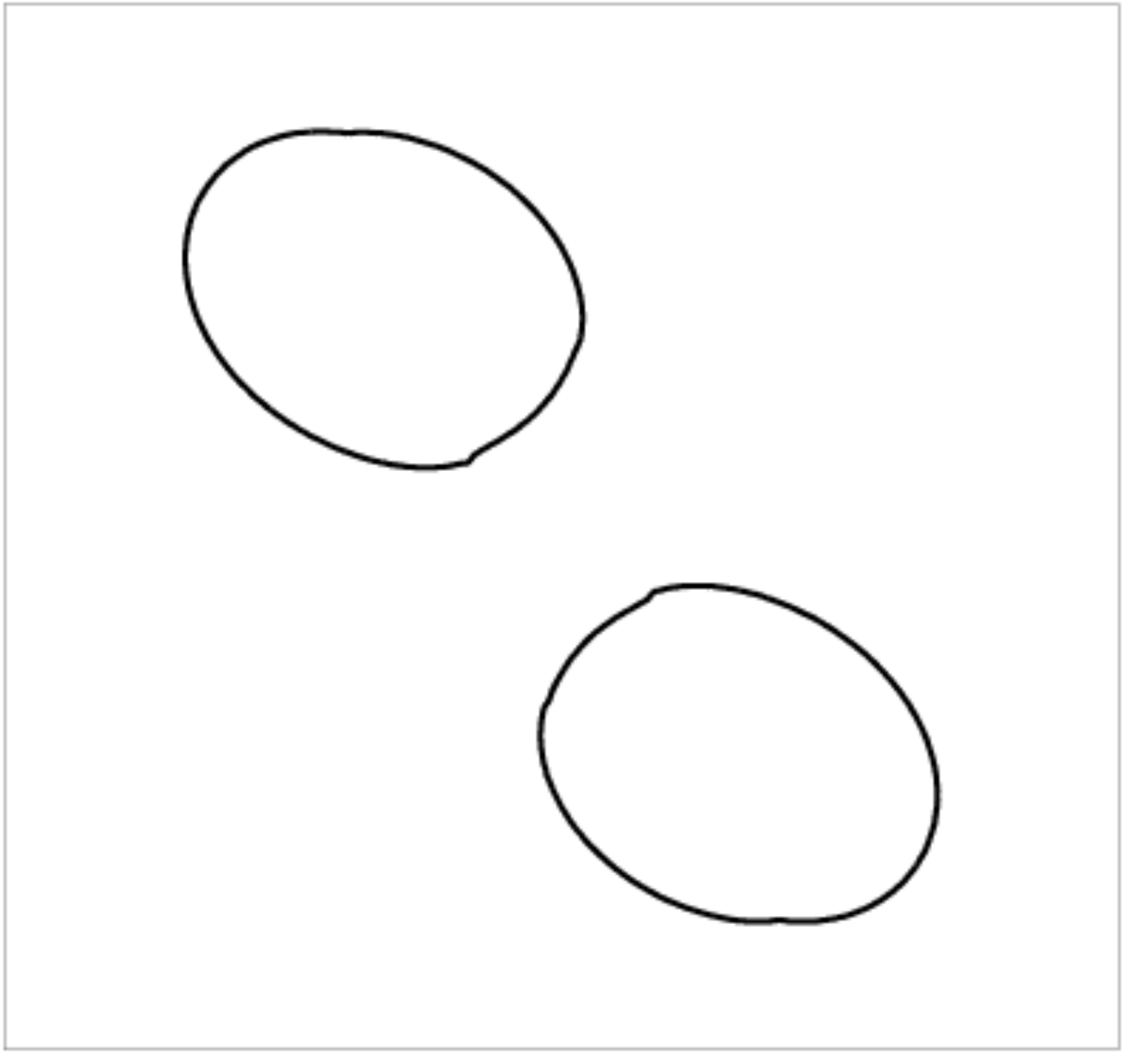

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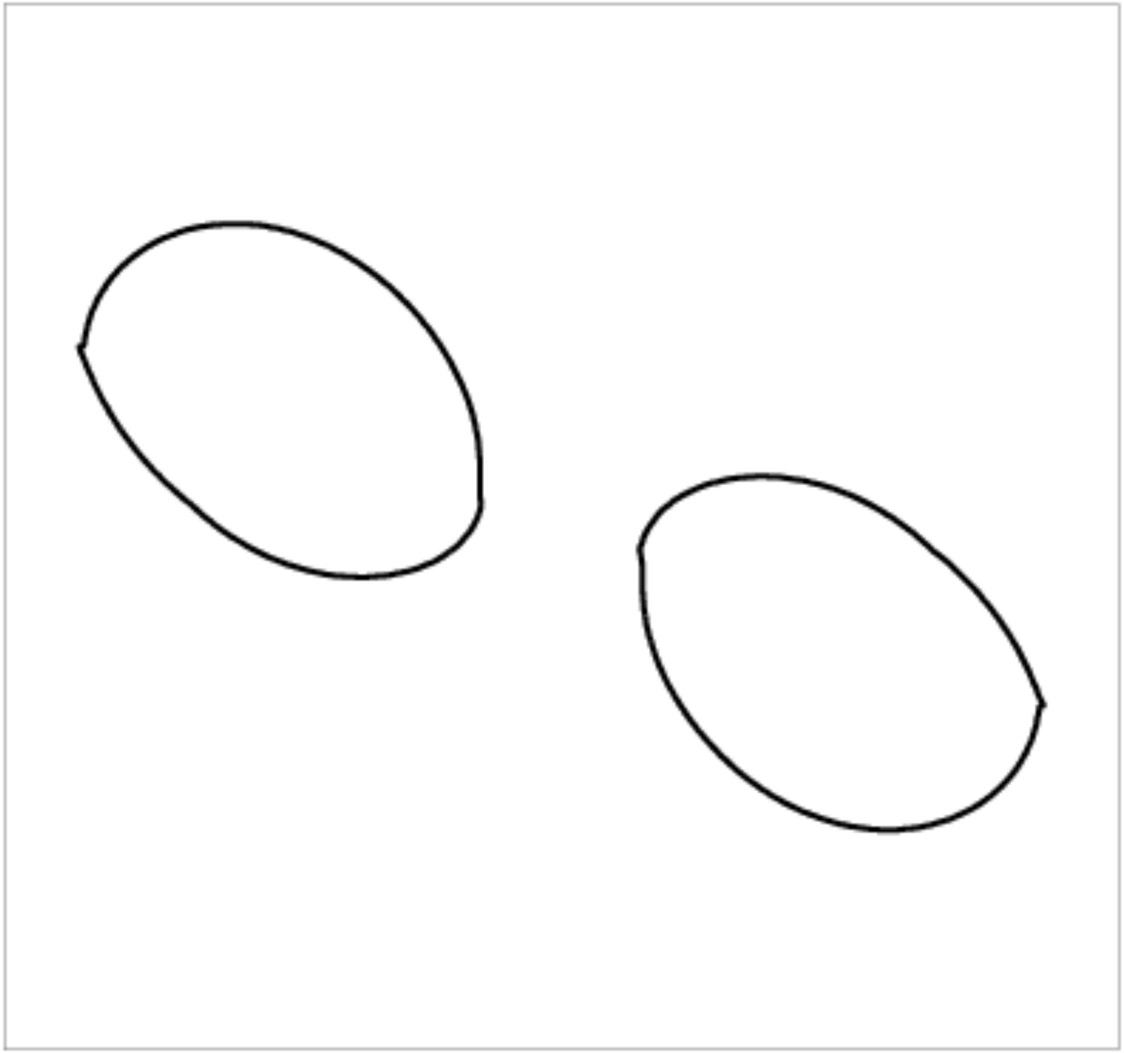

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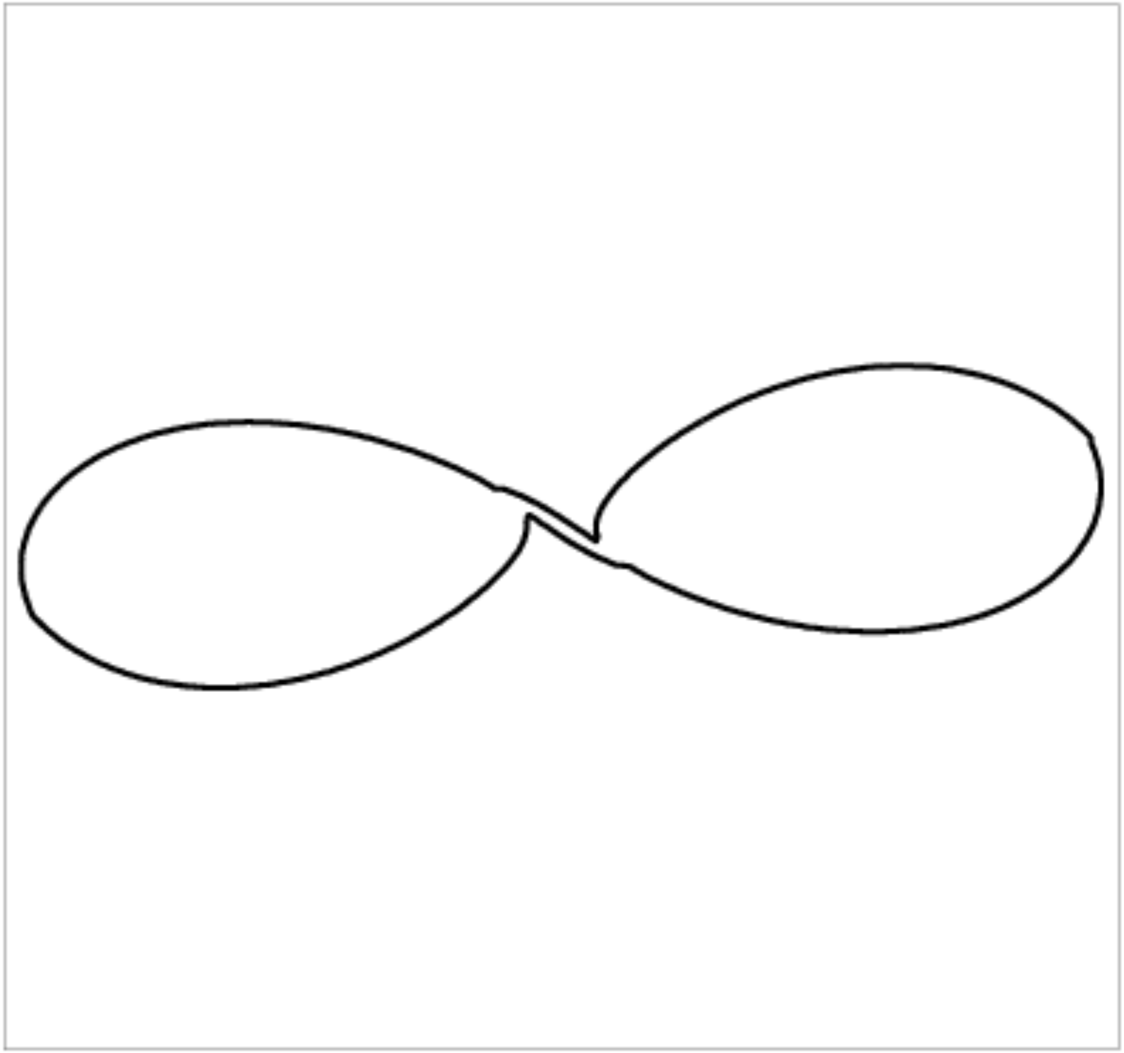

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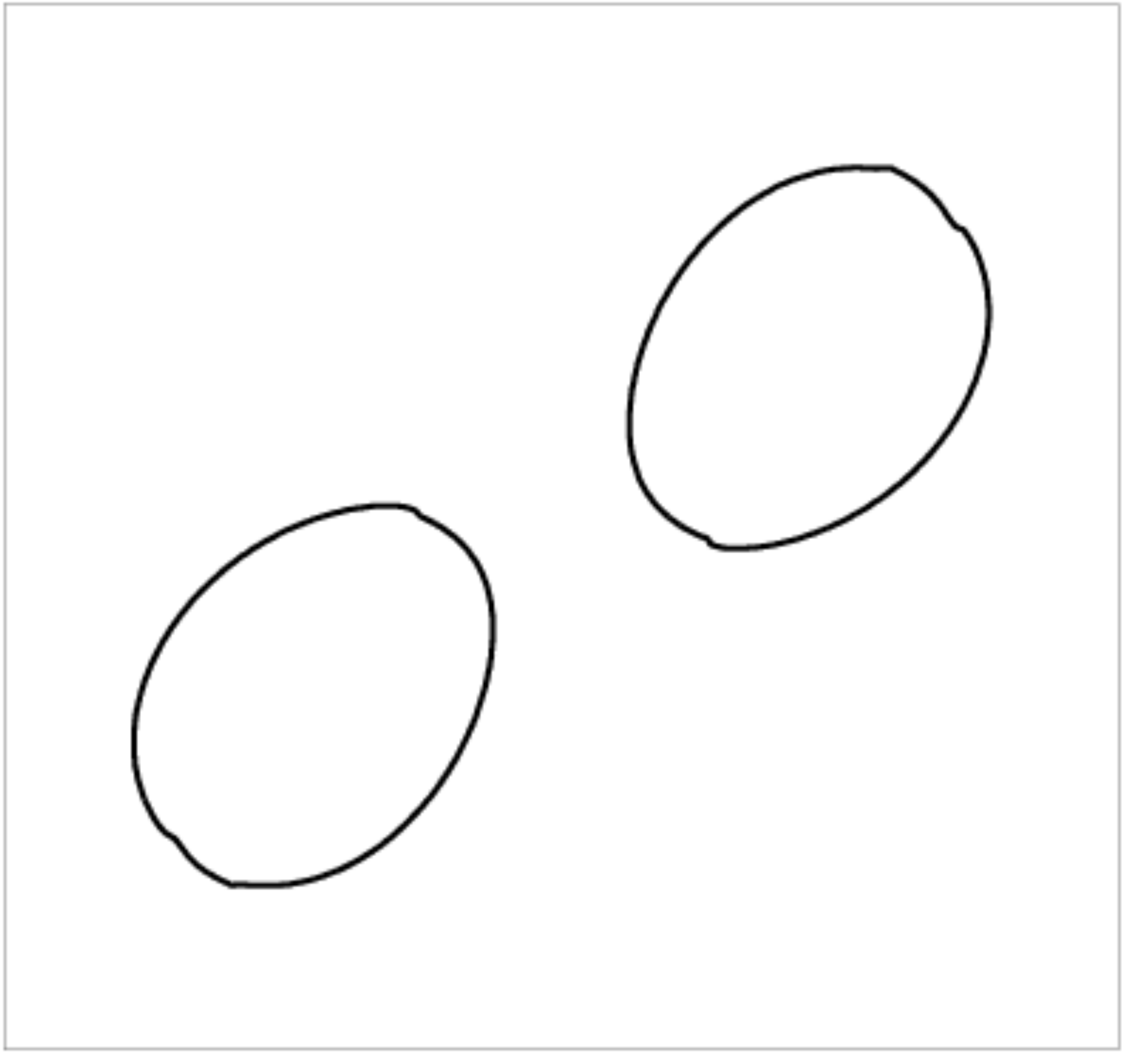

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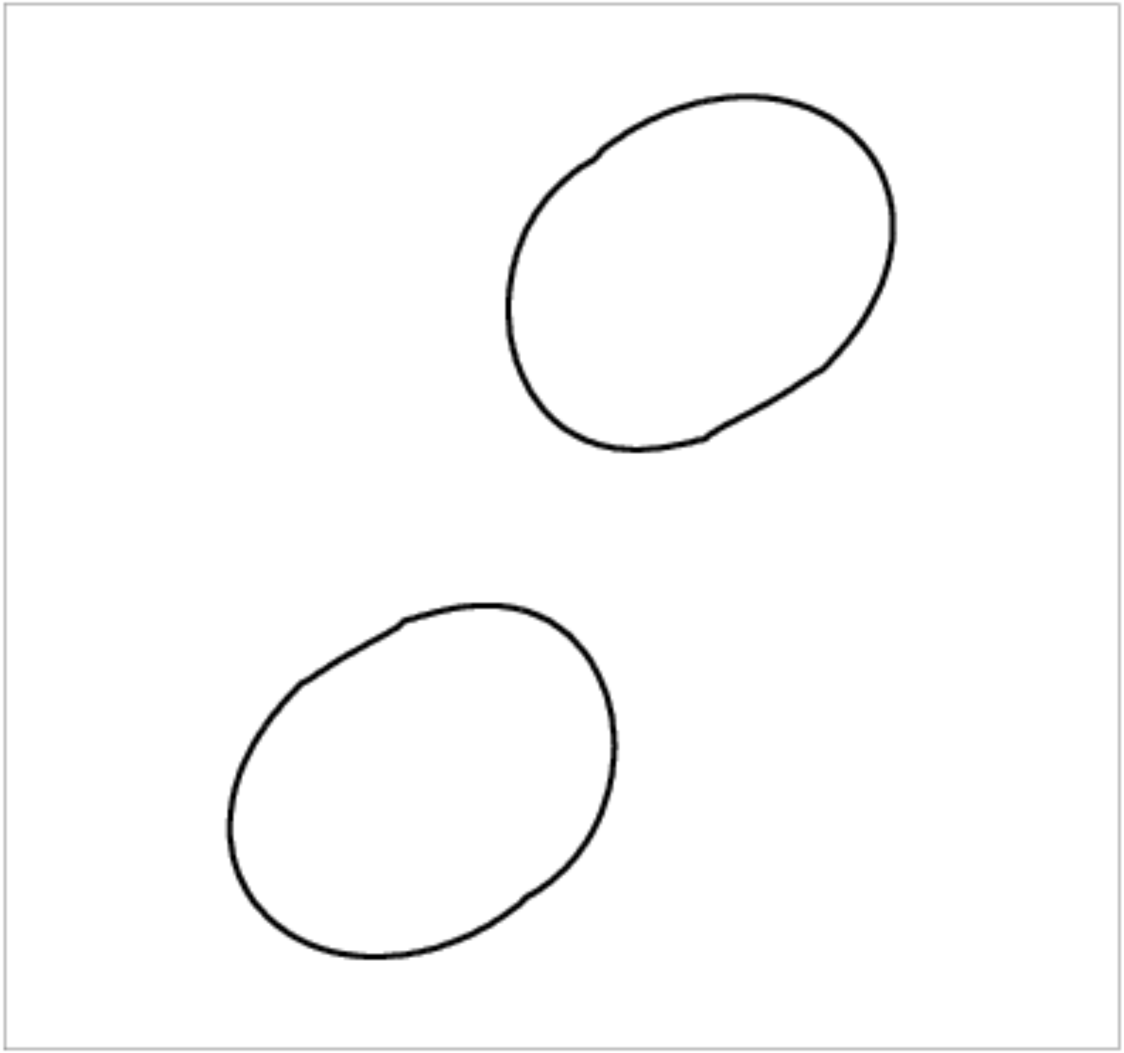

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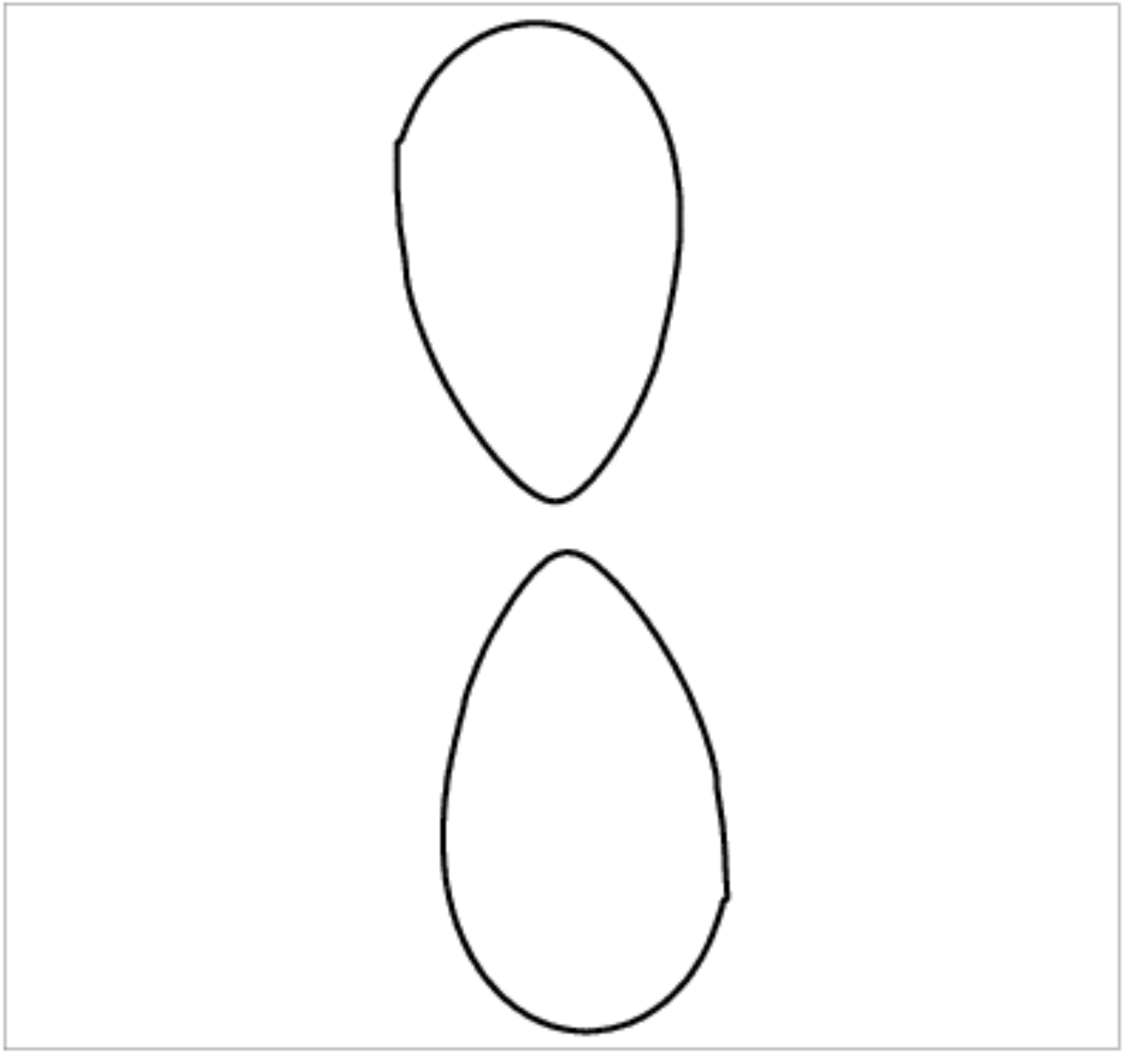

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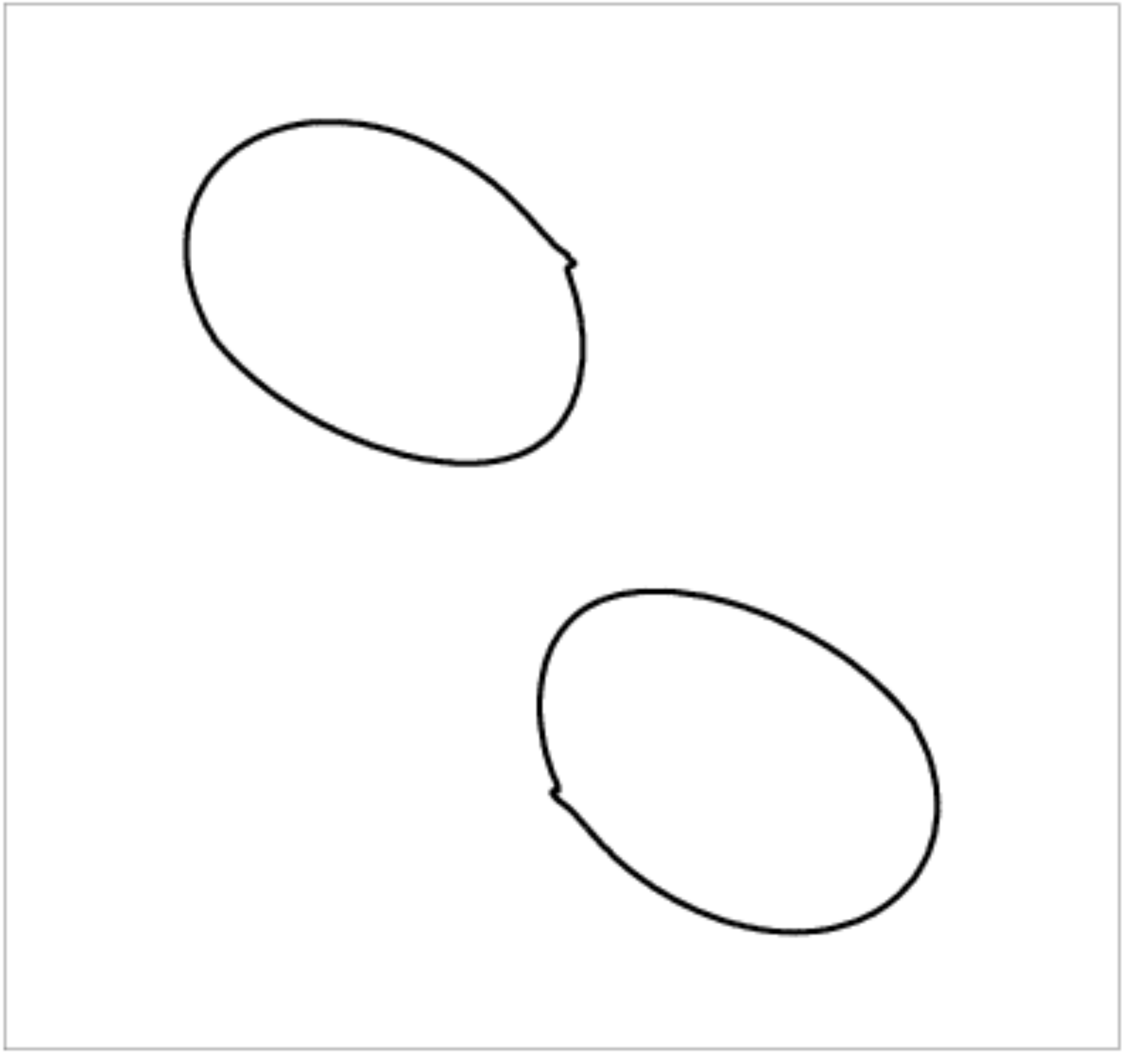

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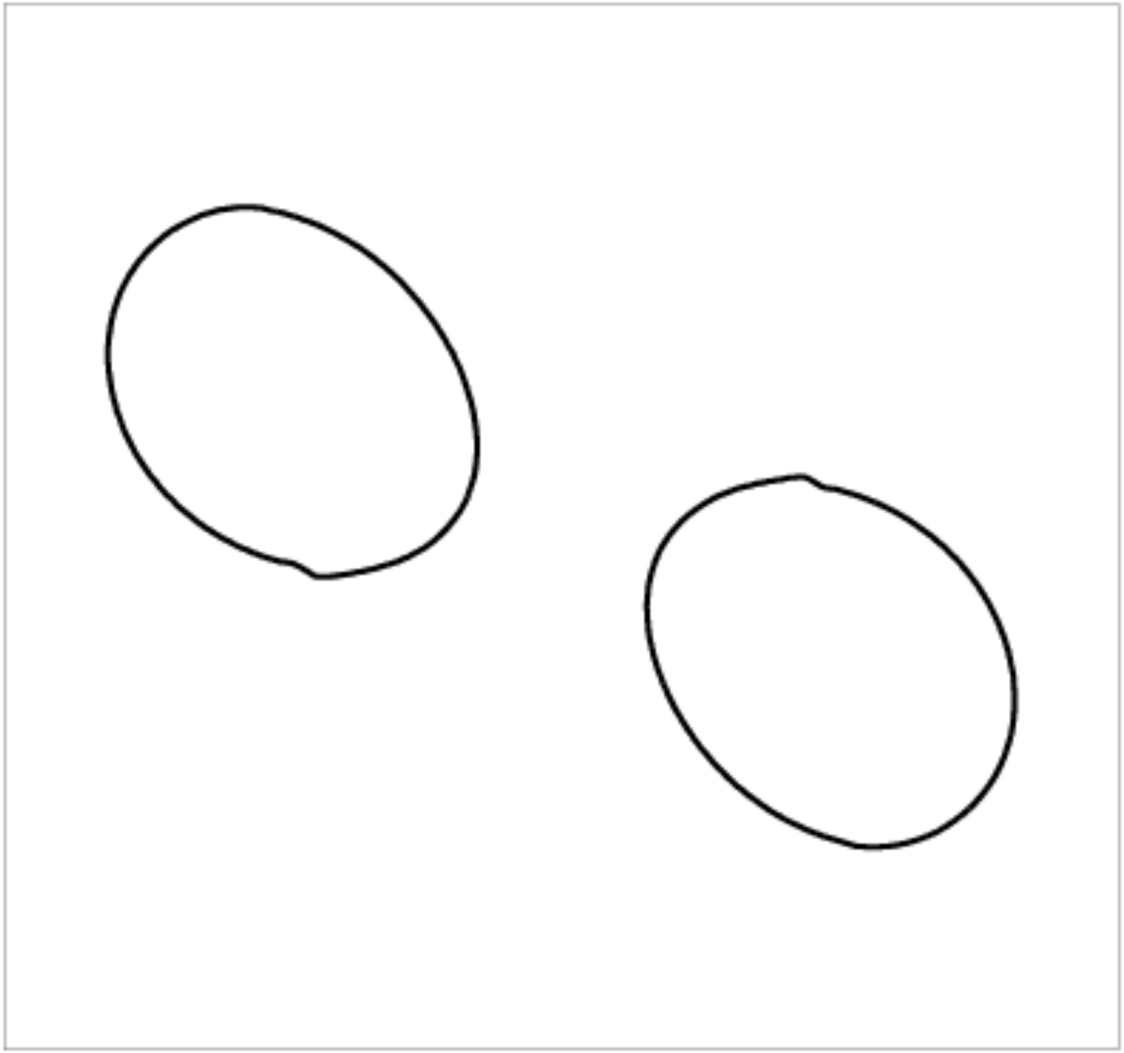

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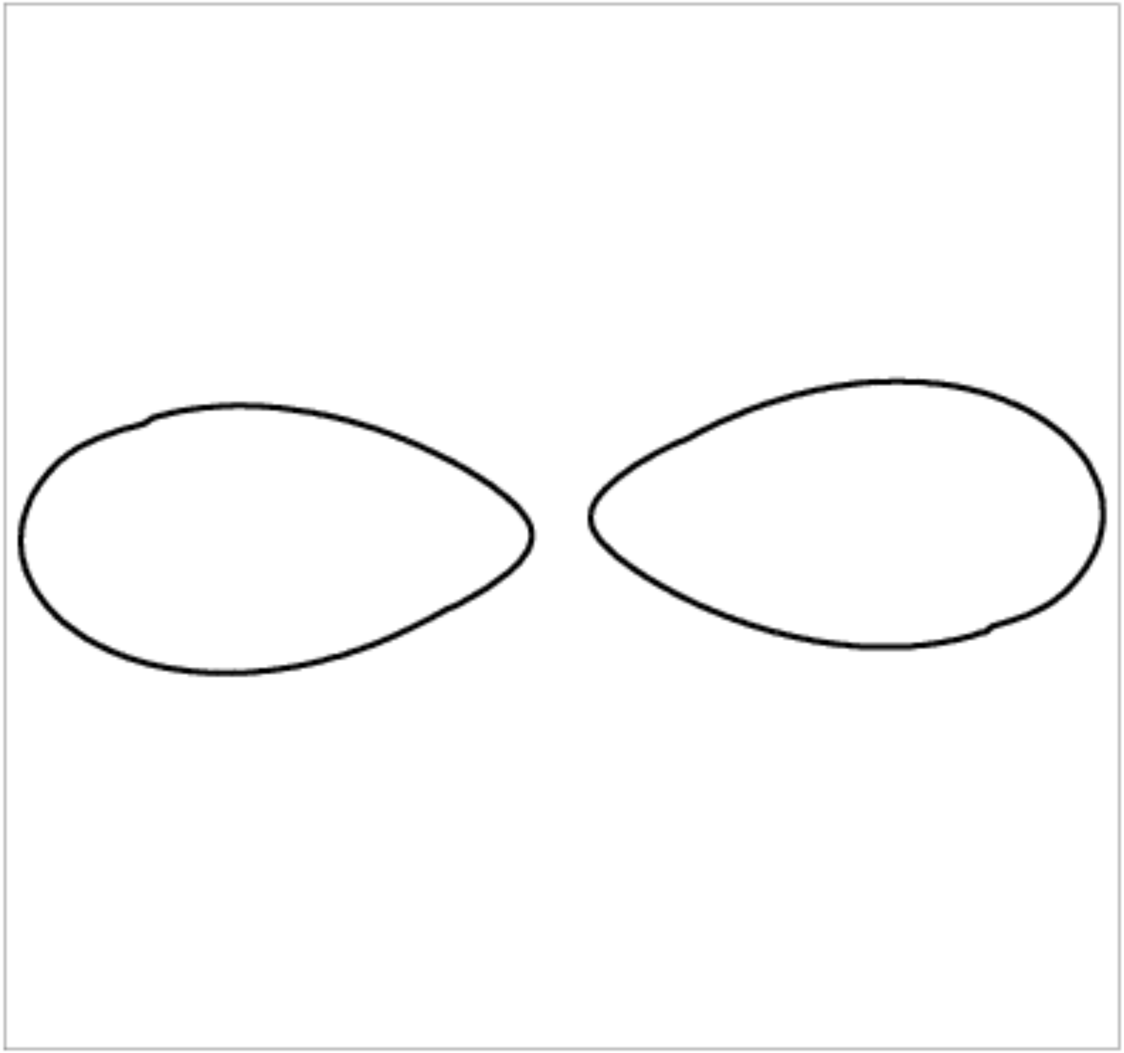

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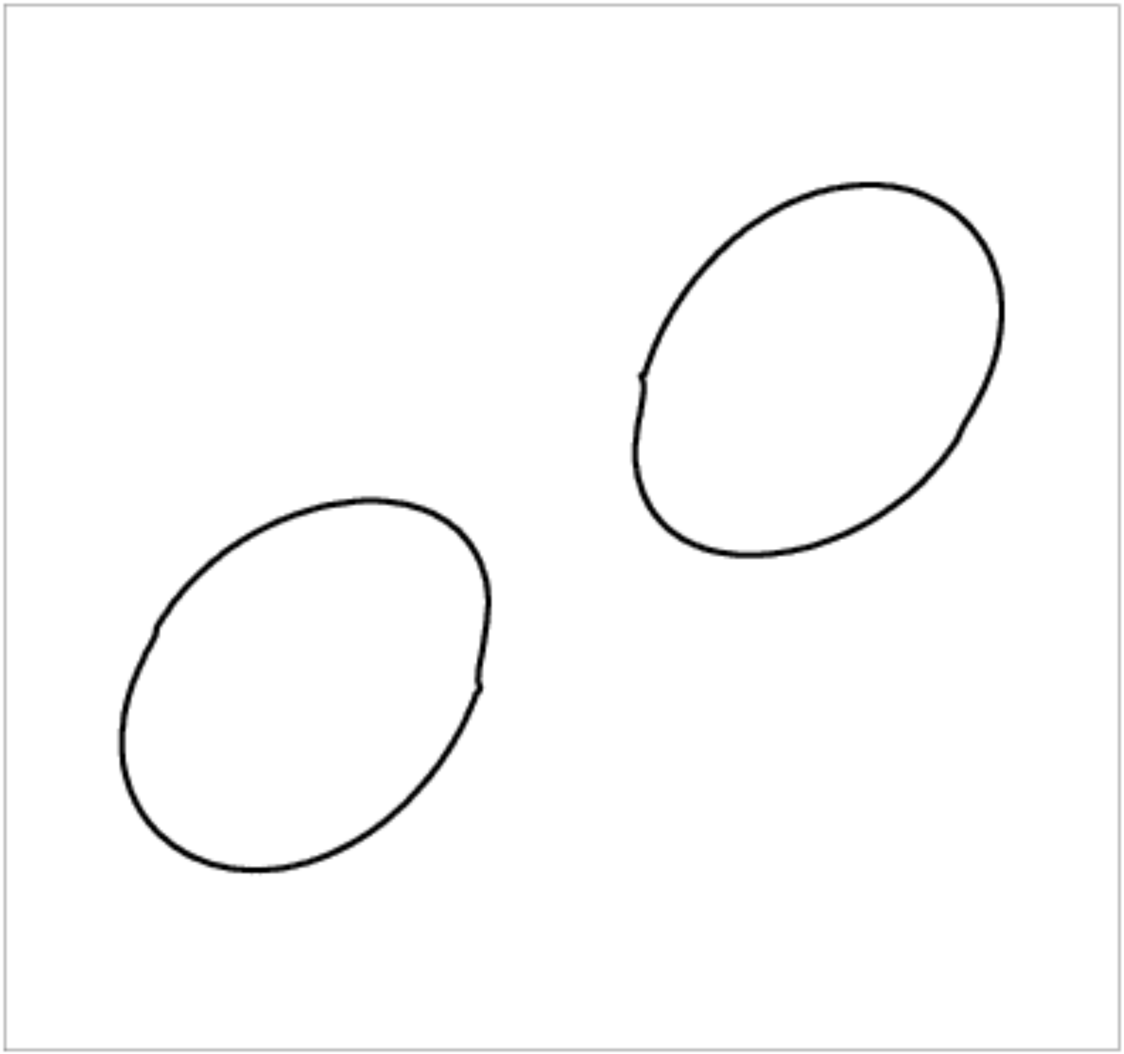

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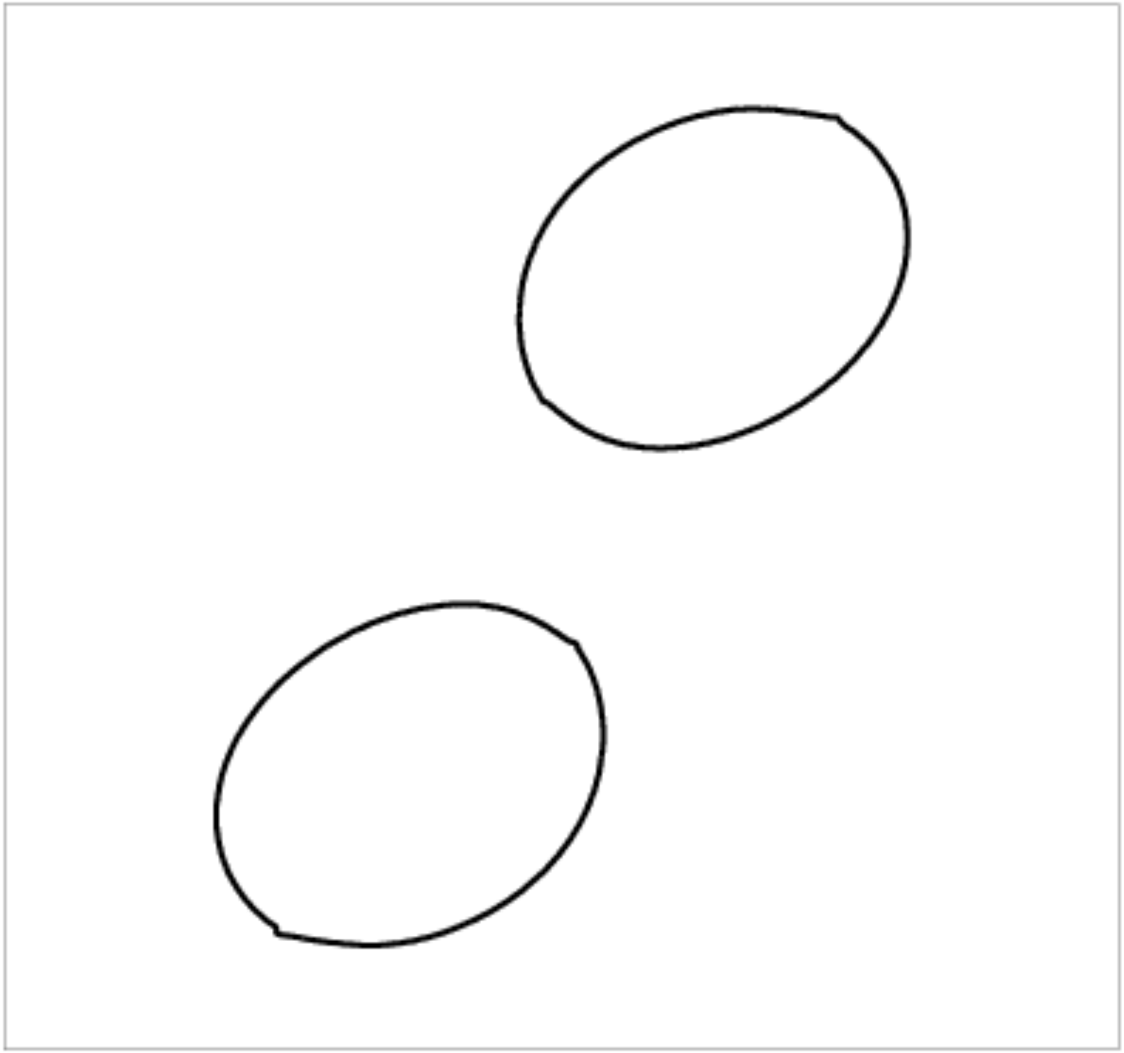

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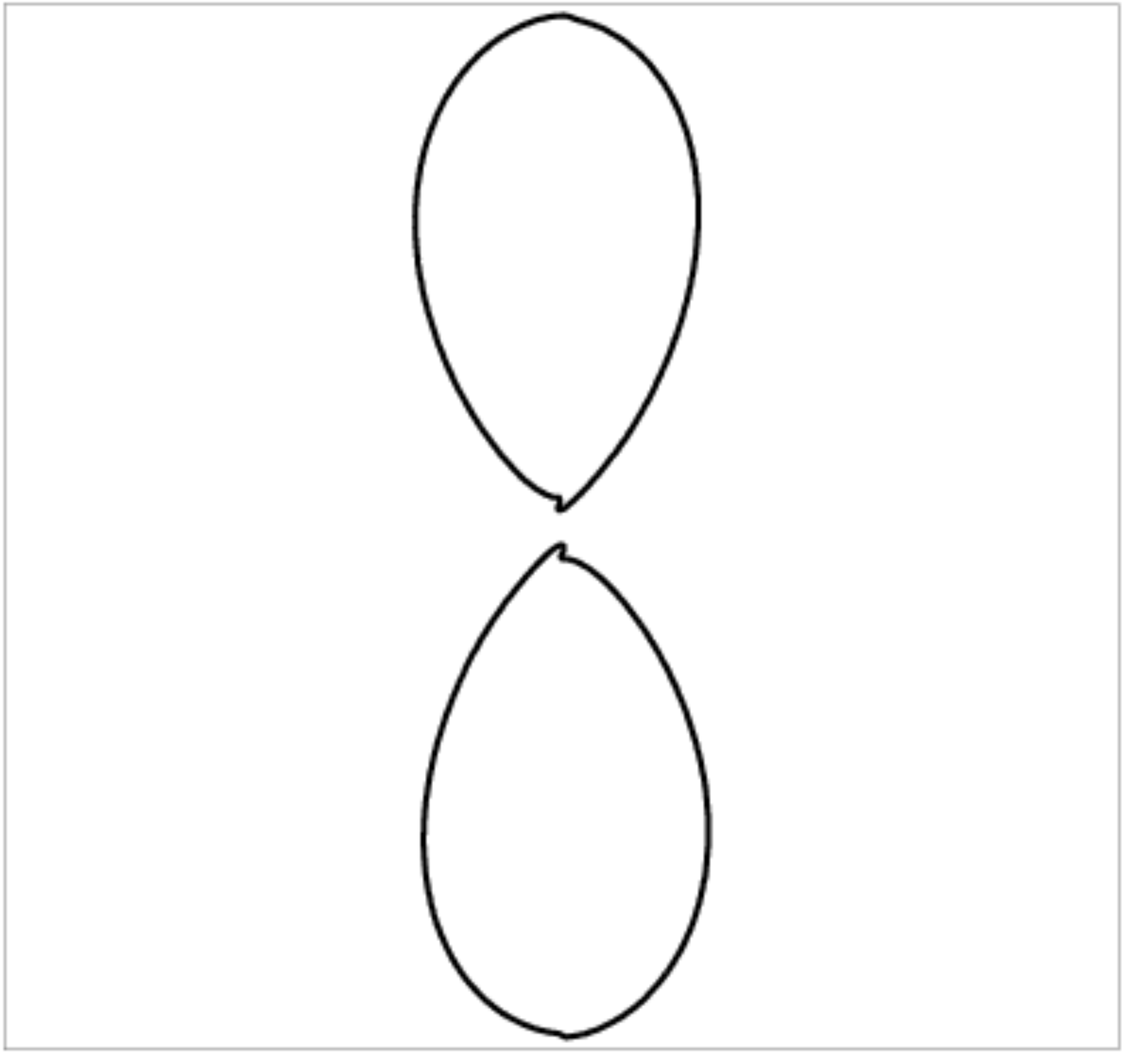

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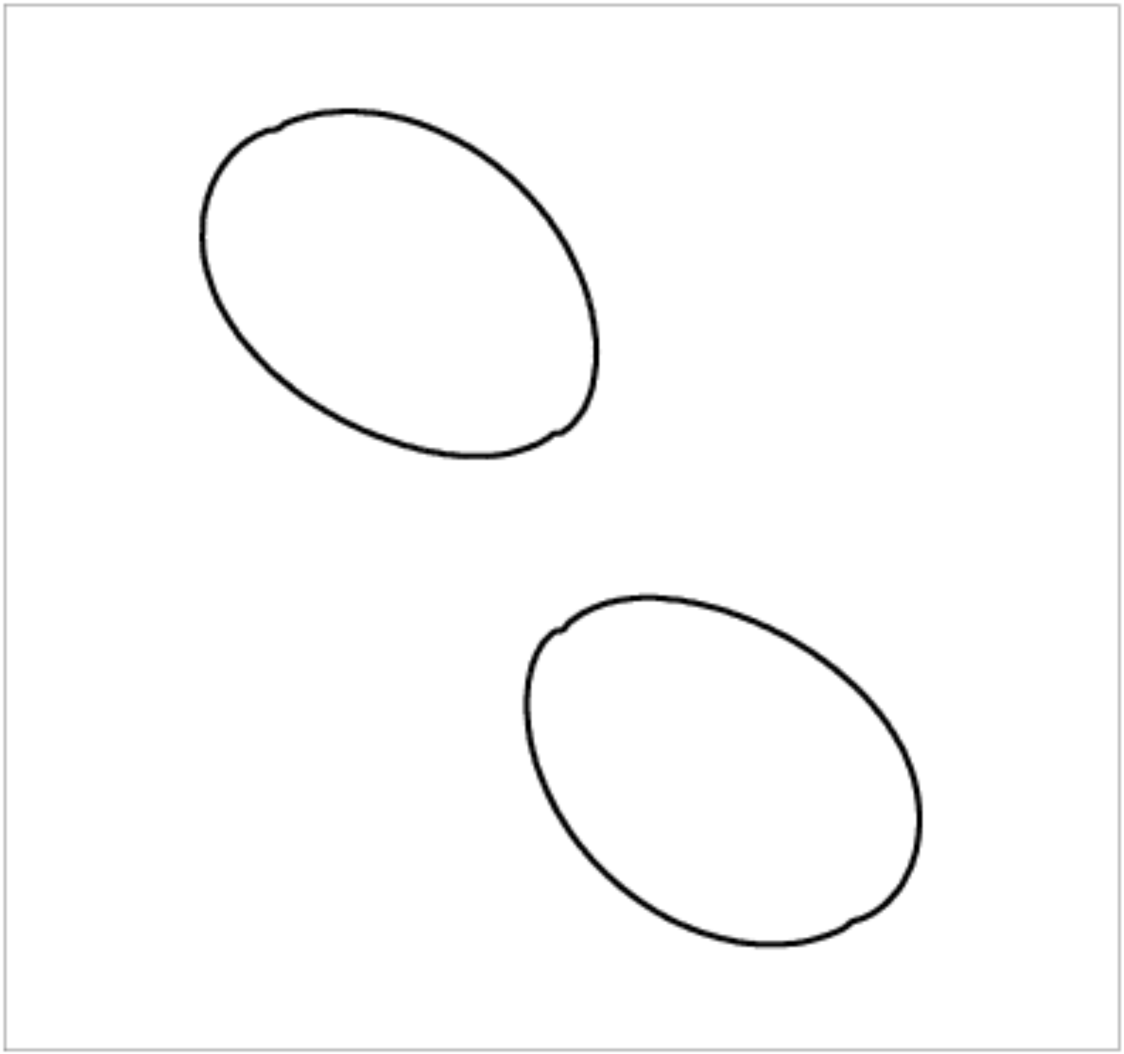

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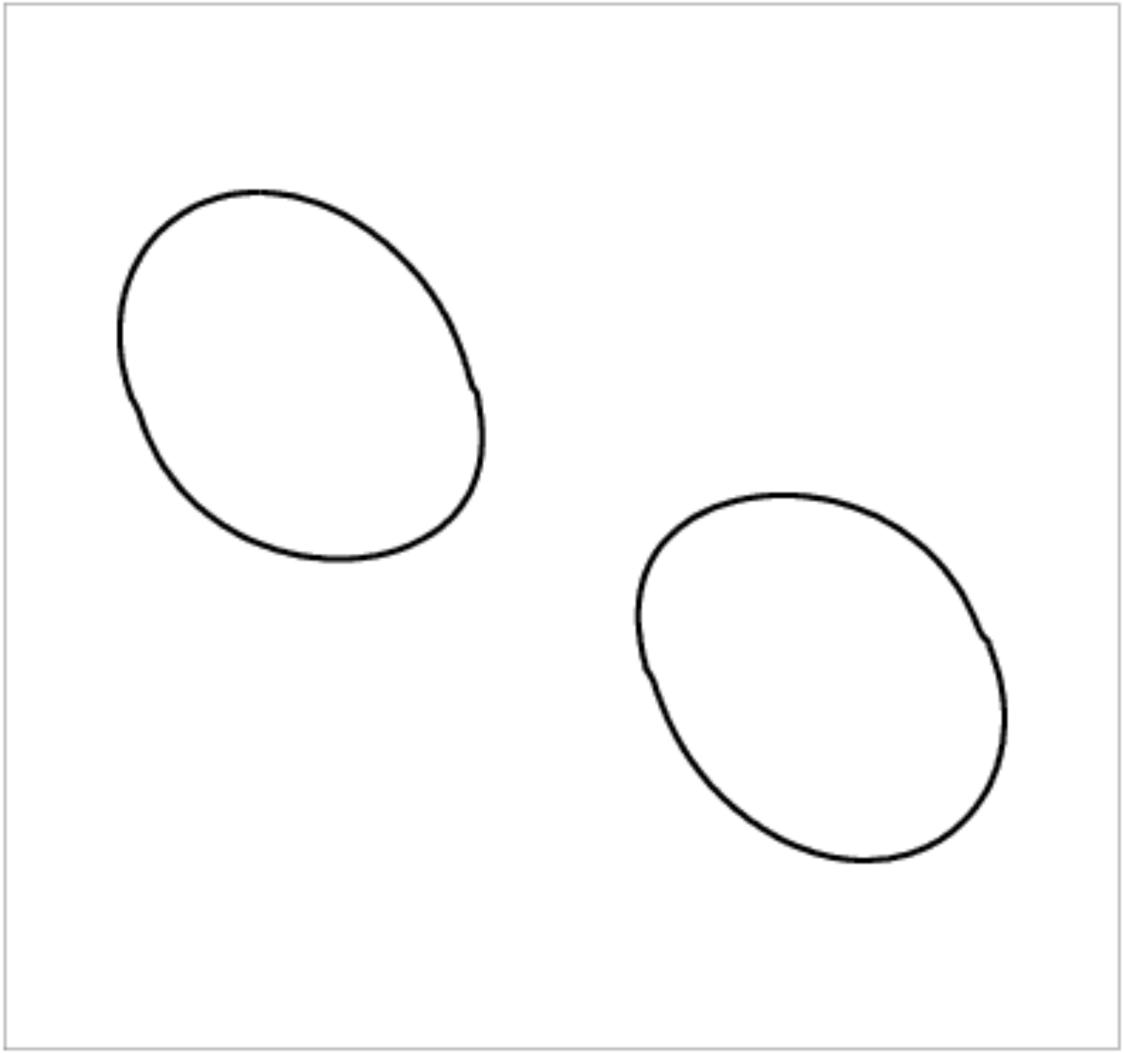
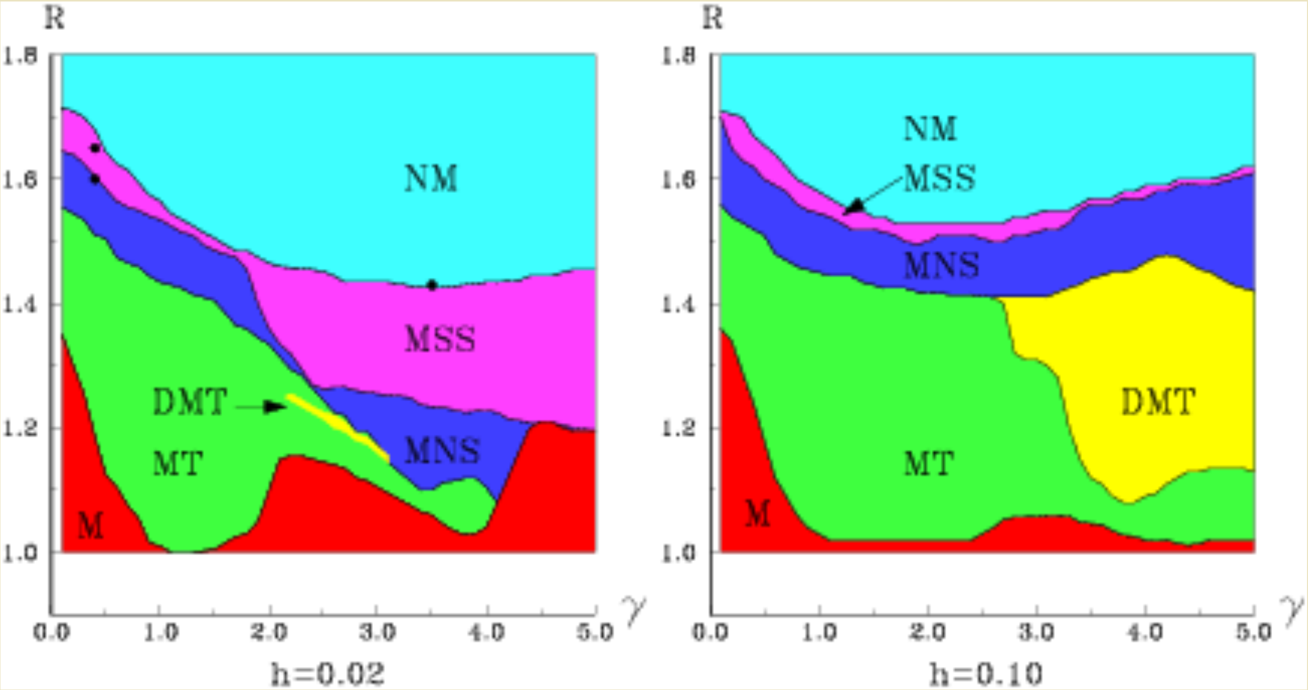


CDM-modeling of interaction of two cyclones of upper layer in two-layer rotating fluid: diagrams of states



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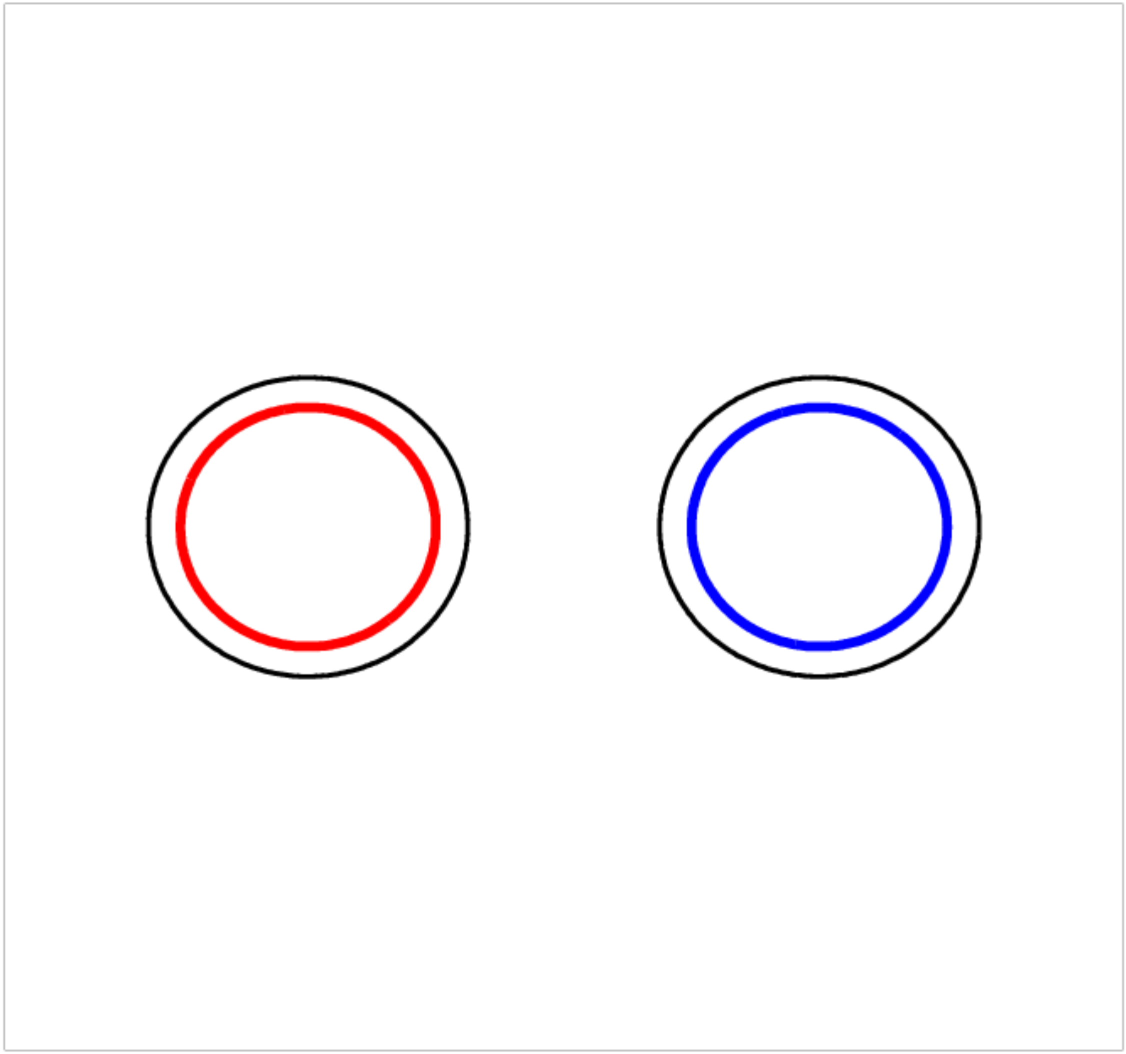
h_1=0.02

γ=0.4, R=1.60

(MNS-type)

t=0



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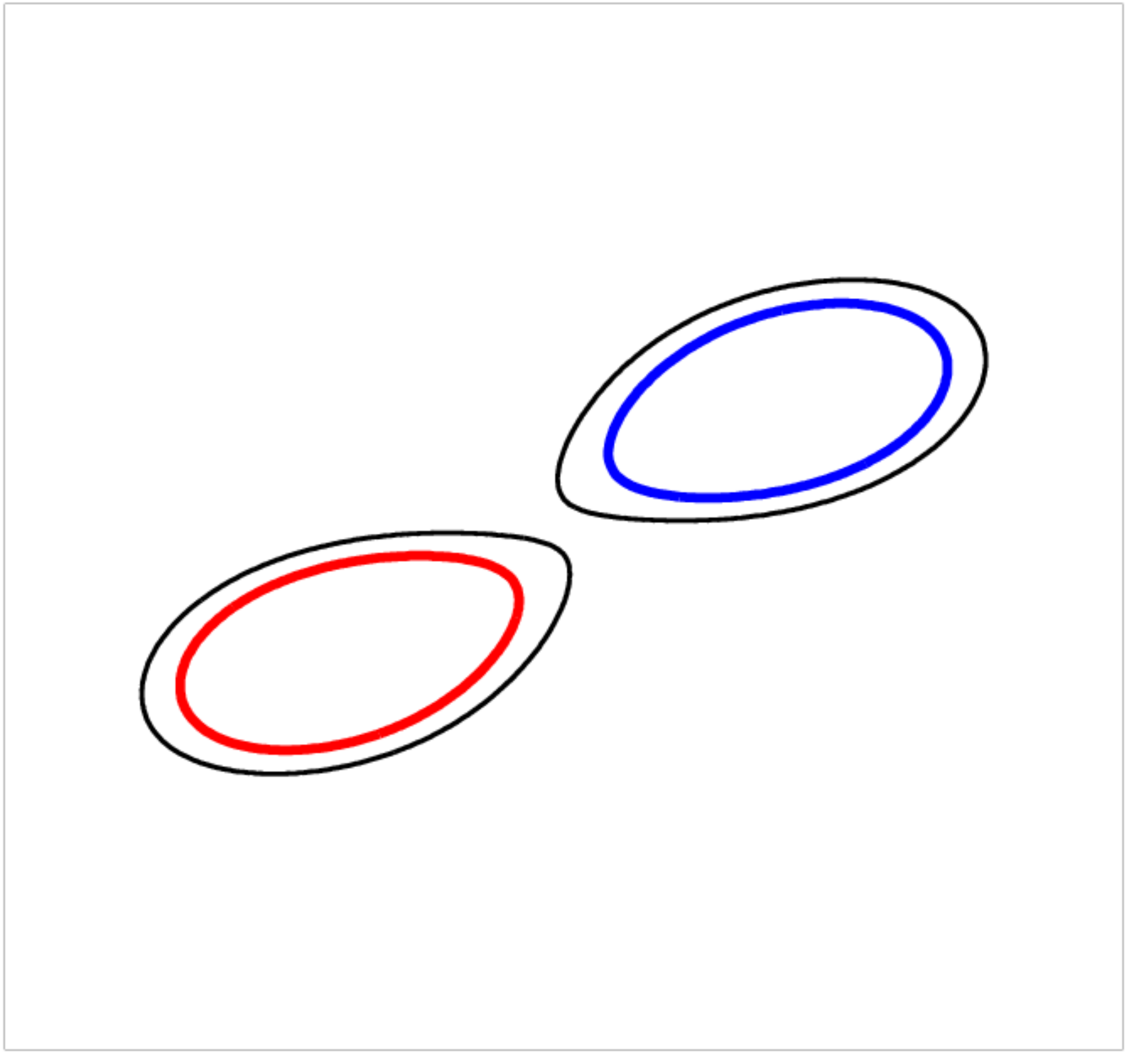

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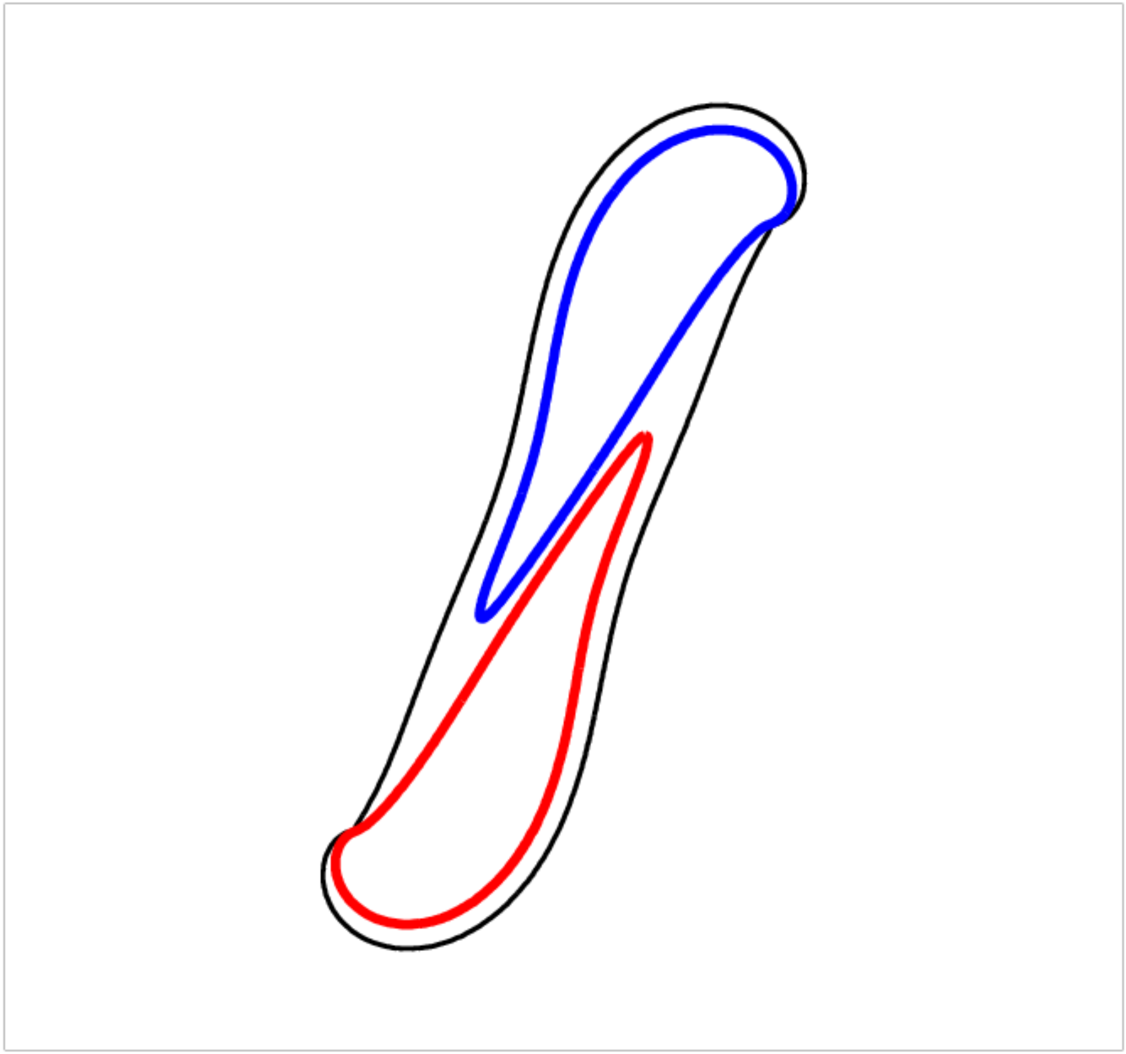

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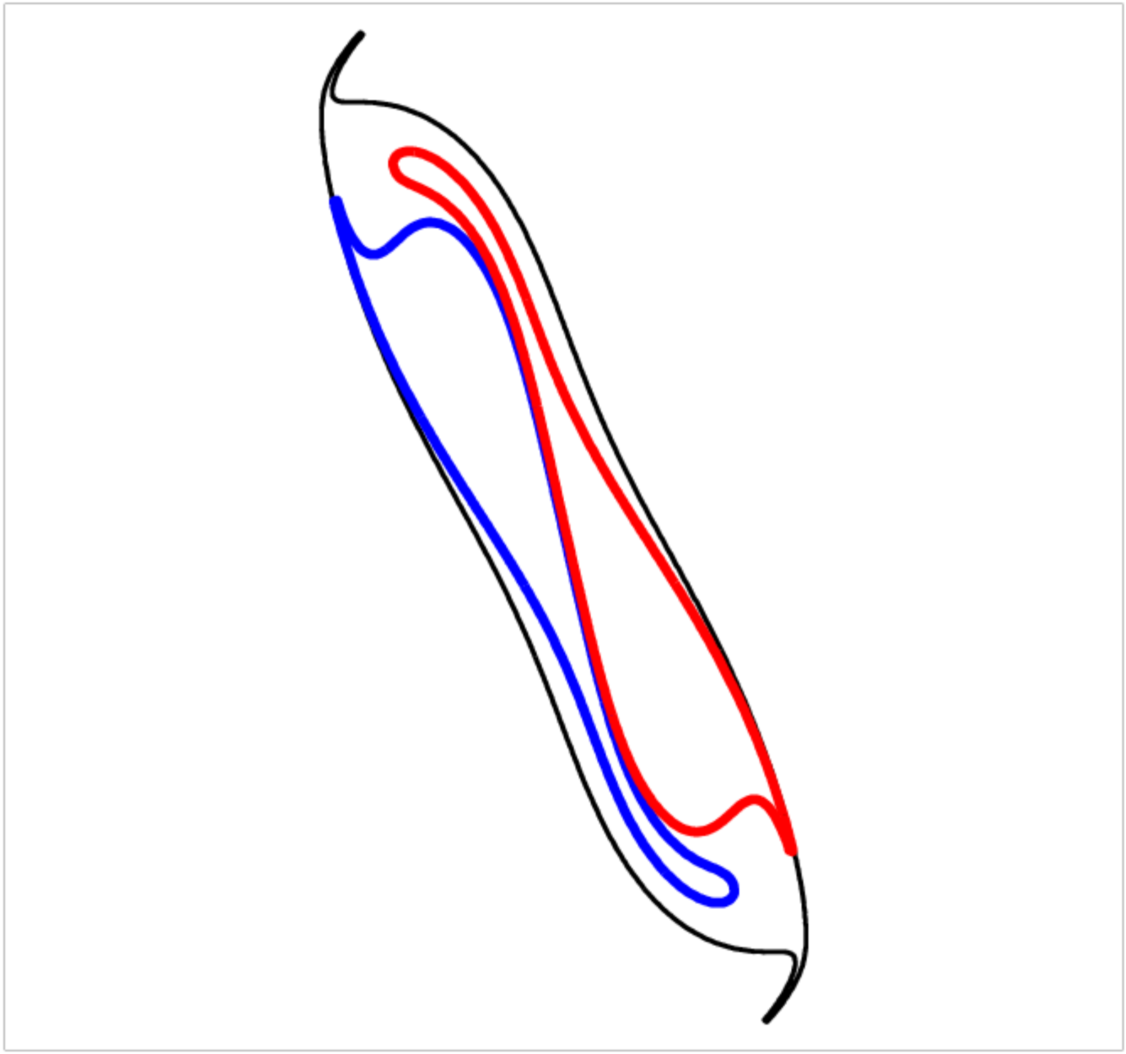

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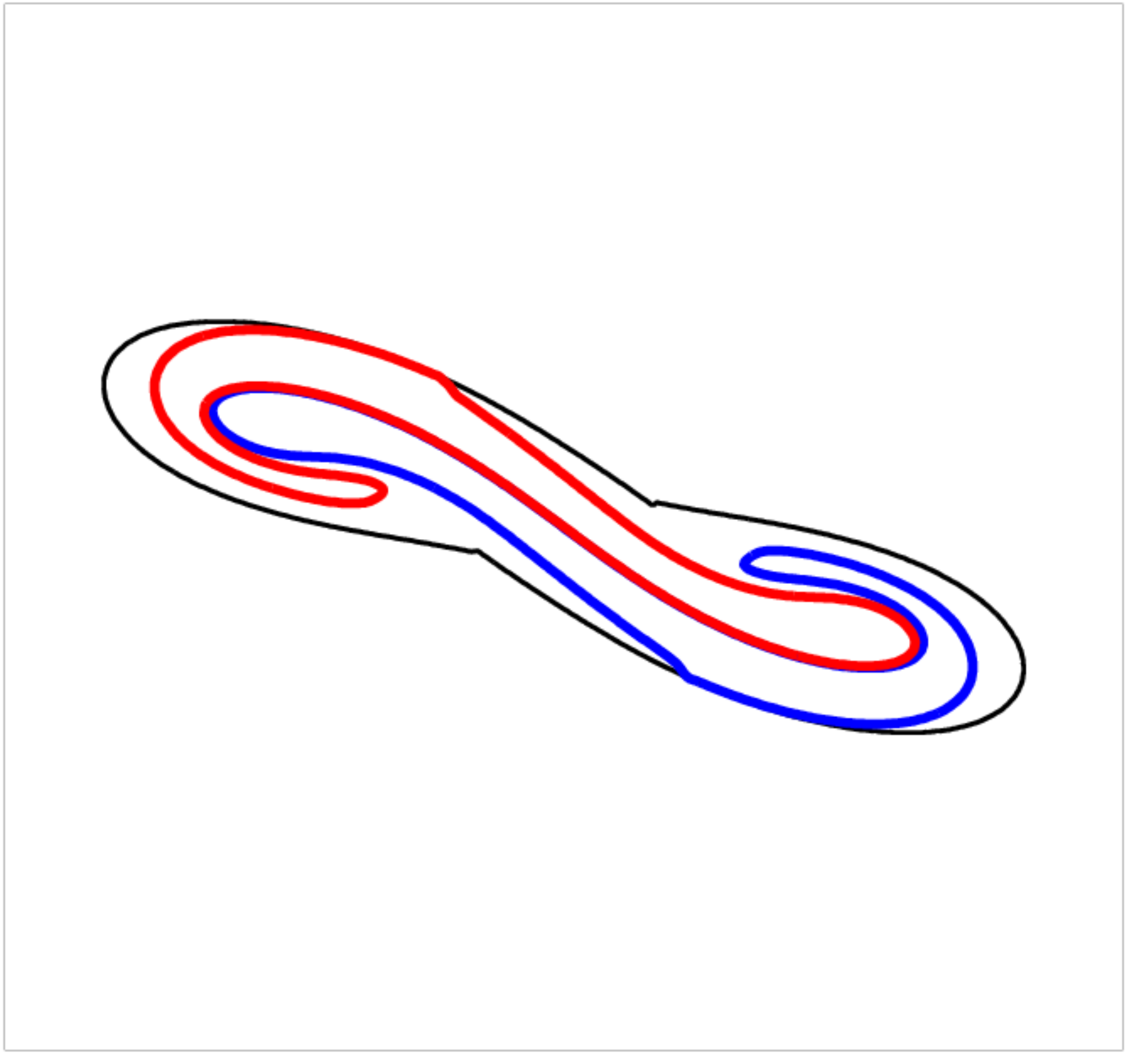

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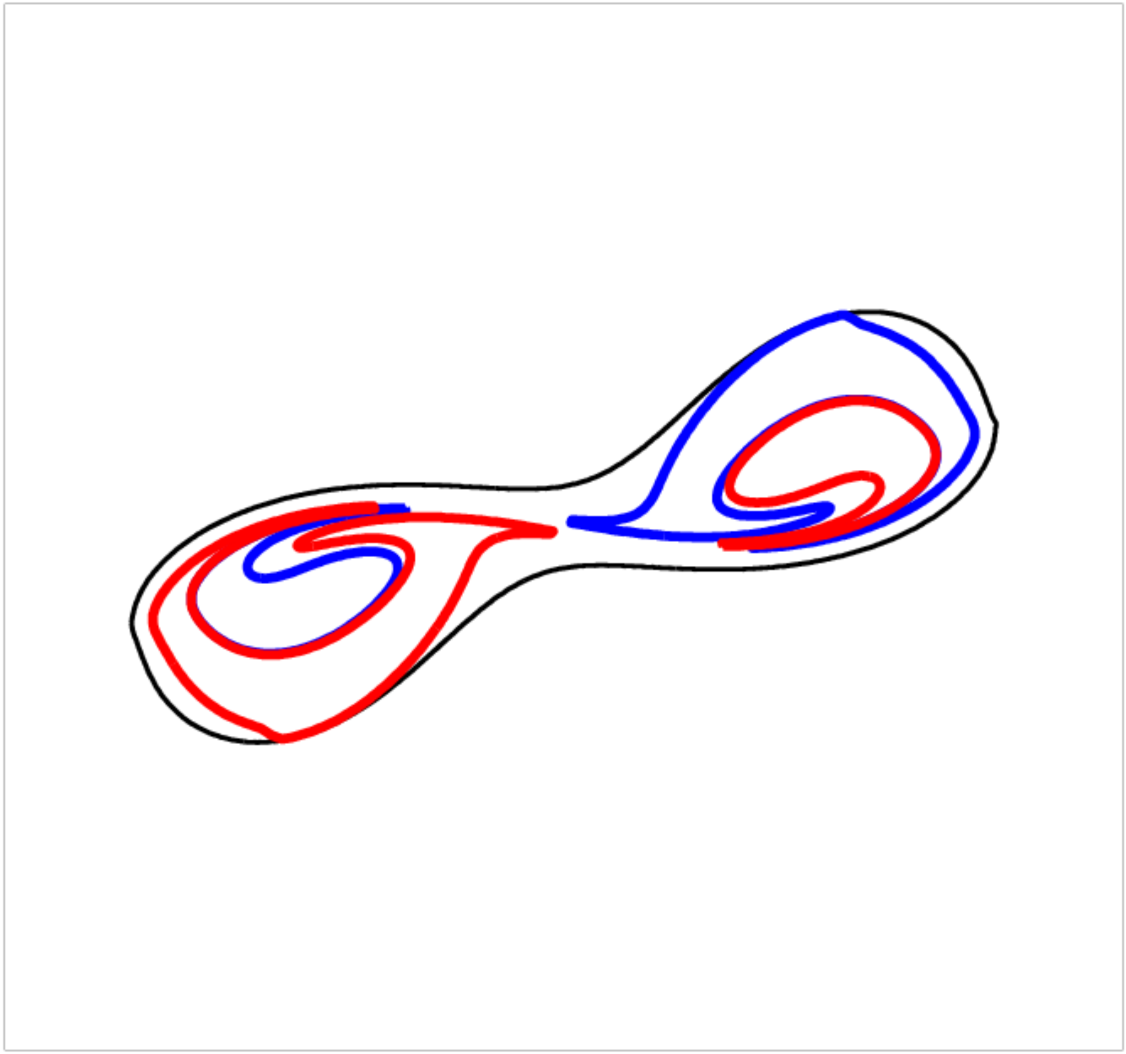

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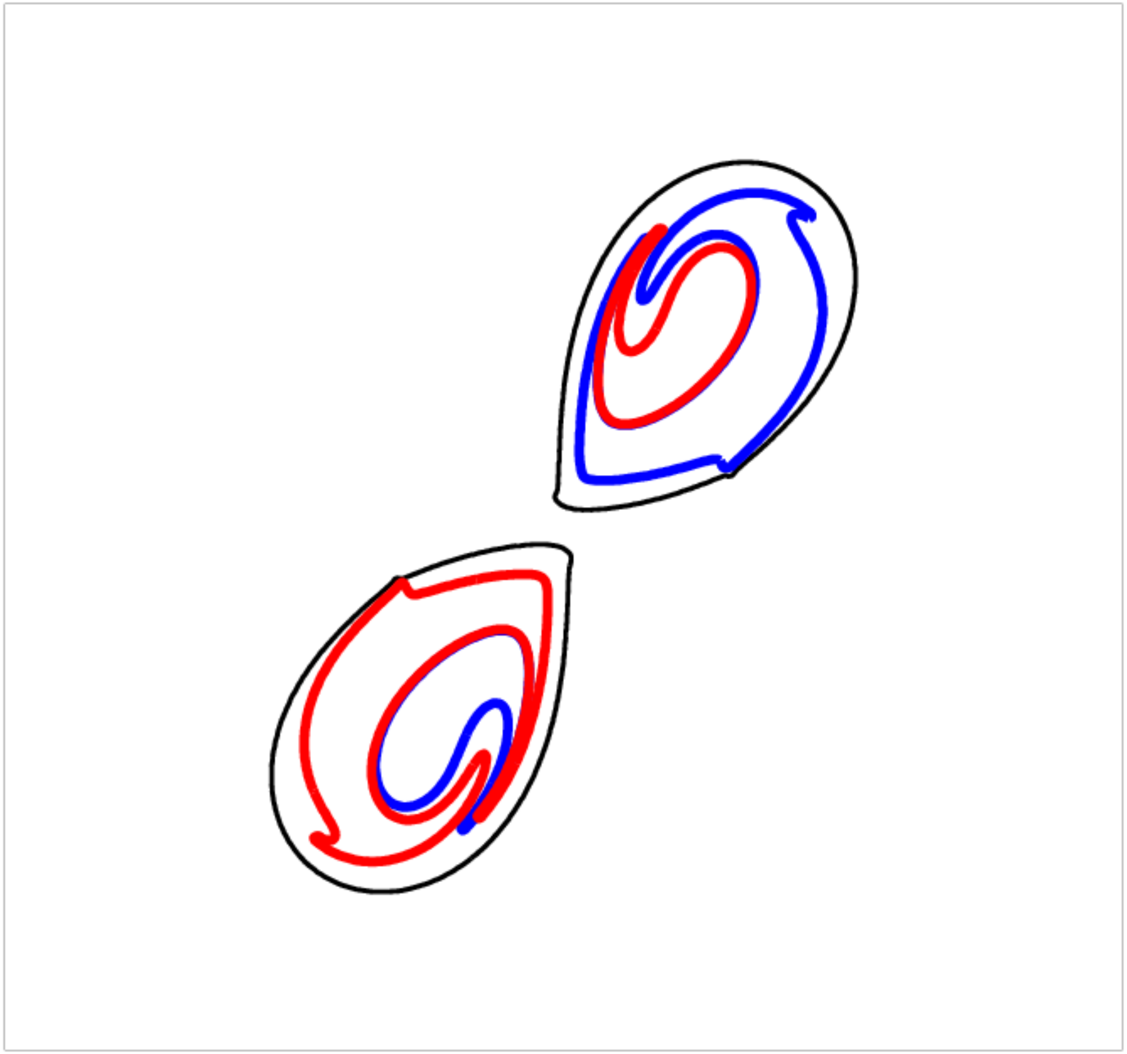

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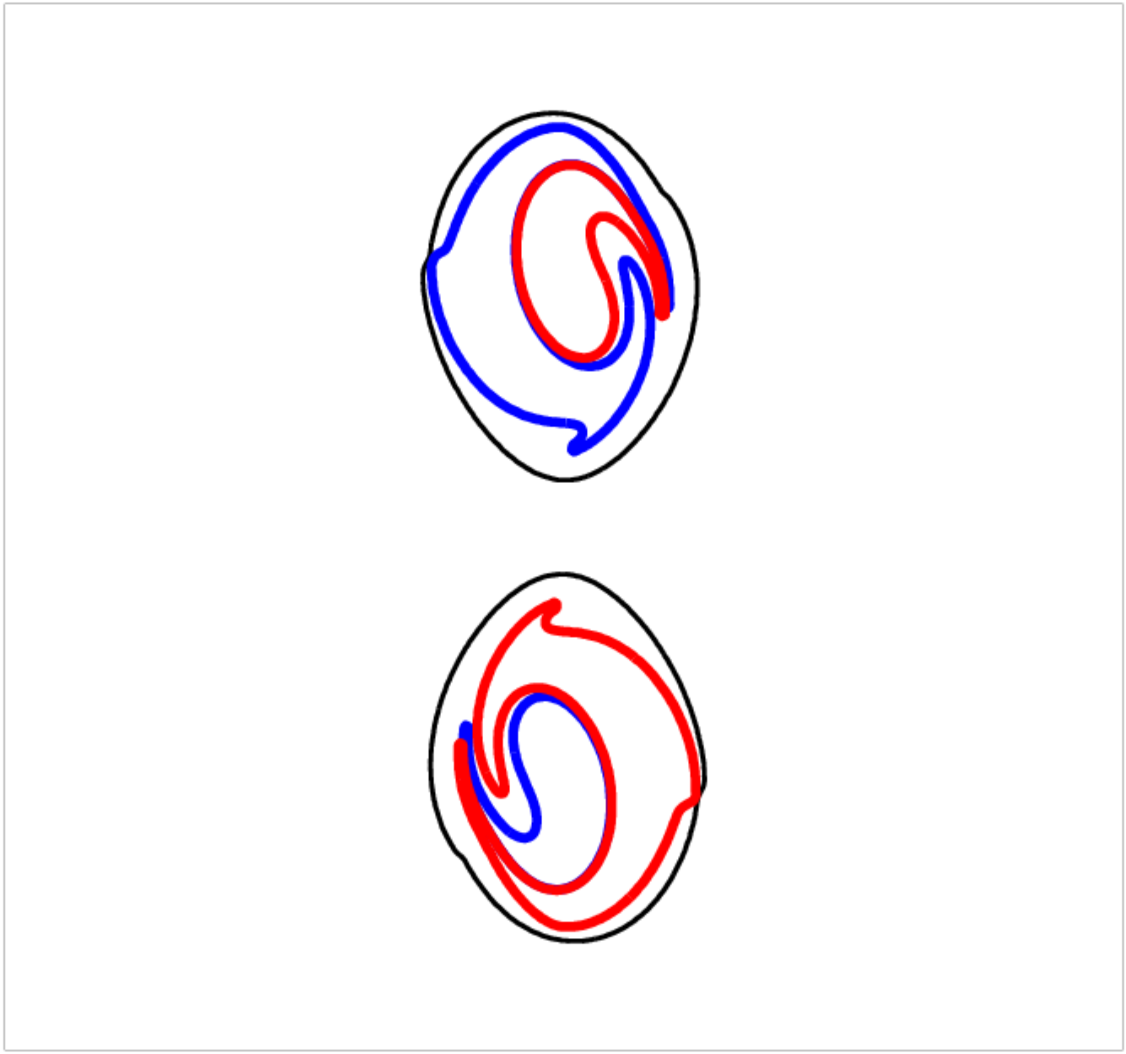

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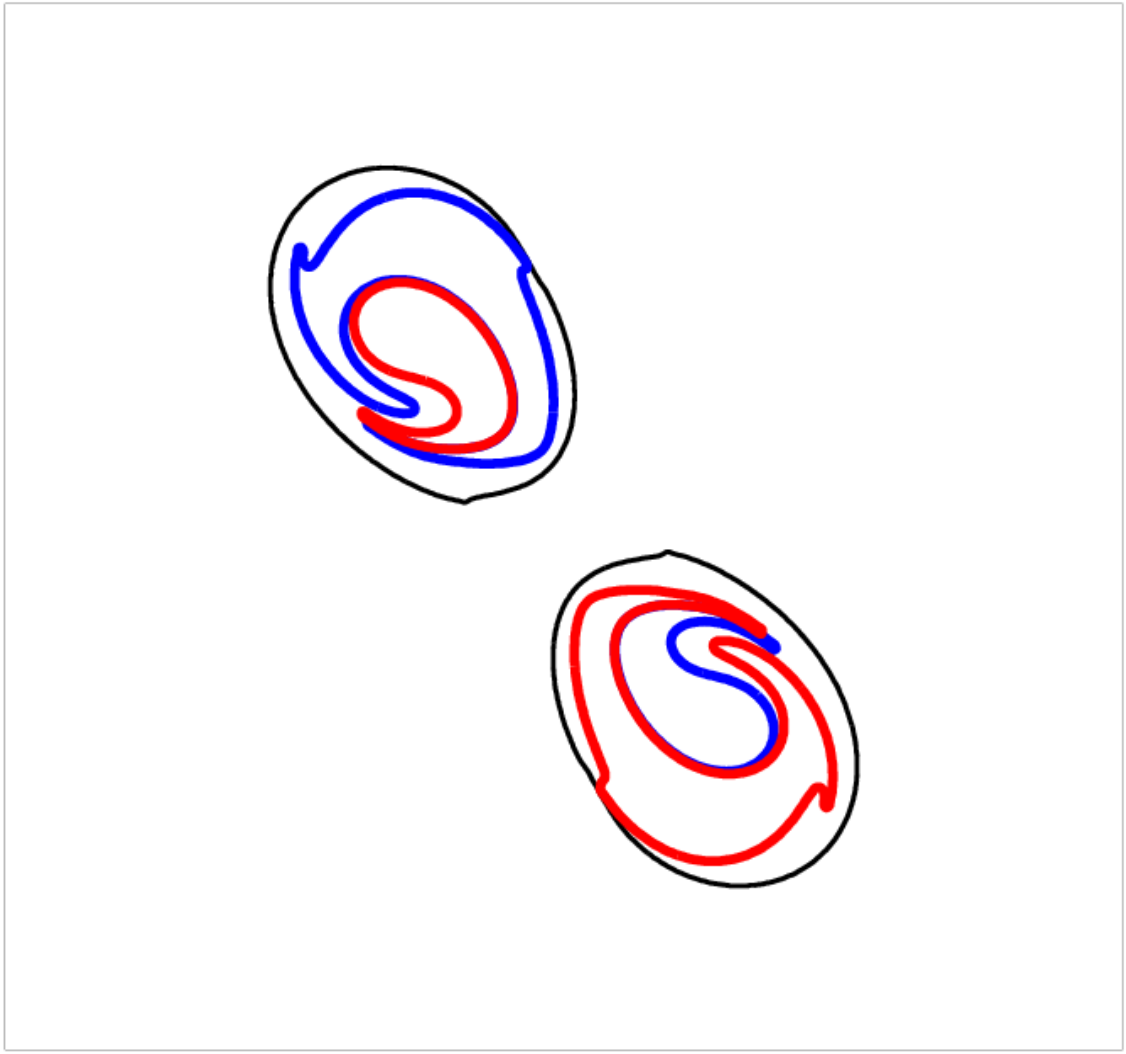

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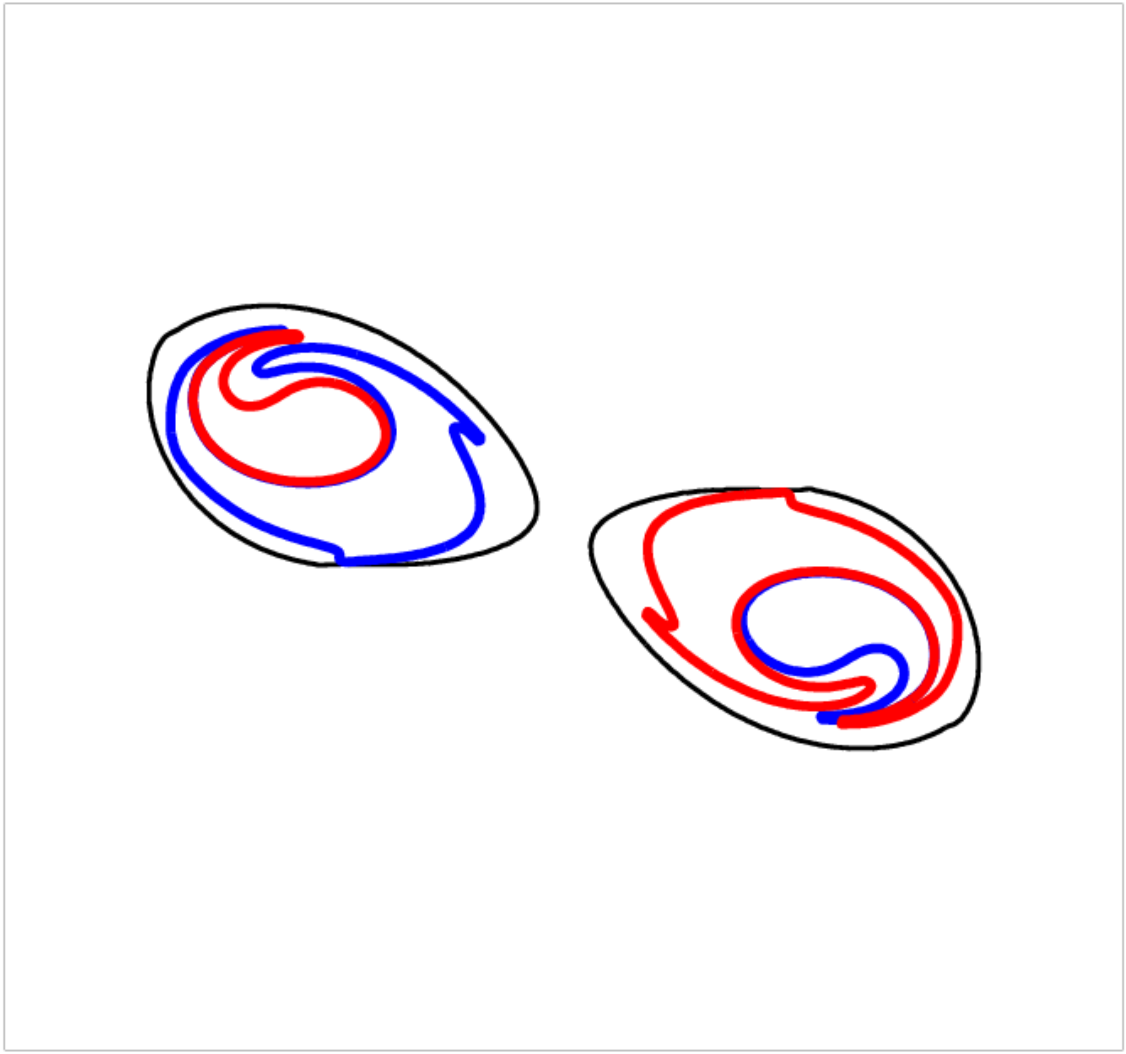

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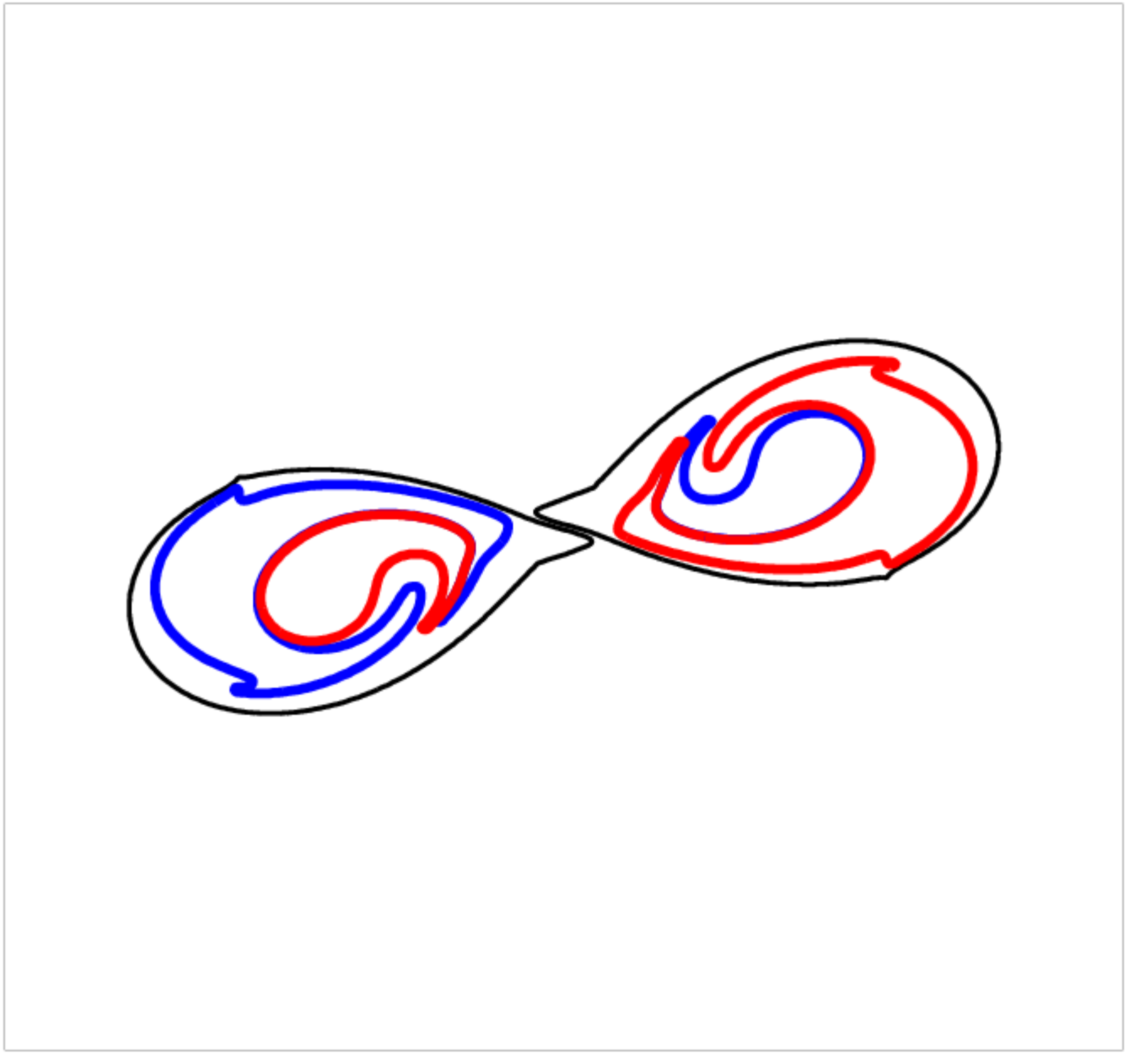

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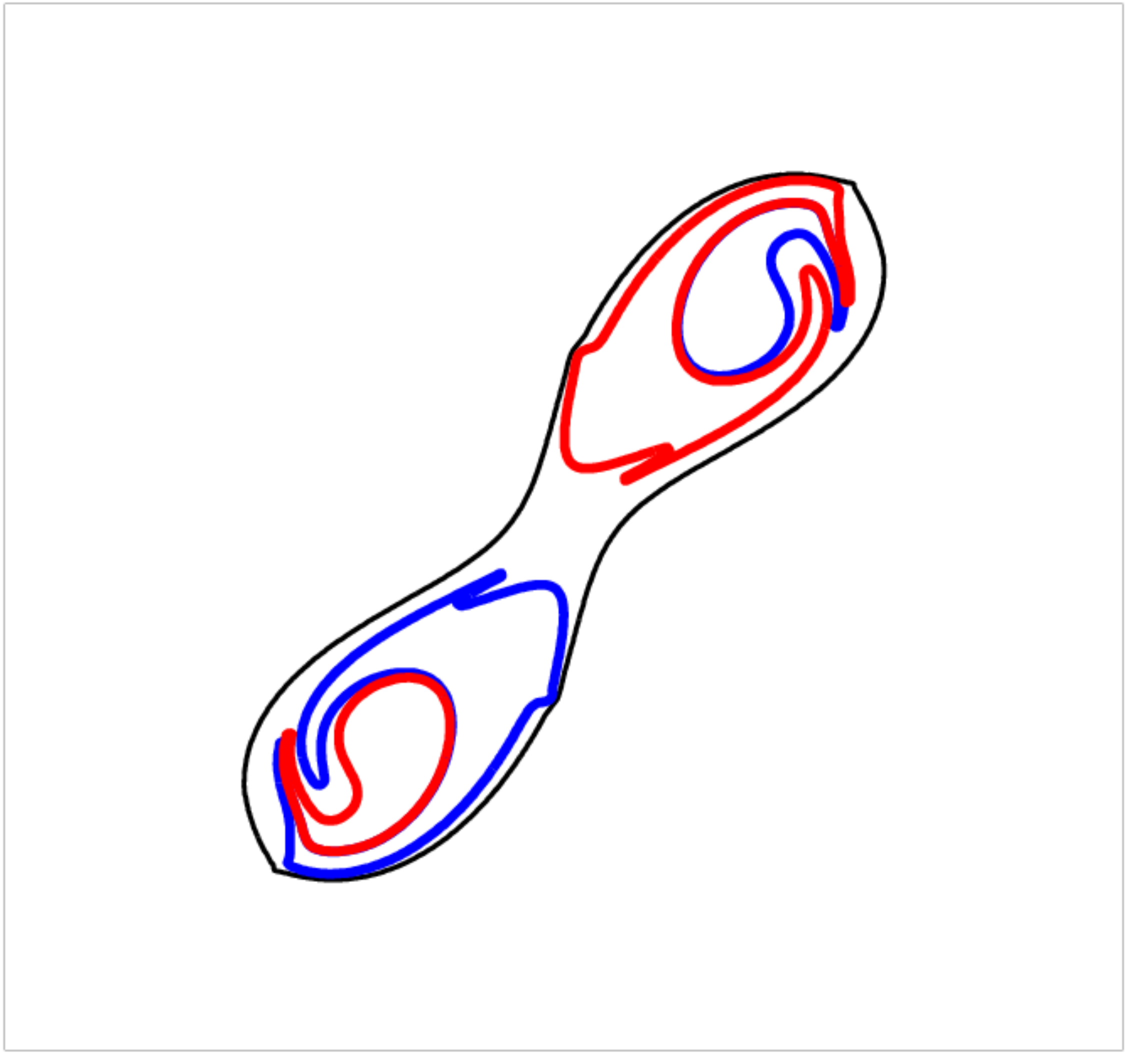

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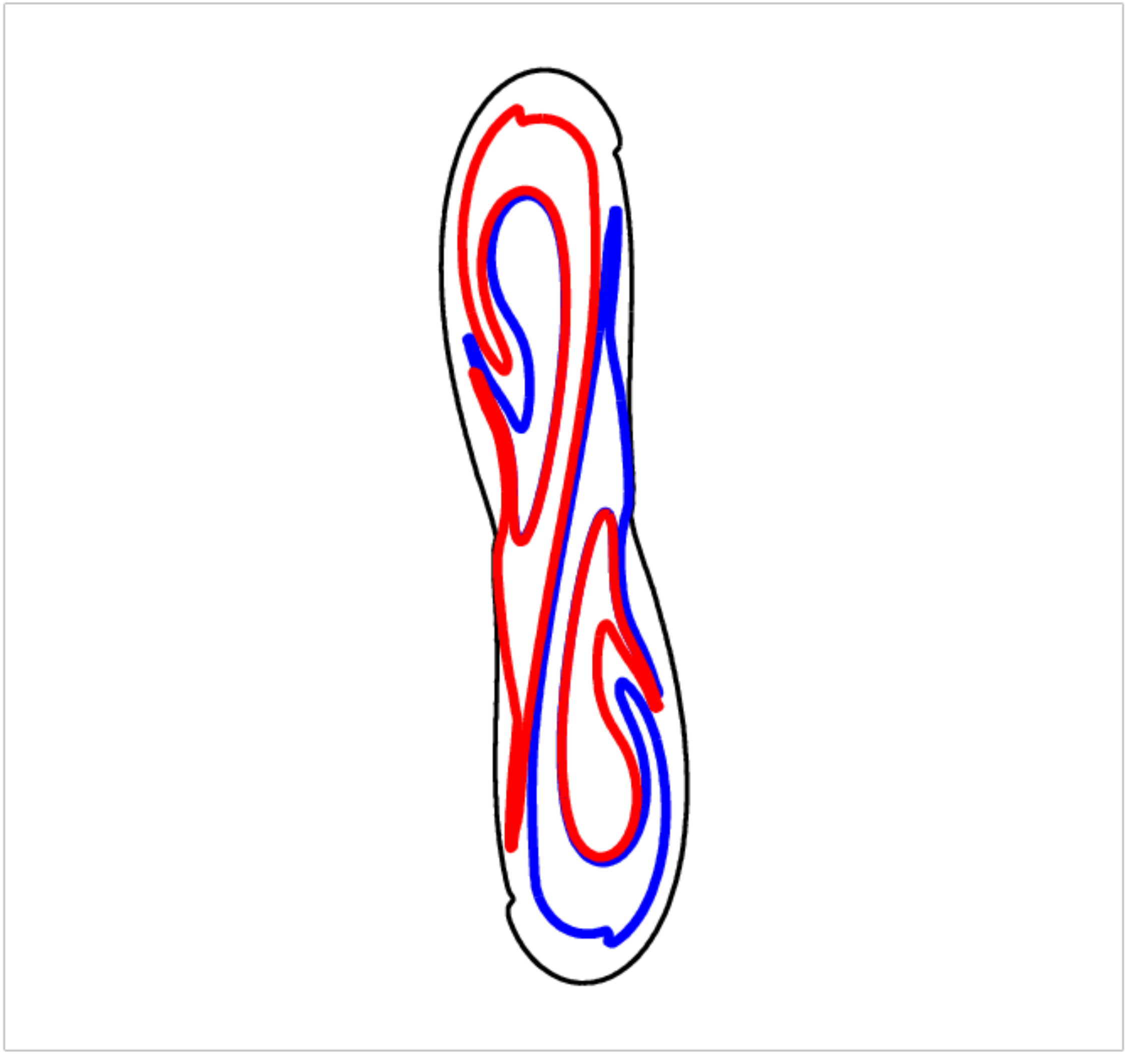

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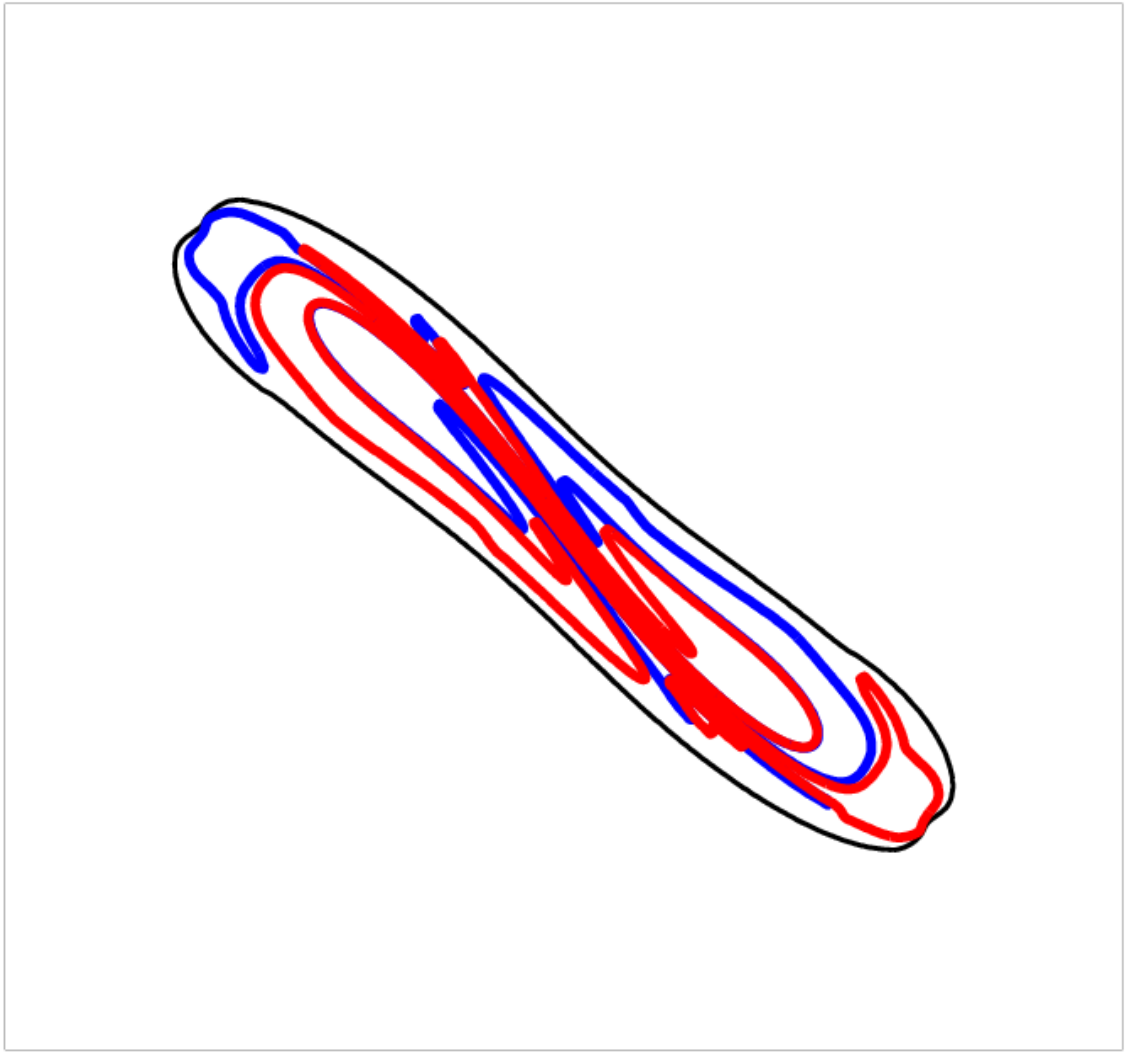

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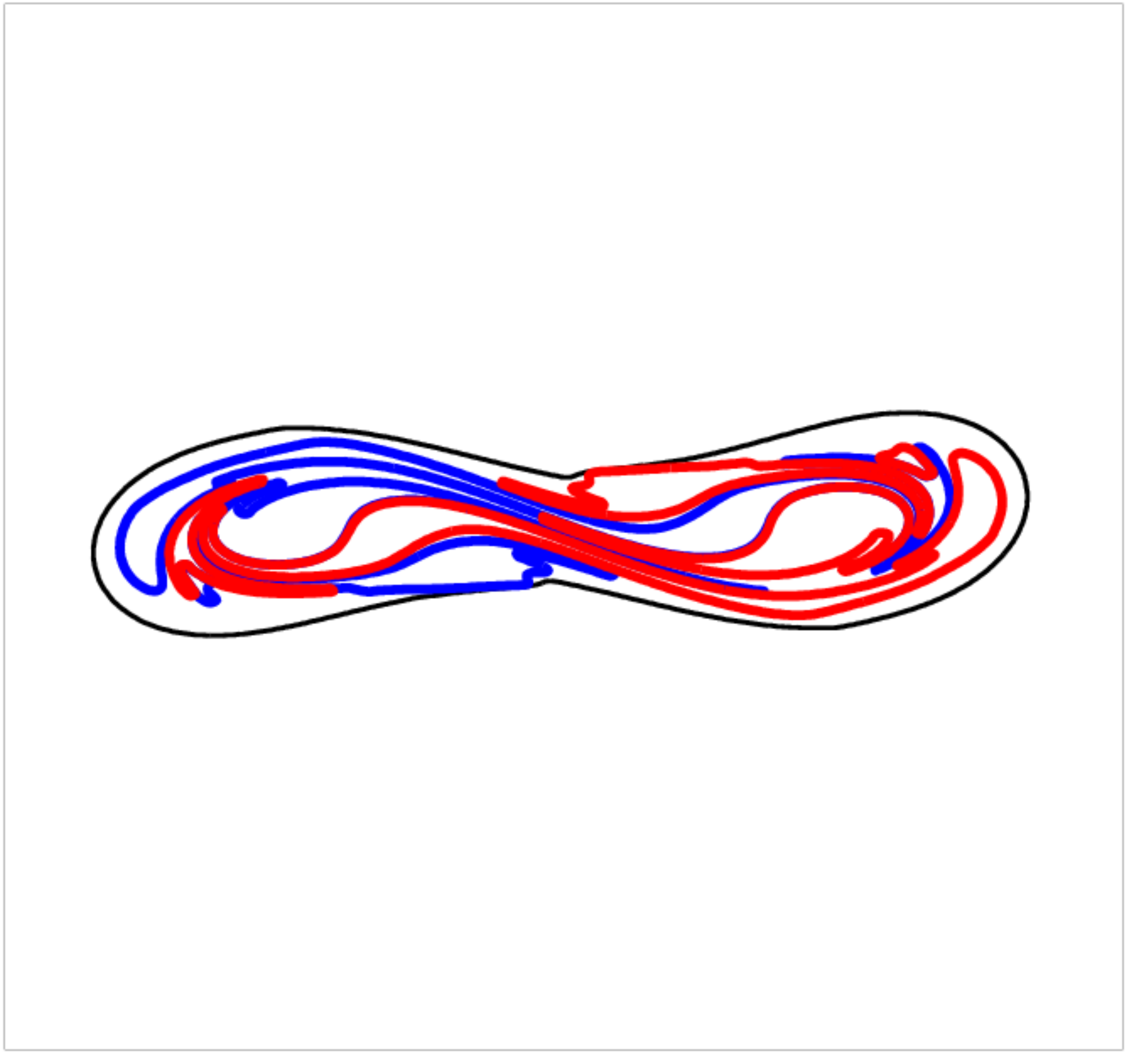

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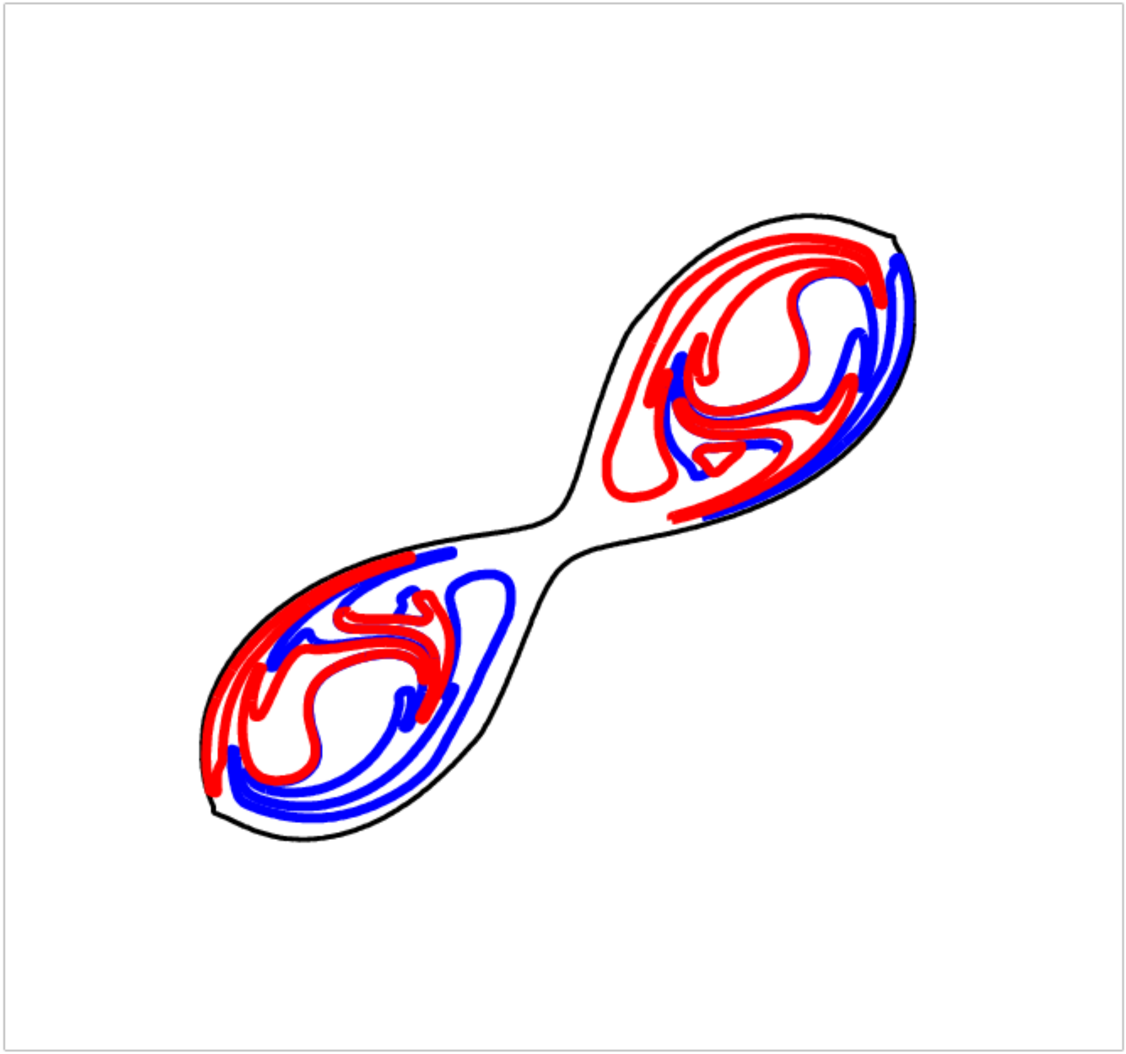

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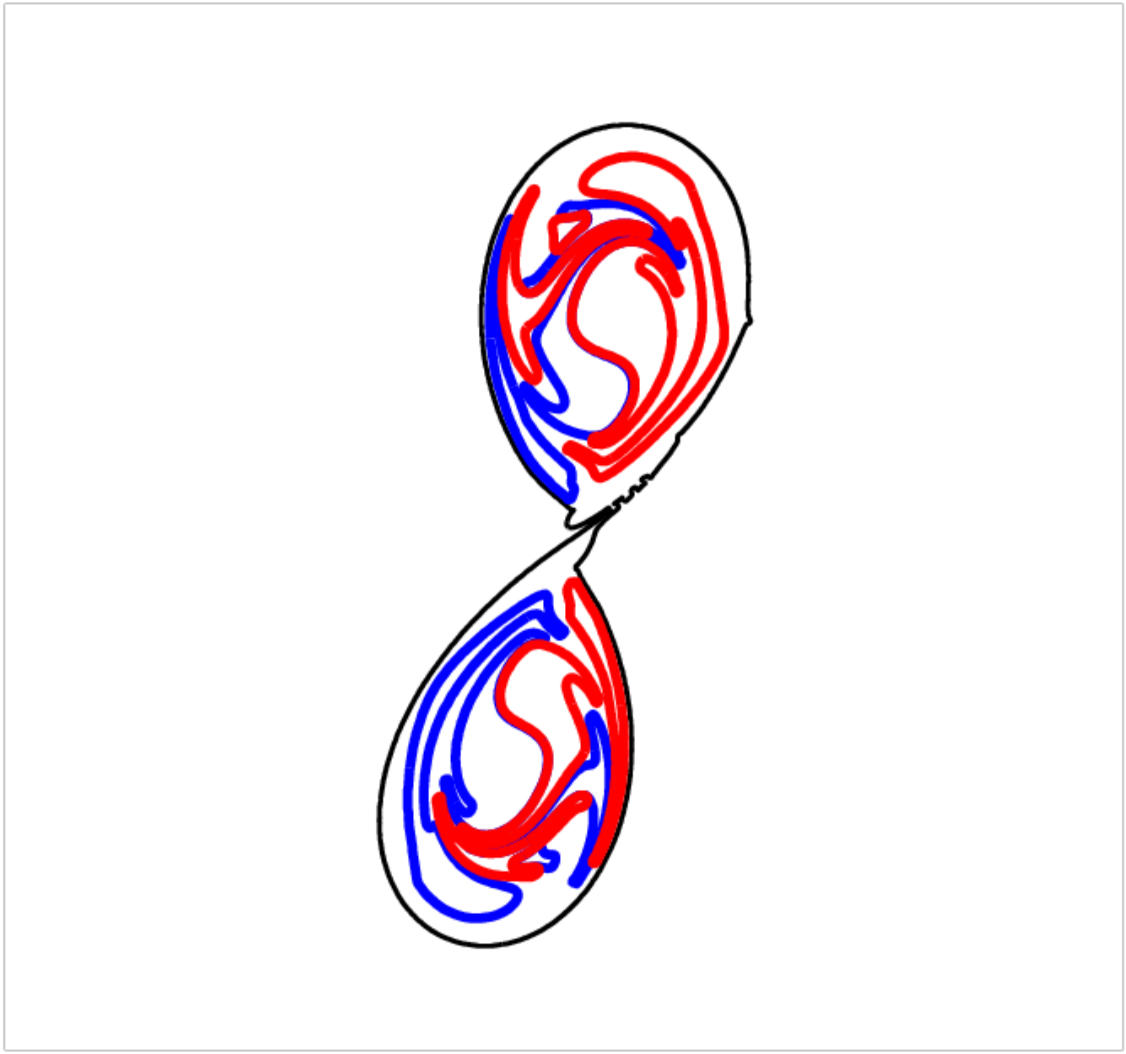

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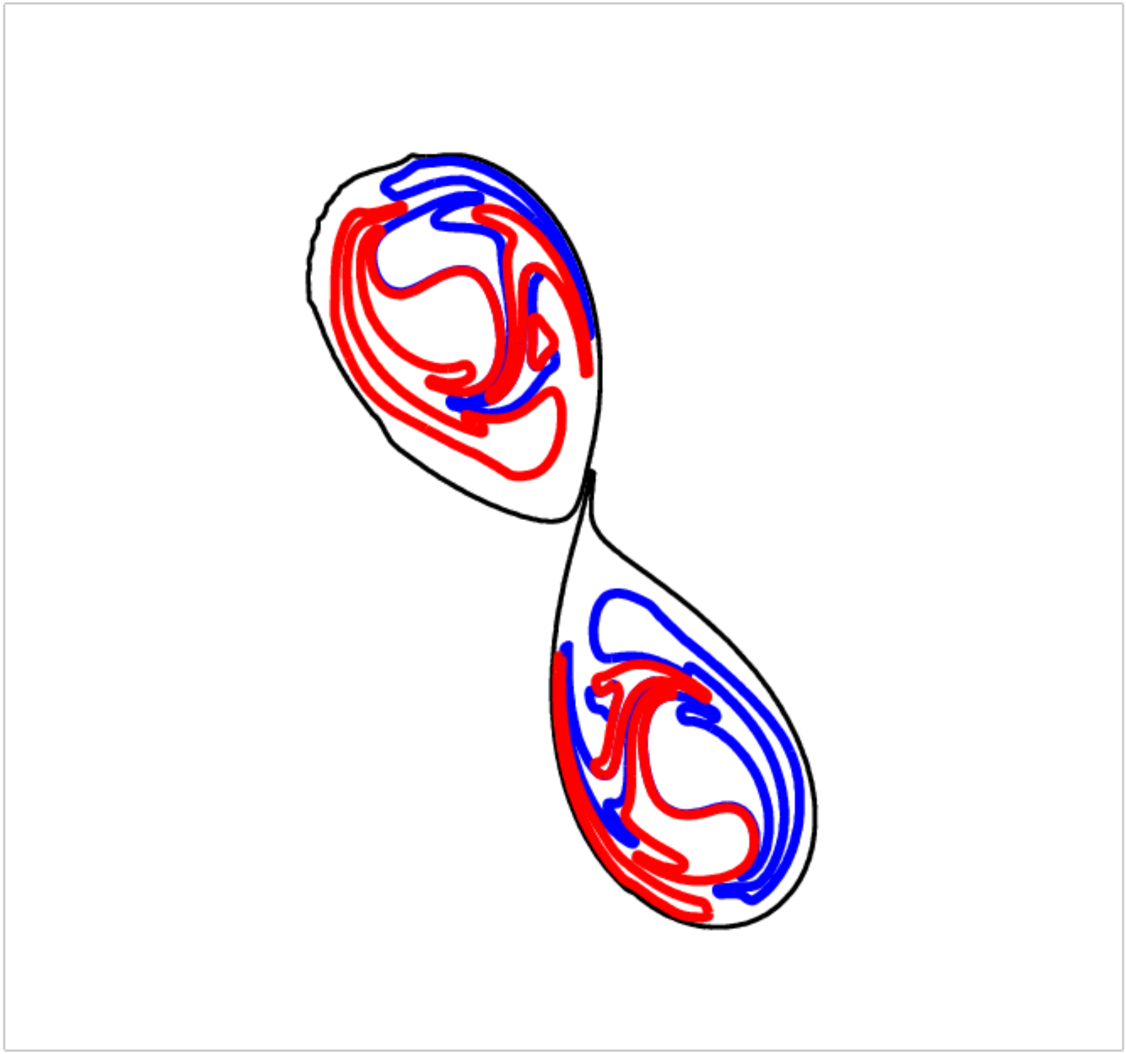

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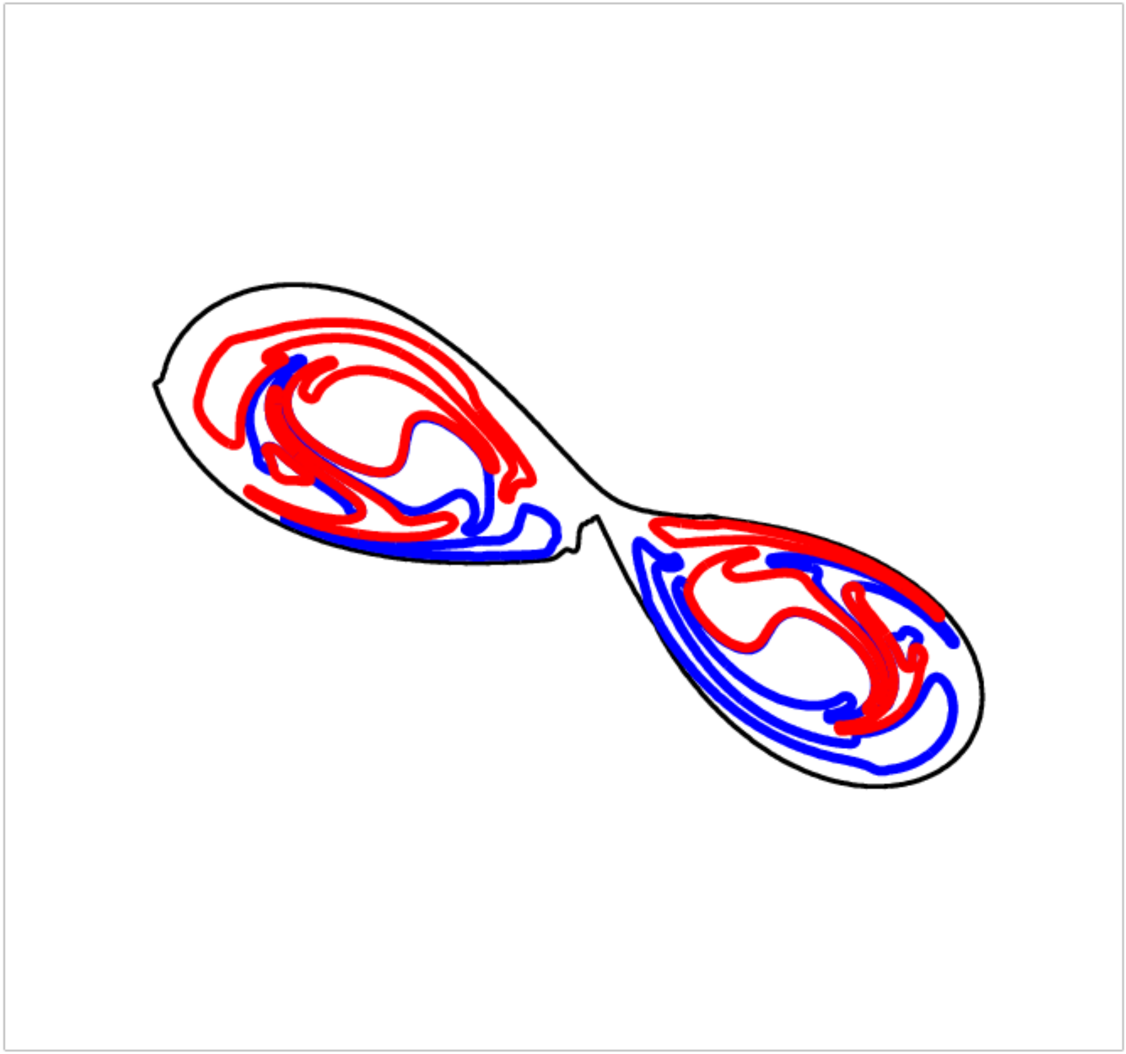

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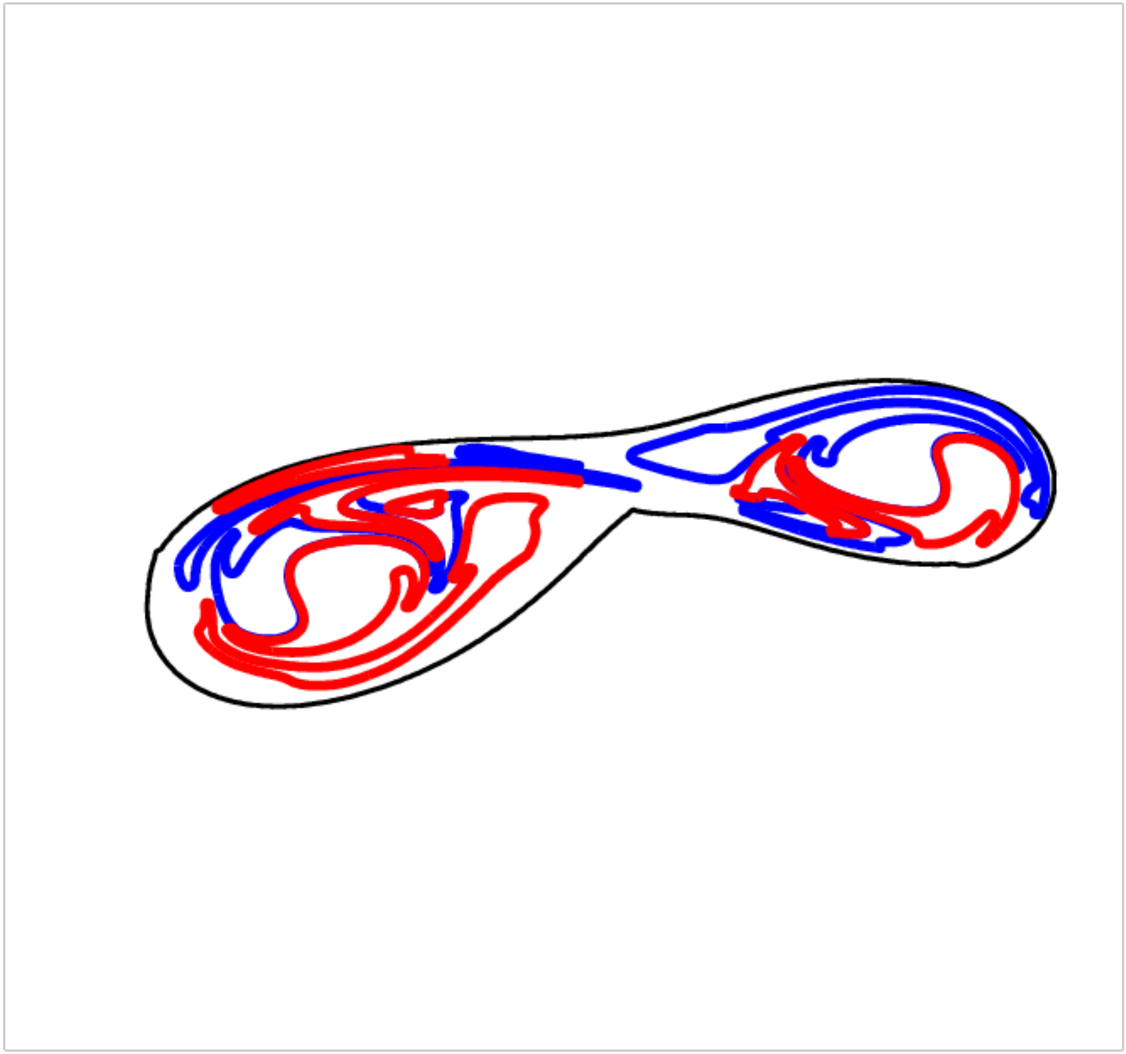

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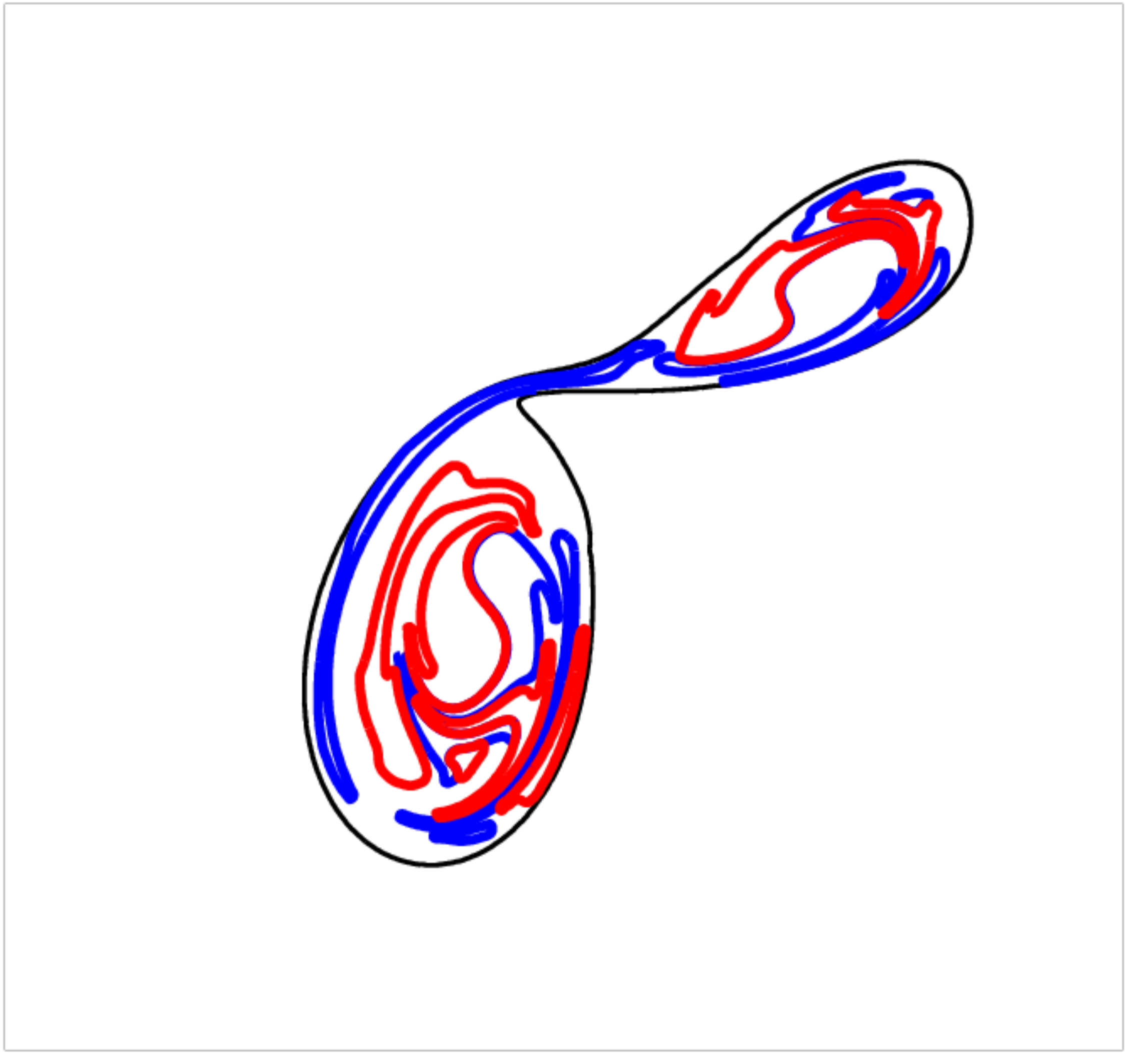

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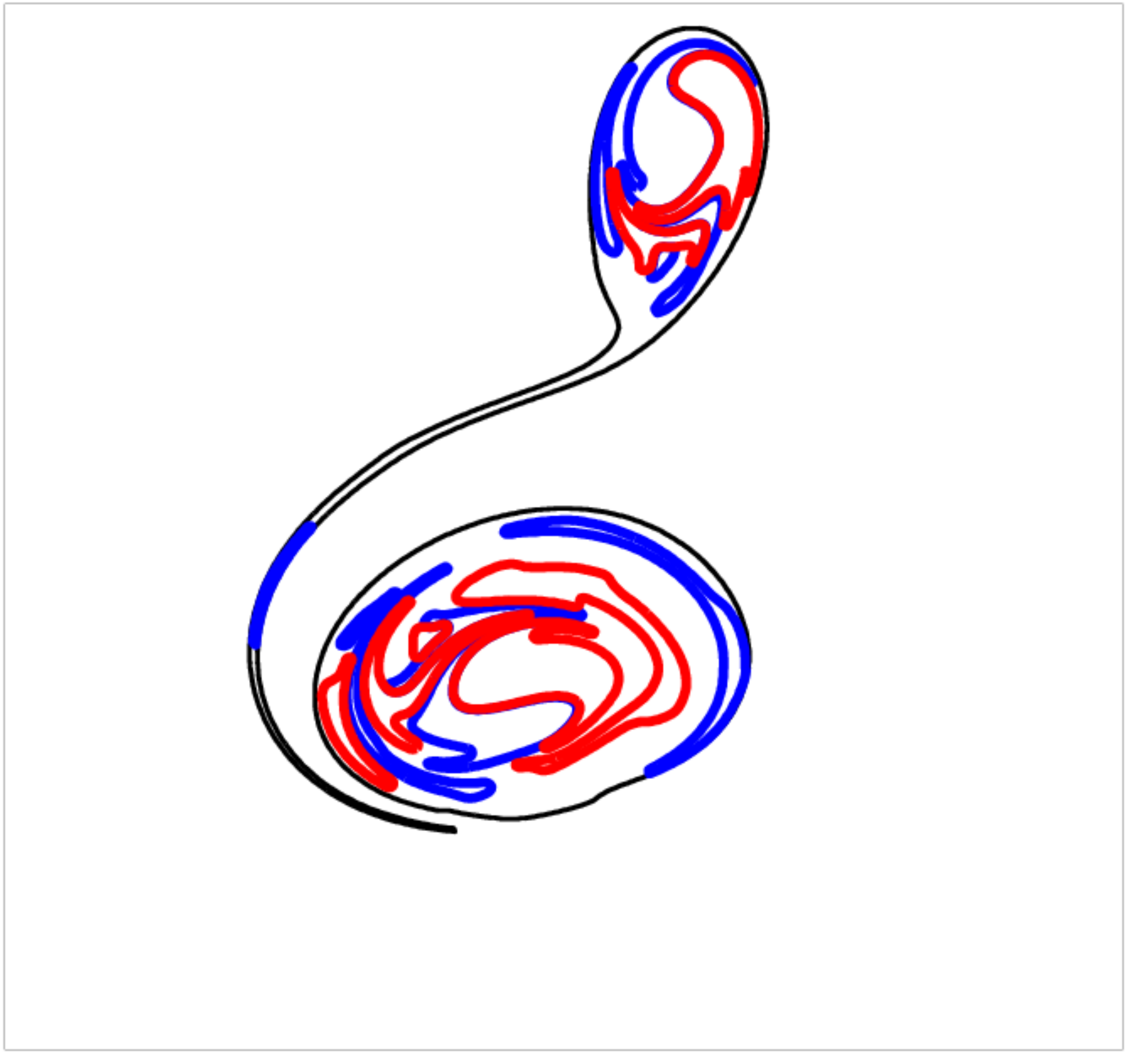

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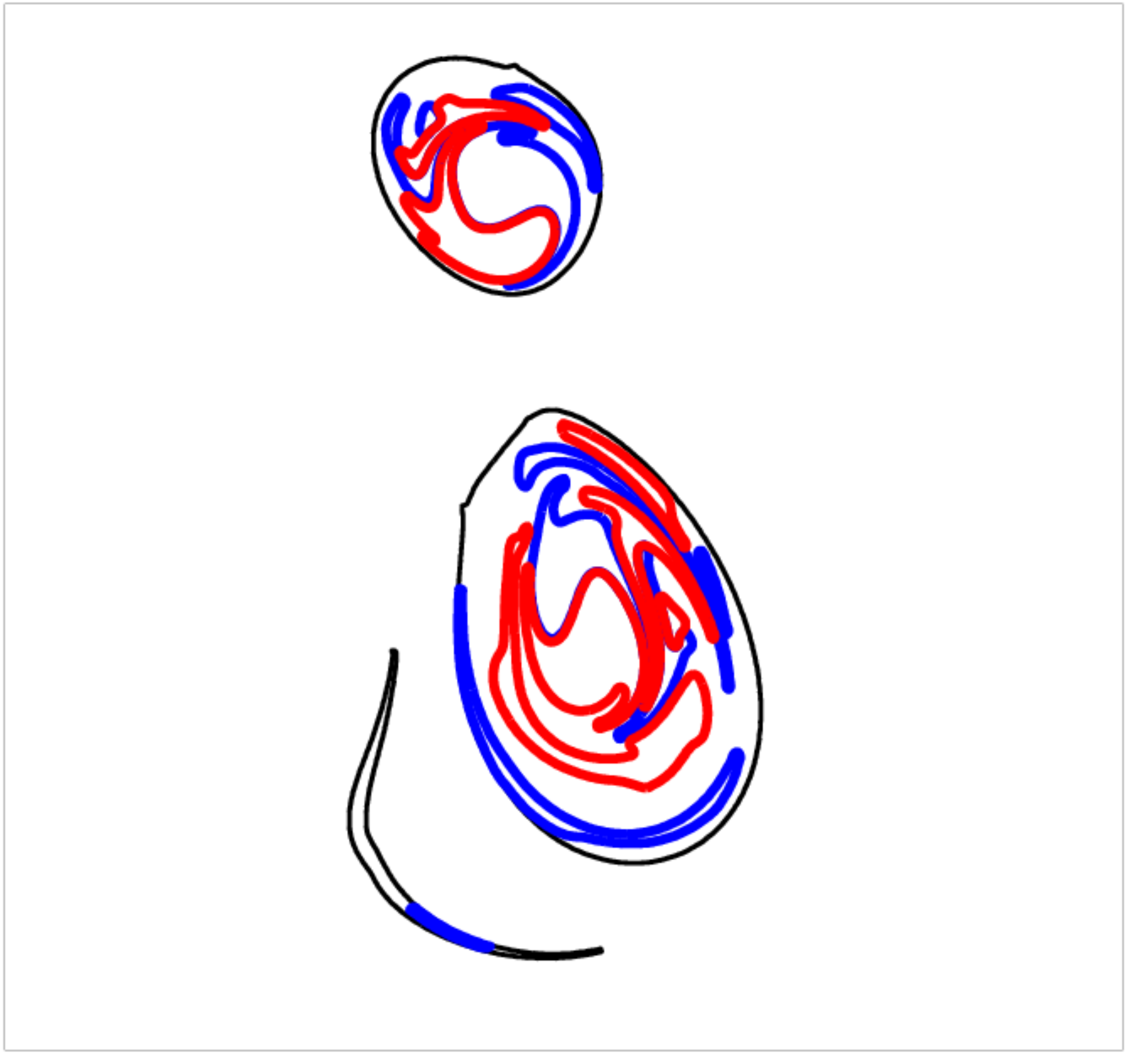

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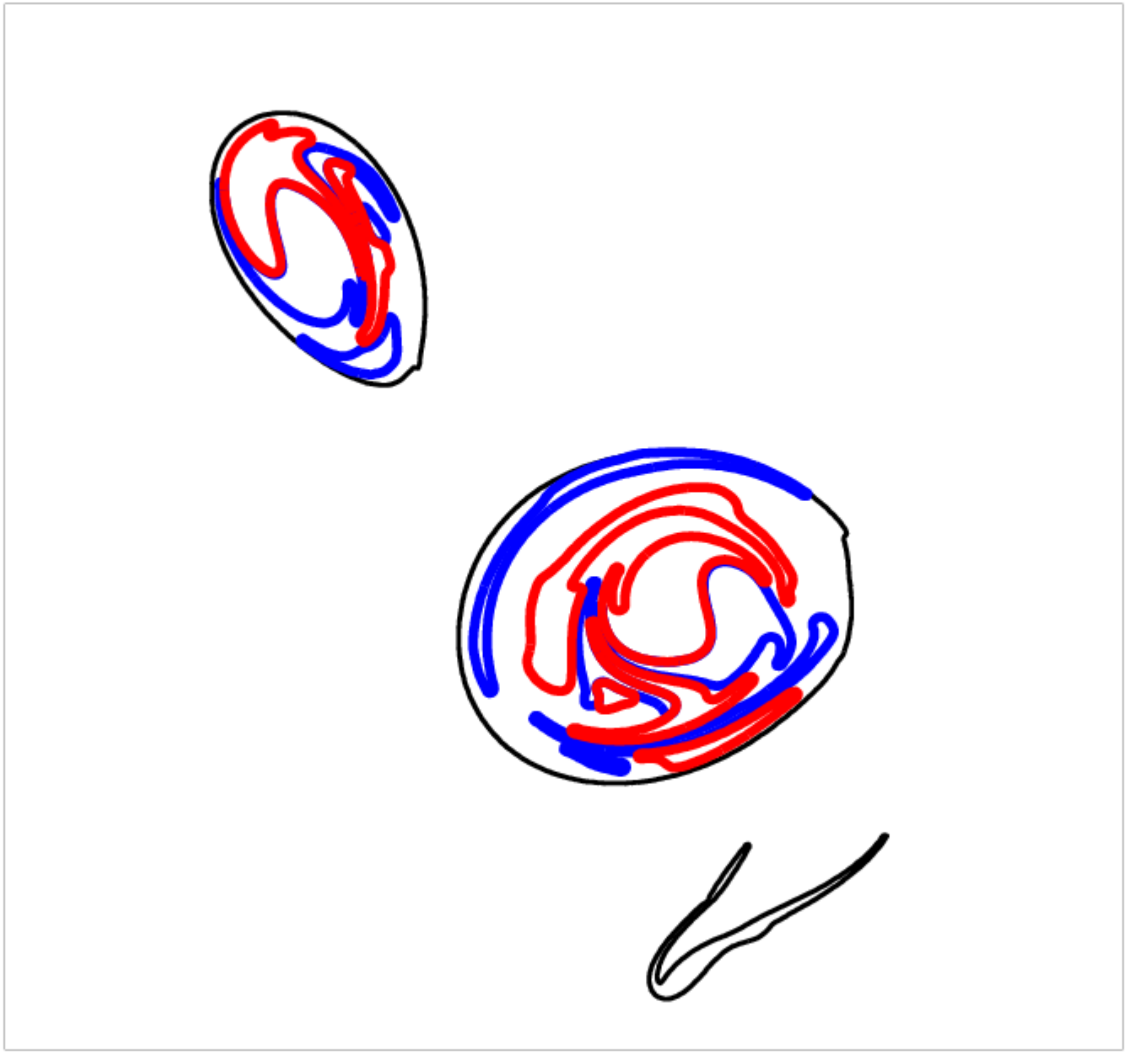
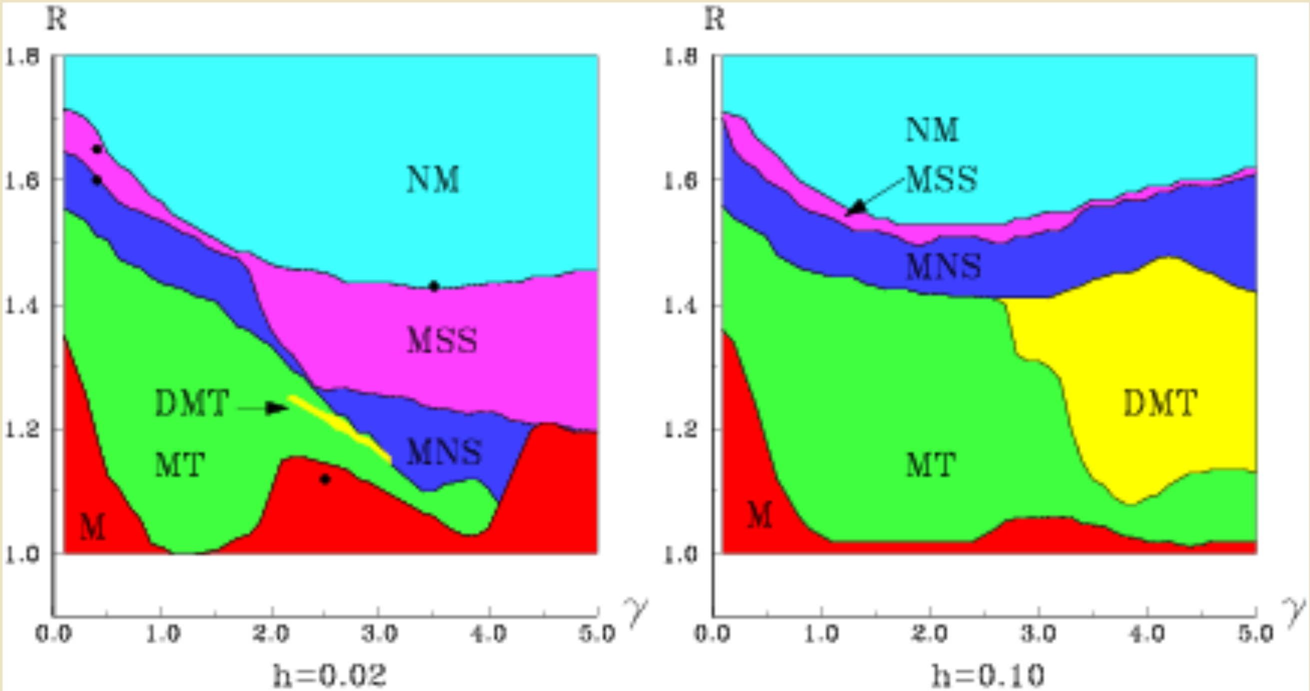


CDM-modeling of interaction of two cyclones of upper layer in two-layer rotating fluid: diagrams of states

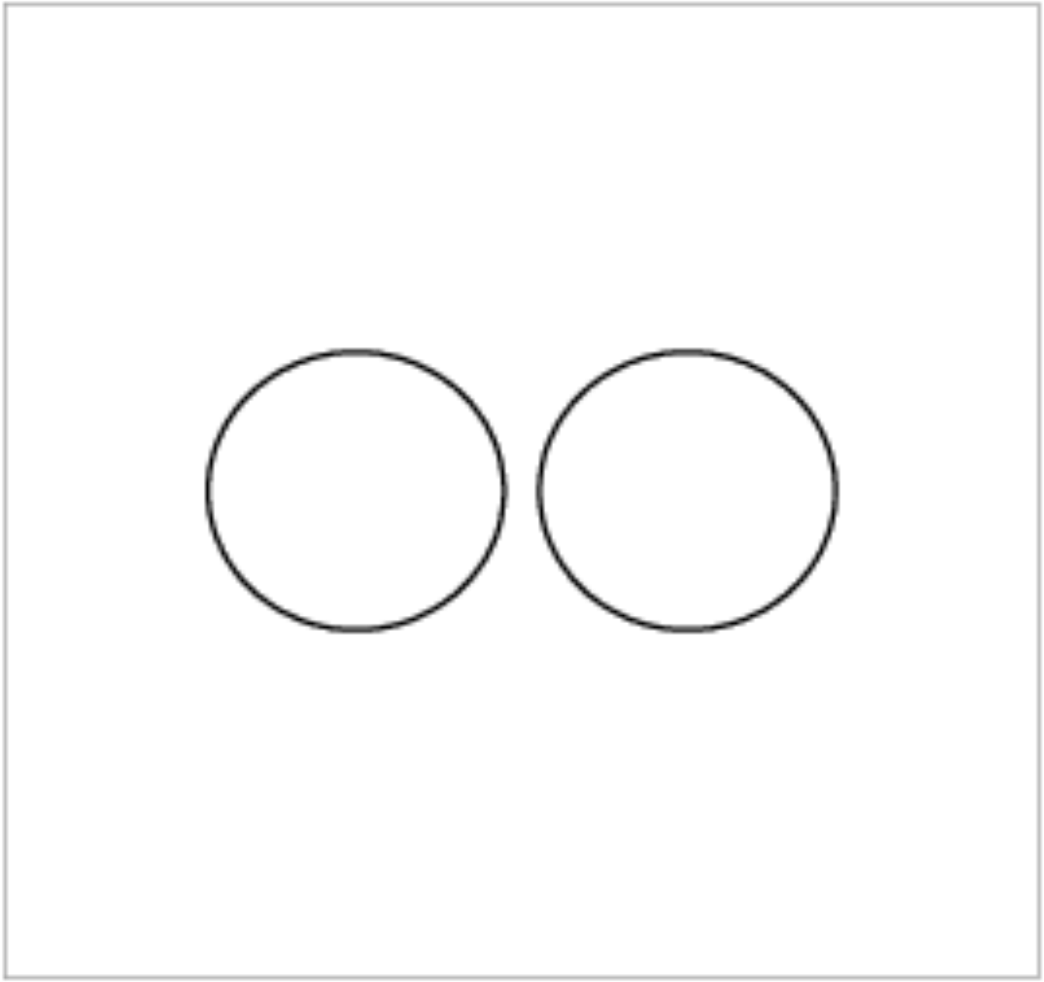


Diagrams in the rectangular domain of plane (γ, R) of possible states of two circular vortices of upper layer with the specified values of the upper-layer thickness: M (merger) - a state, when after the merging of the vortex patches and a short intermediate stage of the thin vortex-line formation, there remains one compact vortex of larger scale. MT (merger/triplet) - merging of vortex patches, and the subsequent formation of a triplet composed of a large central vortex and two peripheral smaller like signed vortices. DMT (double merger/triplet) - the first stage of the evolution is similar to that of MT but later, a new vortex merger occurs leading to the birth of a new triplet. MNS (merger/non-symmetric separation) - a merging, followed by separation into unequal vortex patches. MSS (merger/symmetric separation) - the division is symmetrical, i.e. after a temporary merging, two identical vortex patches are formed again. NM (no merger) - vortex patches, pulsating, rotate around a common center of vorticity without merging.

h_1=0.02, R=1.12, γ=2.5

(M-type)

t=0



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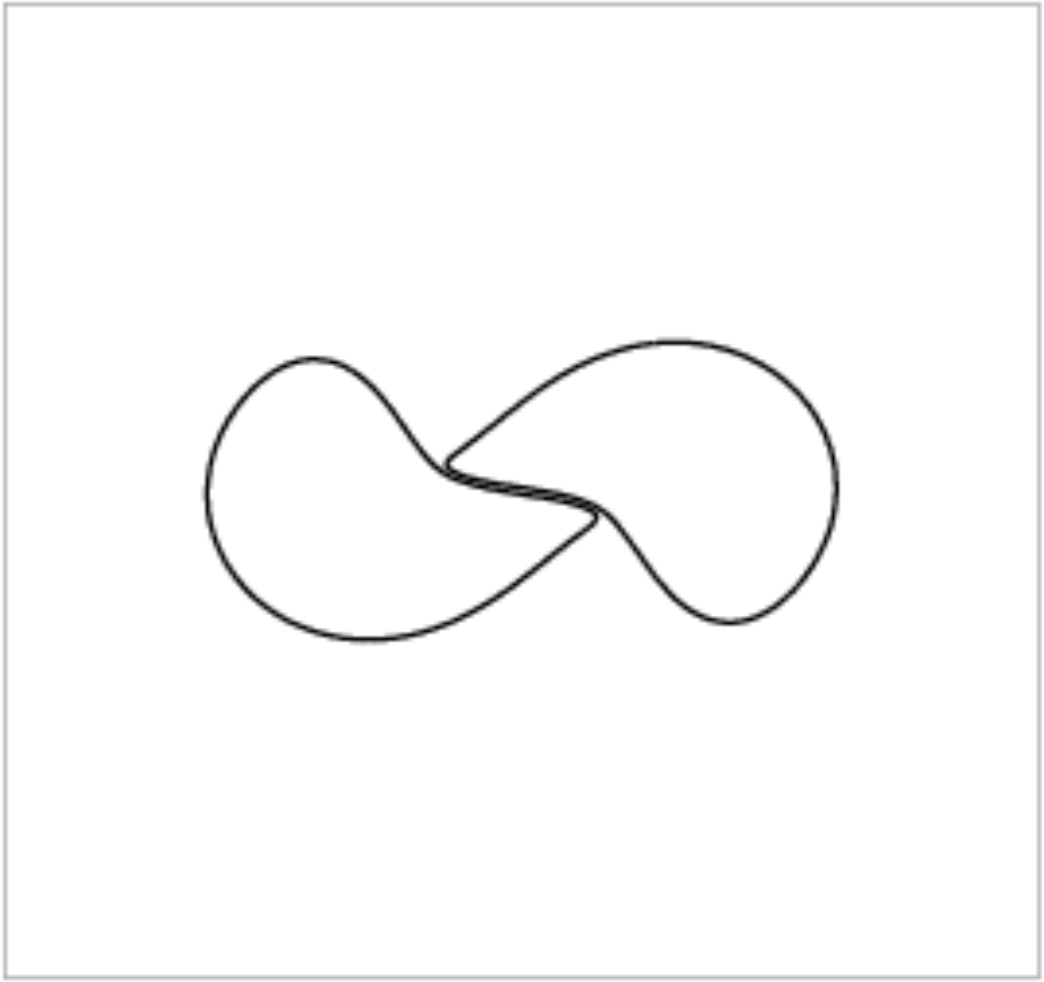

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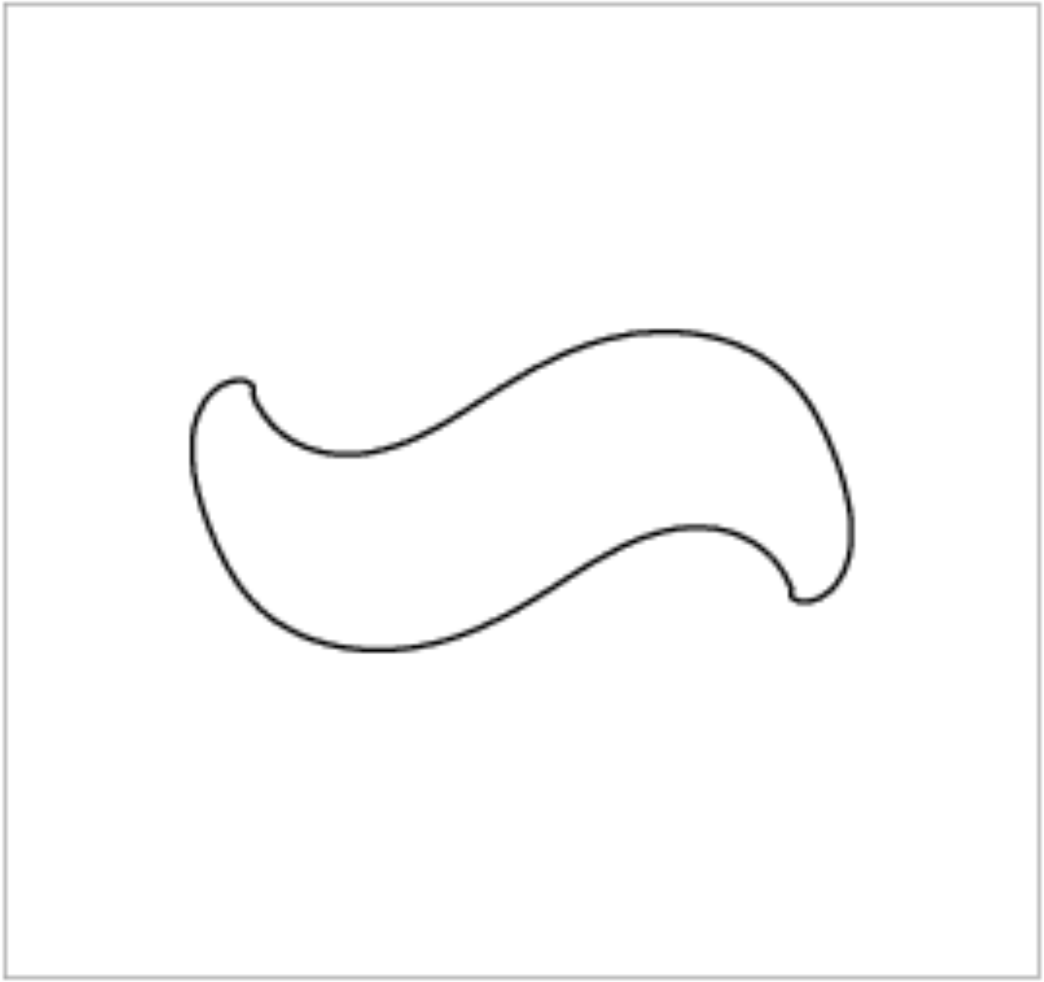

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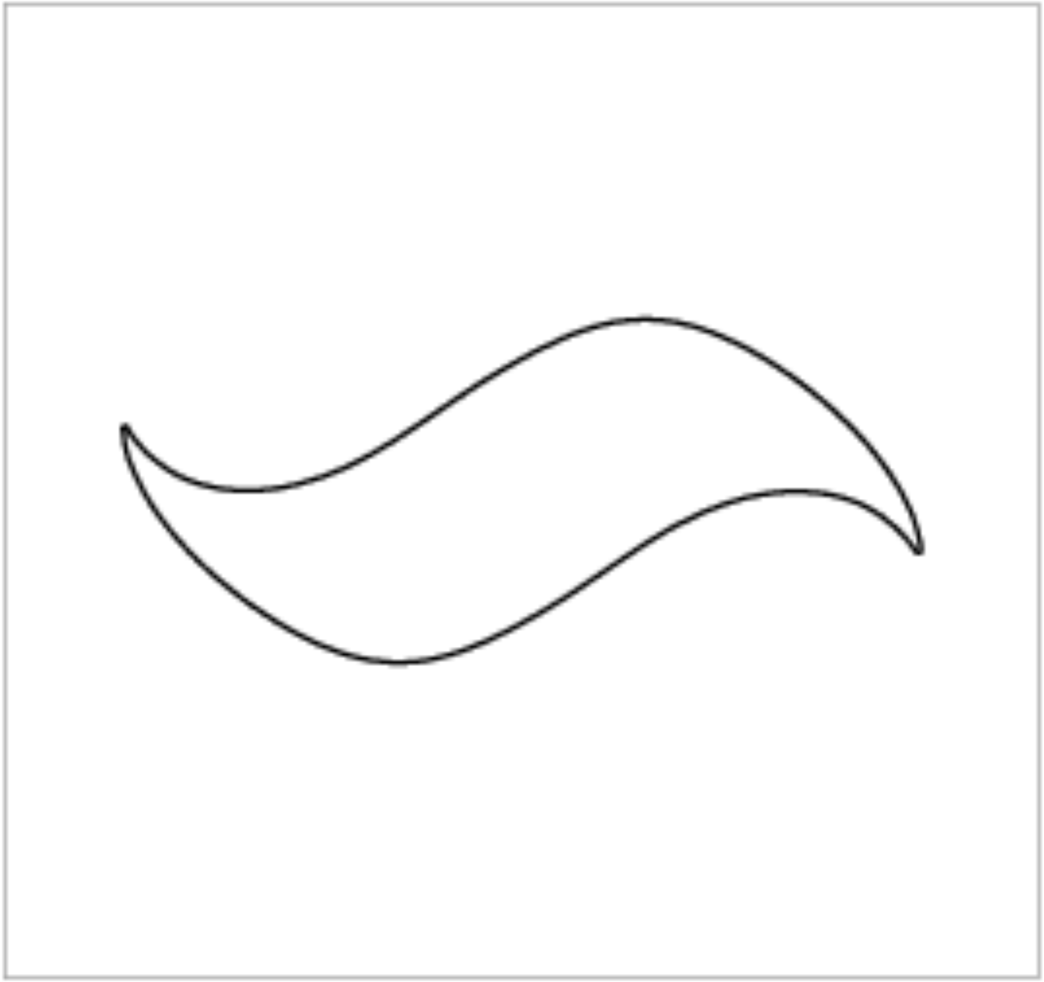

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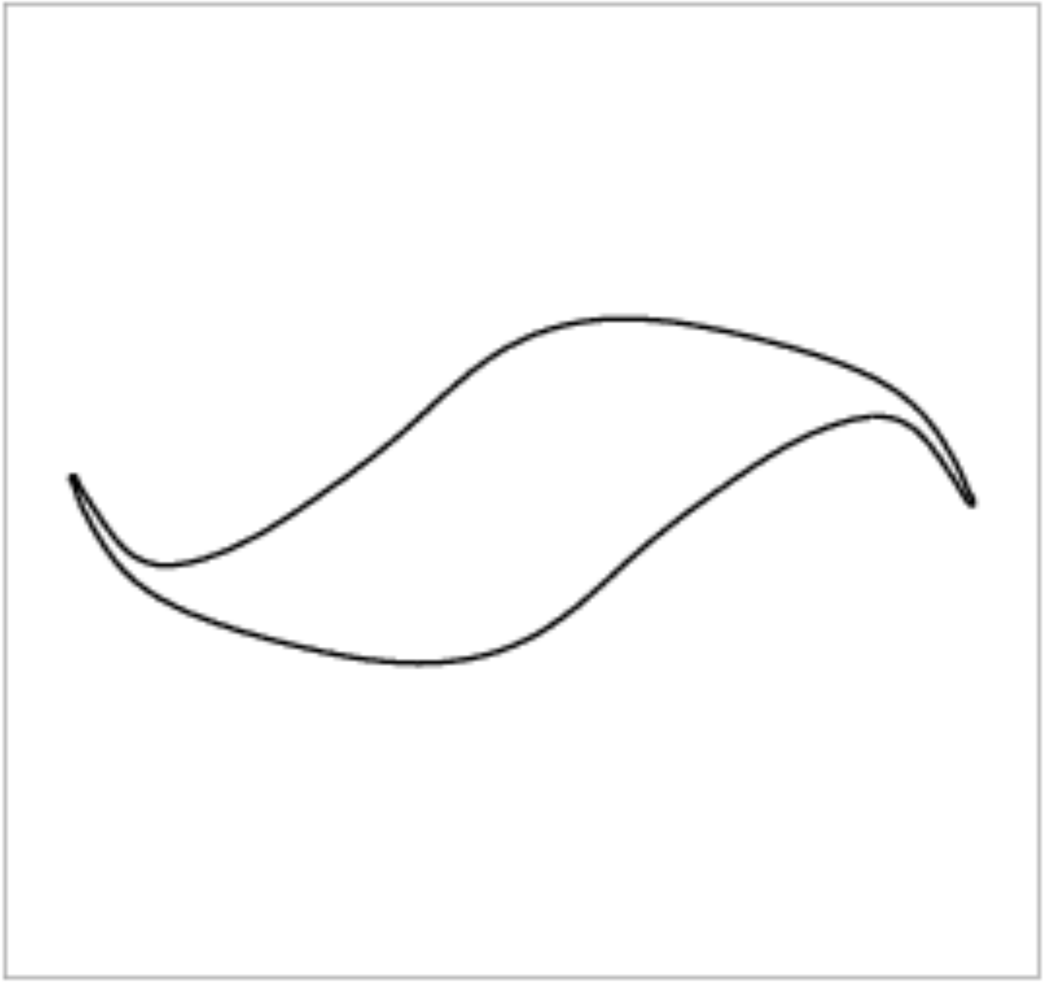

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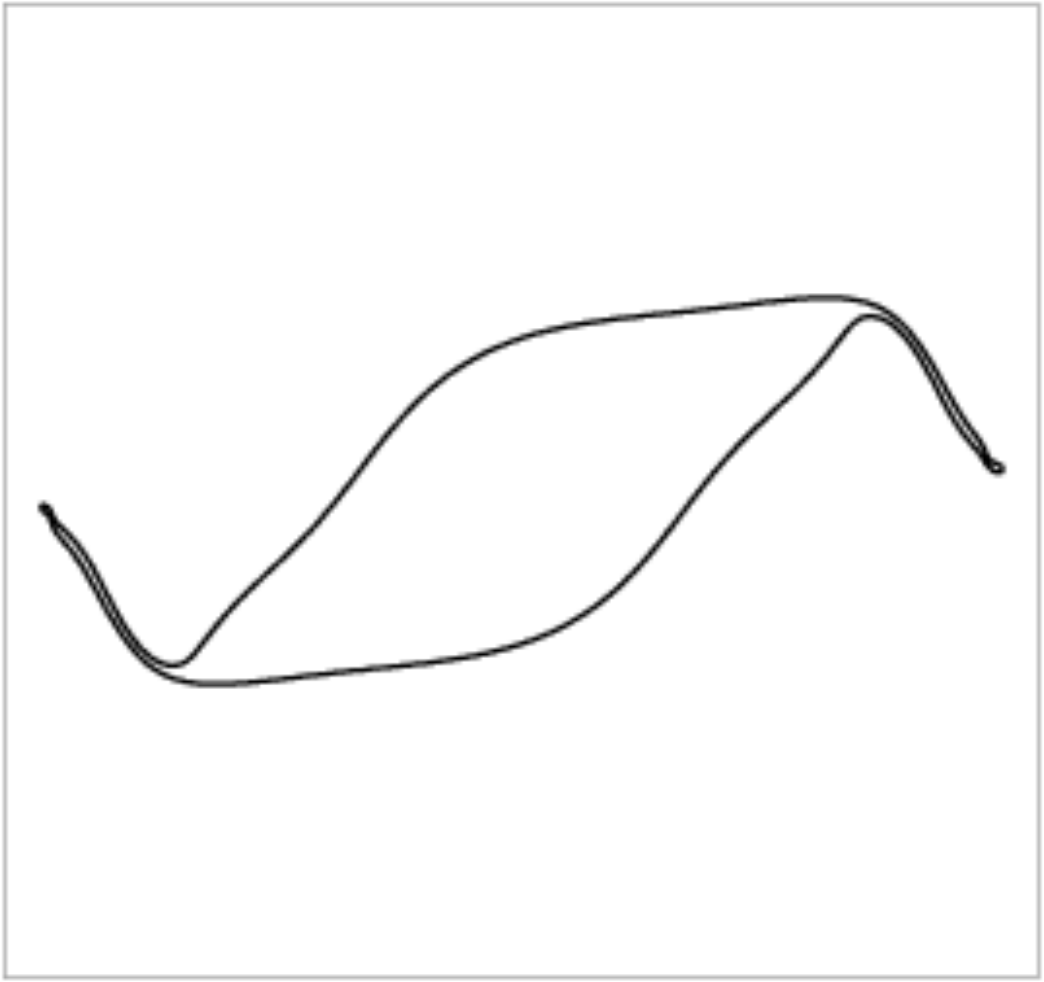

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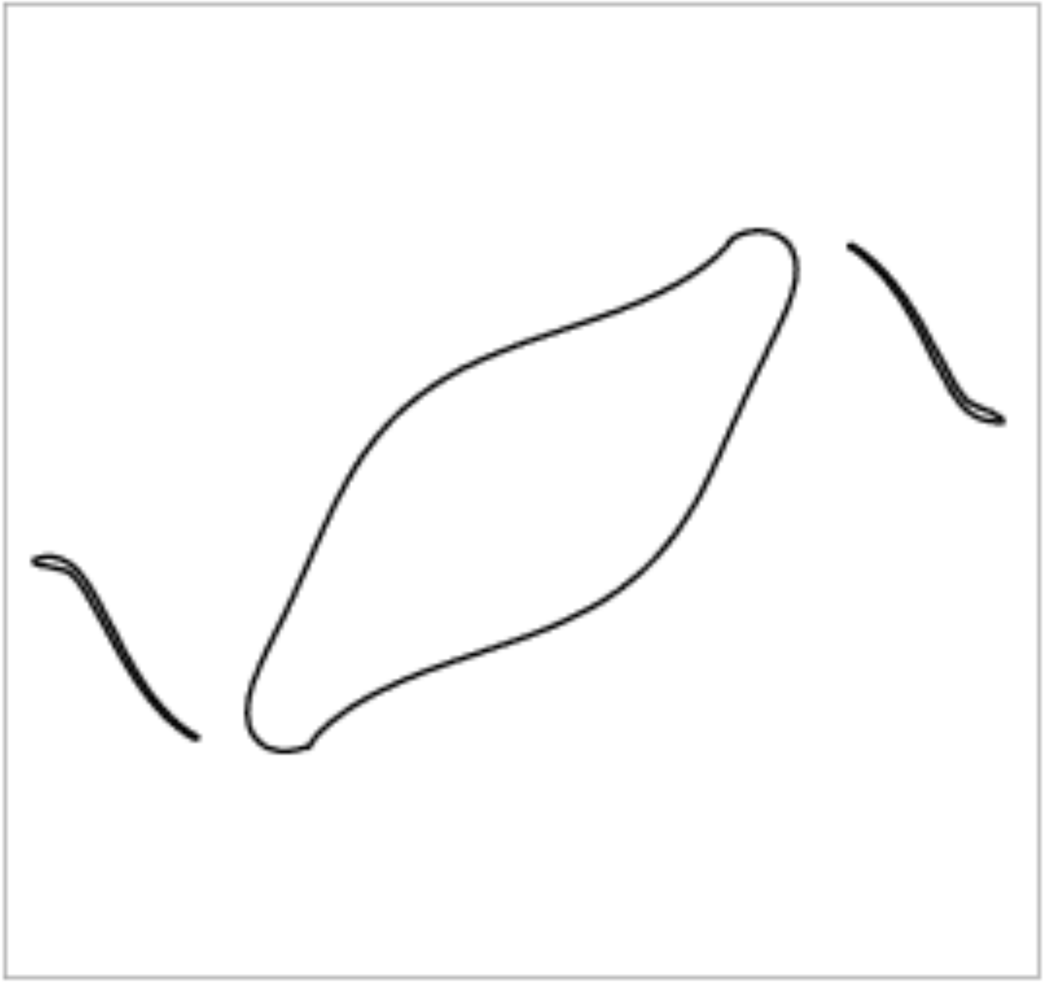

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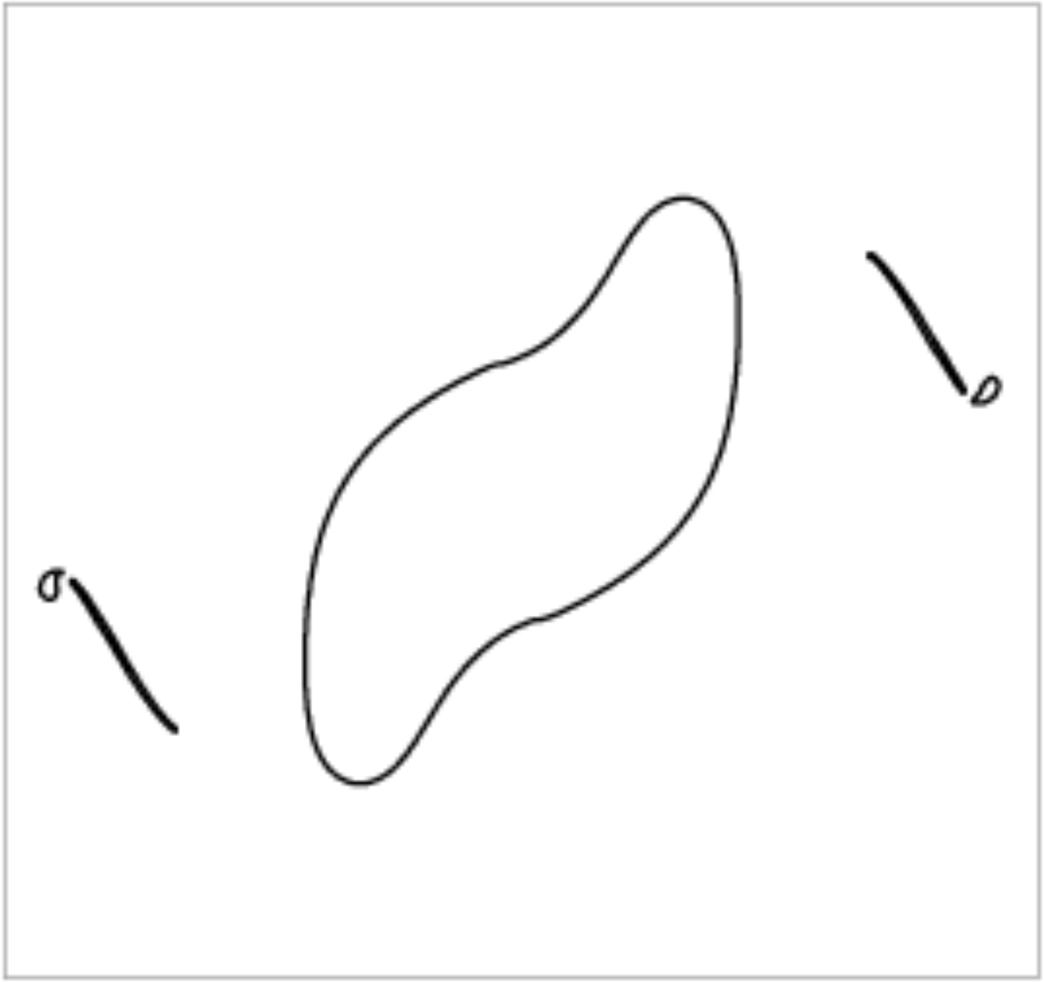

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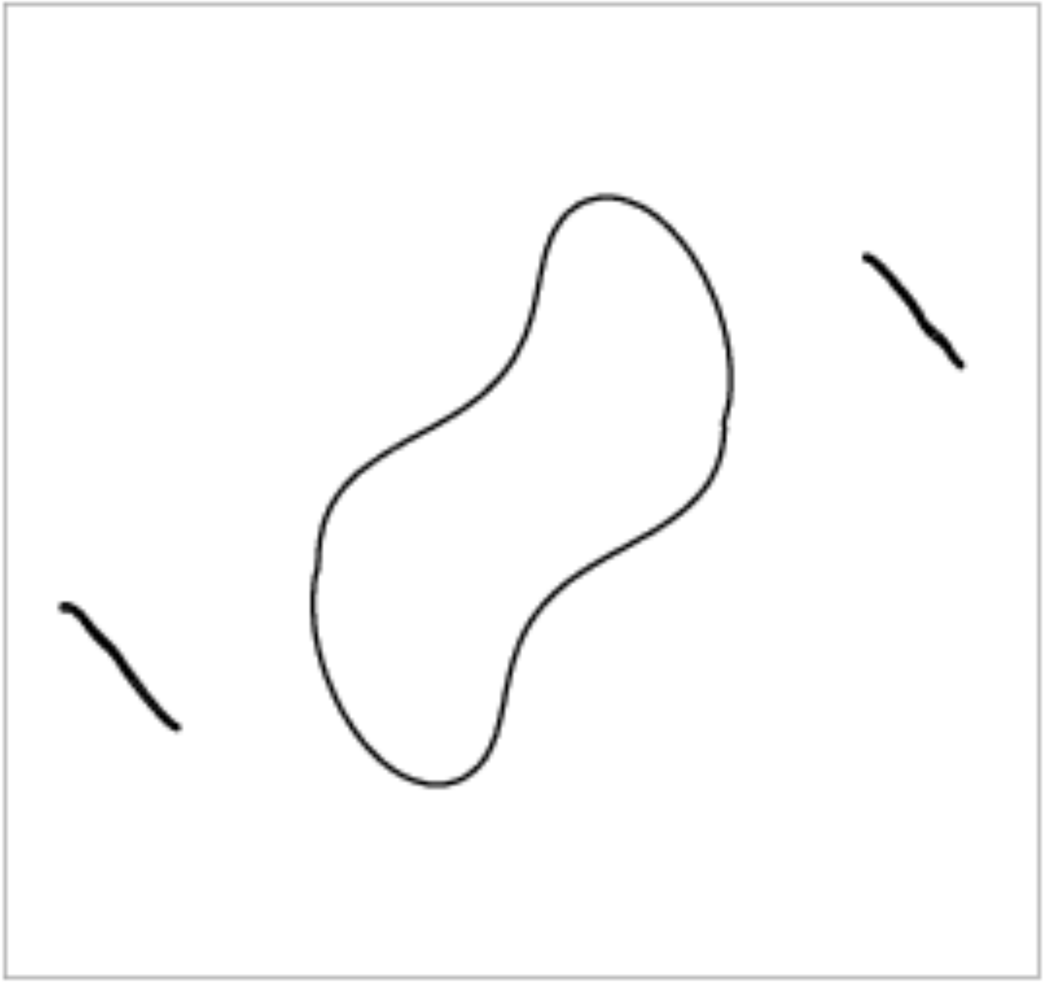

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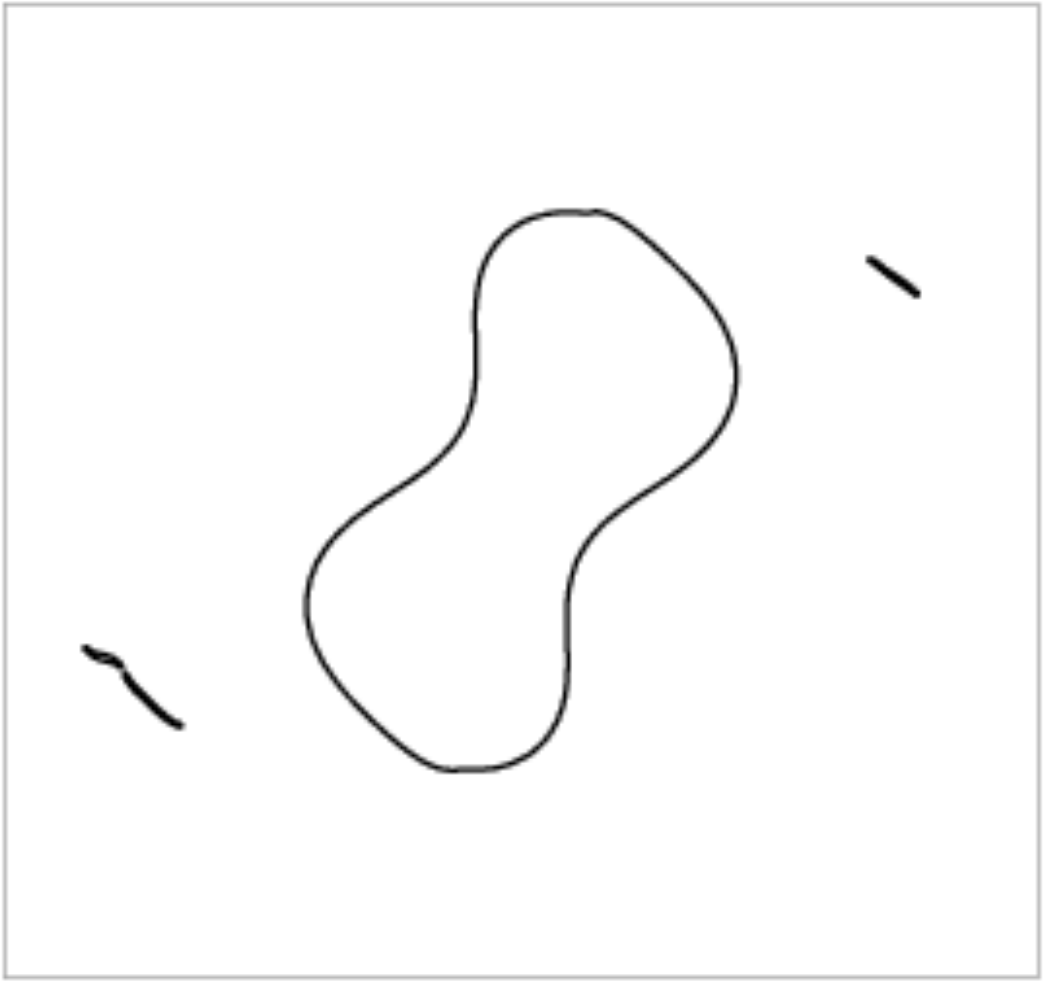

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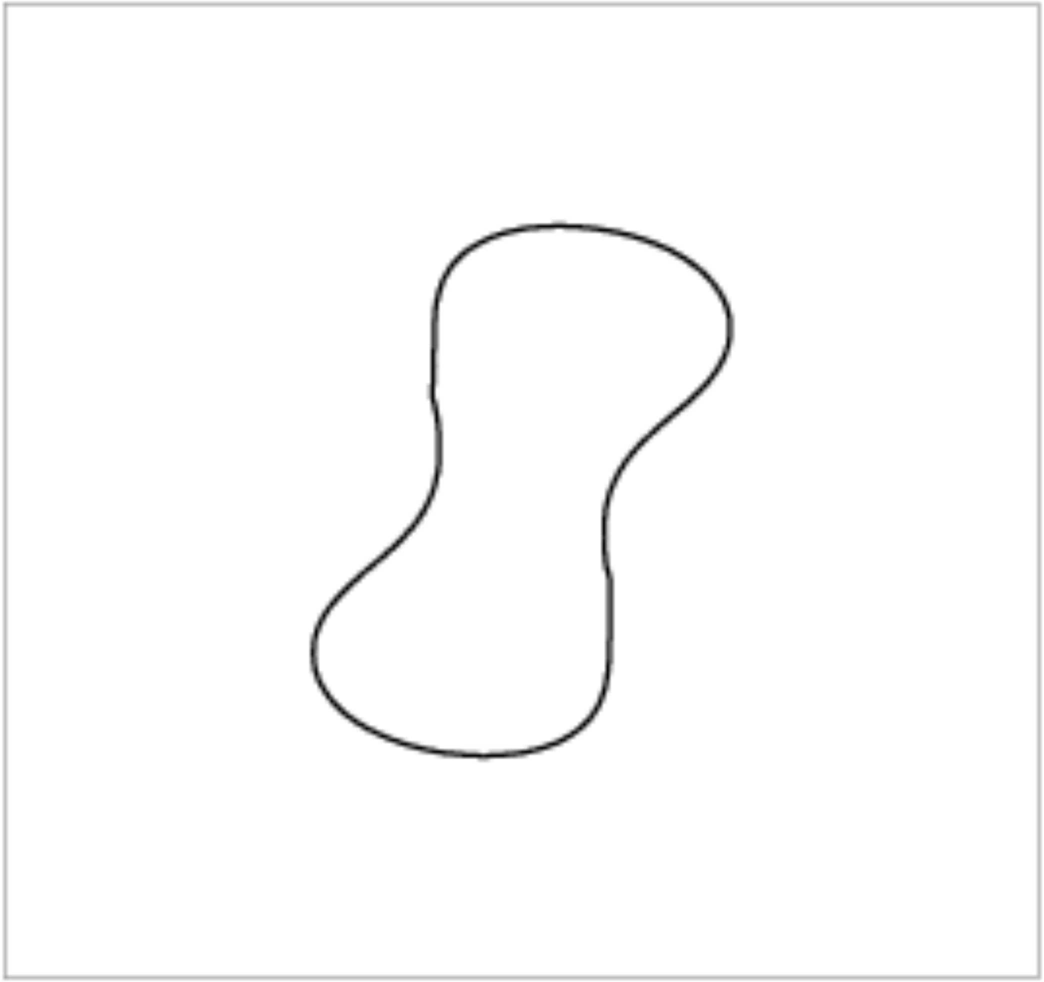

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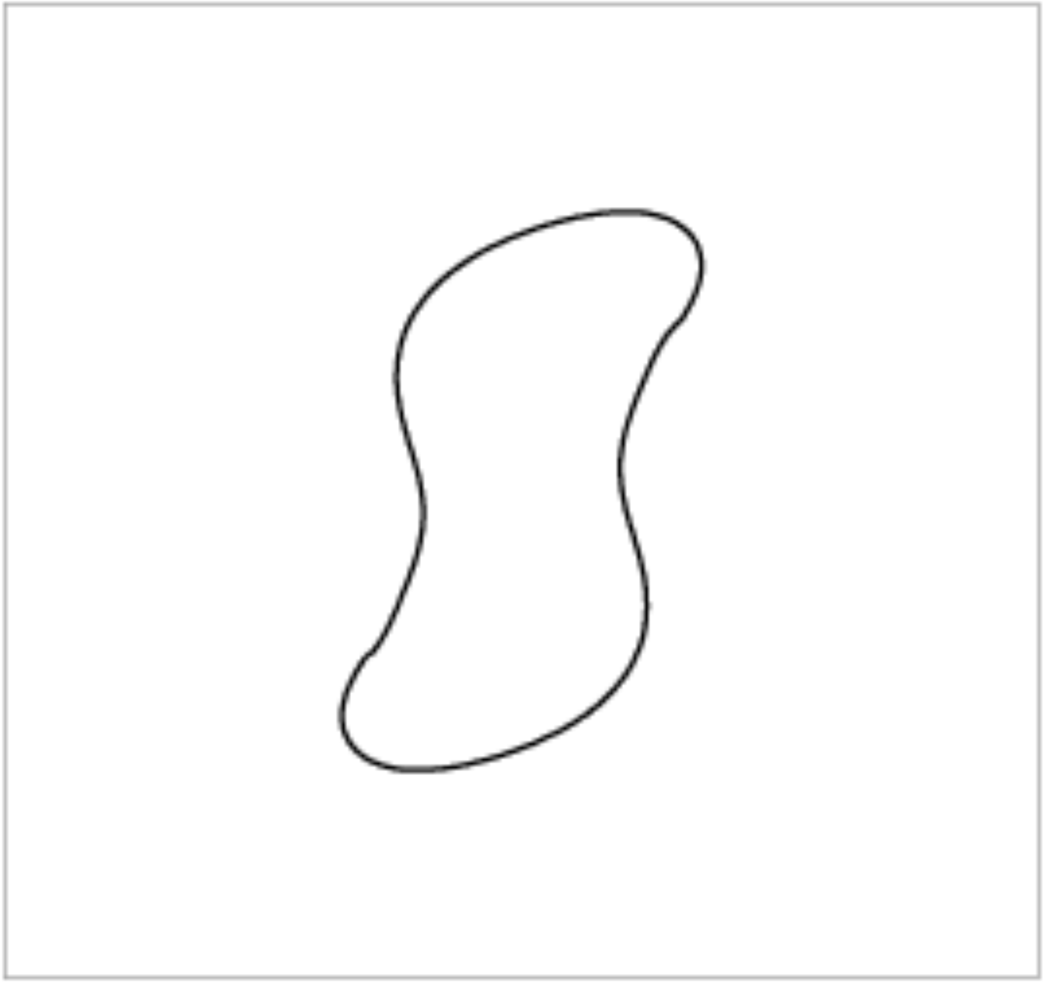

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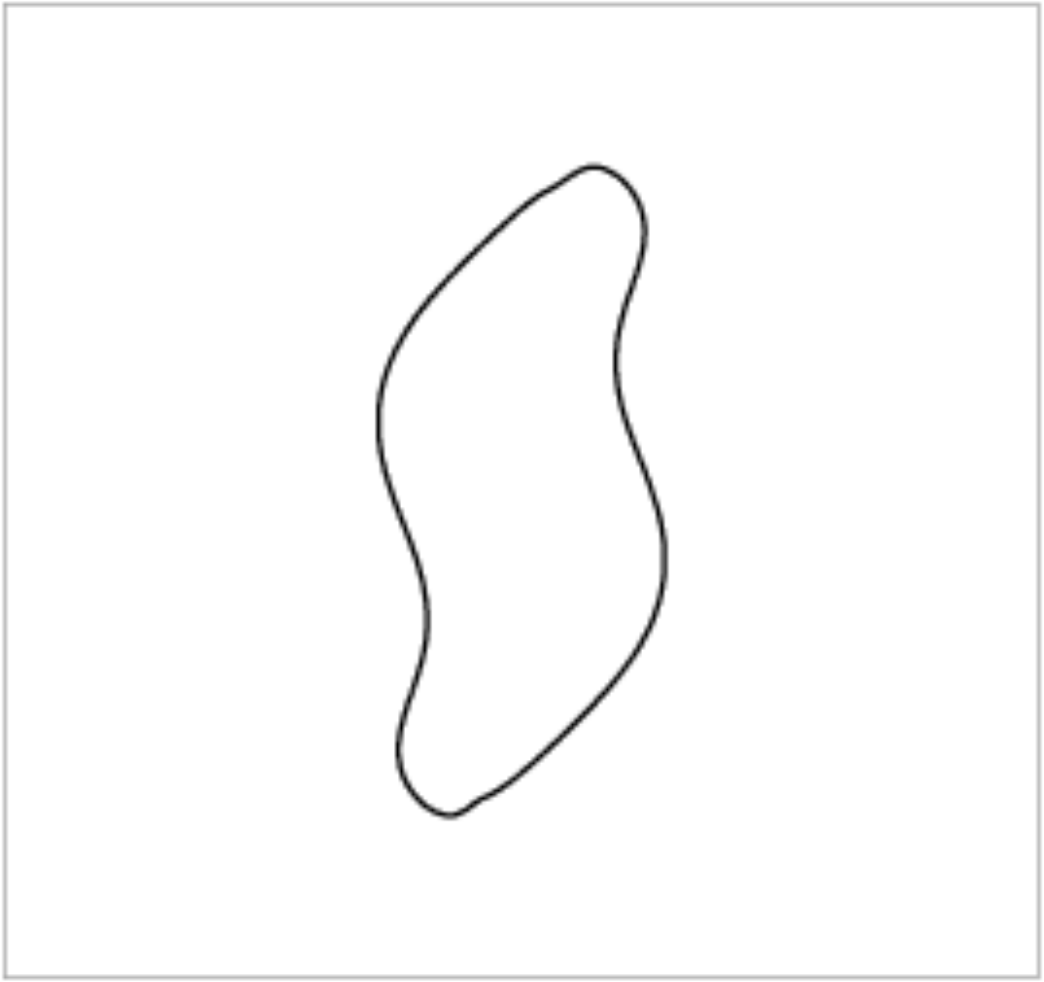

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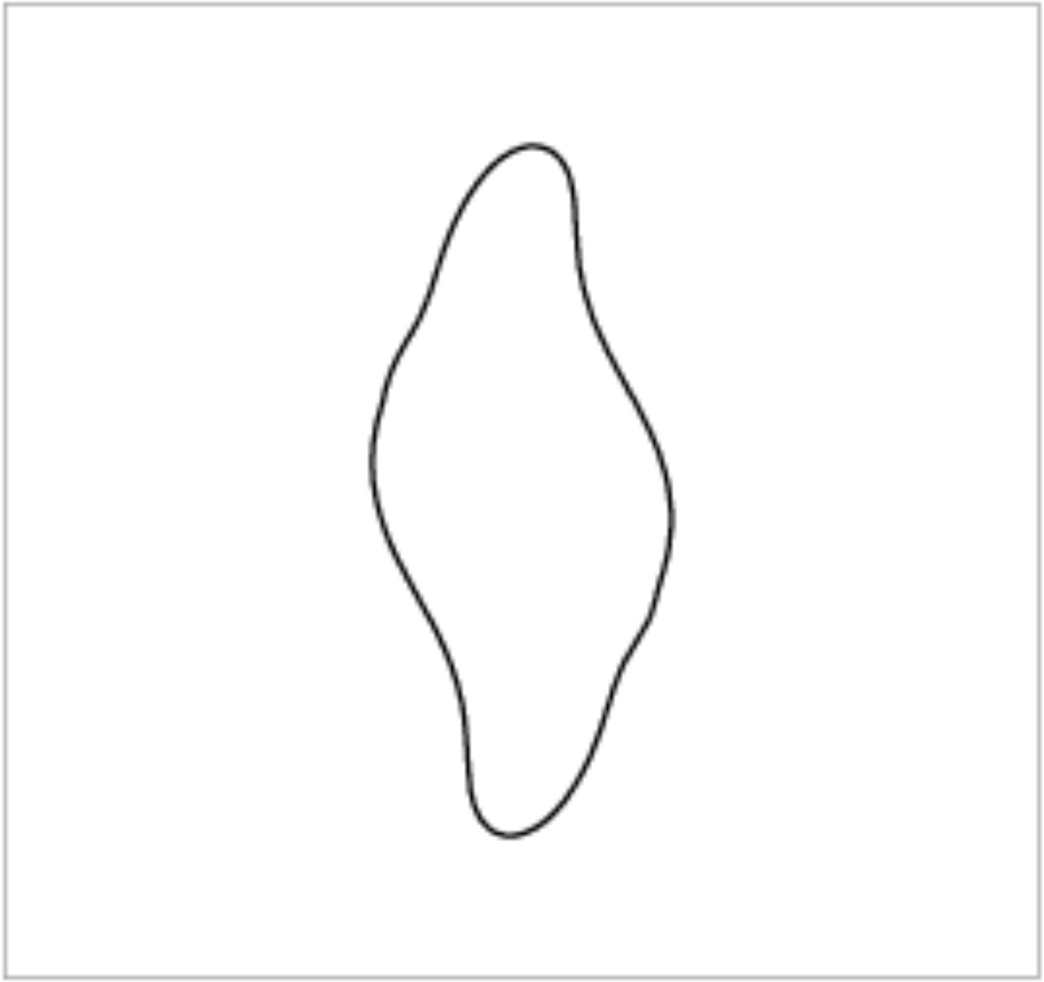

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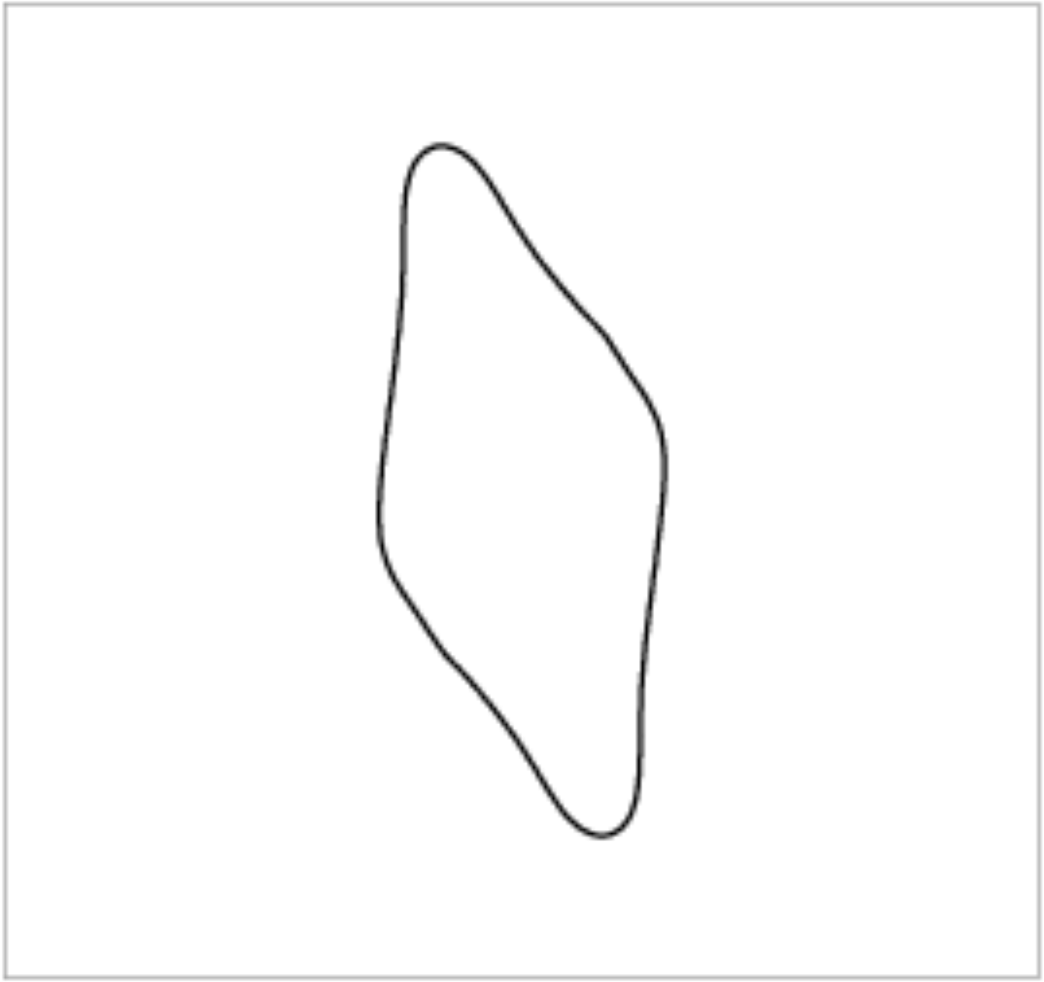

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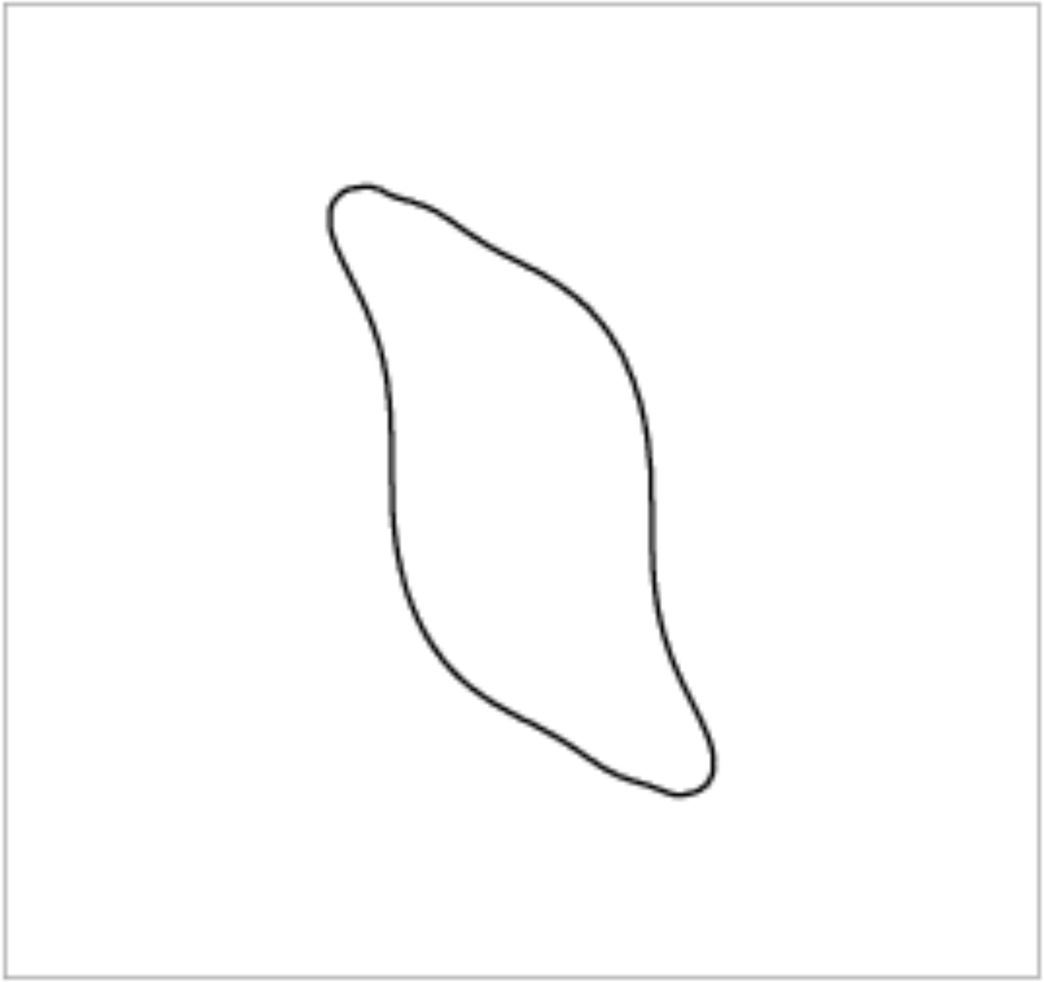

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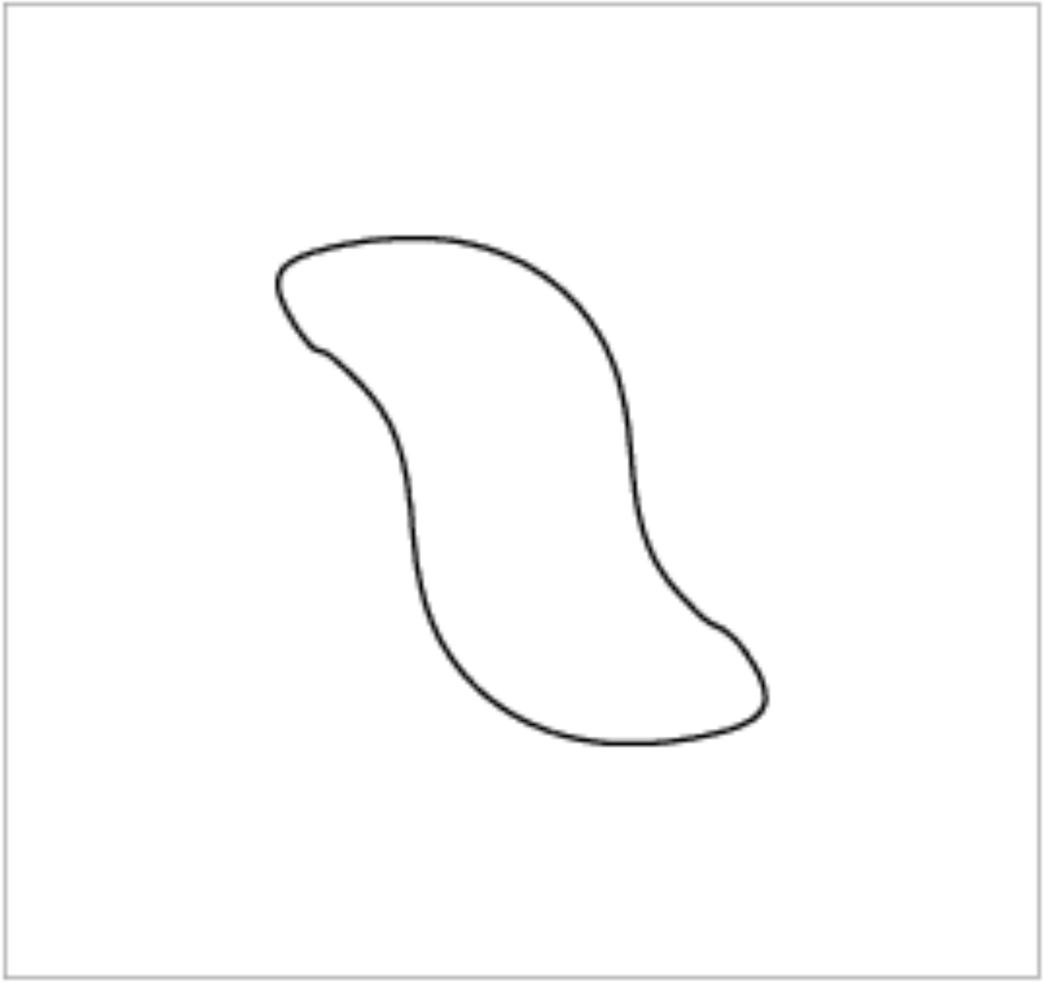

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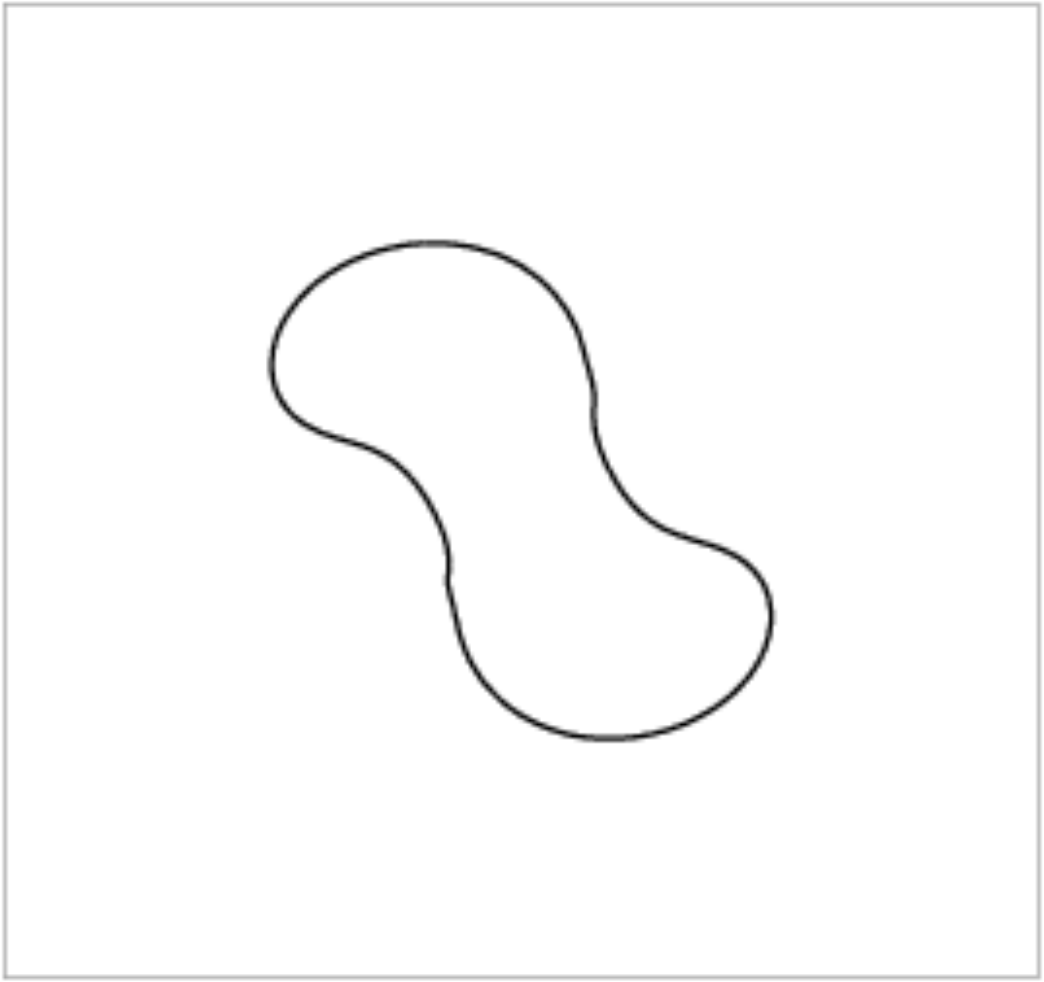

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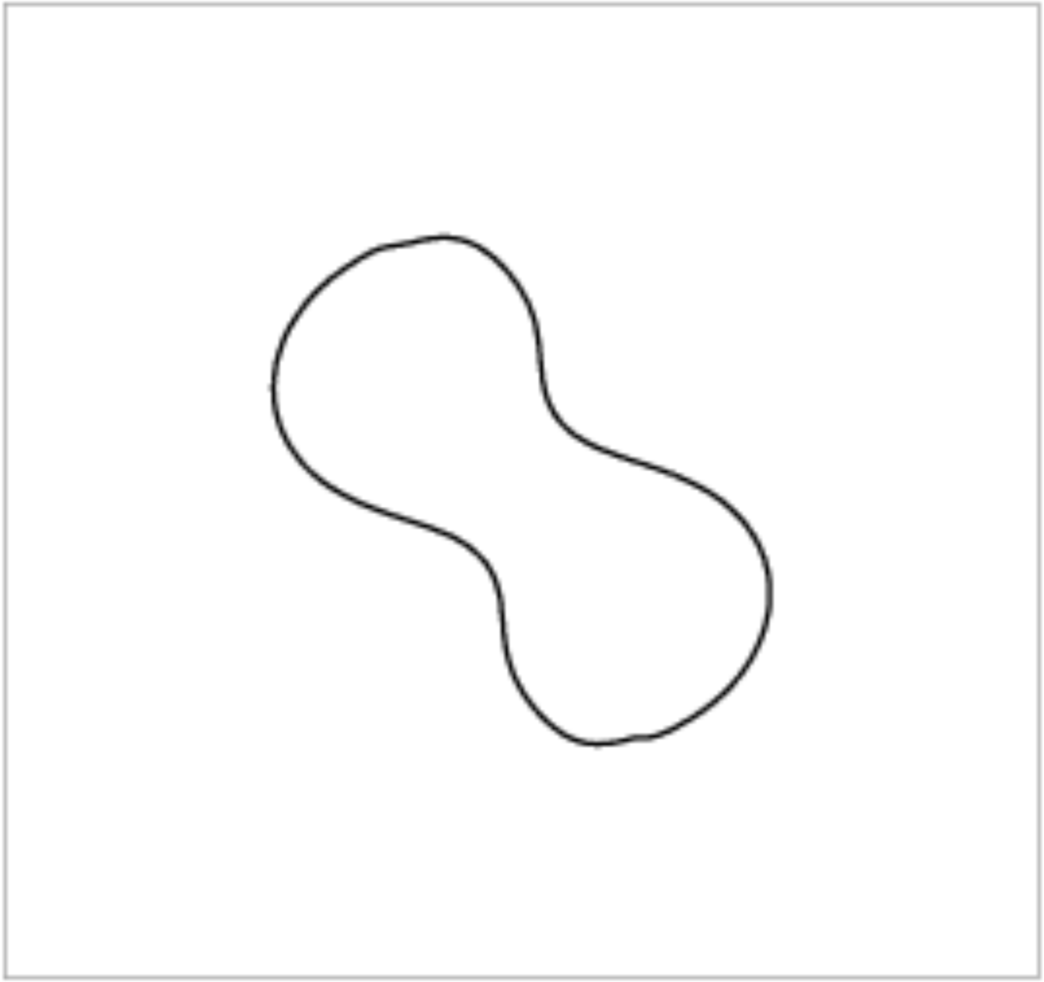

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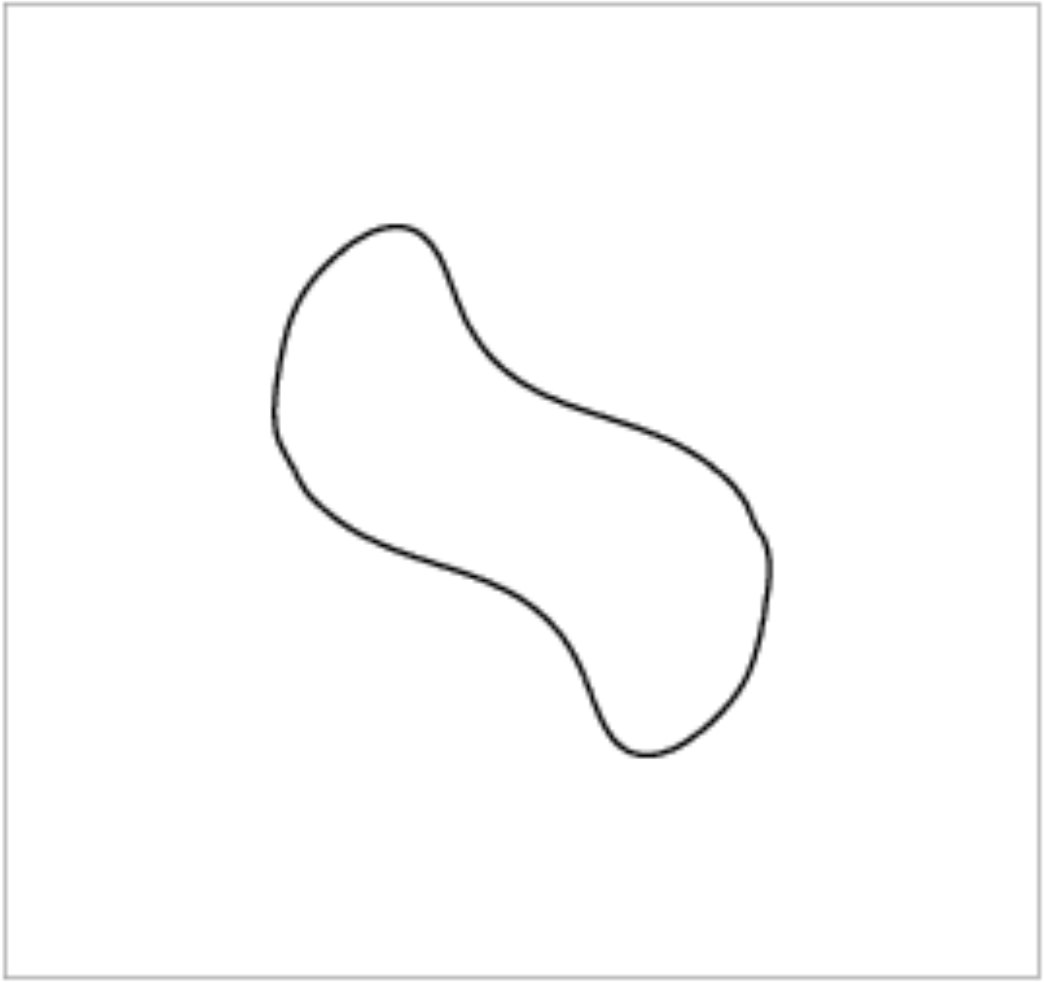

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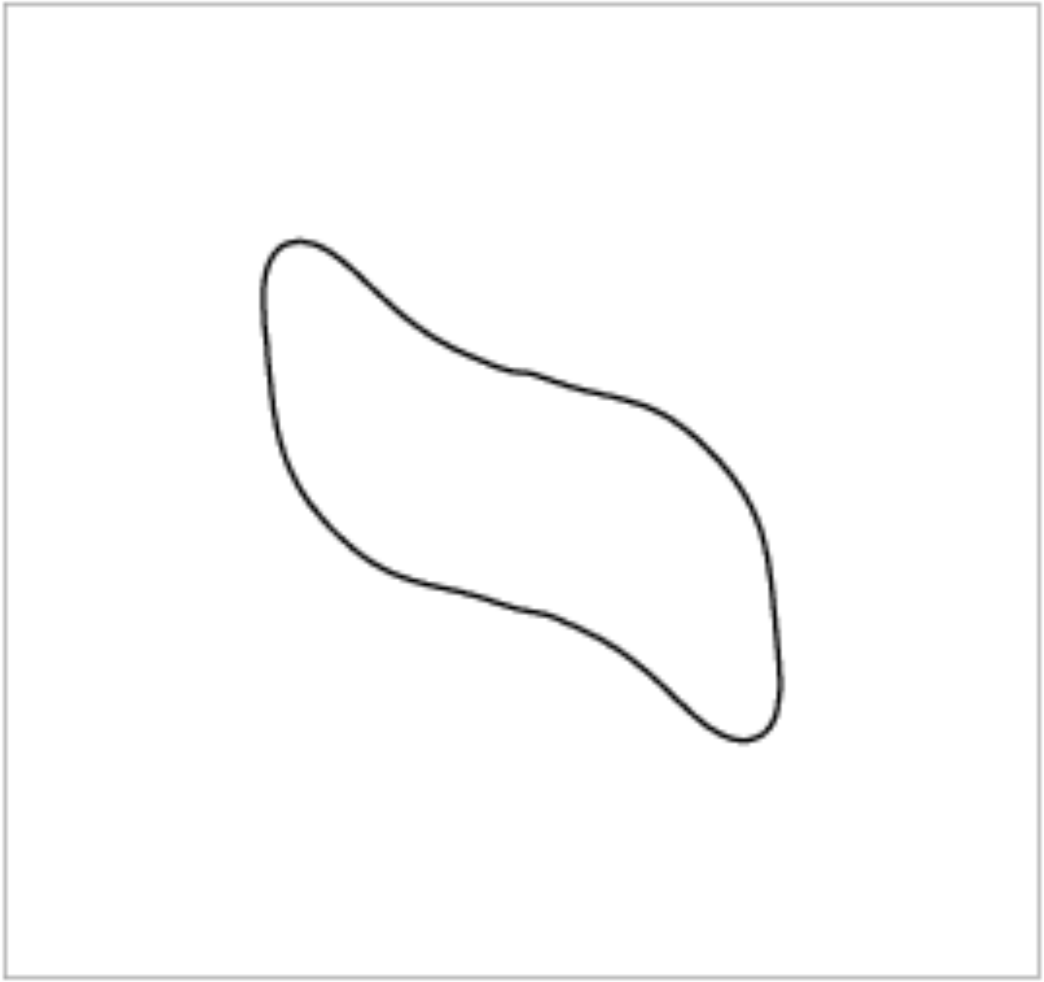

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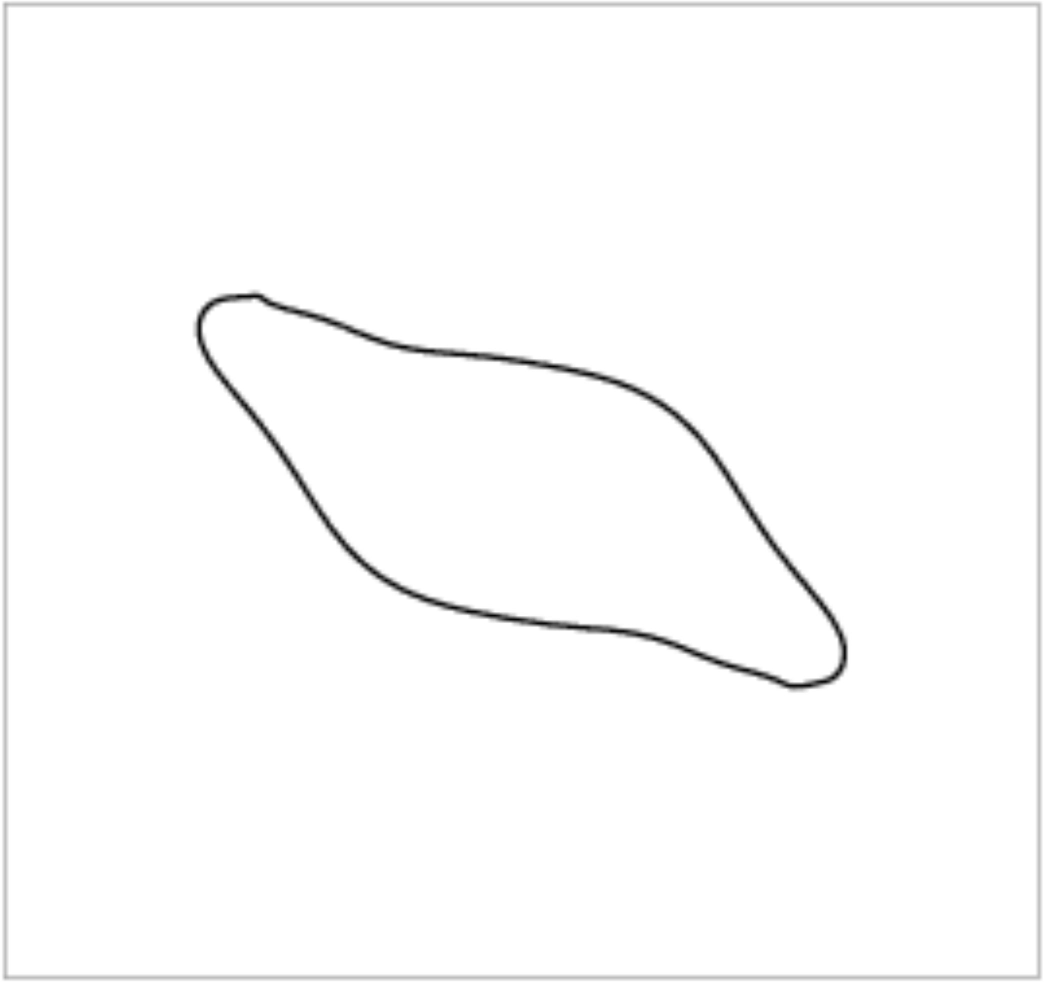

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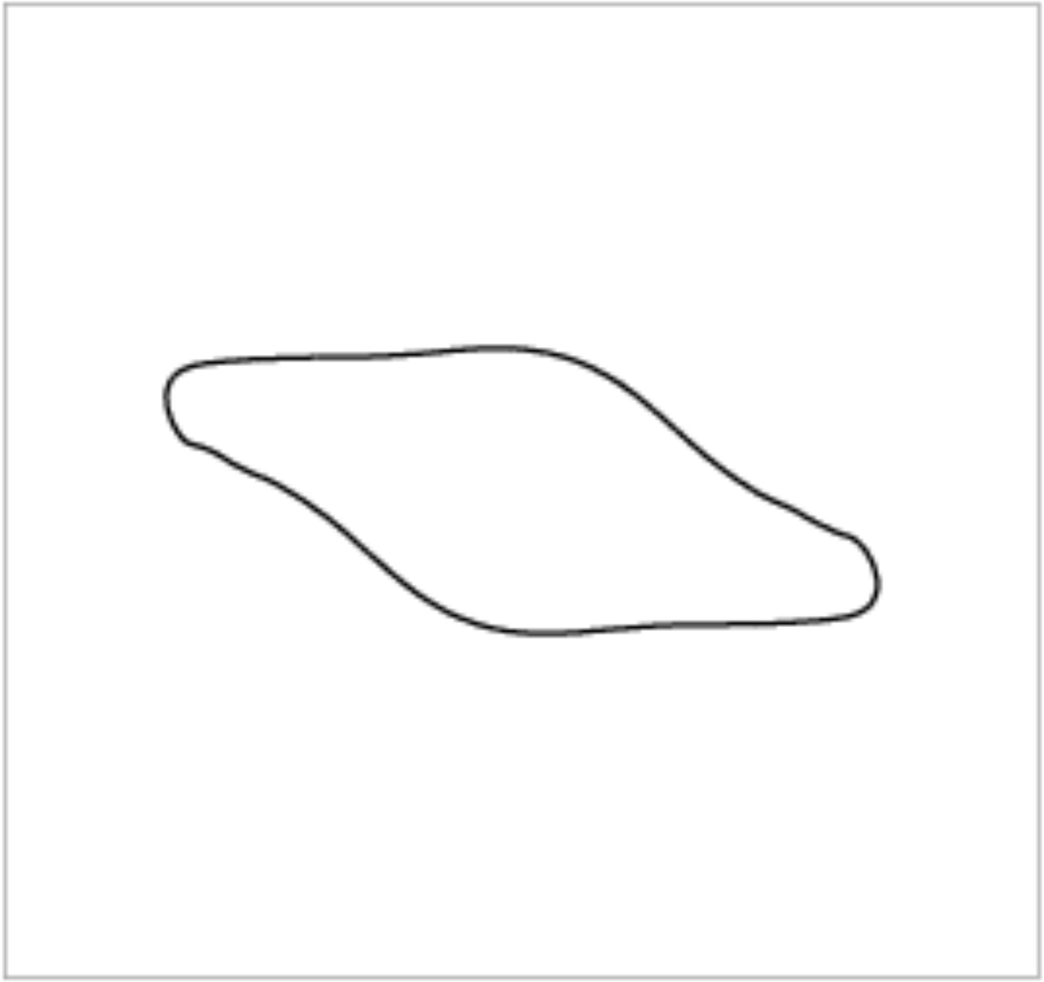

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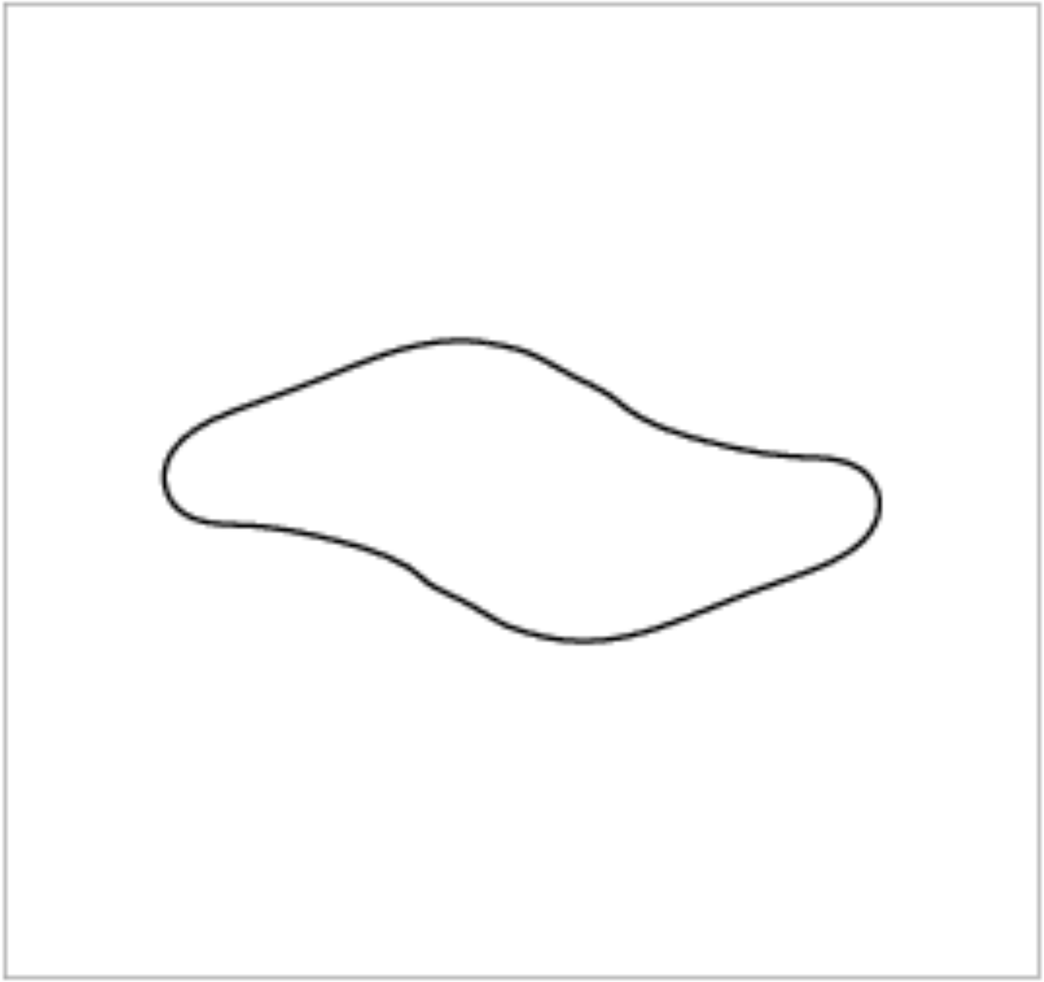

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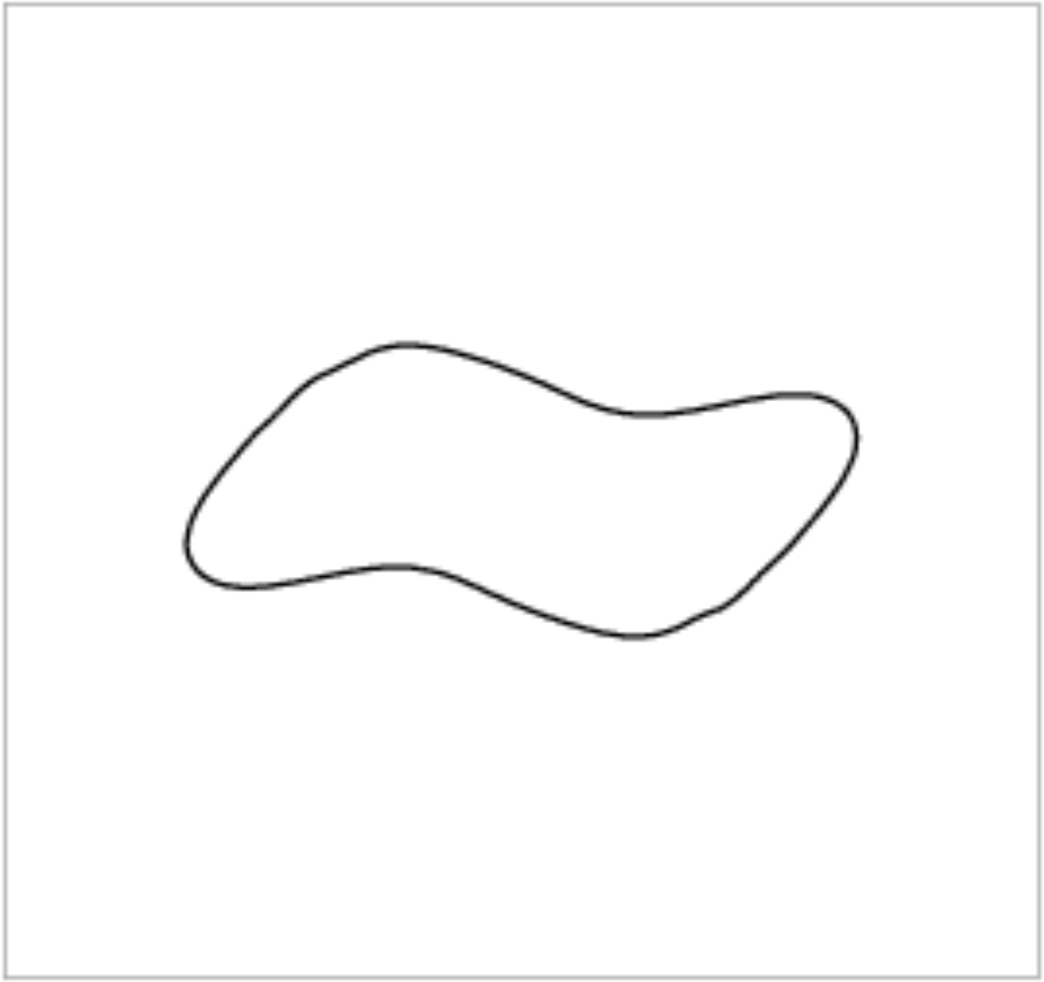

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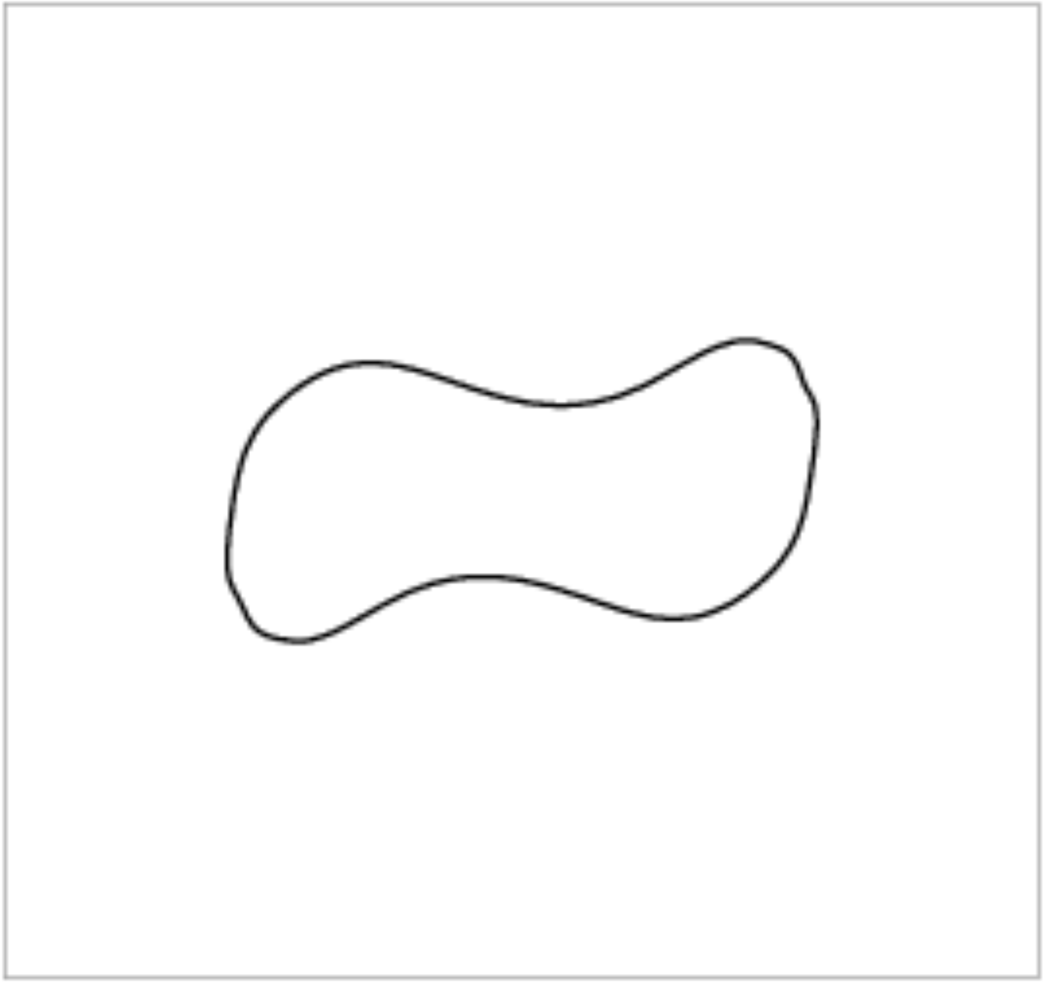

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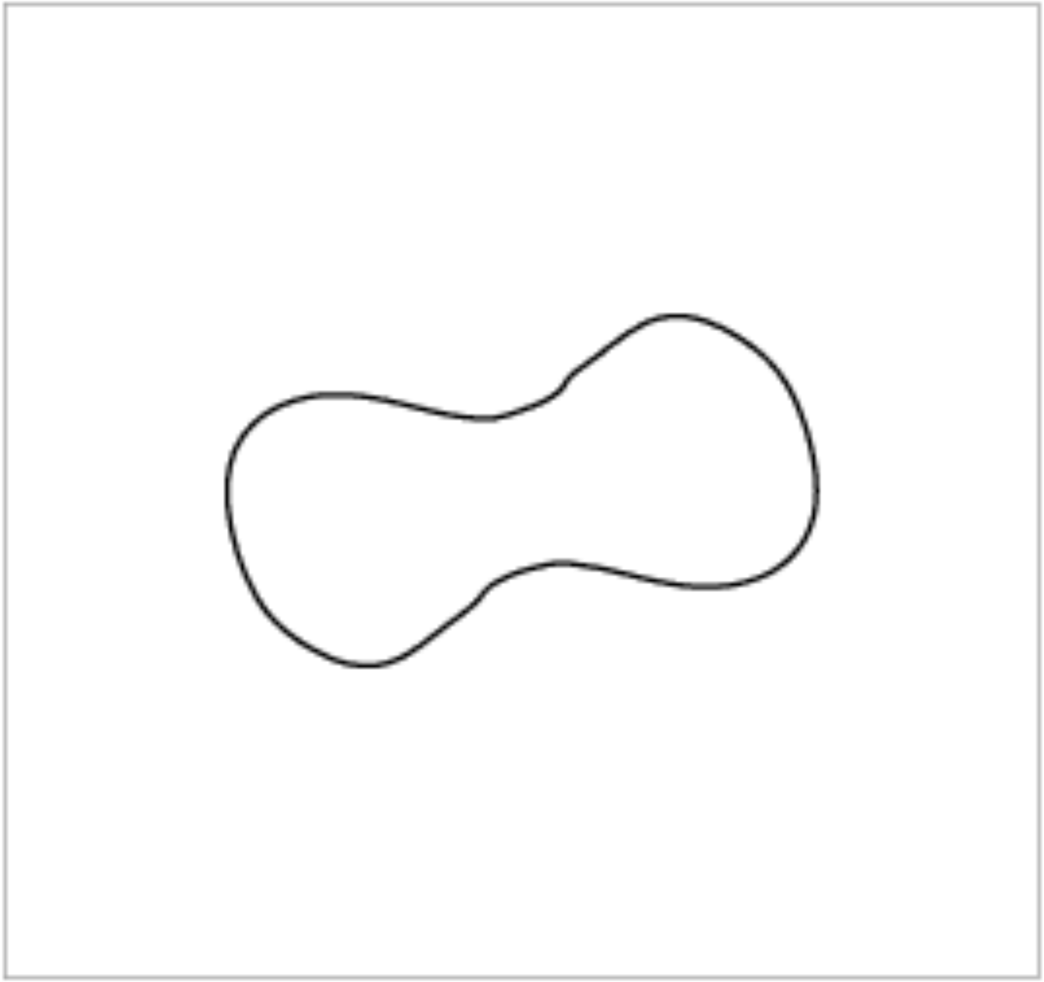

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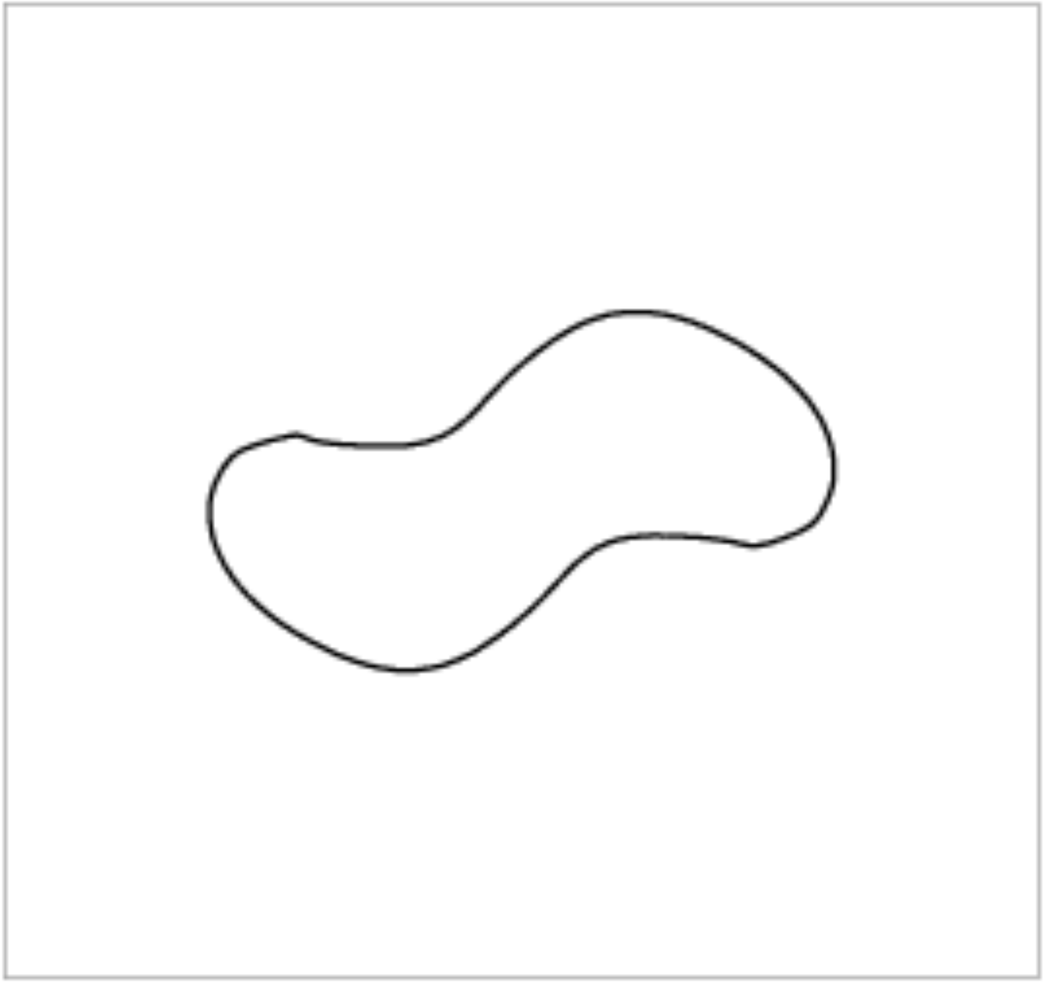

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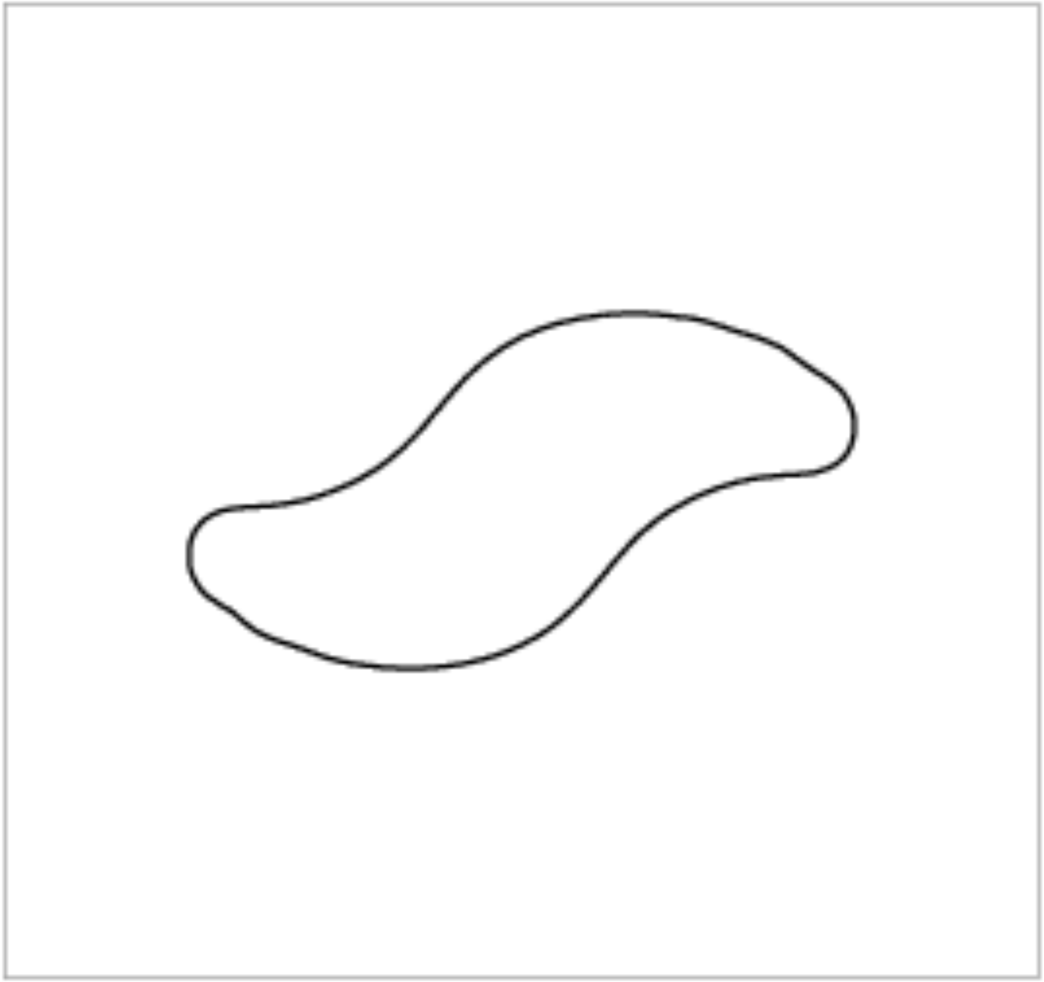

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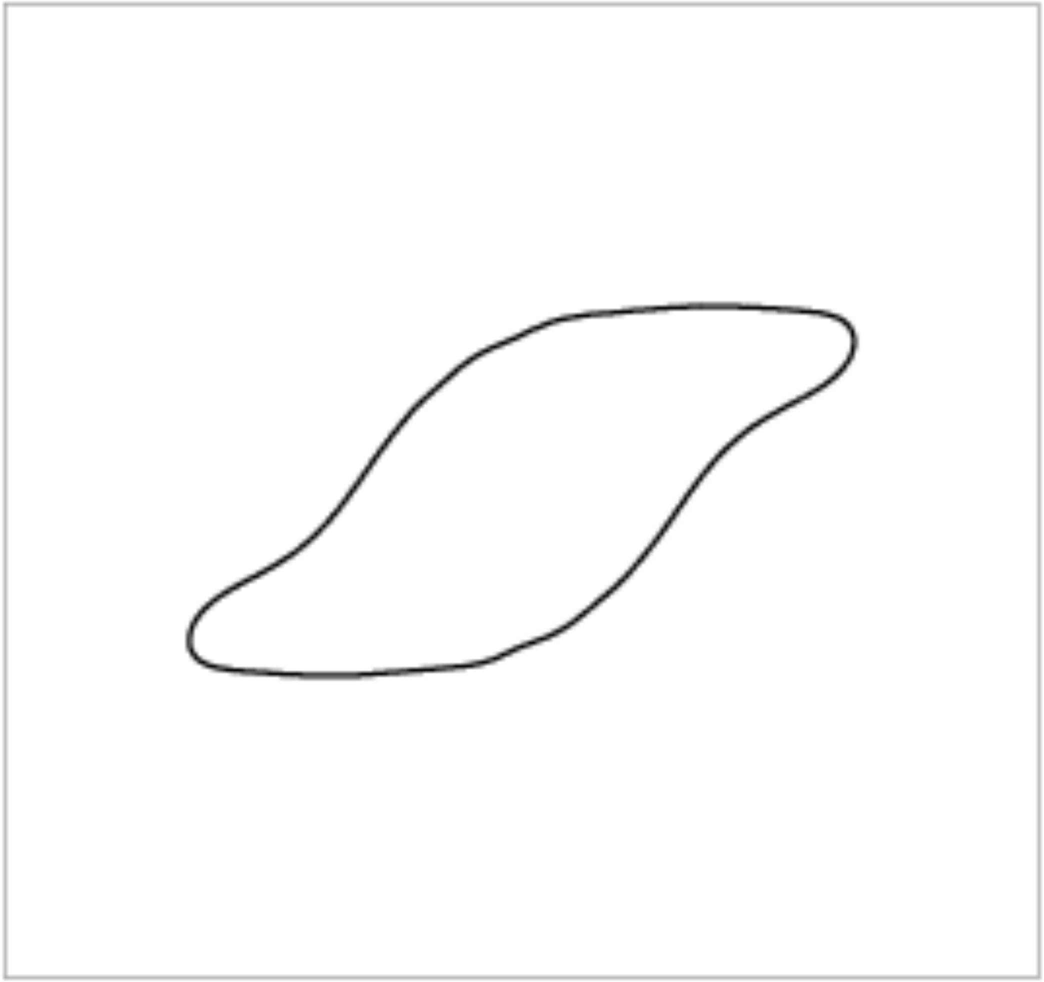

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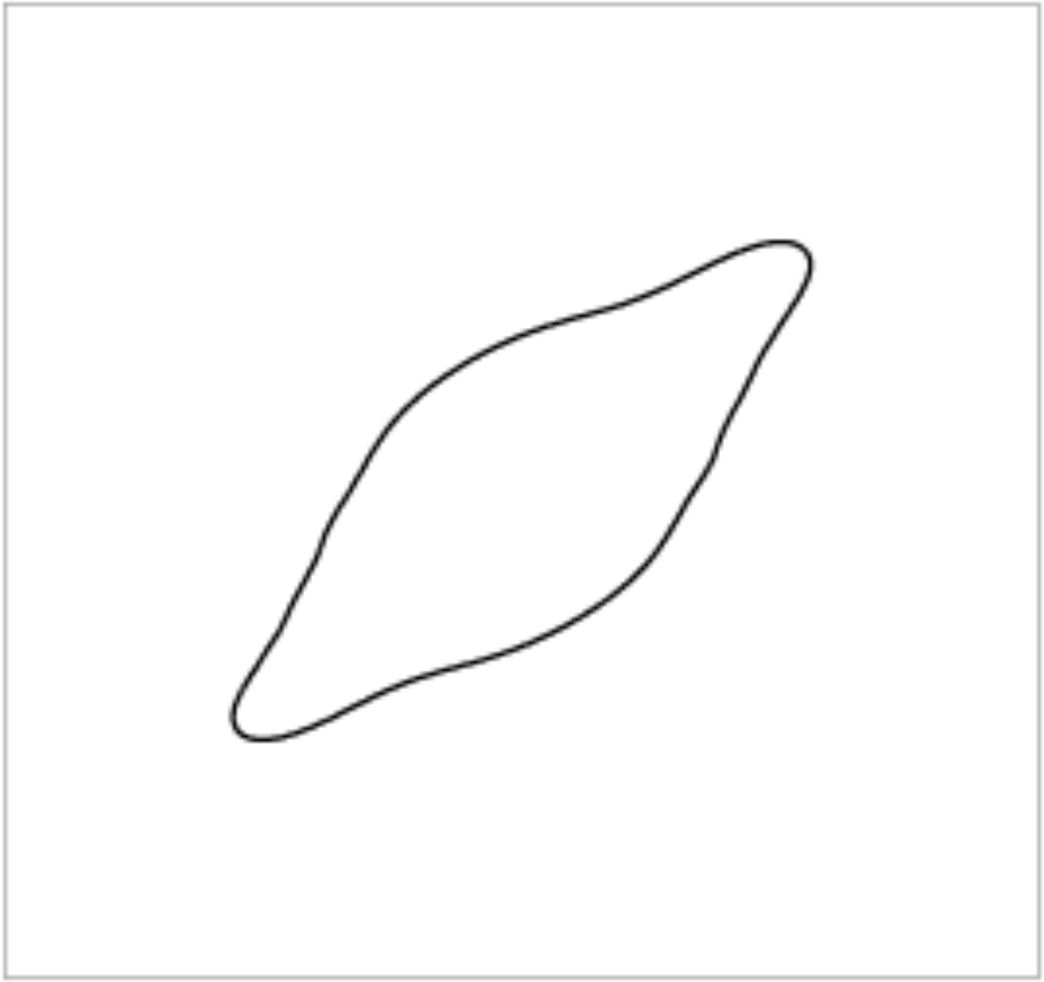

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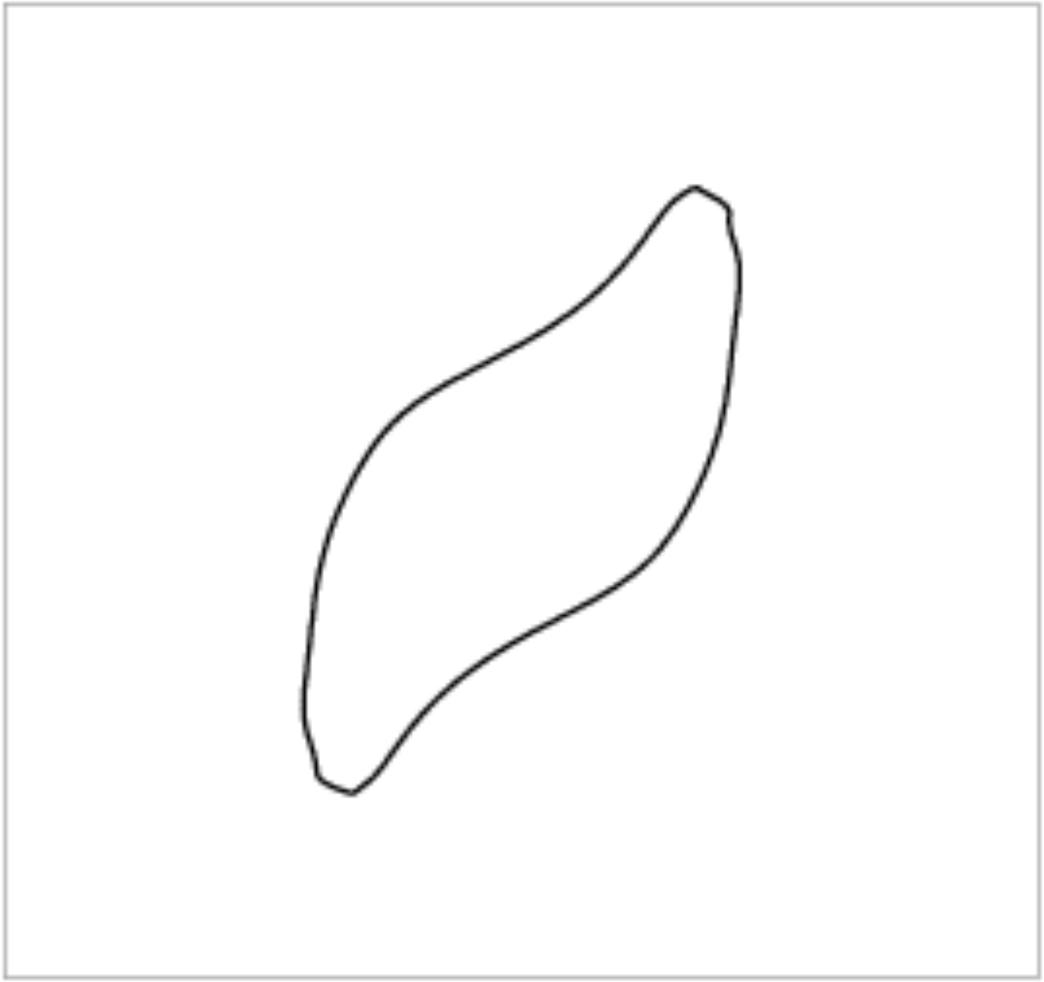

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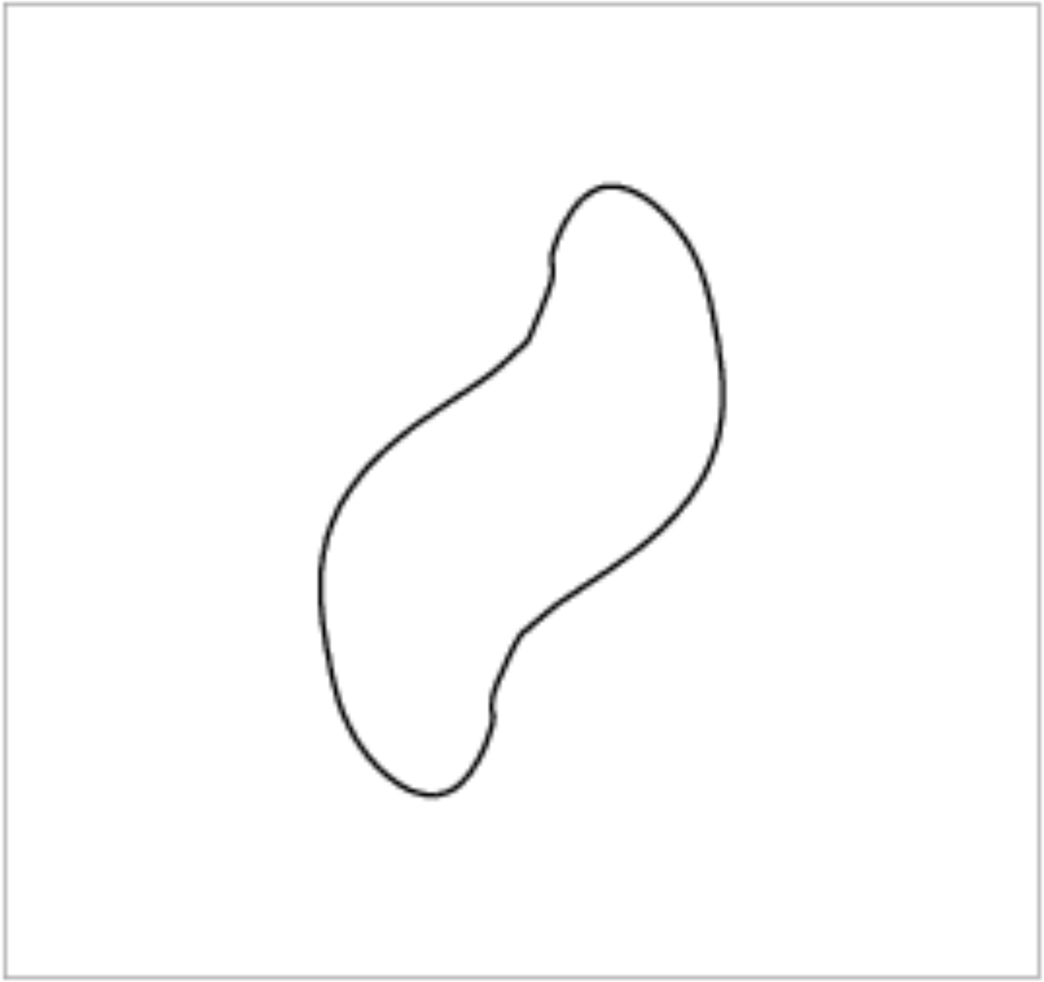

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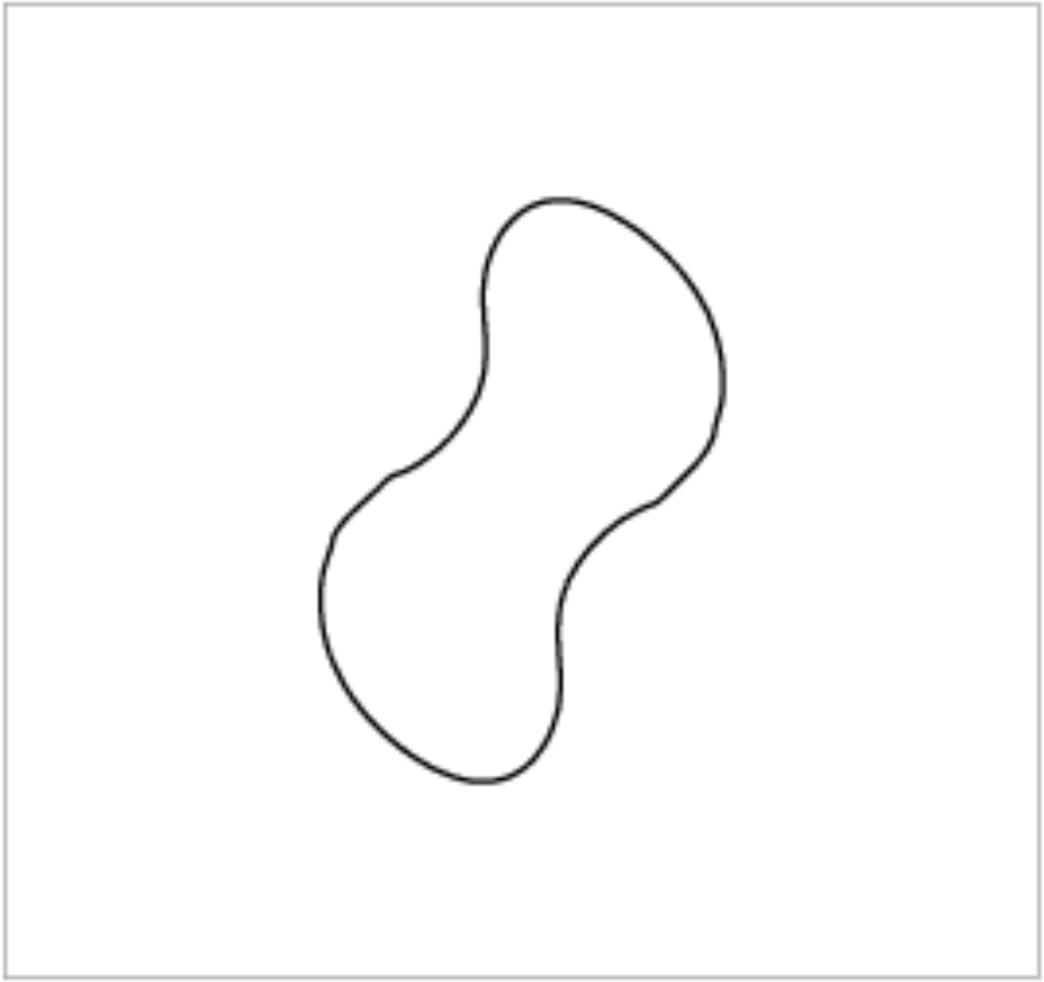

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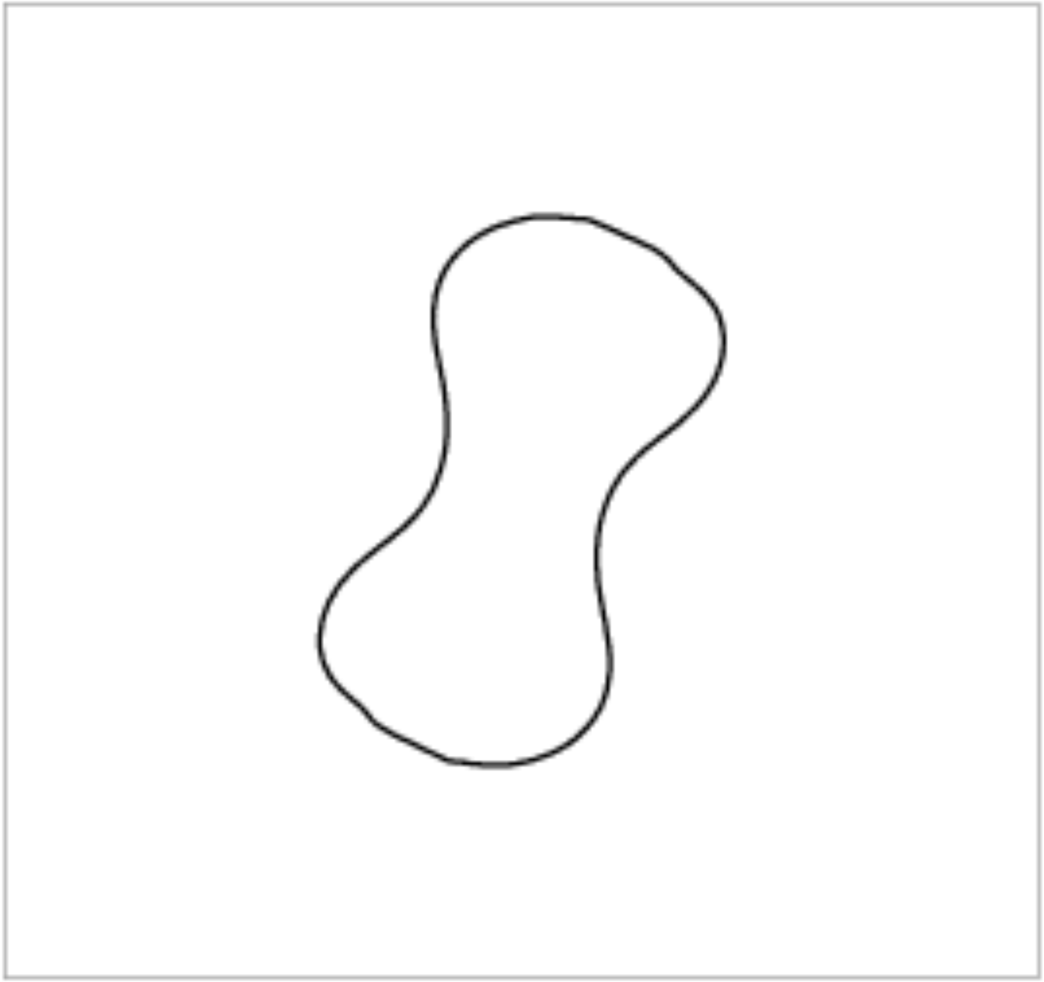

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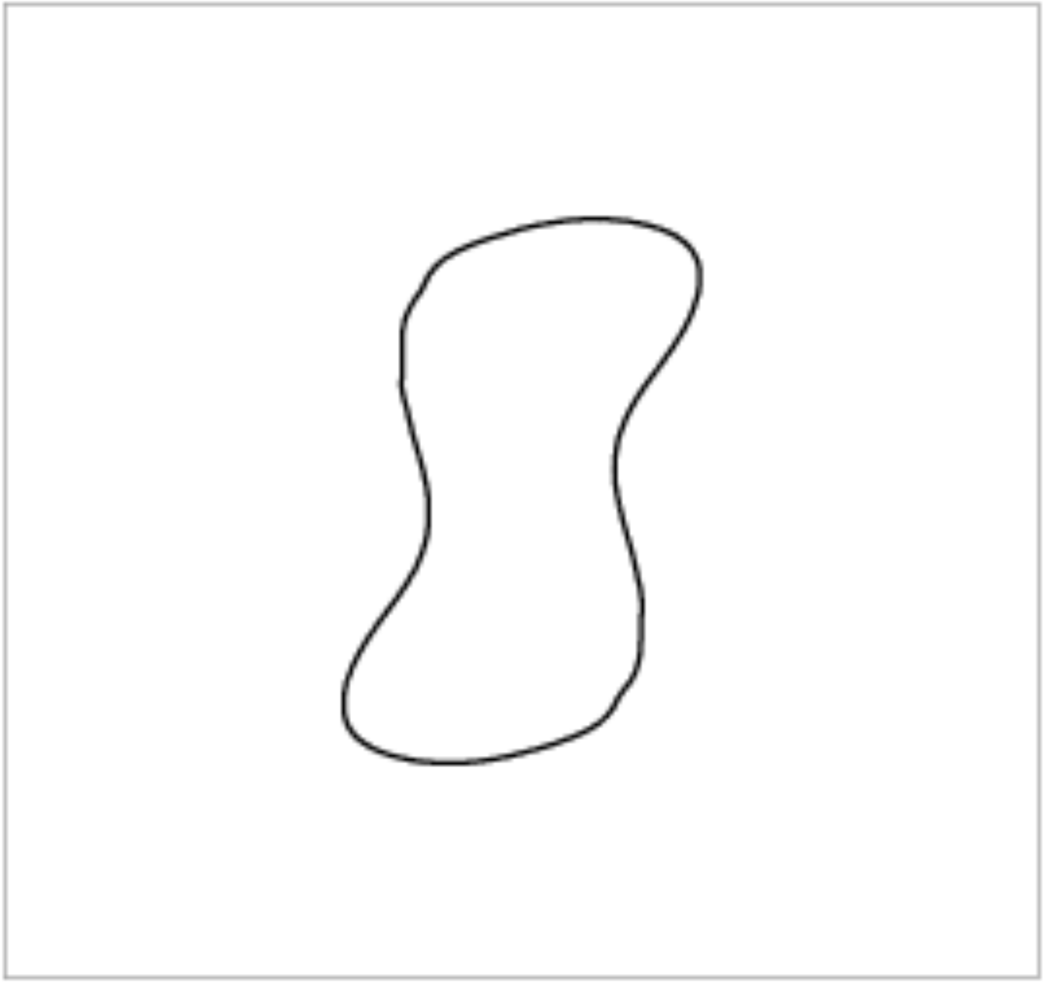

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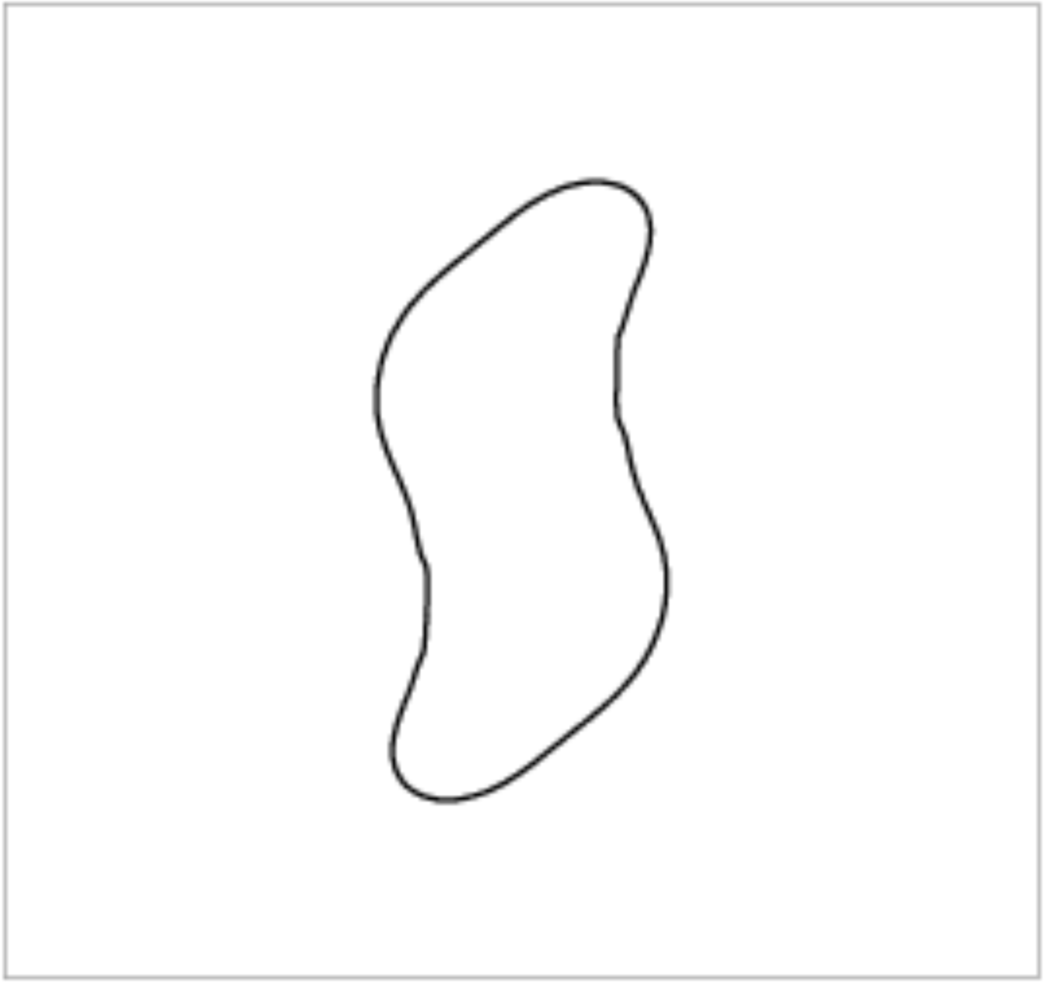

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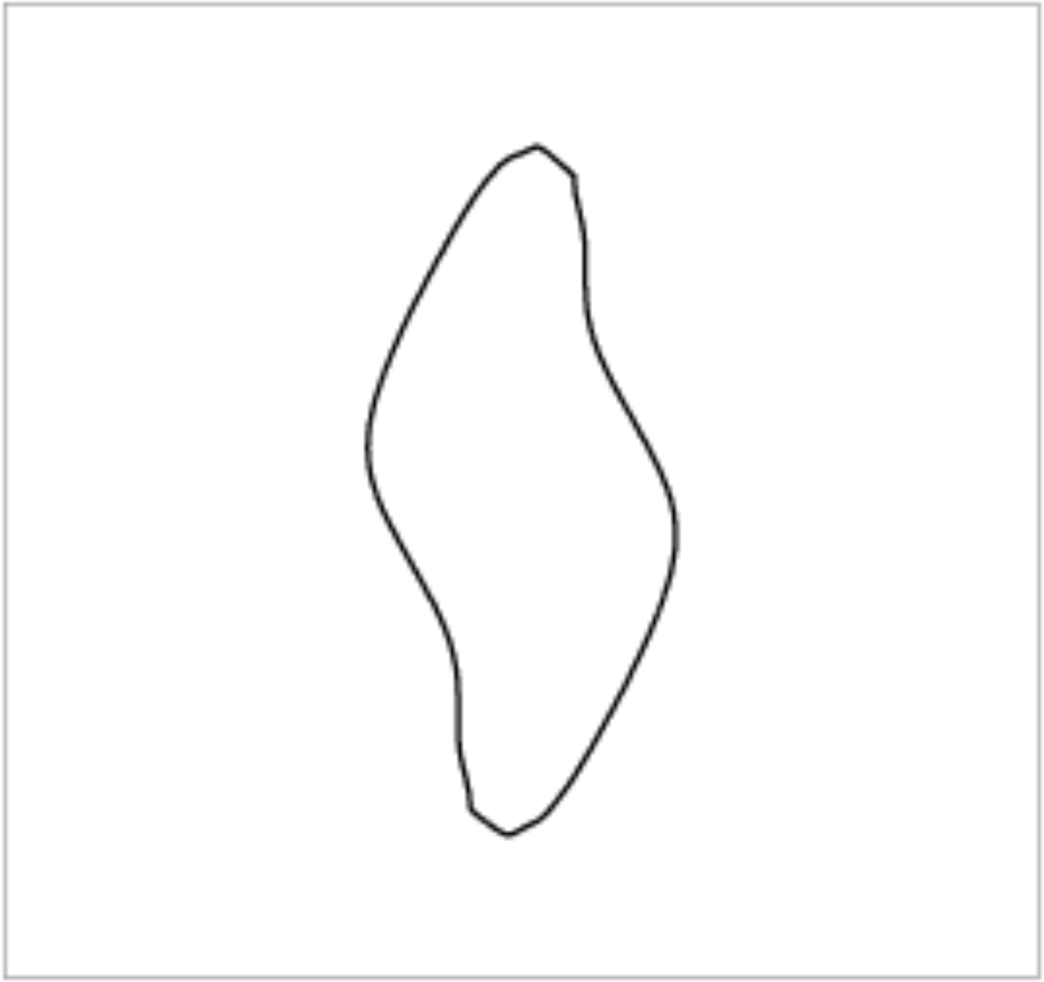

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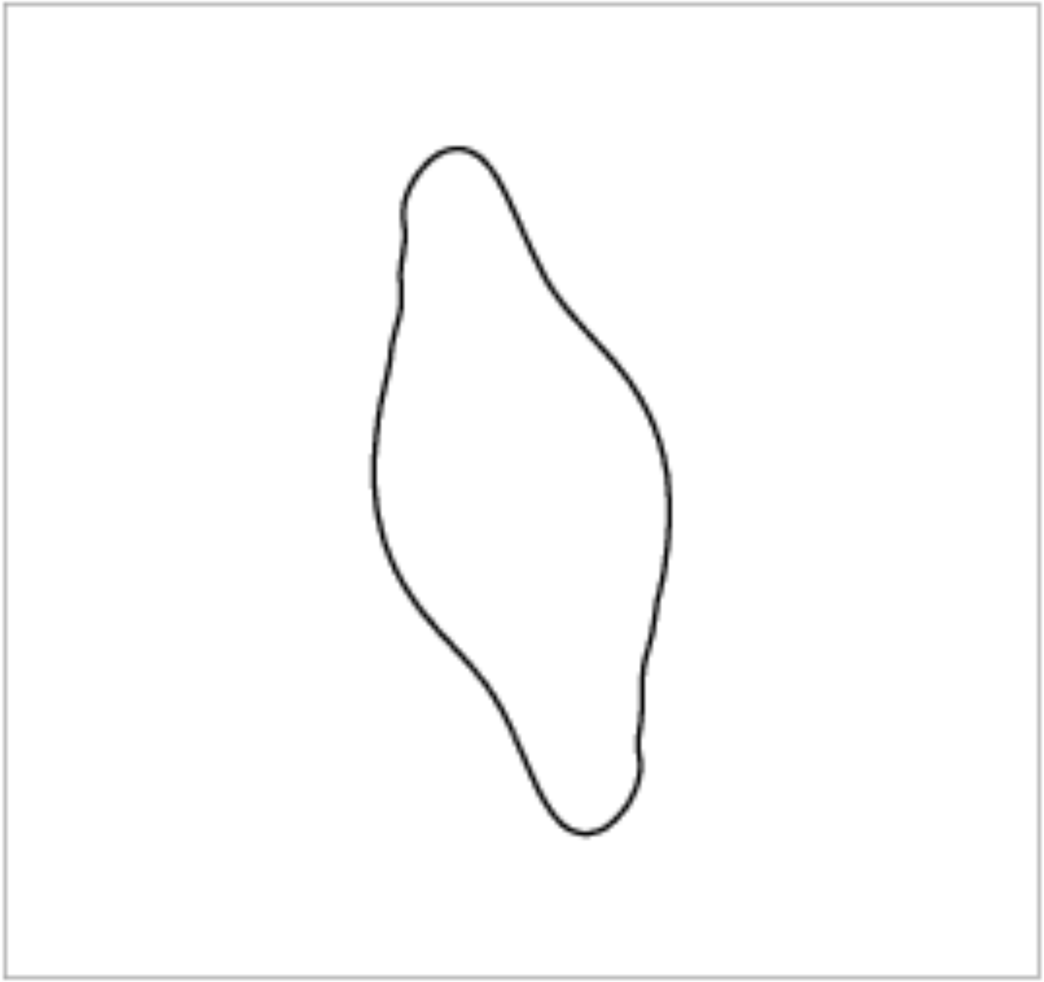

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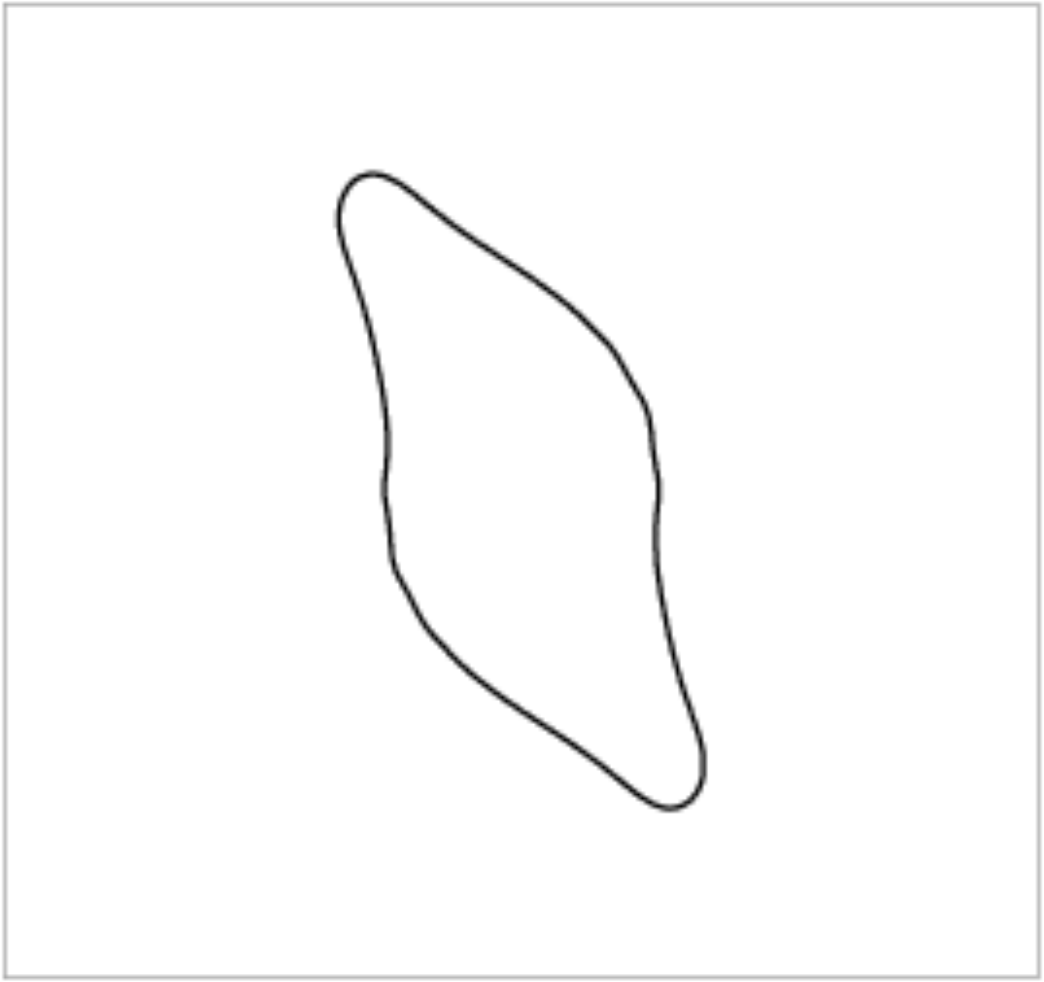
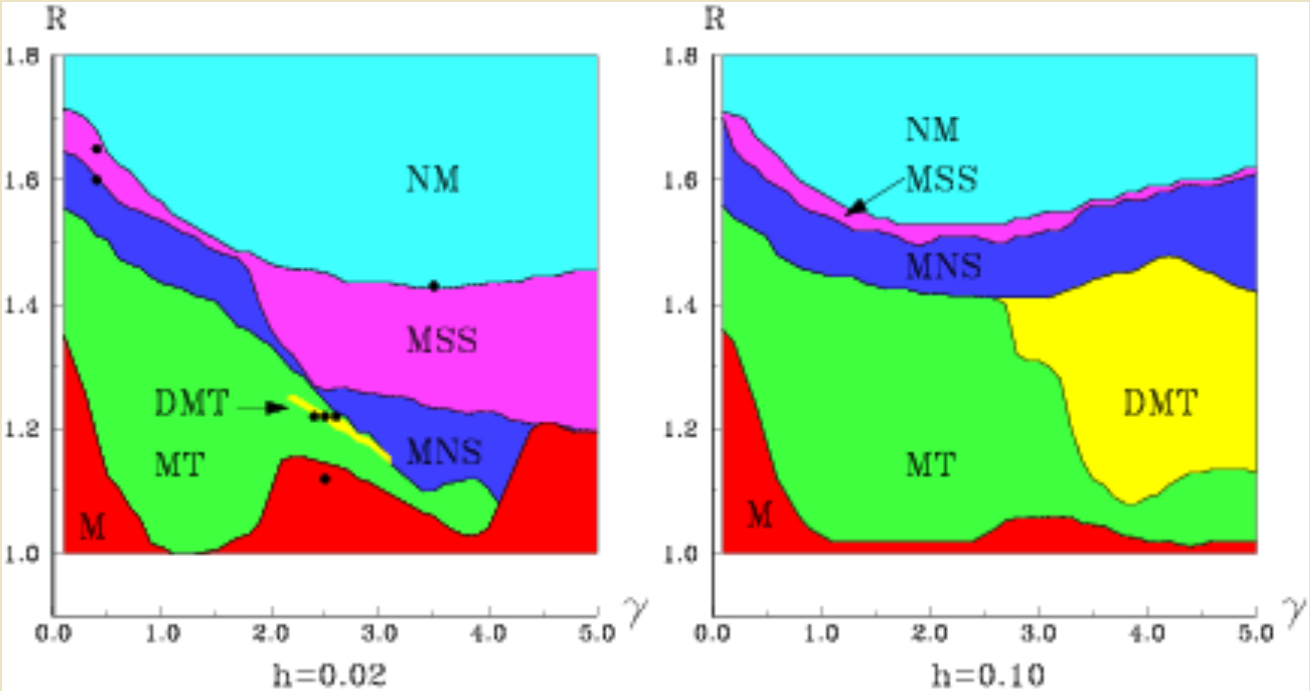


CDM-modeling of interaction of two cyclones of upper layer in two-layer rotating fluid: diagrams of states



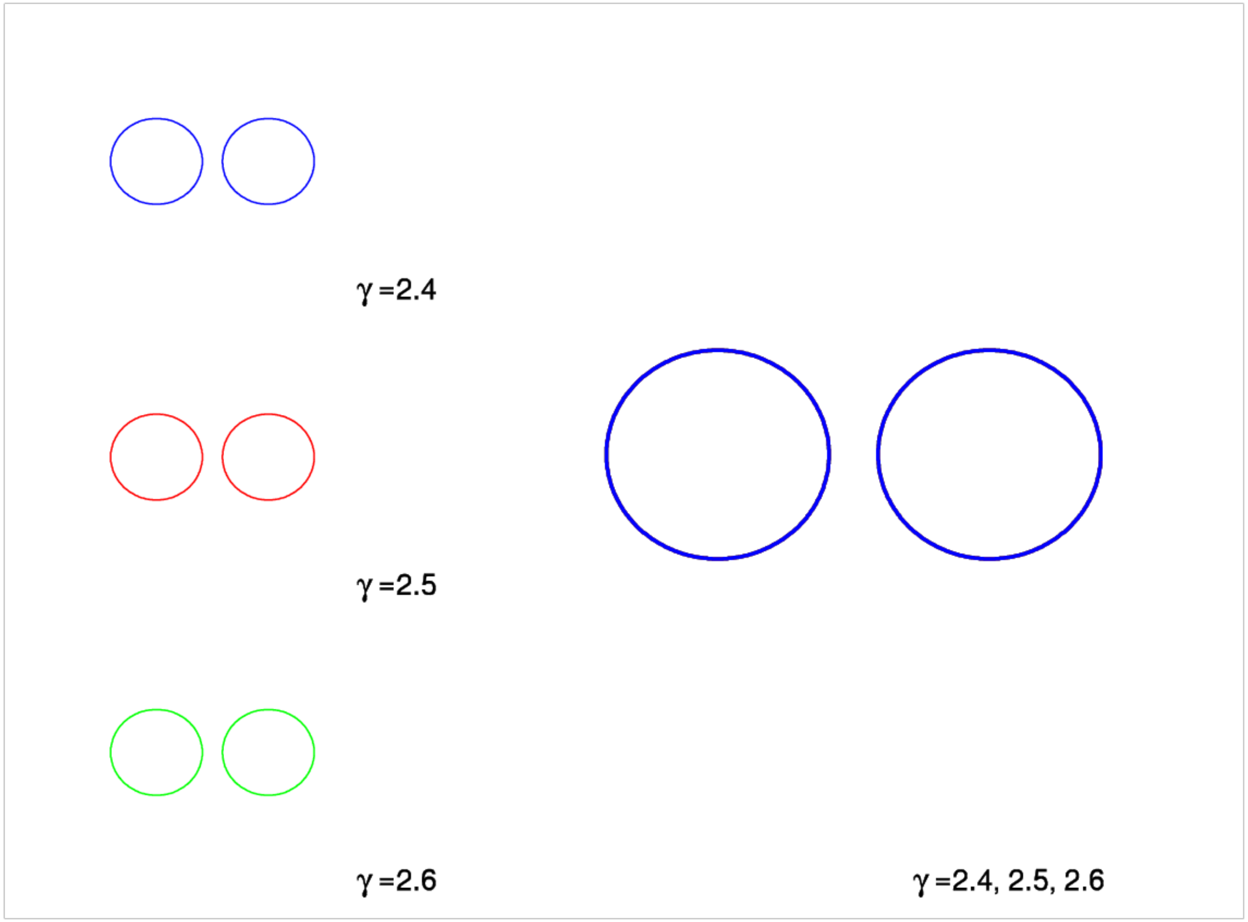
Diagrams in the rectangular domain of plane (γ, R) of possible states of two circular vortices of upper layer with the specified values of the upper-layer thickness: M (merger) - a state, when after the merging of the vortex patches and a short intermediate stage of the thin vortex-line formation, there remains one compact vortex of larger scale. MT (merger/triplet) - merging of vortex patches, and the subsequent formation of a triplet composed of a large central vortex and two peripheral smaller like signed vortices. DMT (double merger/triplet) - the first stage of the evolution is similar to that of MT but later, a new vortex merger occurs leading to the birth of a new triplet. MNS (merger/non-symmetric separation) - a merging, followed by separation into unequal vortex patches. MSS (merger/symmetric separation) - the division is symmetrical, i.e. after a temporary merging, two identical vortex patches are formed again. NM (no merger) - vortex patches, pulsating, rotate around a common center of vorticity without merging.

h_1=0.02, R=1.22:

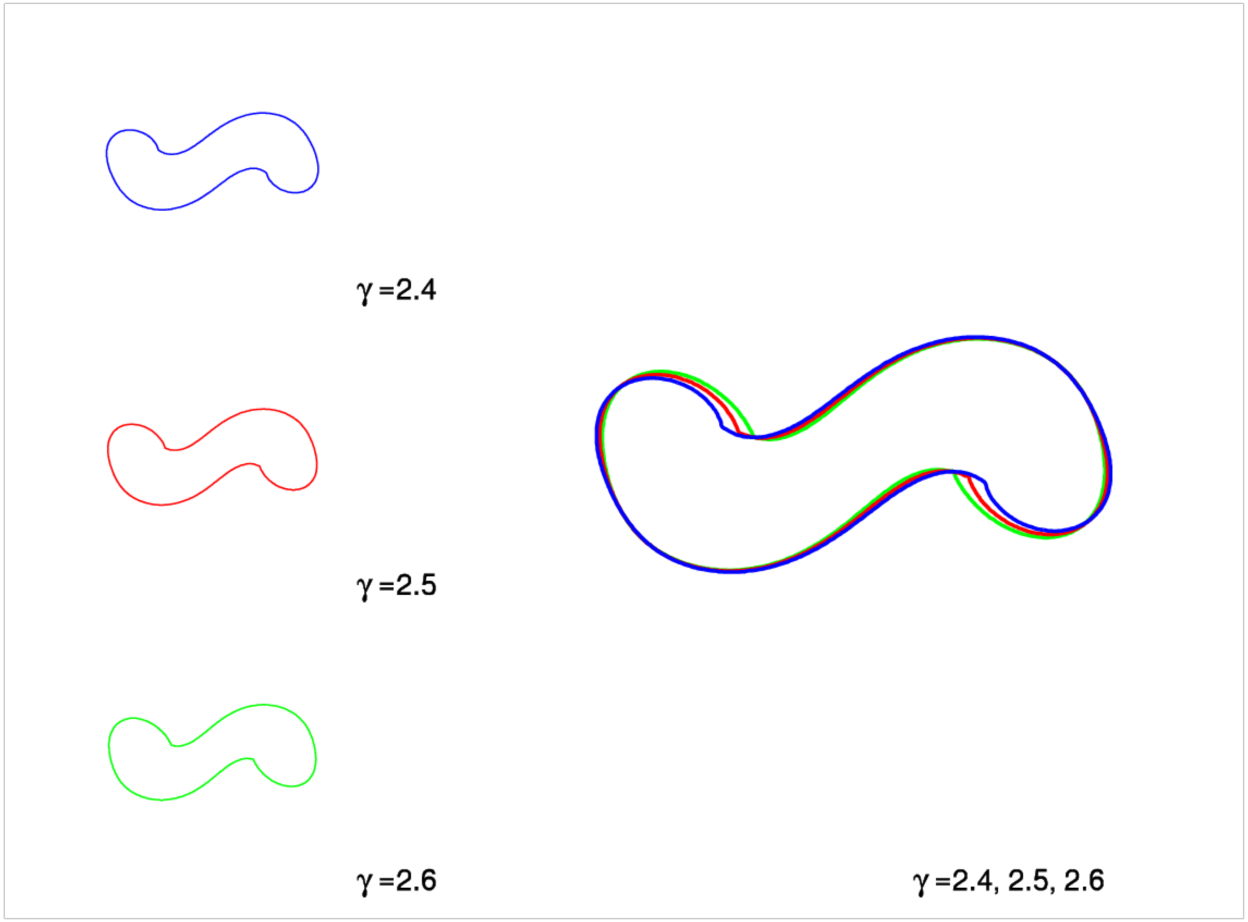
(a) γ=2.4, (b) γ=2.5, (c) γ=2.6

(MT/DMT/MT-types)

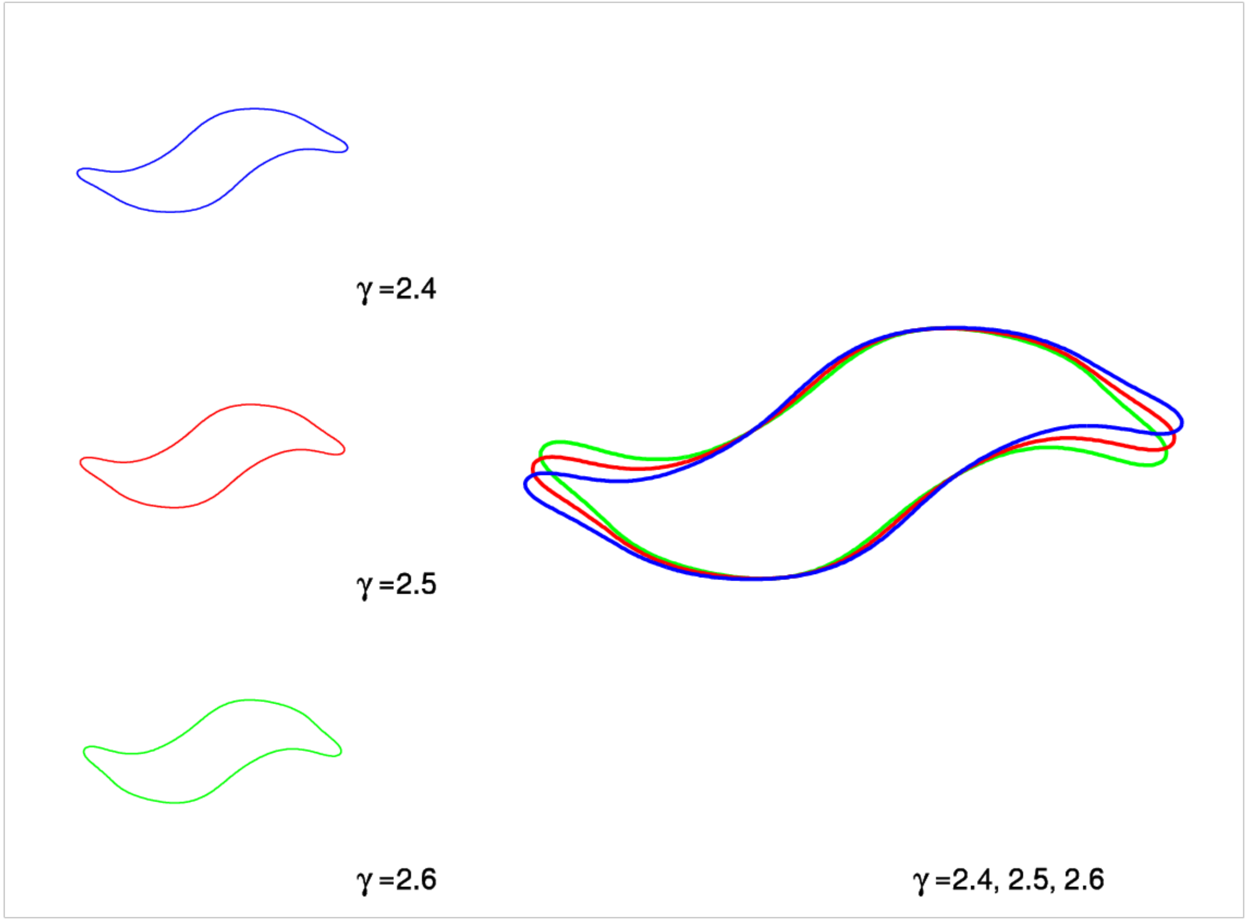
t=0



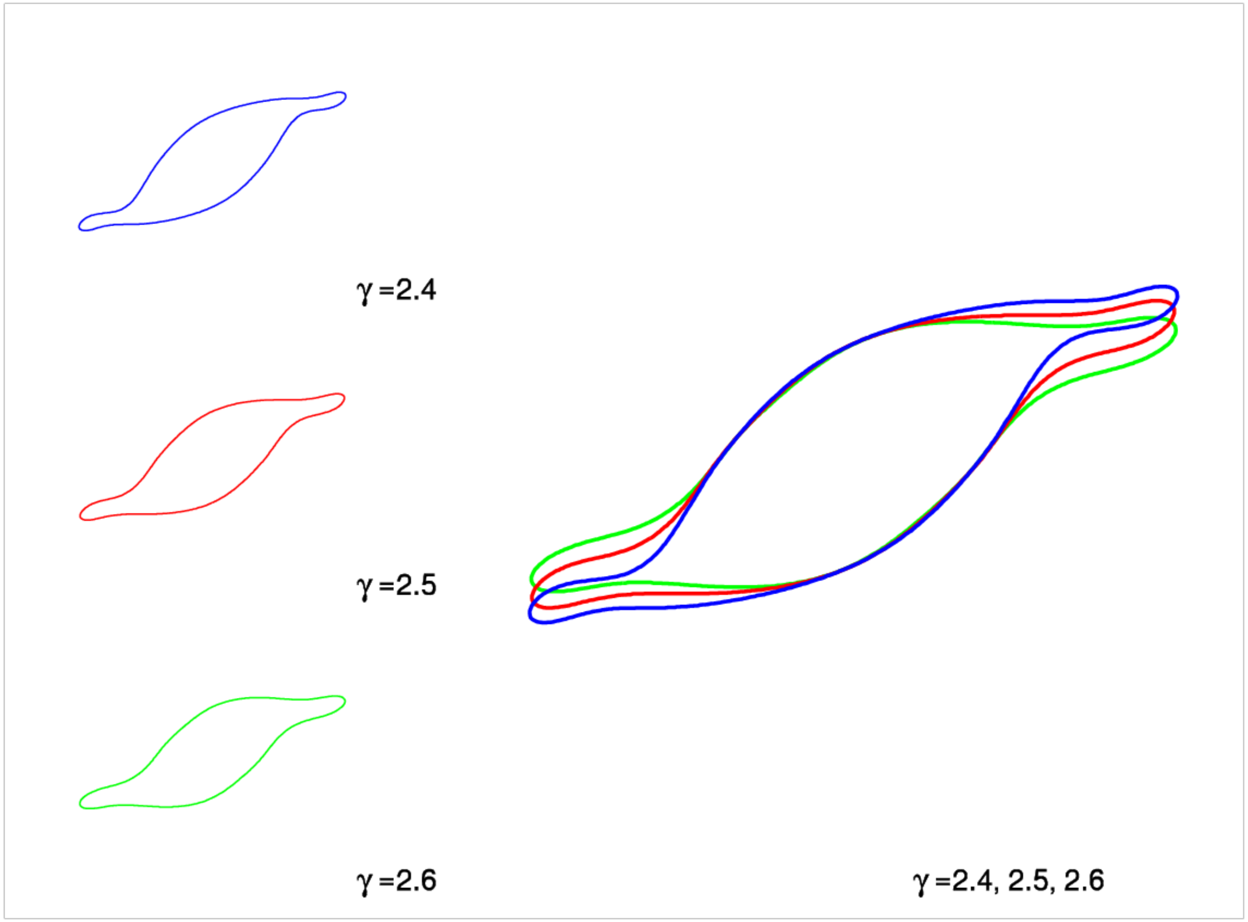
t=1



t=2



t=3



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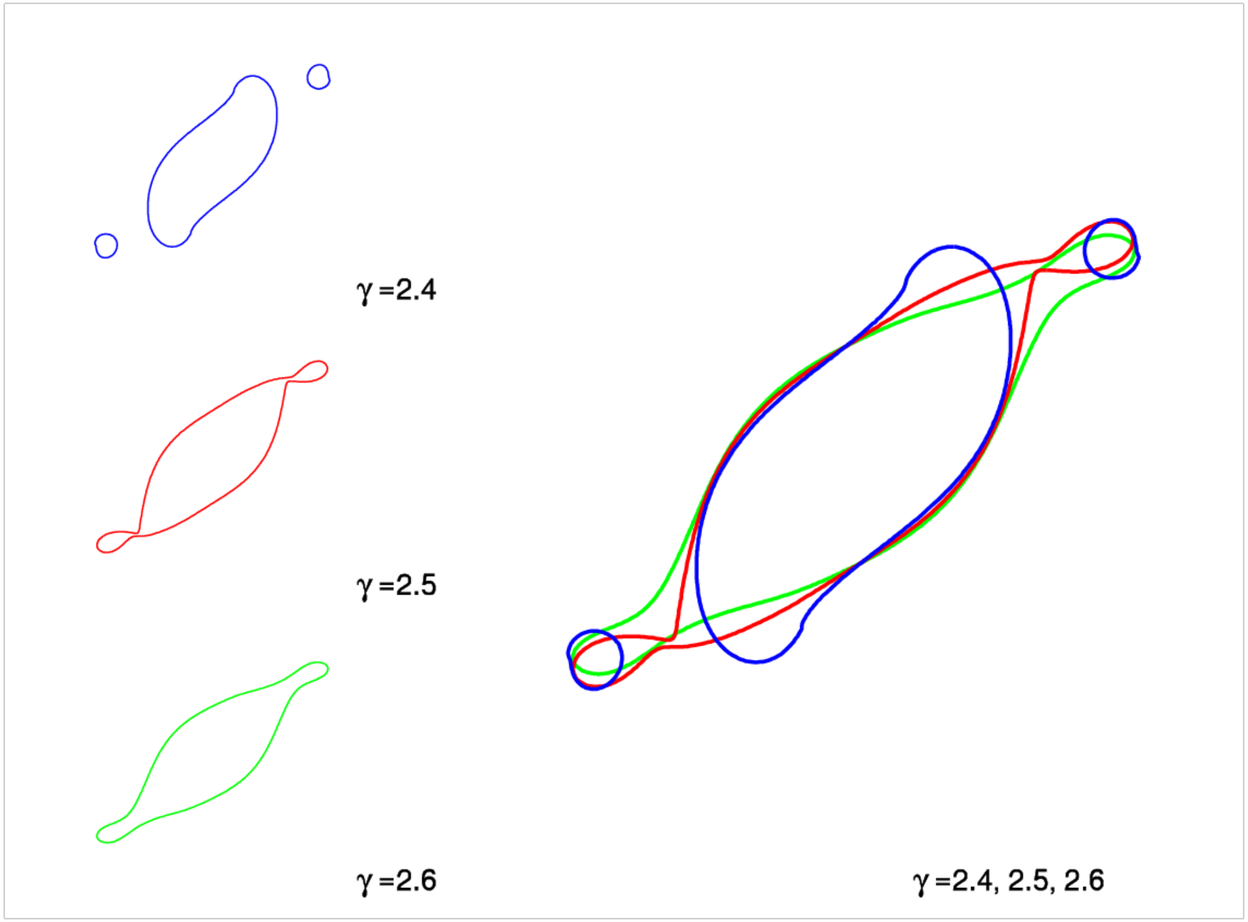

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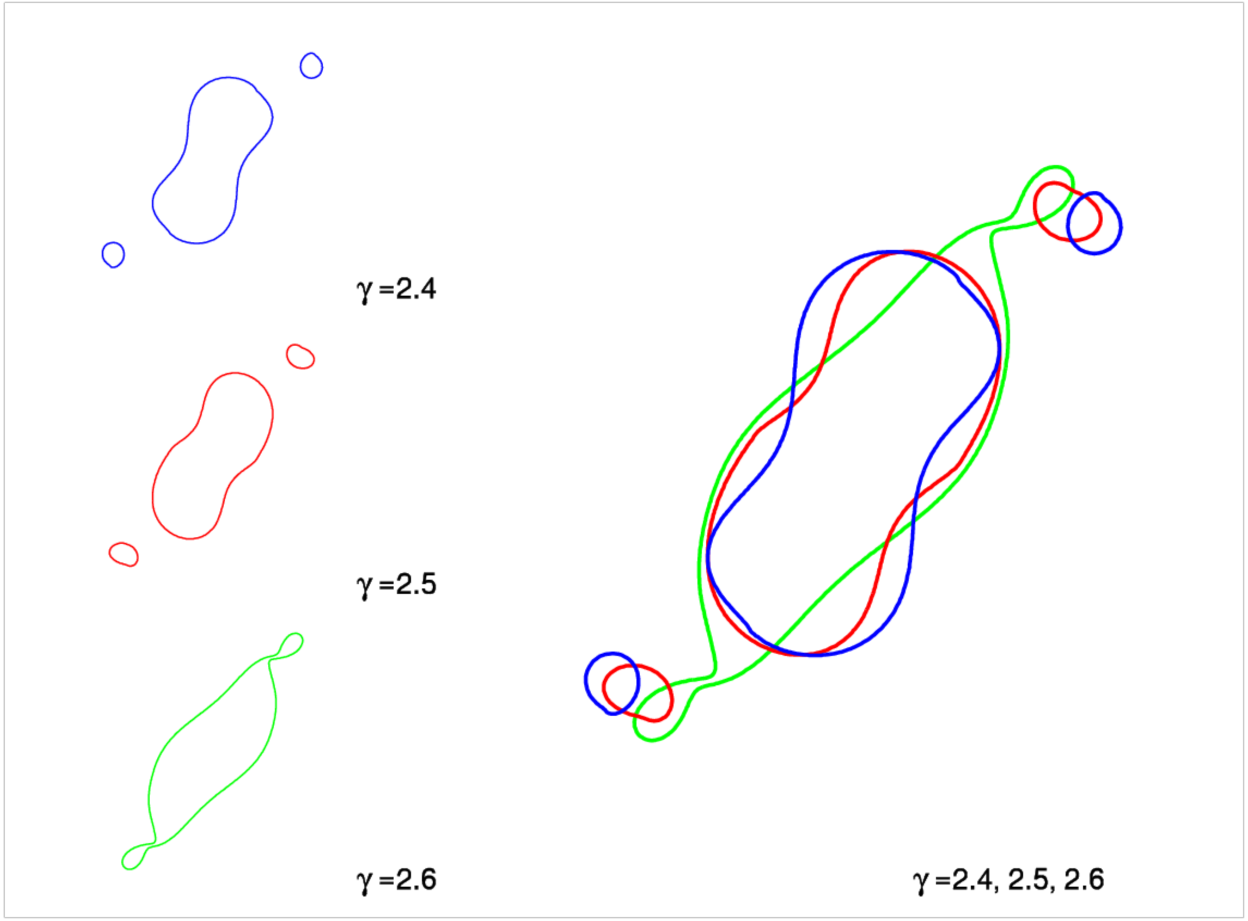

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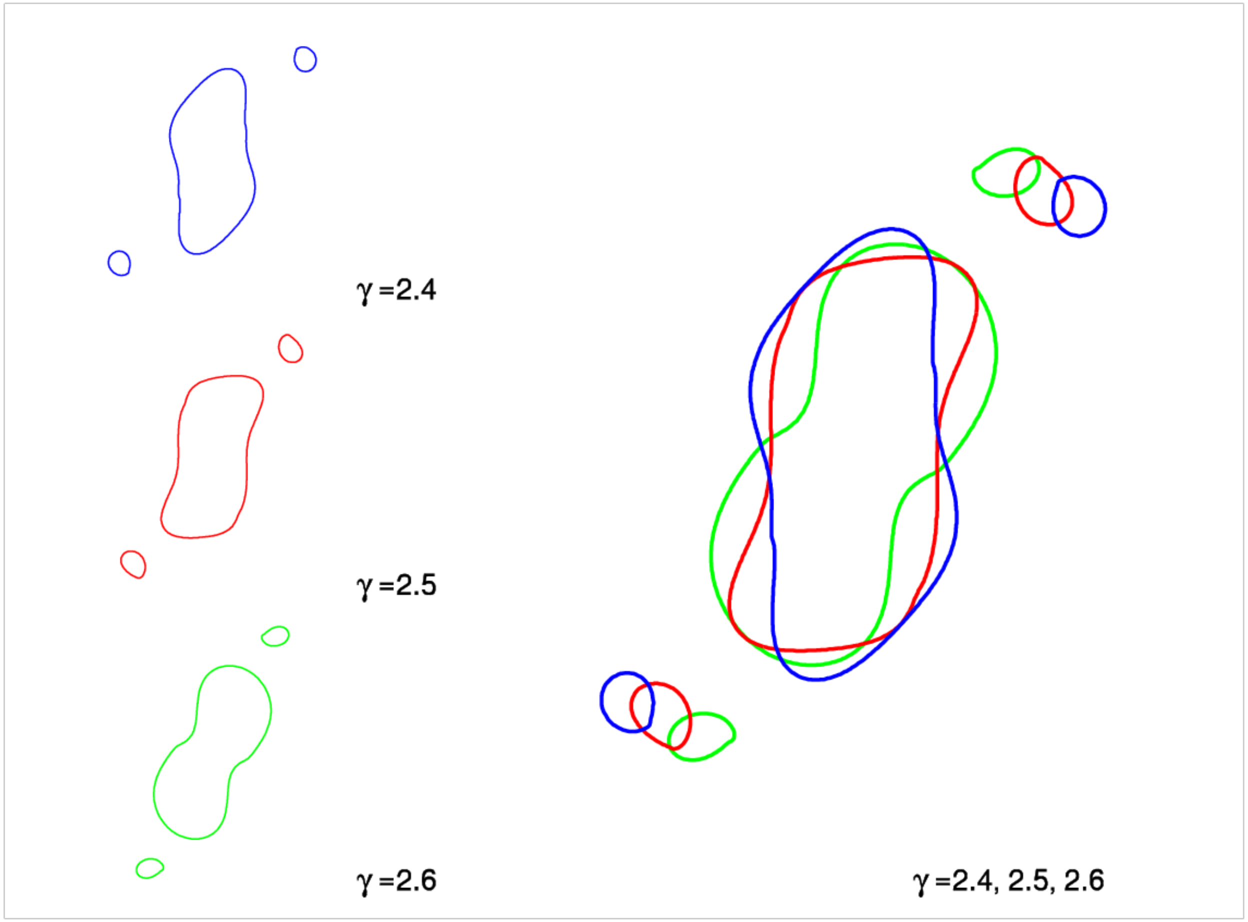

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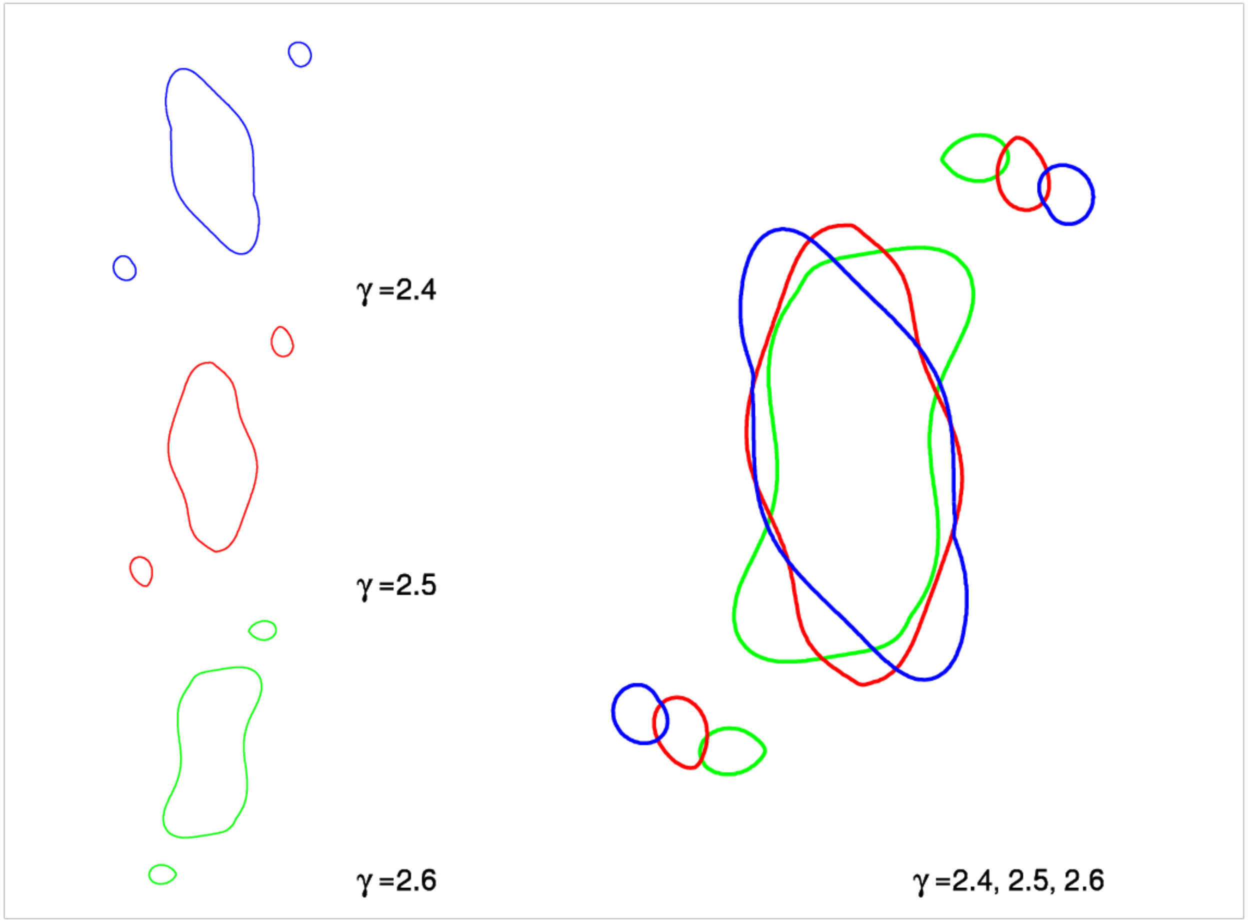

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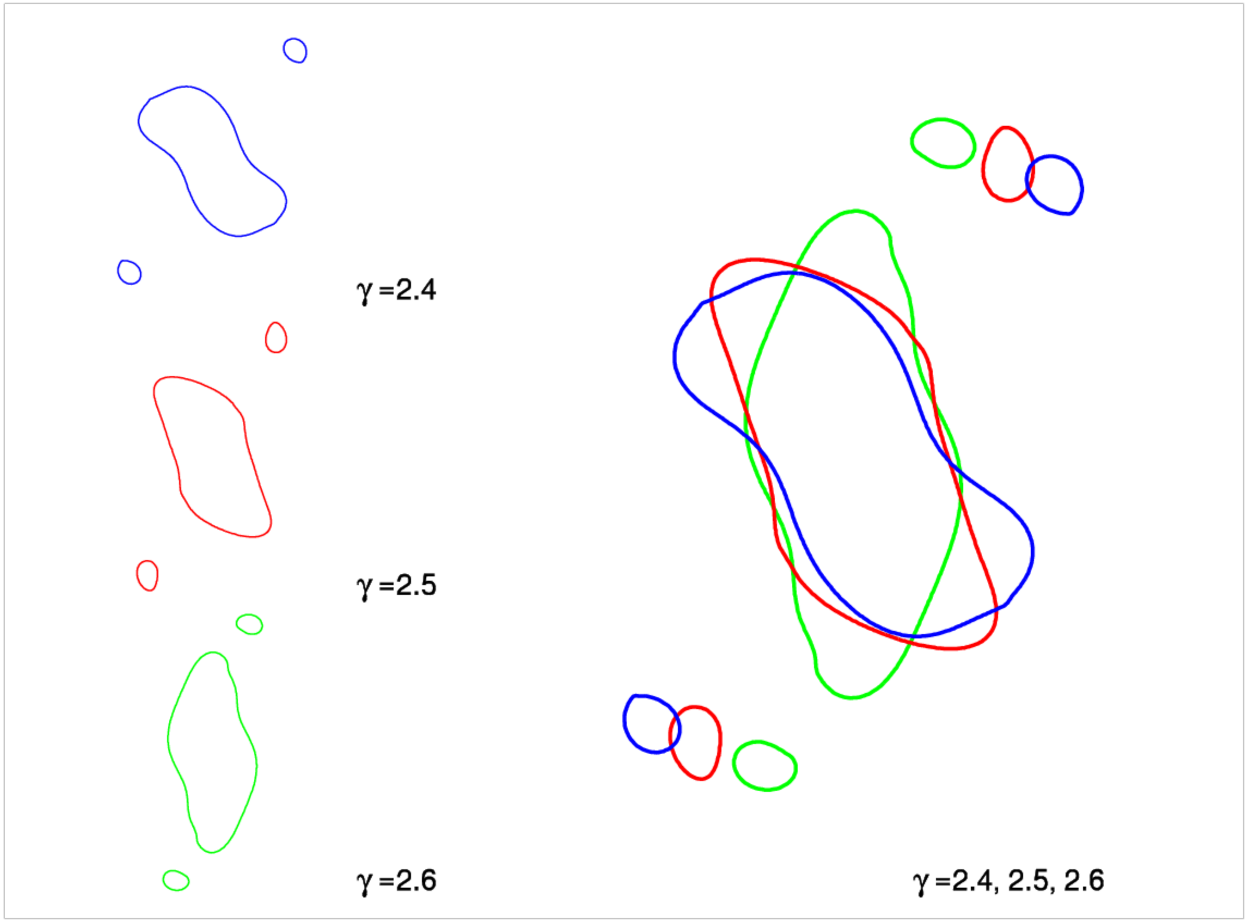

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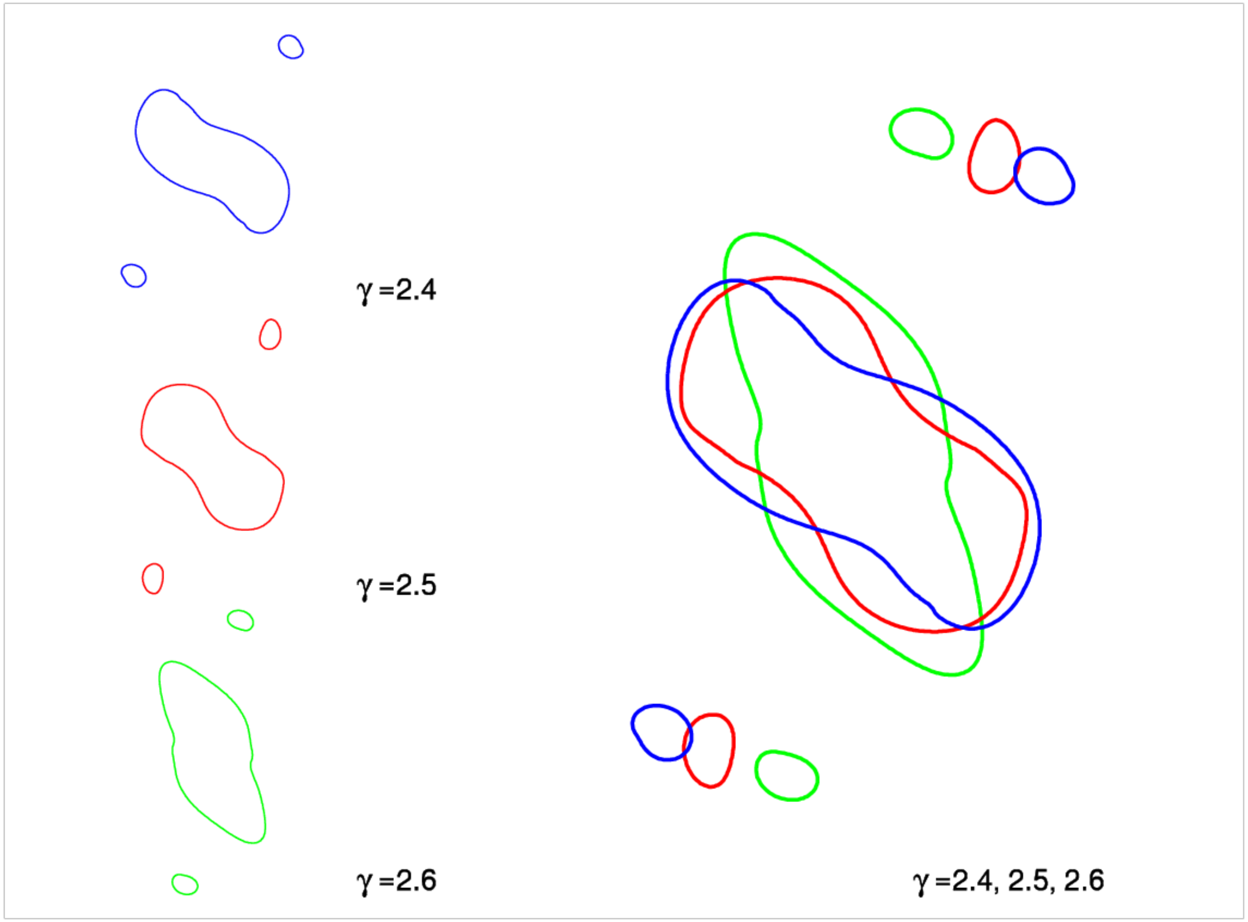

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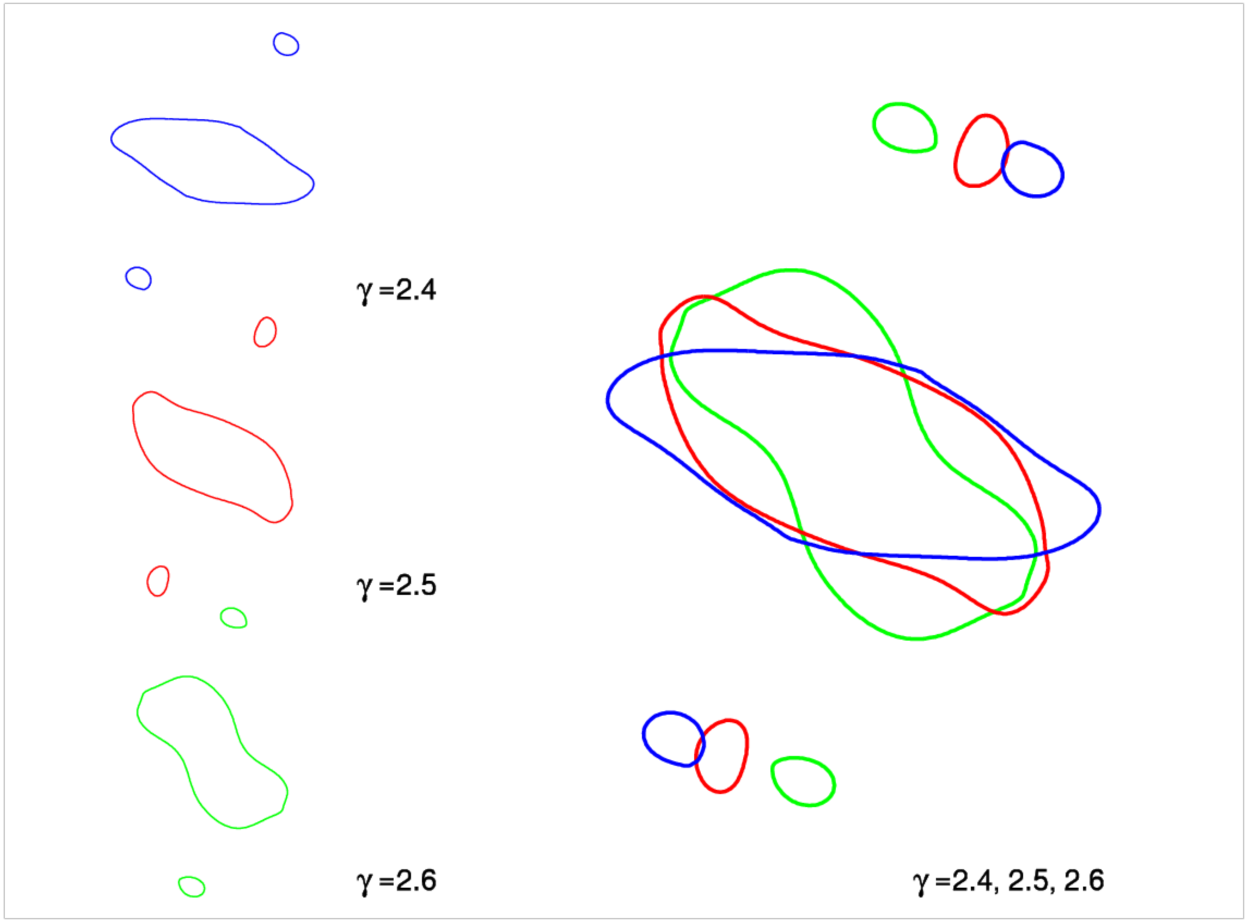

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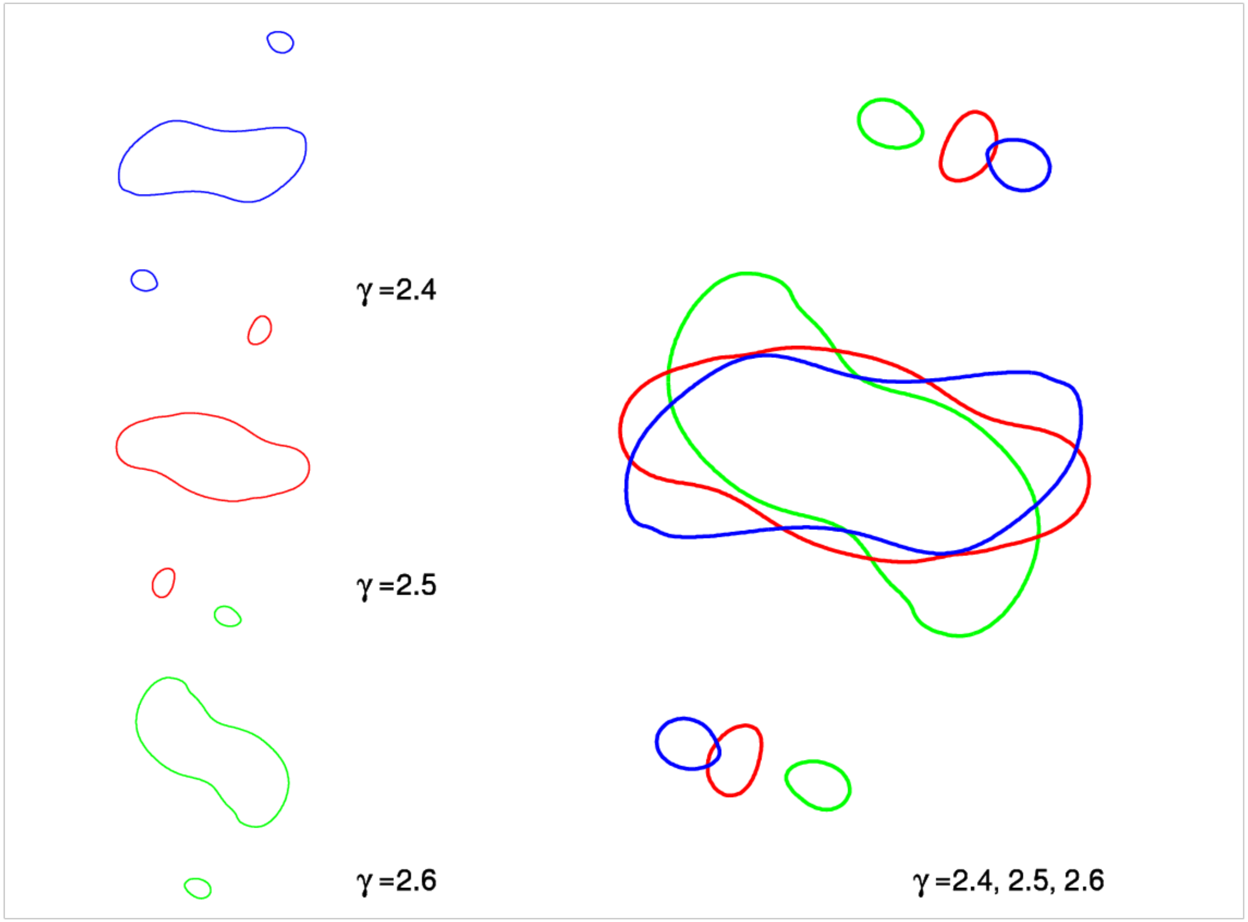

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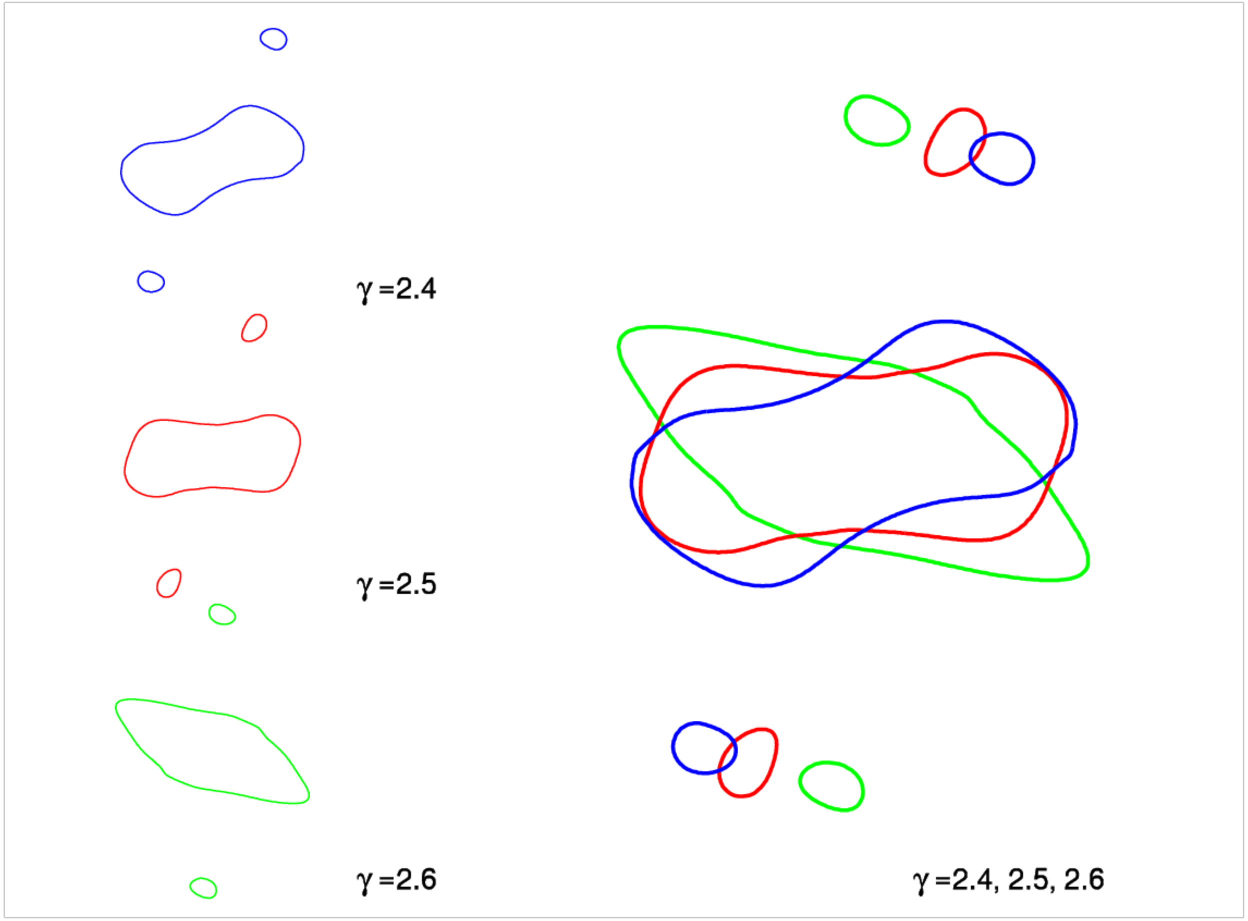

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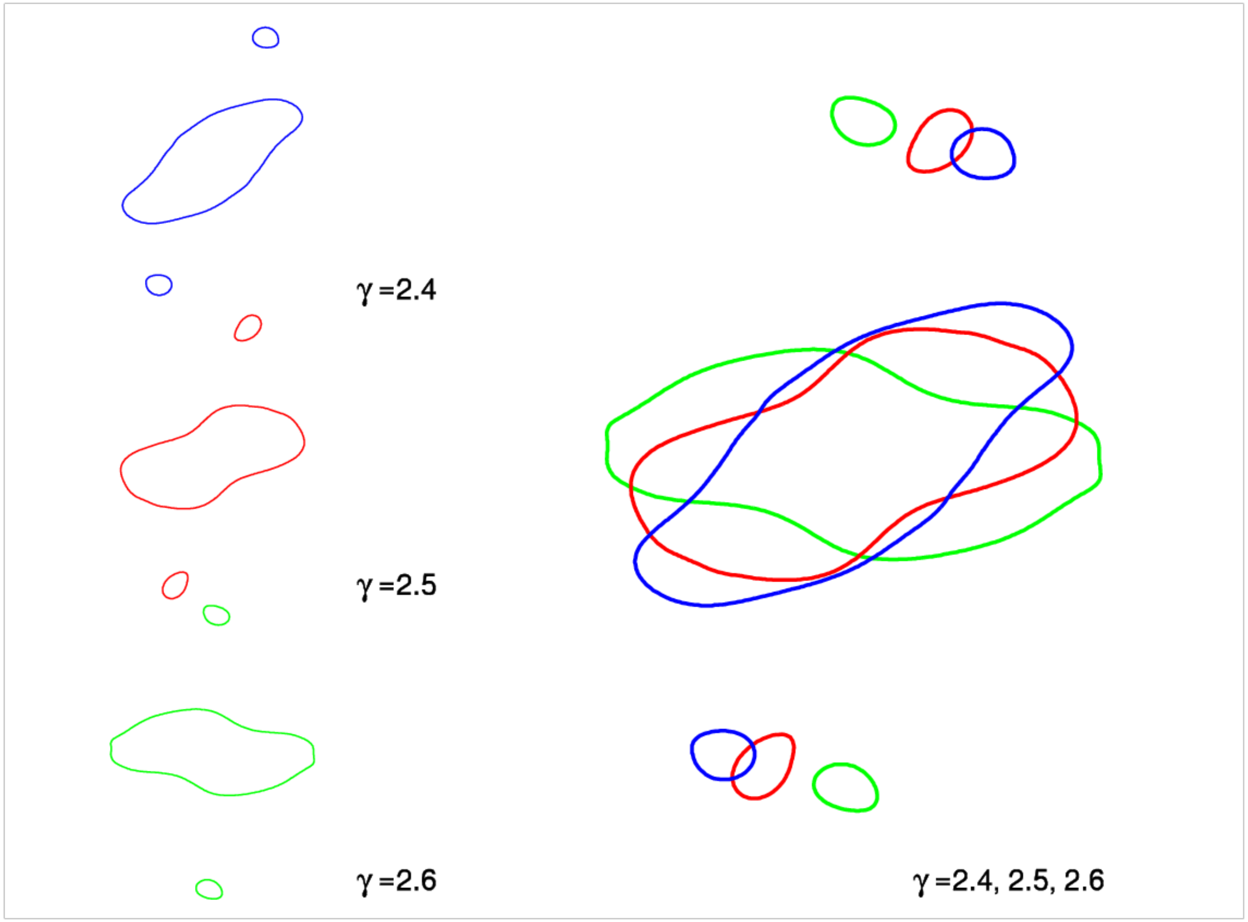

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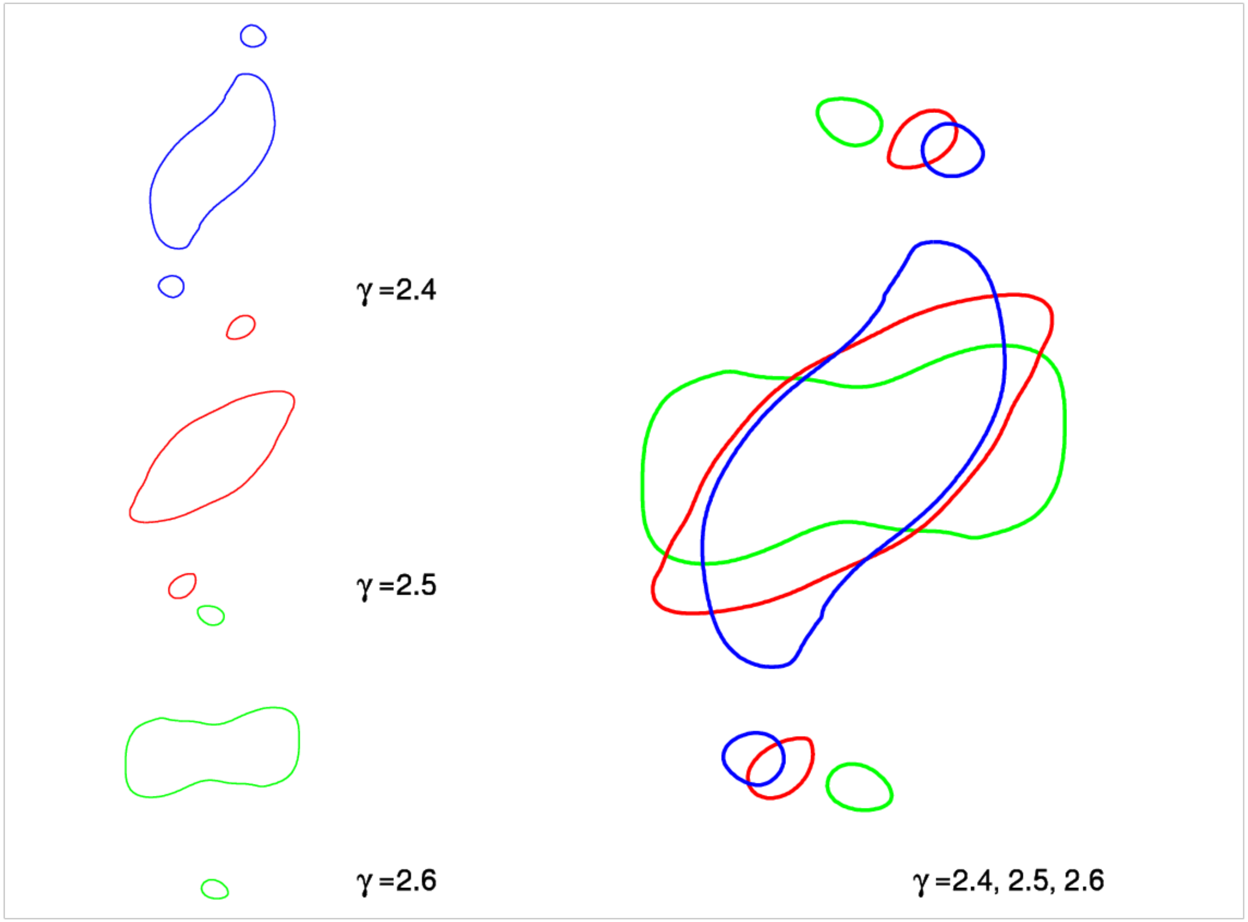

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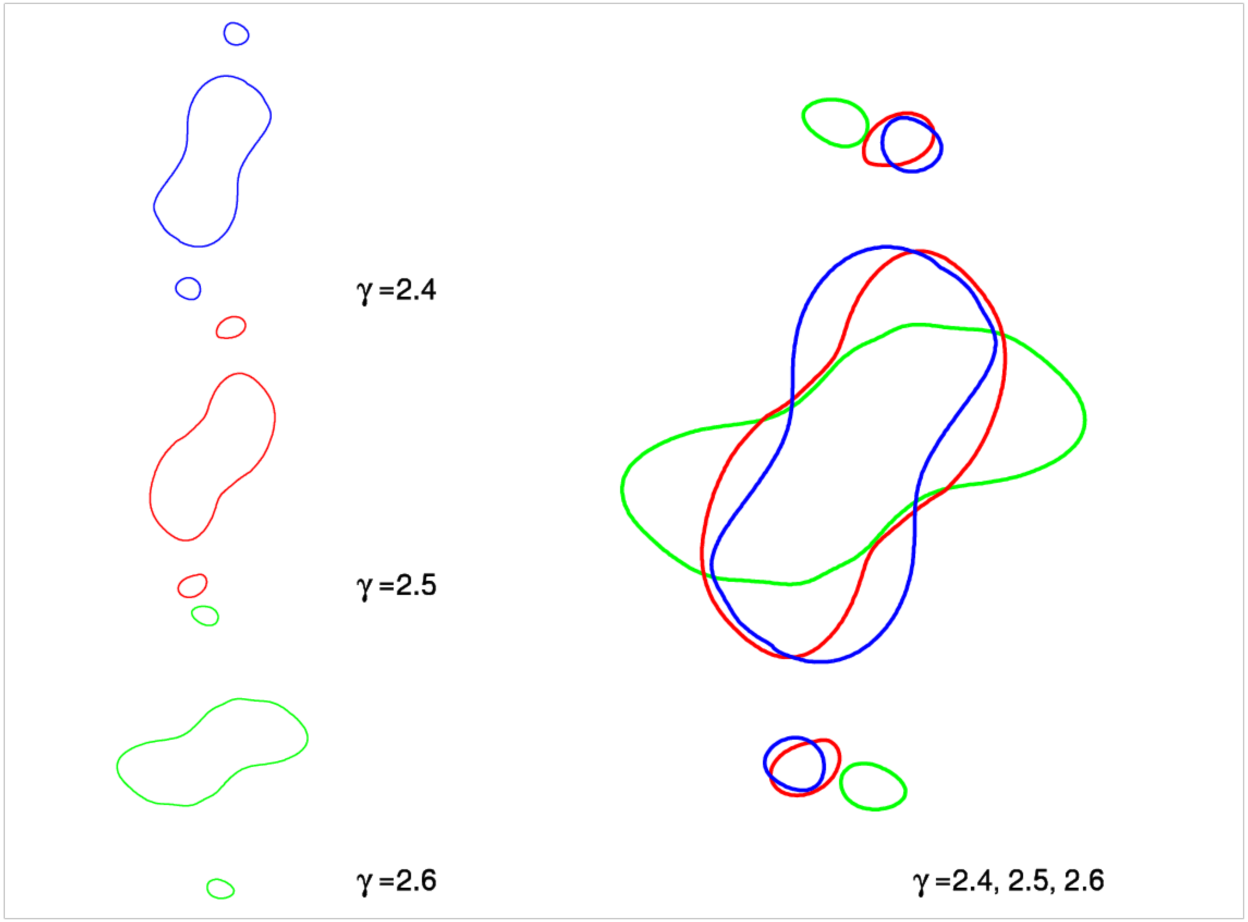

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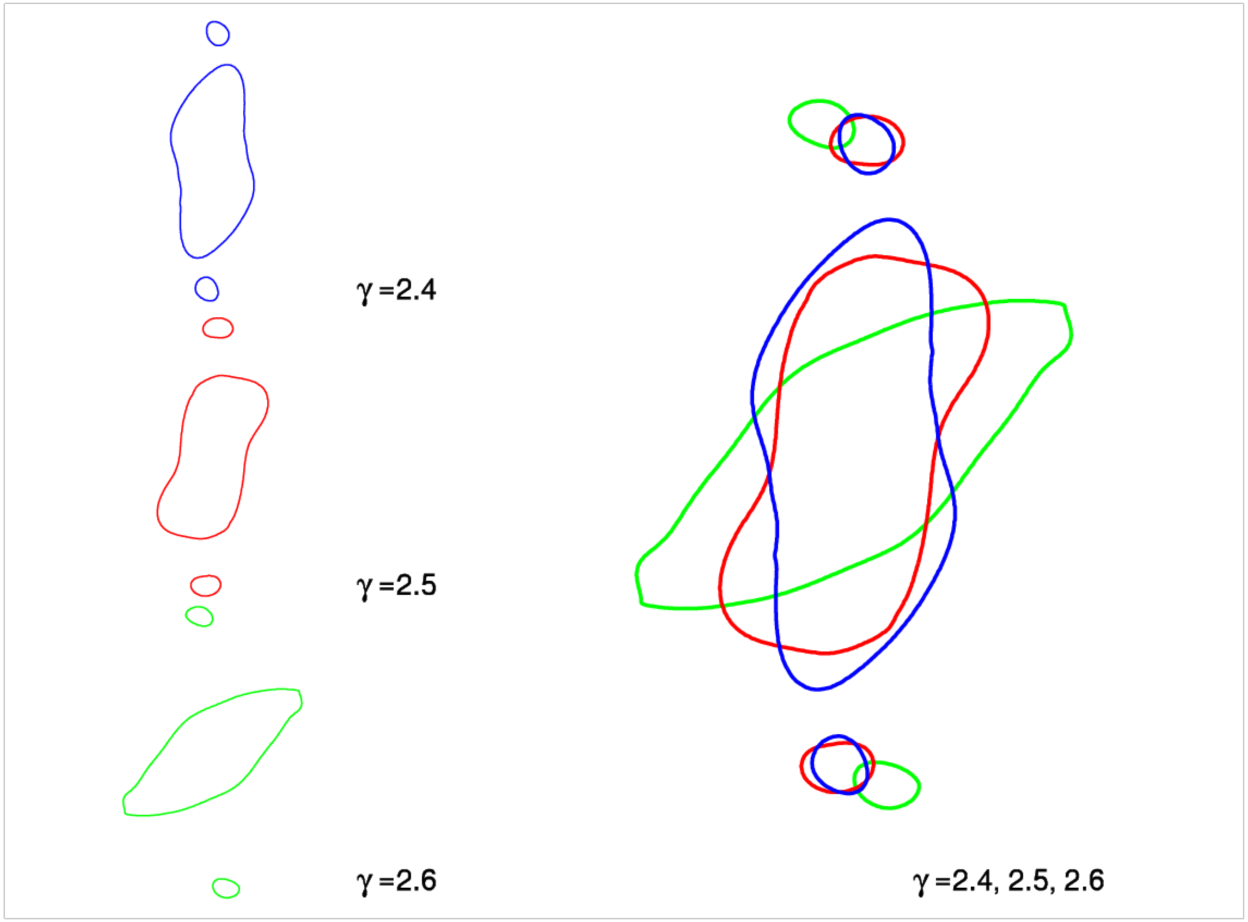

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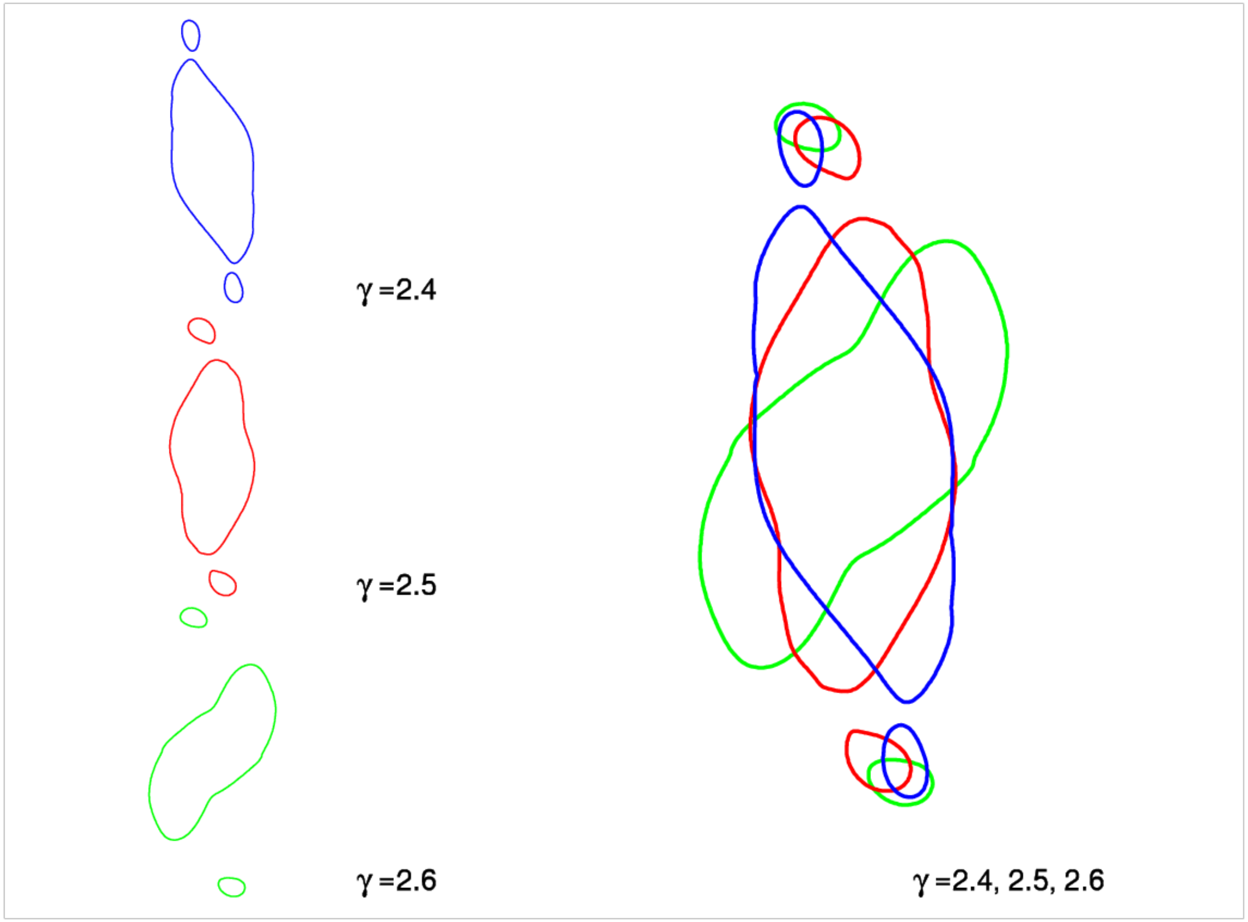

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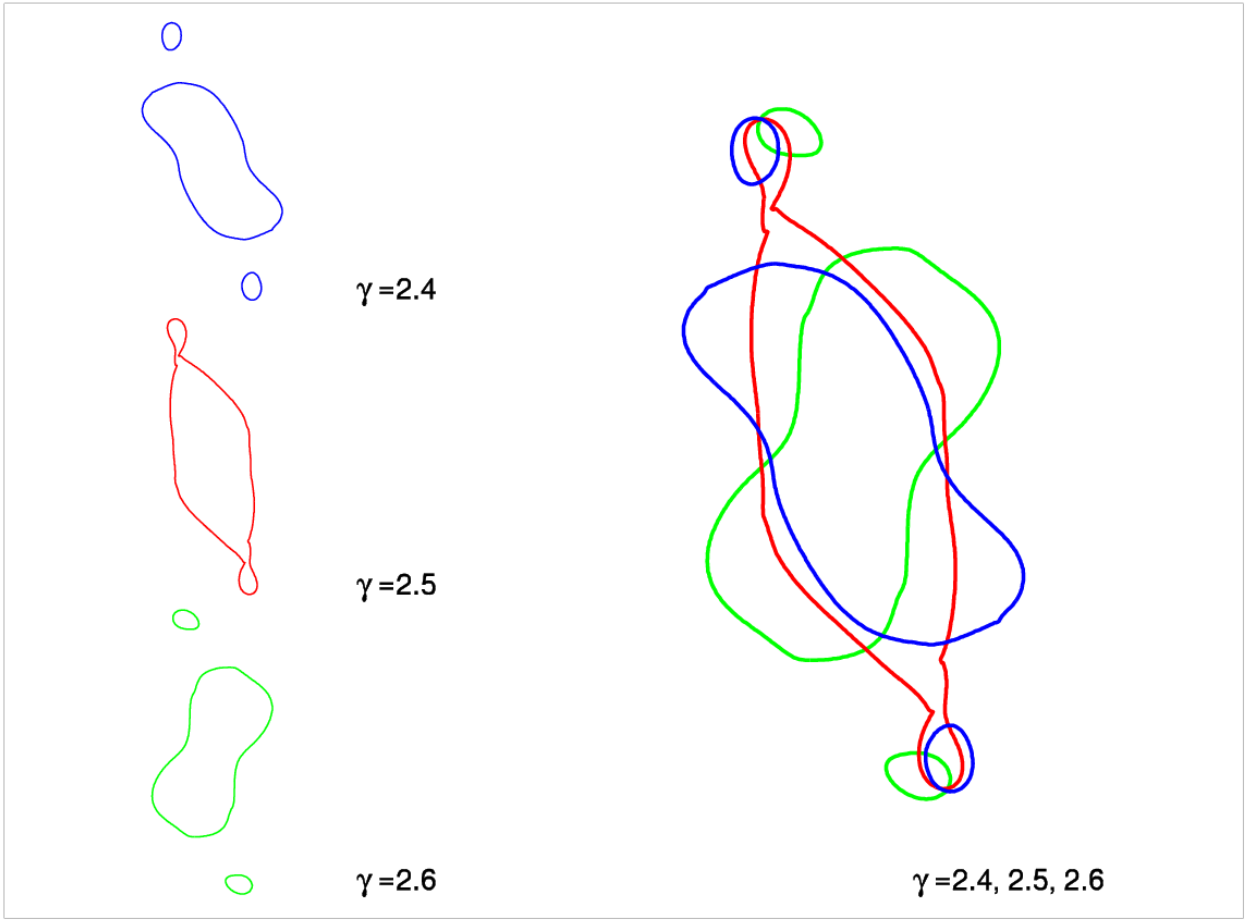

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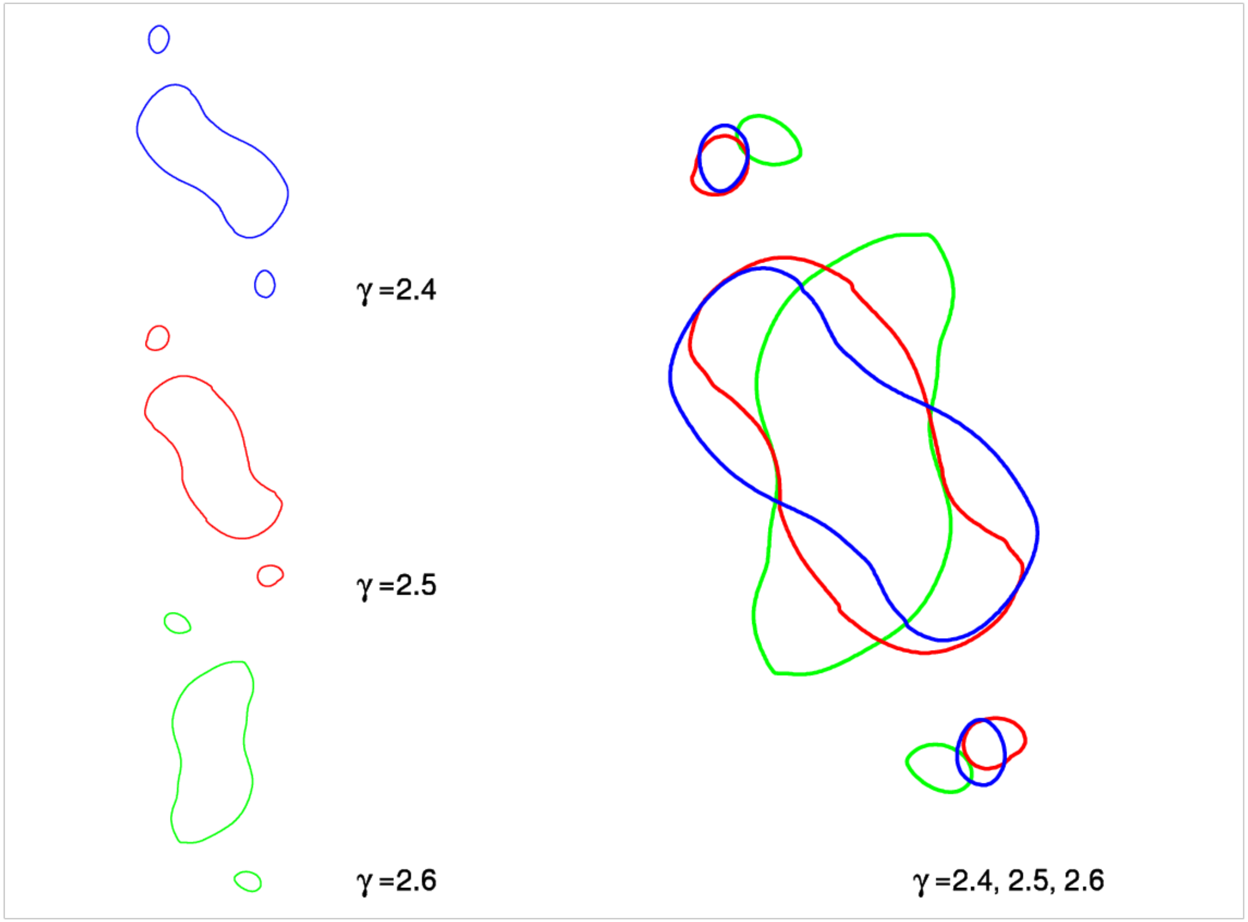

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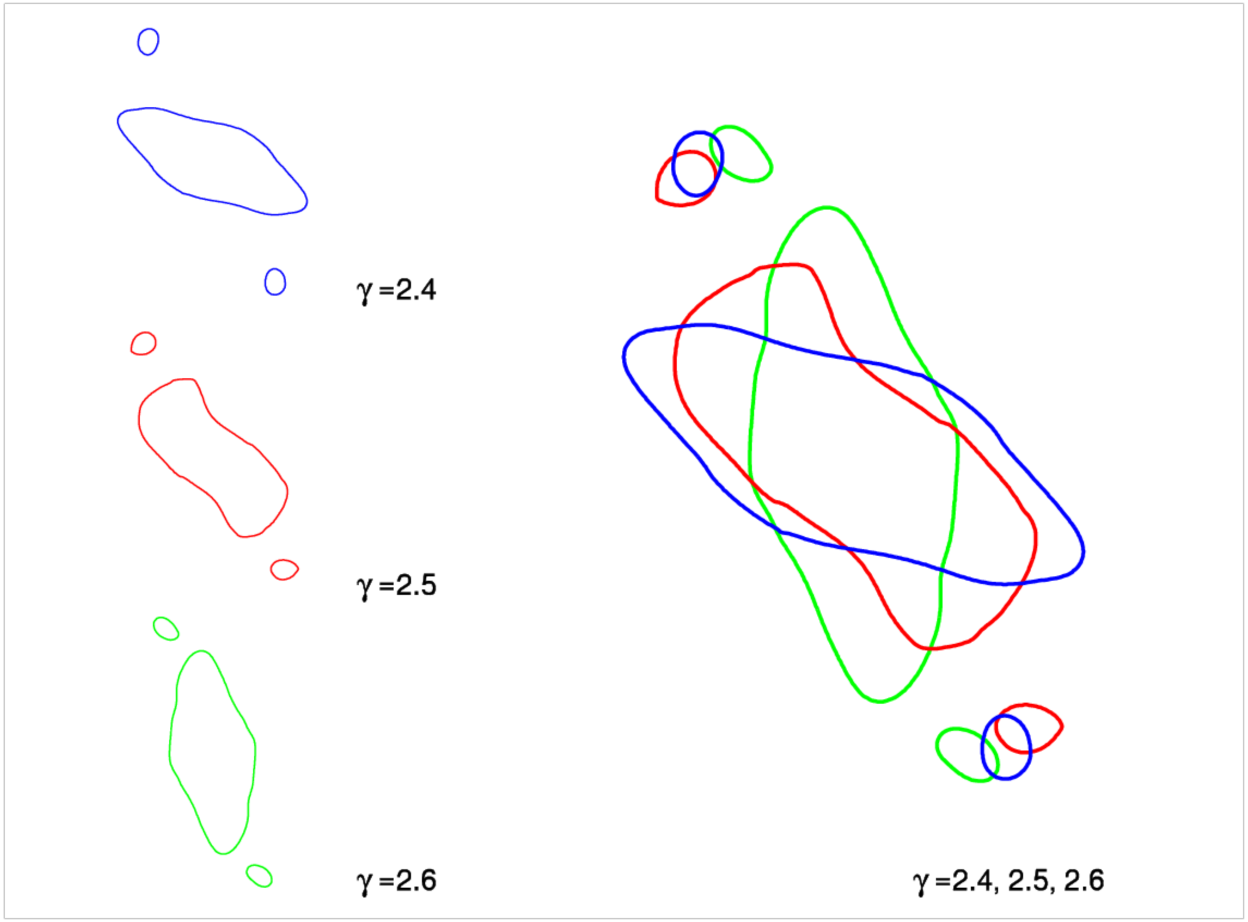

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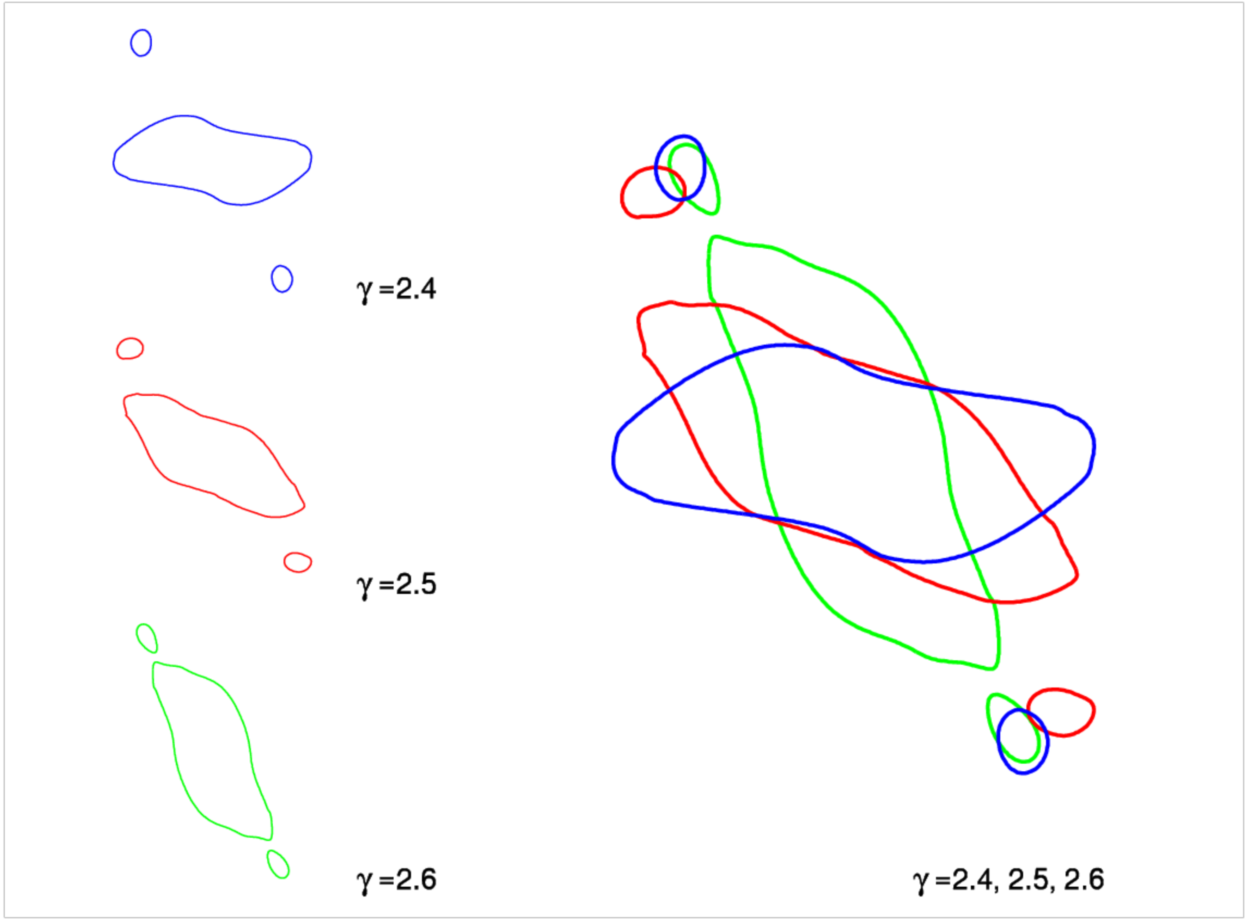

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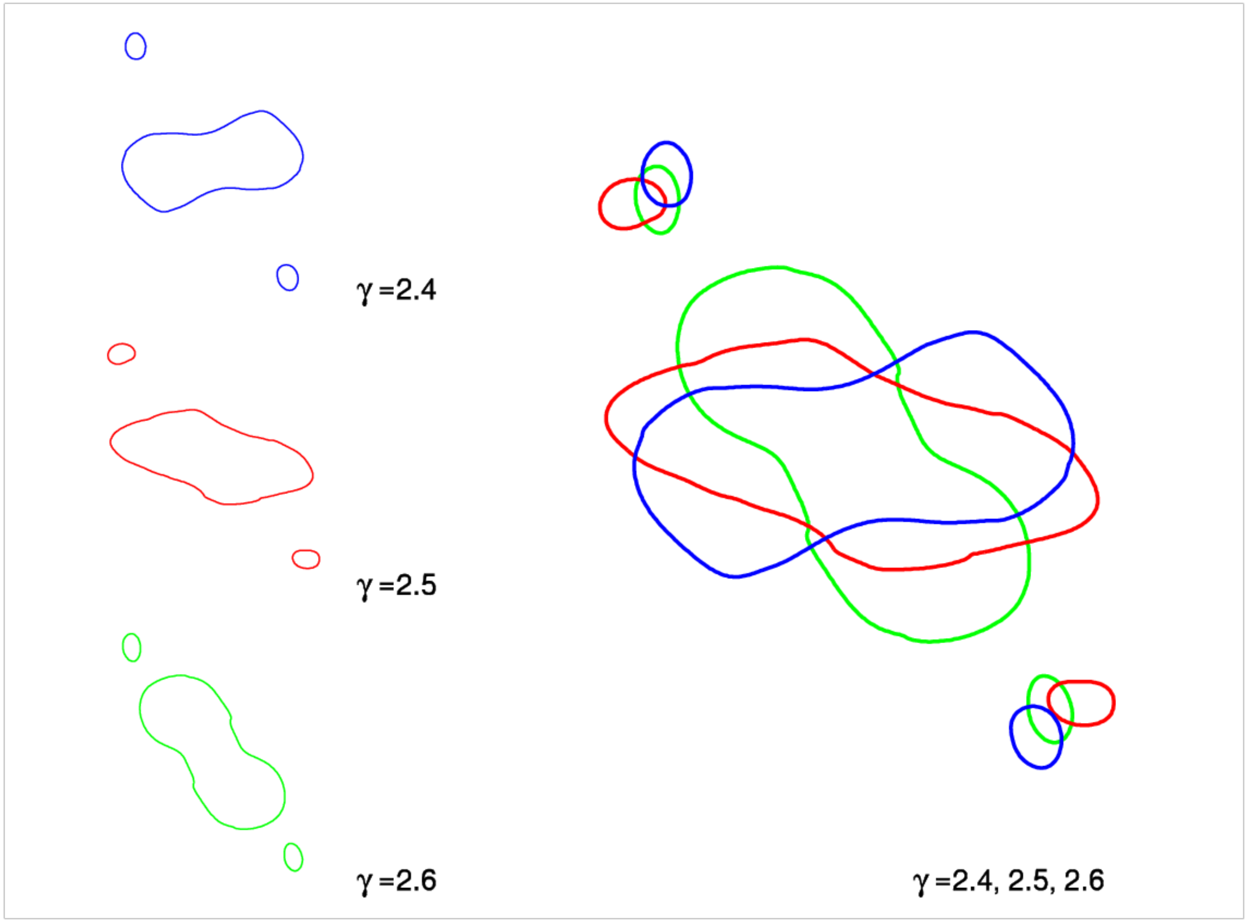

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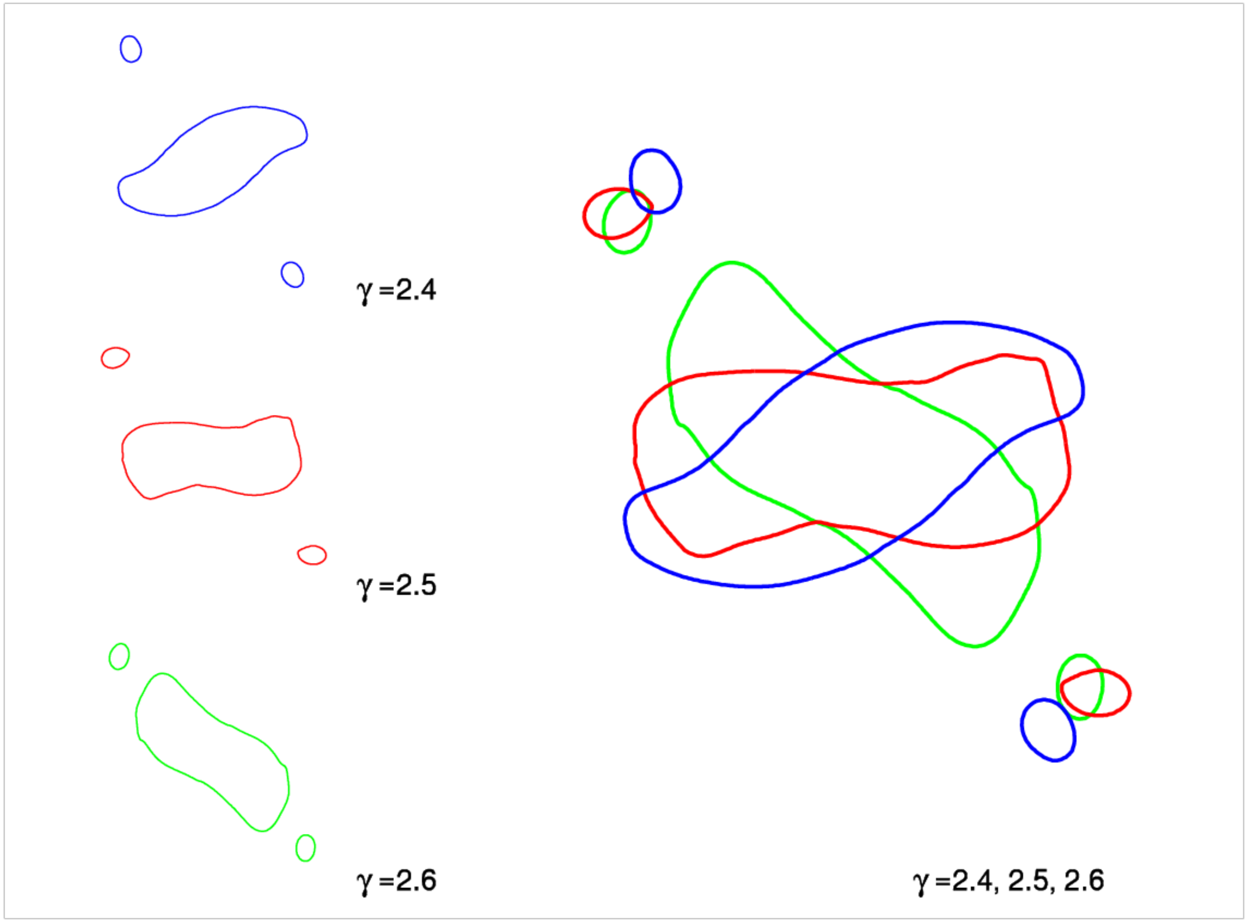

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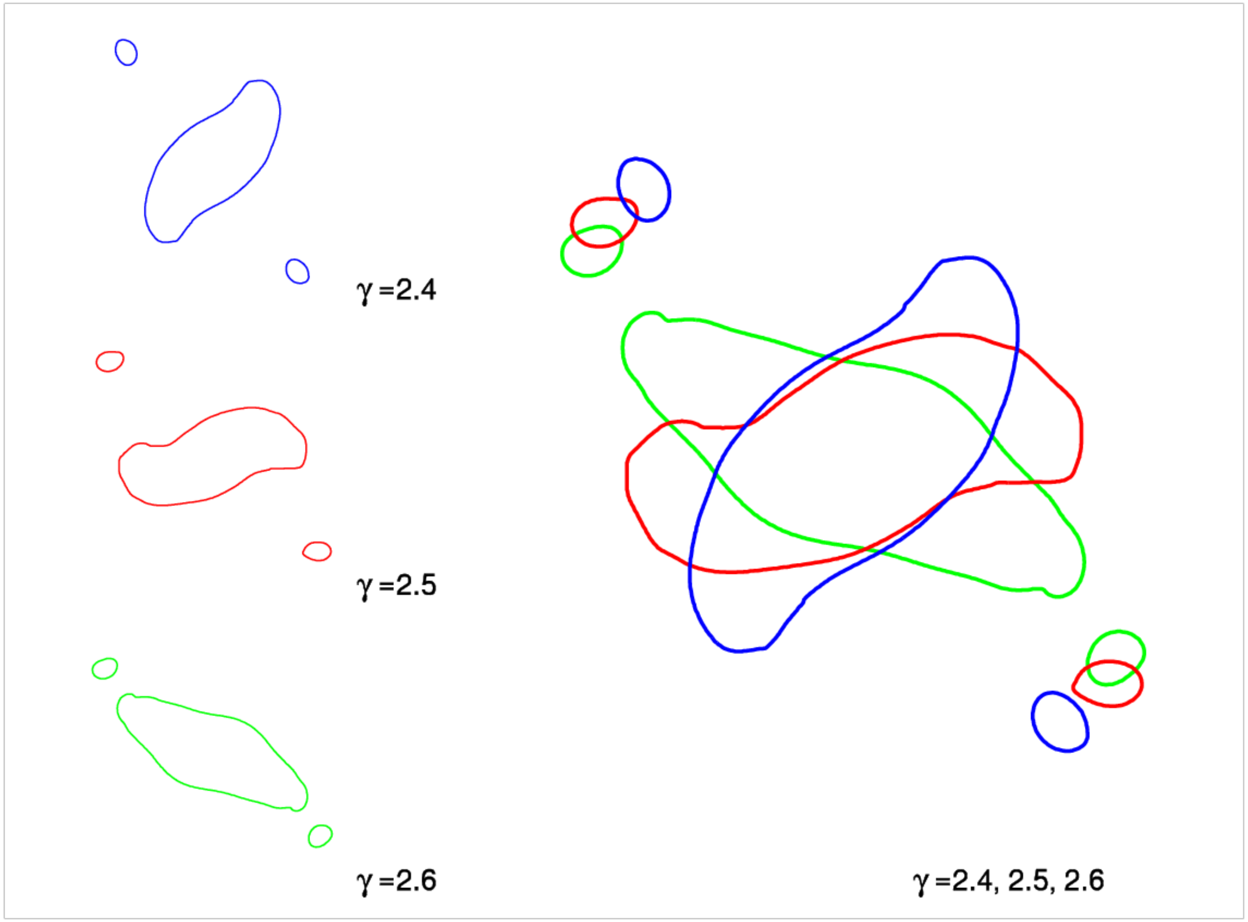

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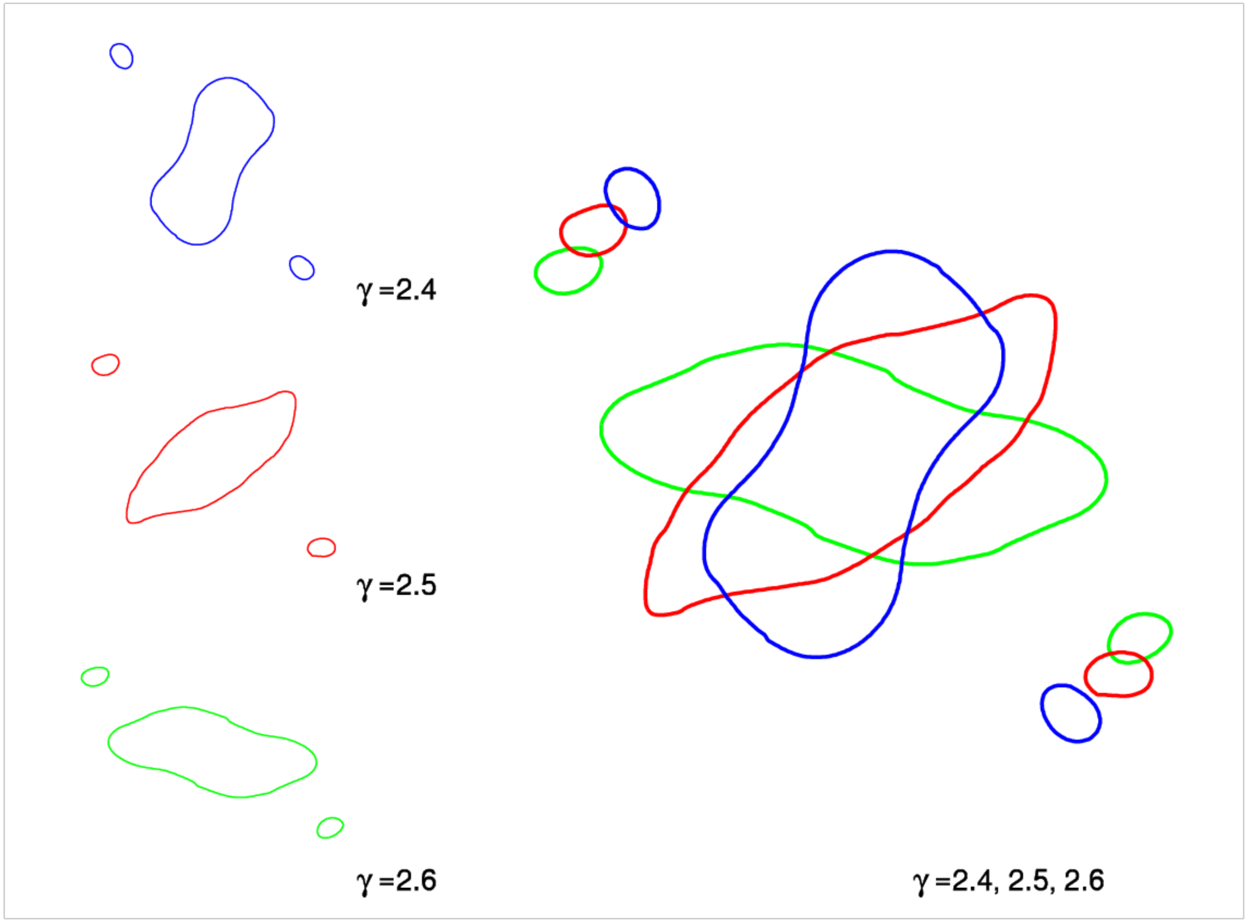

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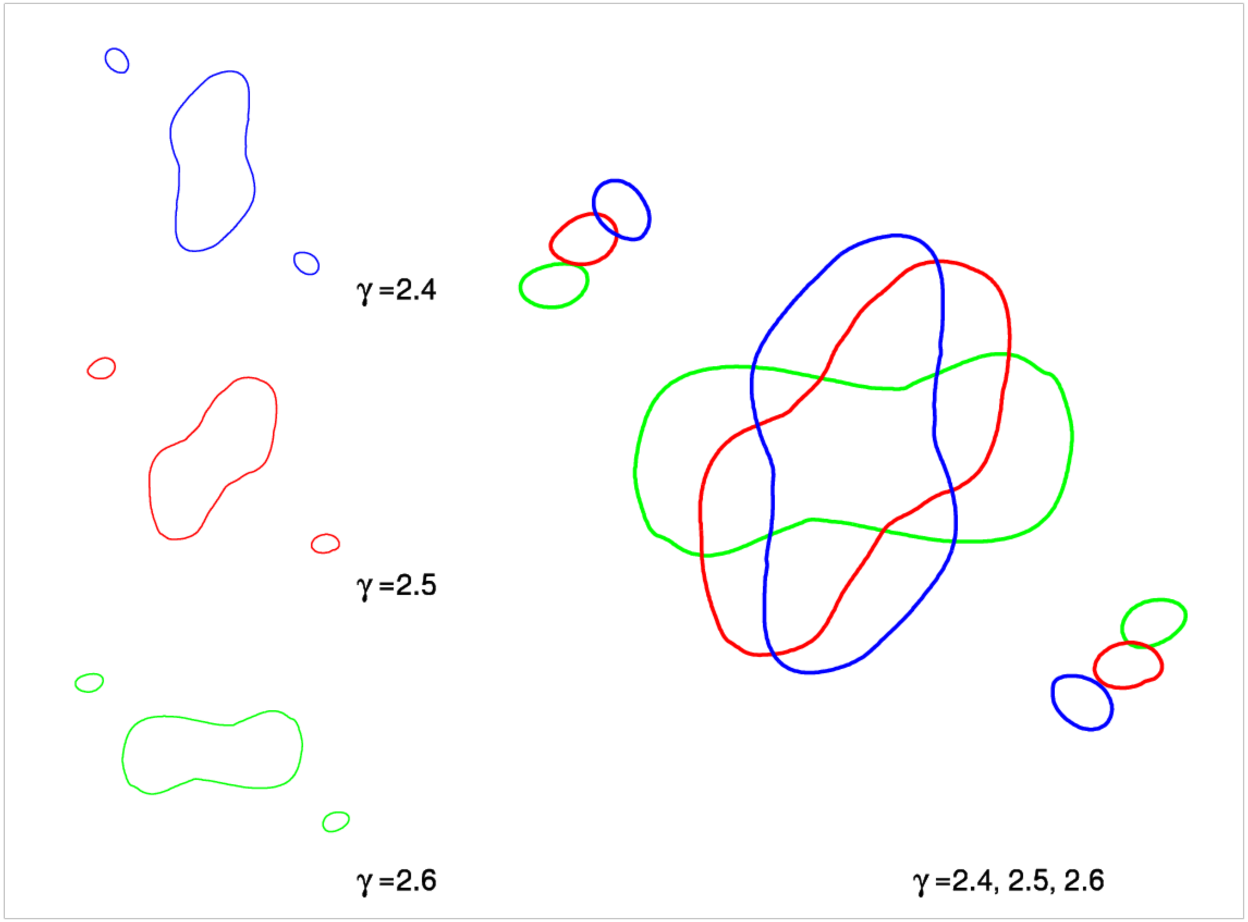

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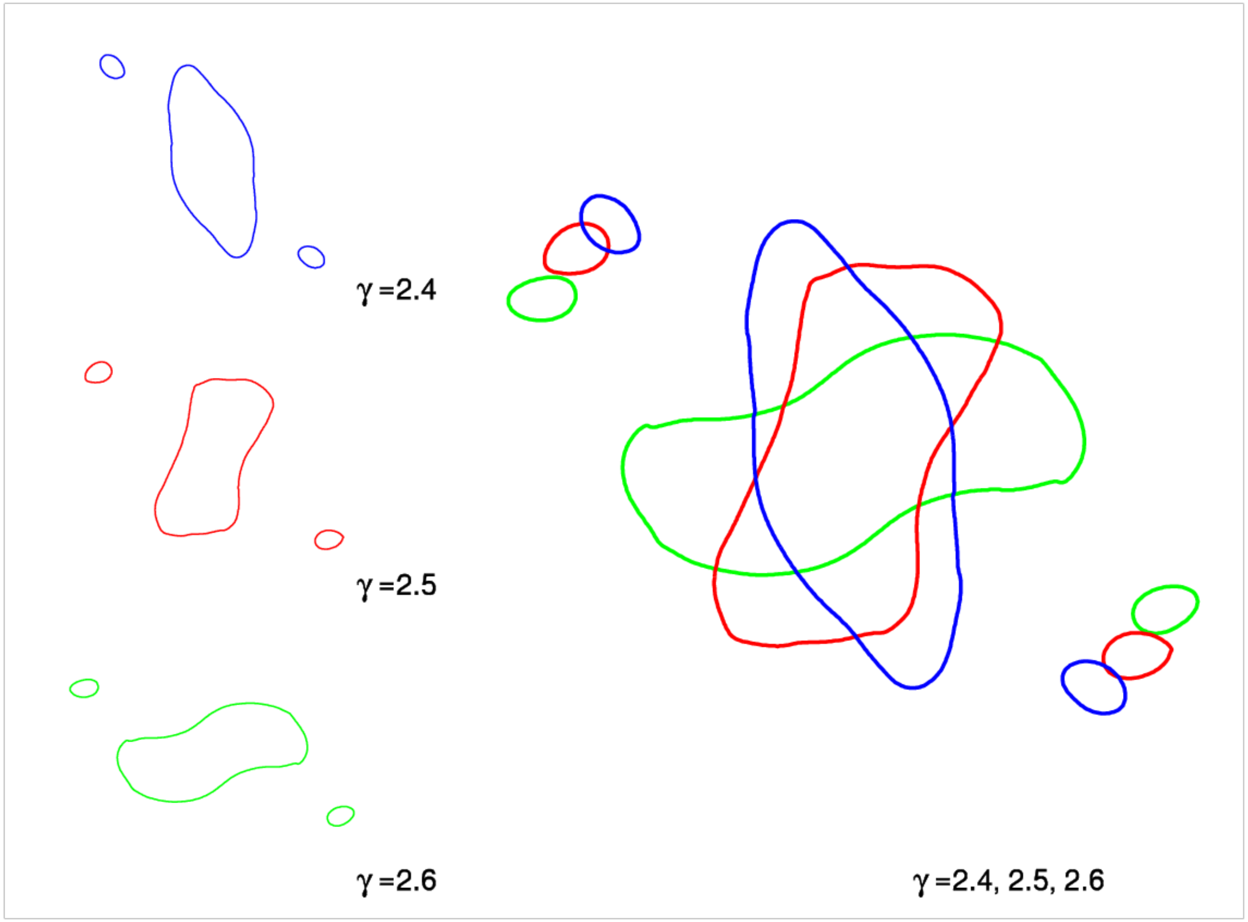

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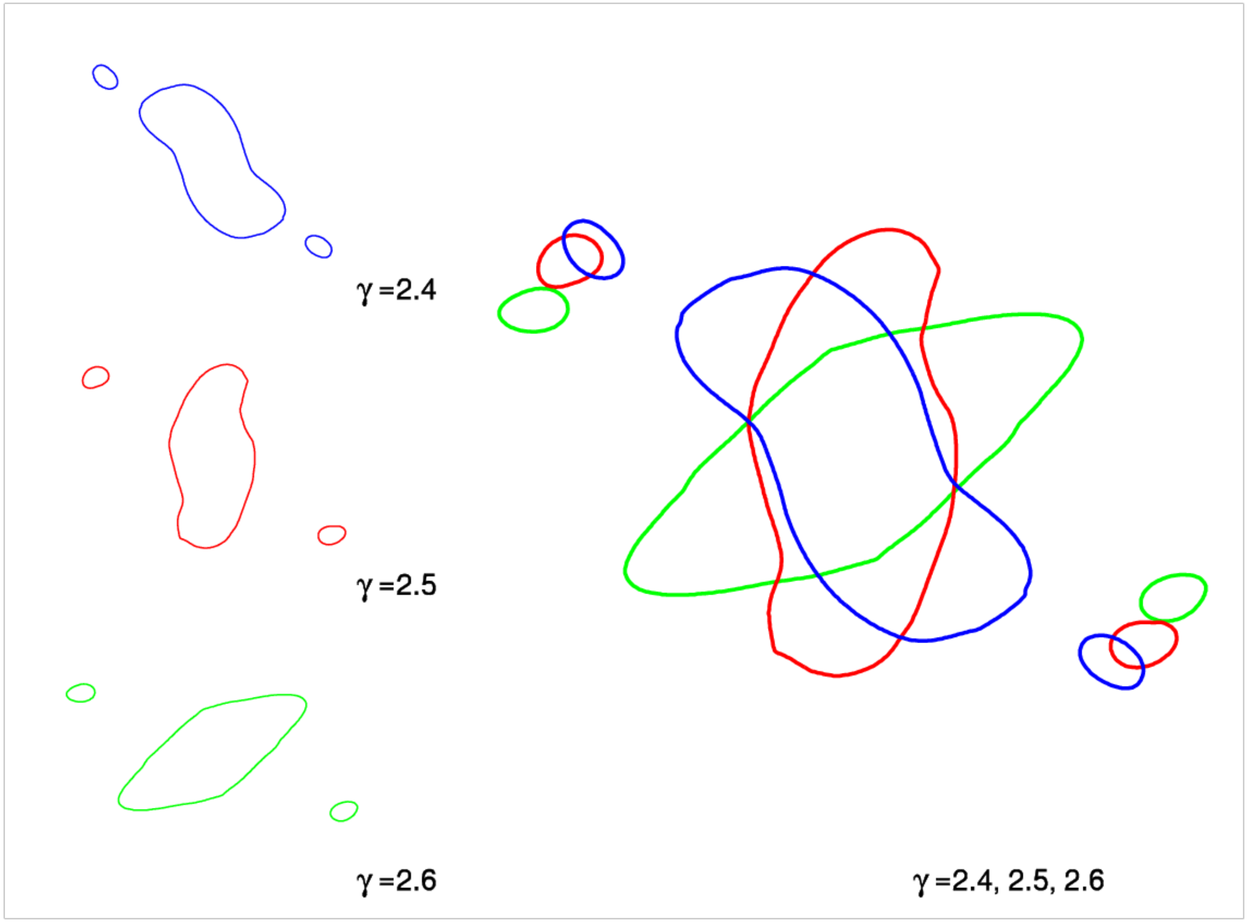

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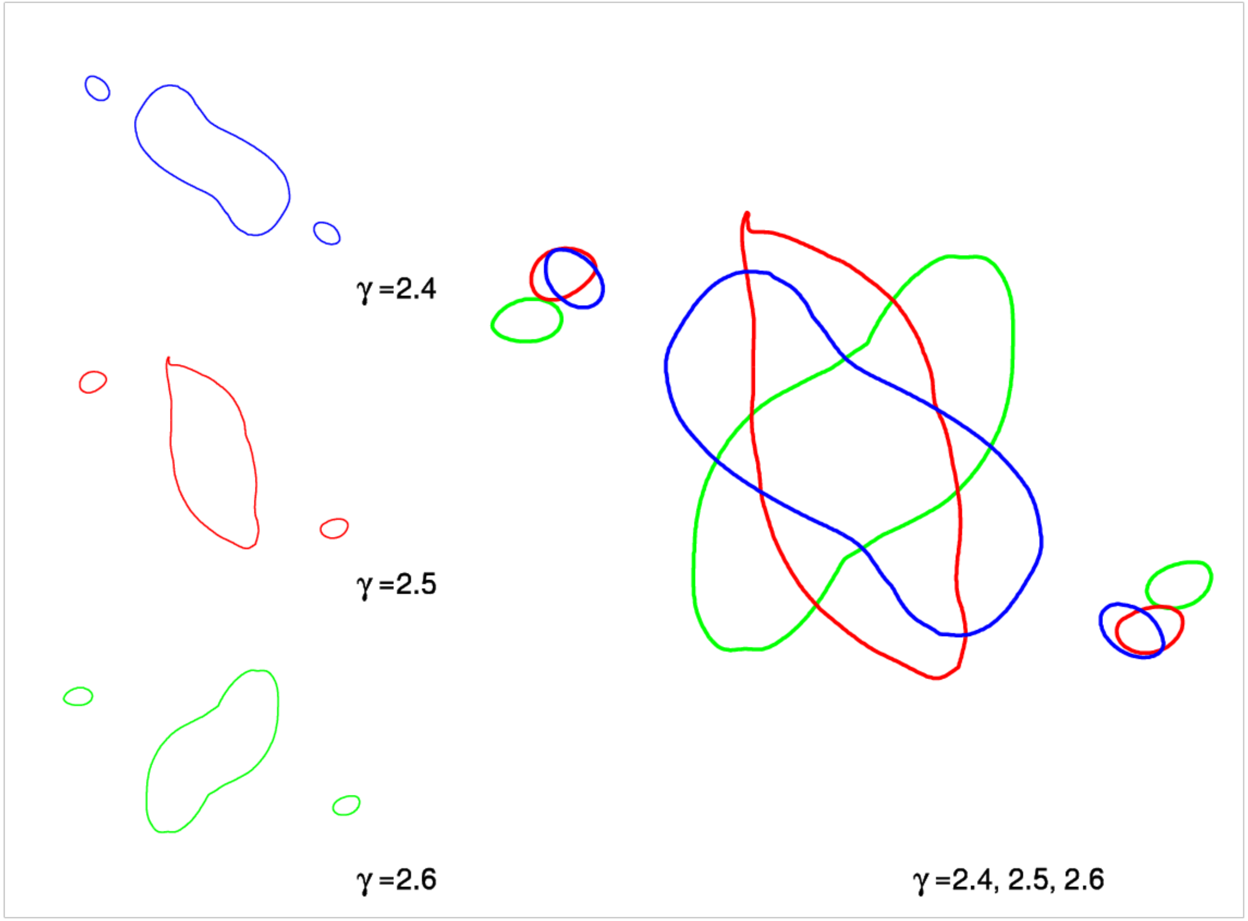

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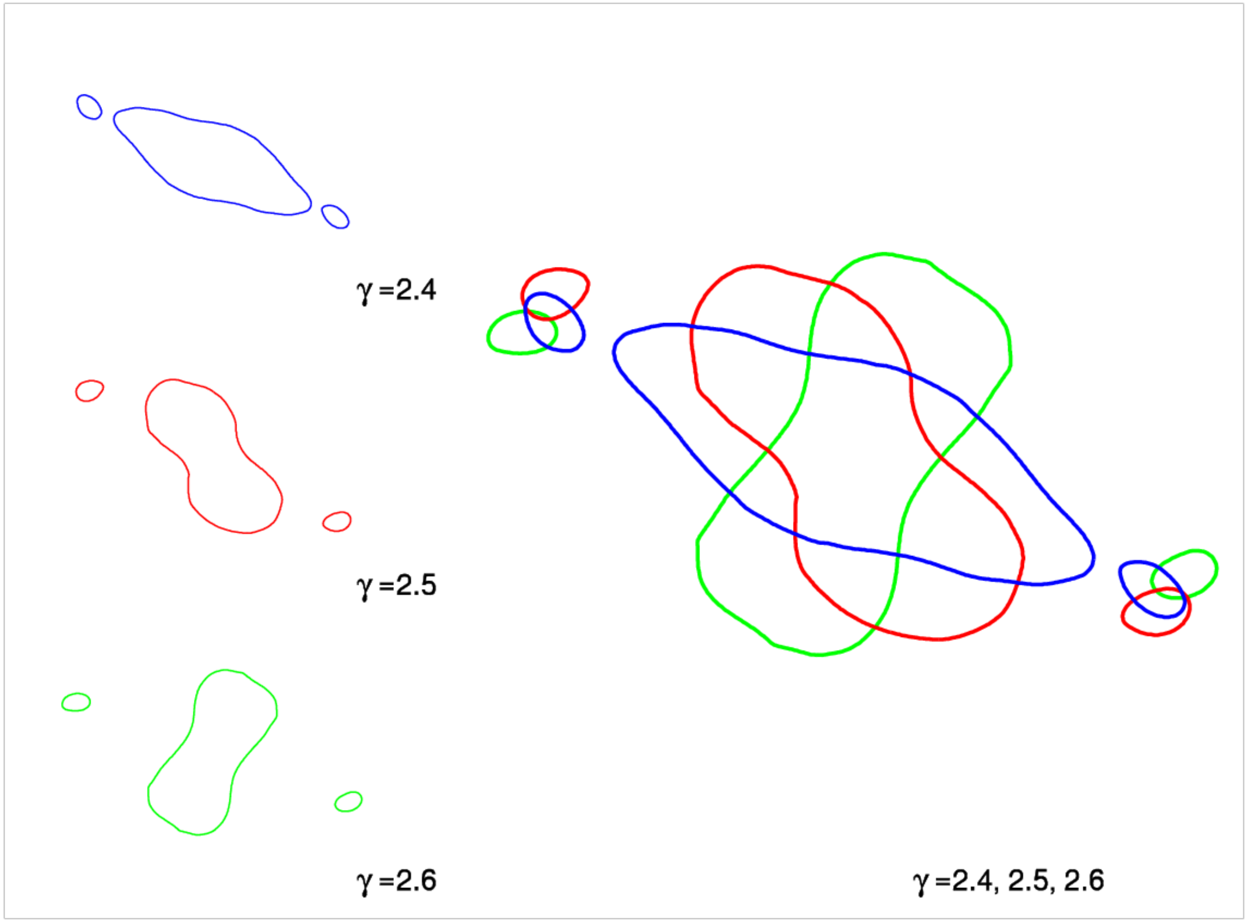

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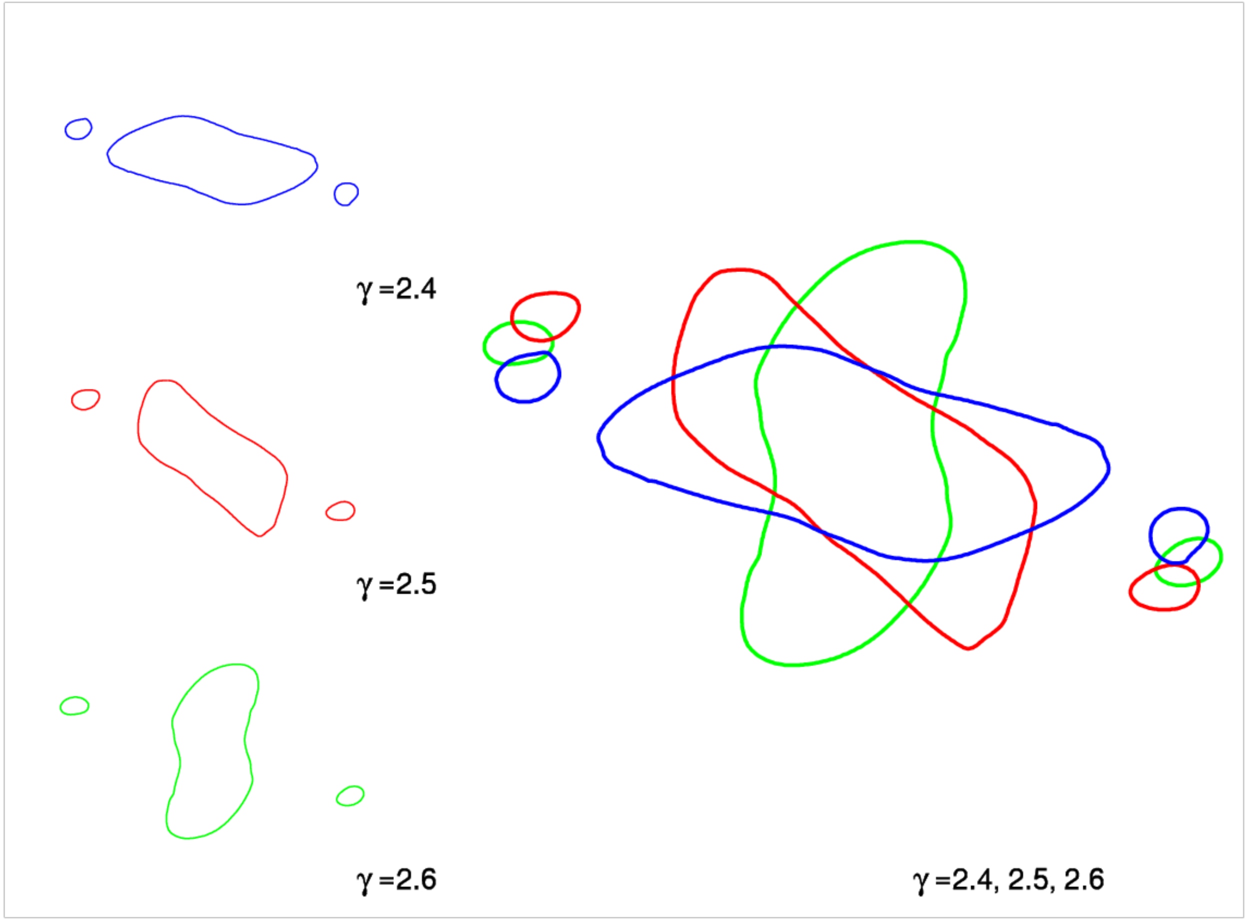

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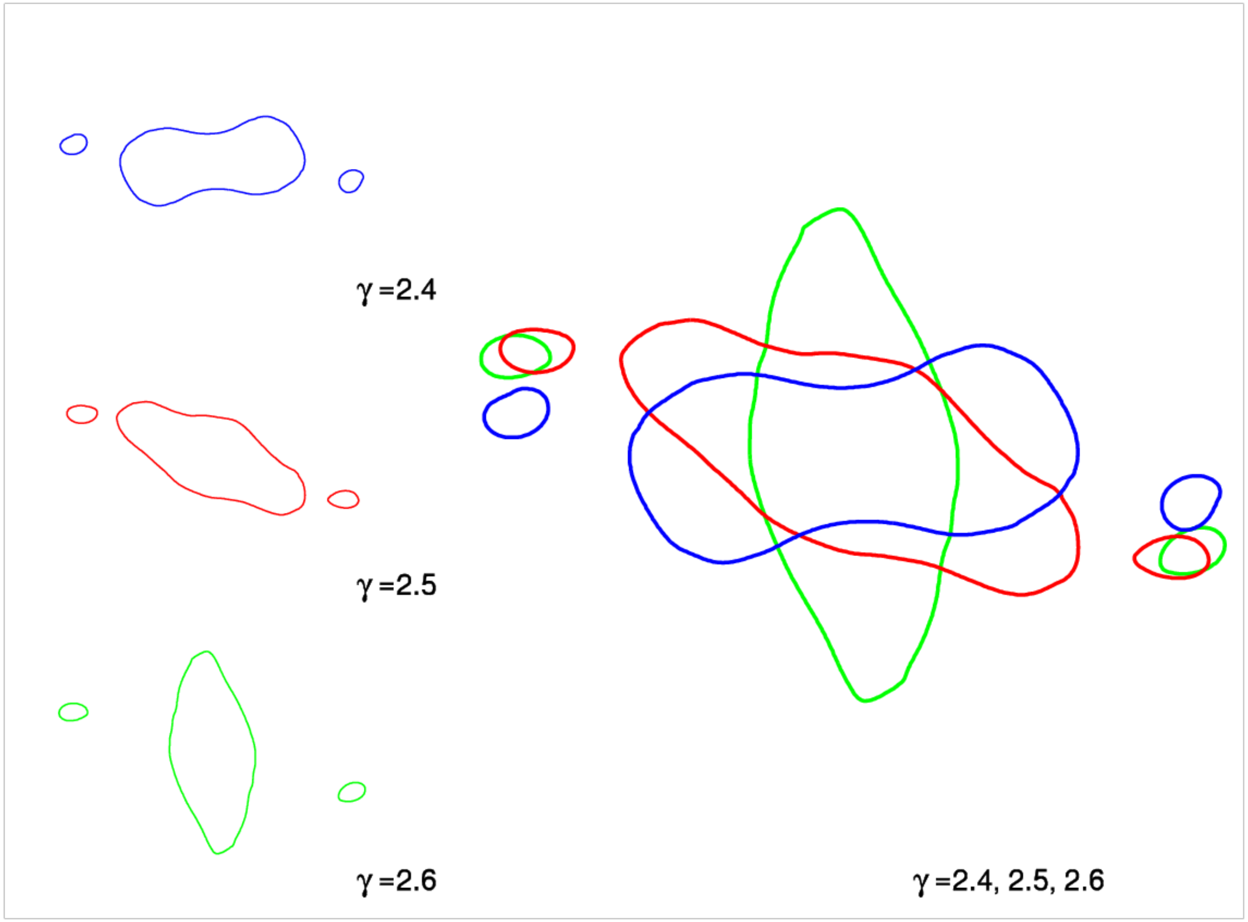

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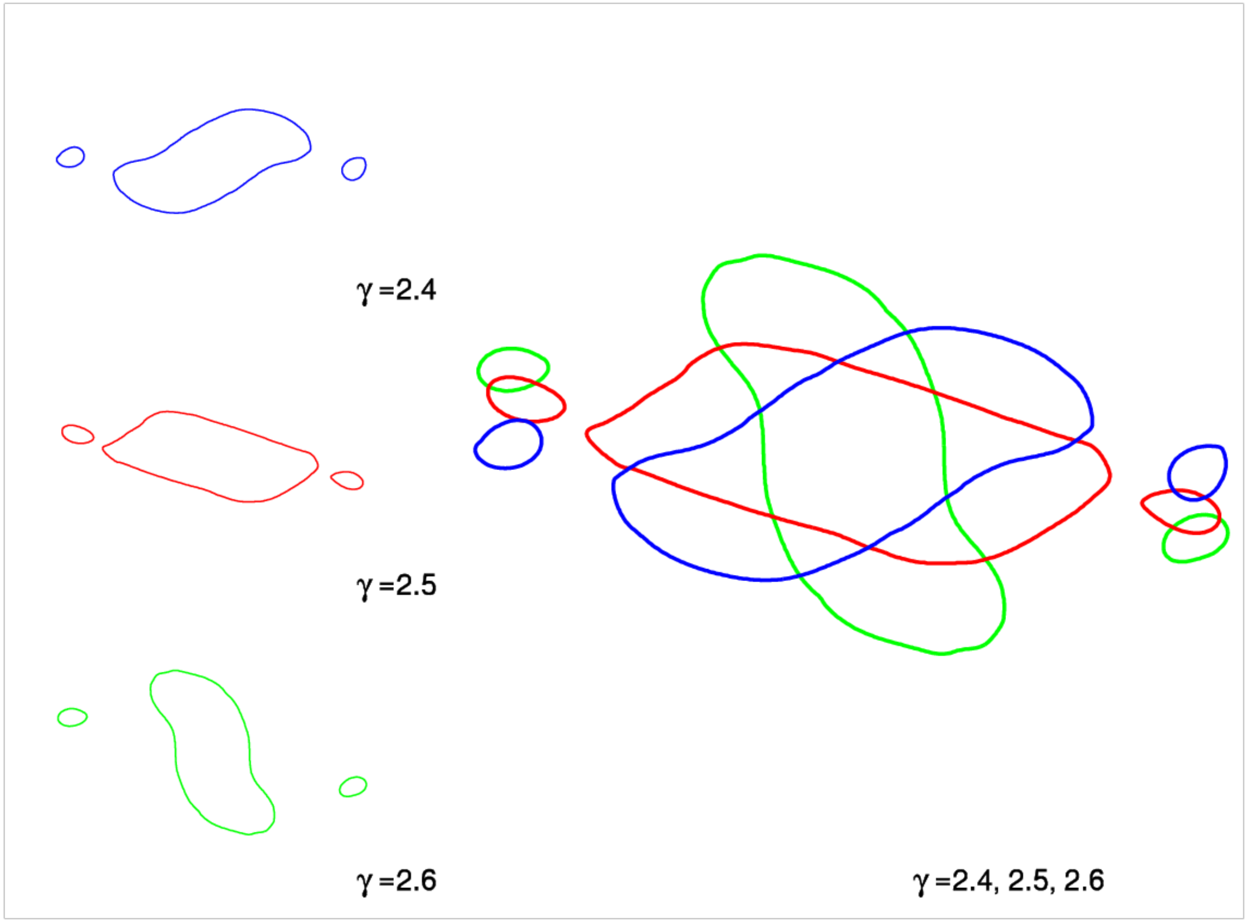

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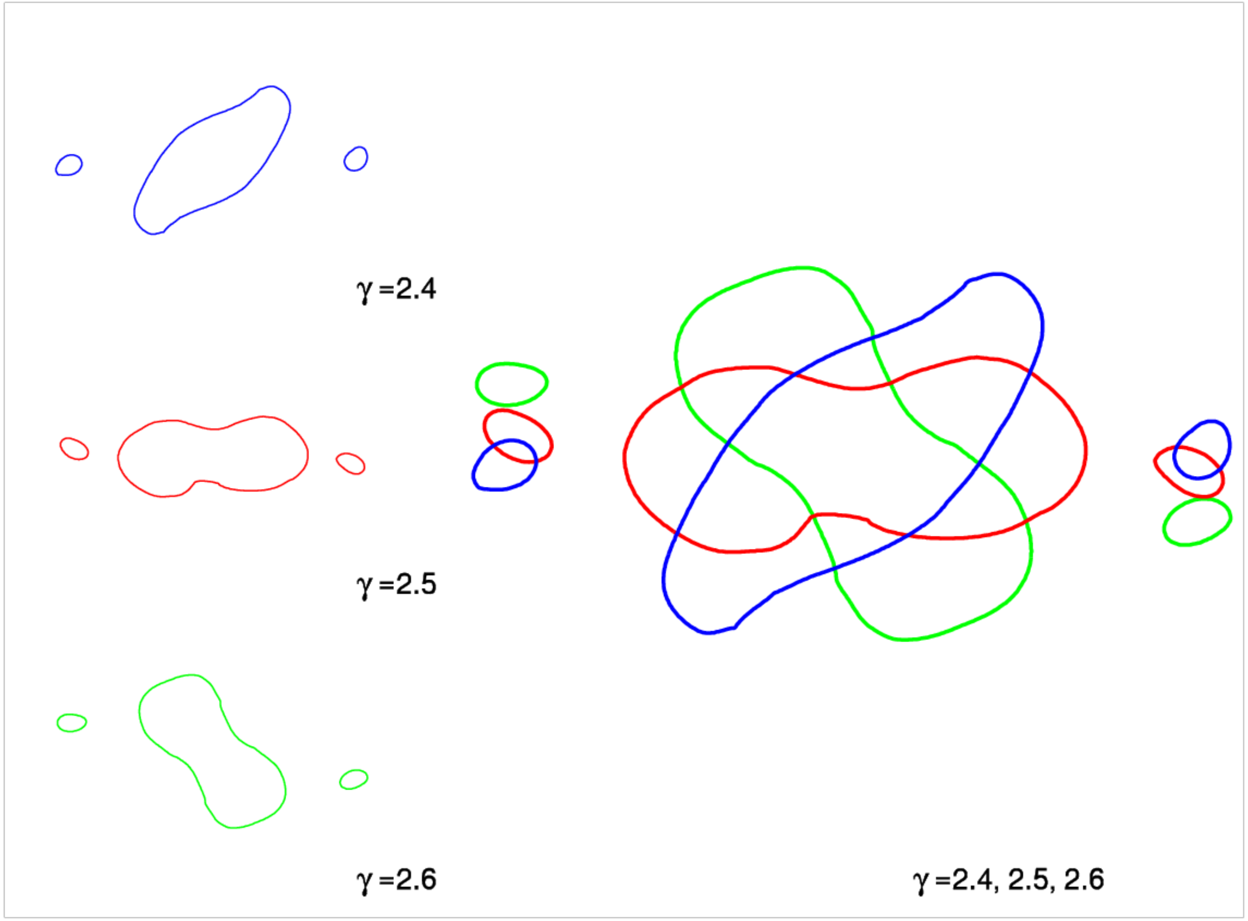

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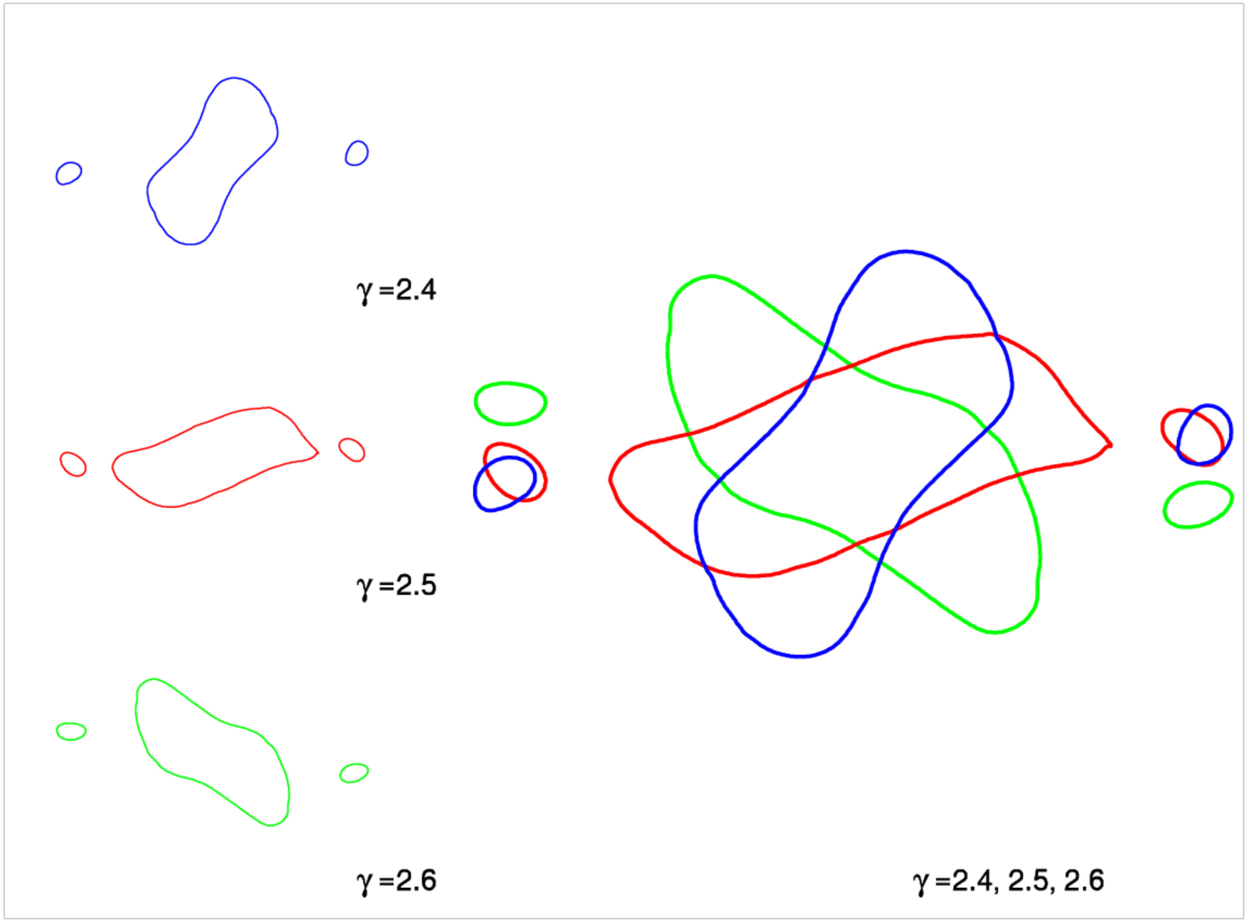

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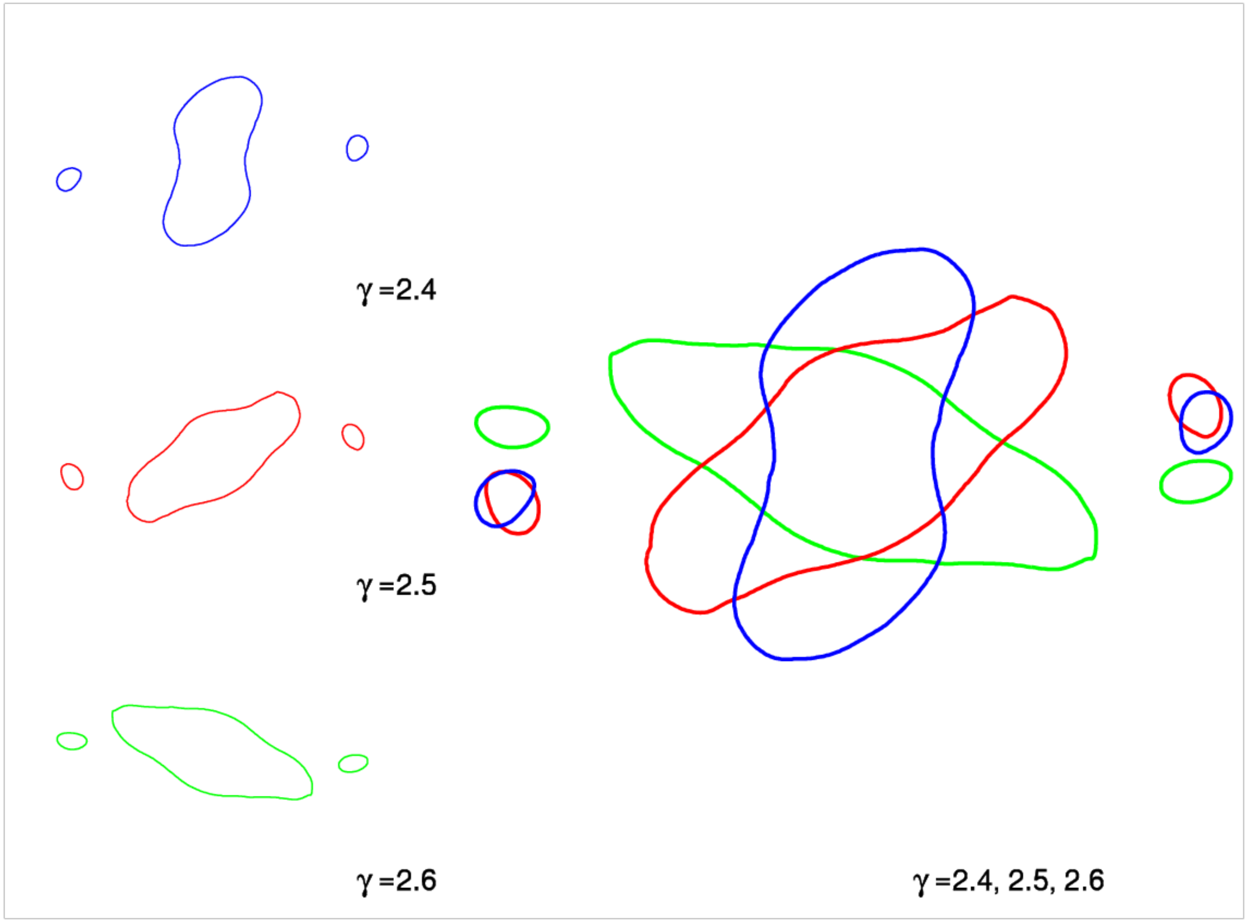

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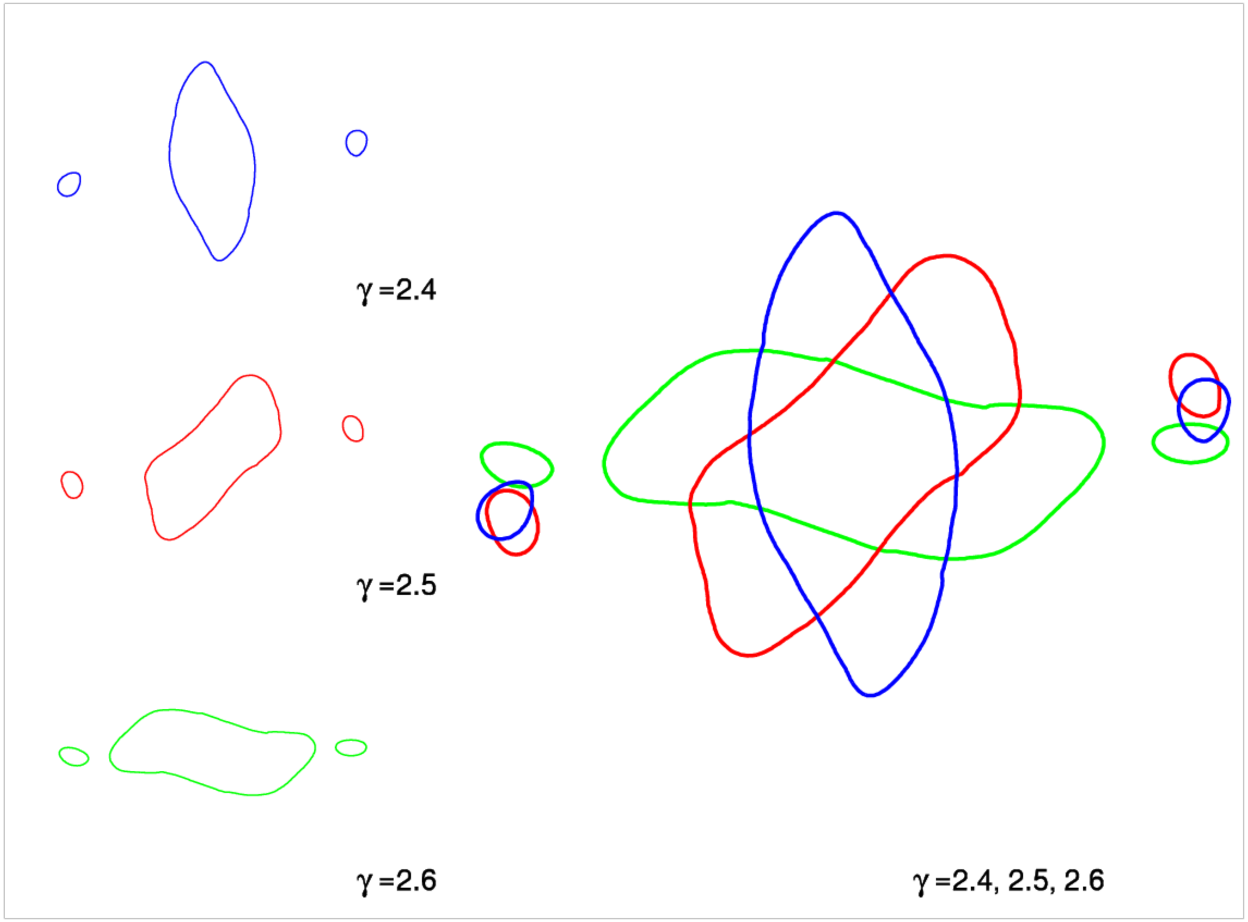

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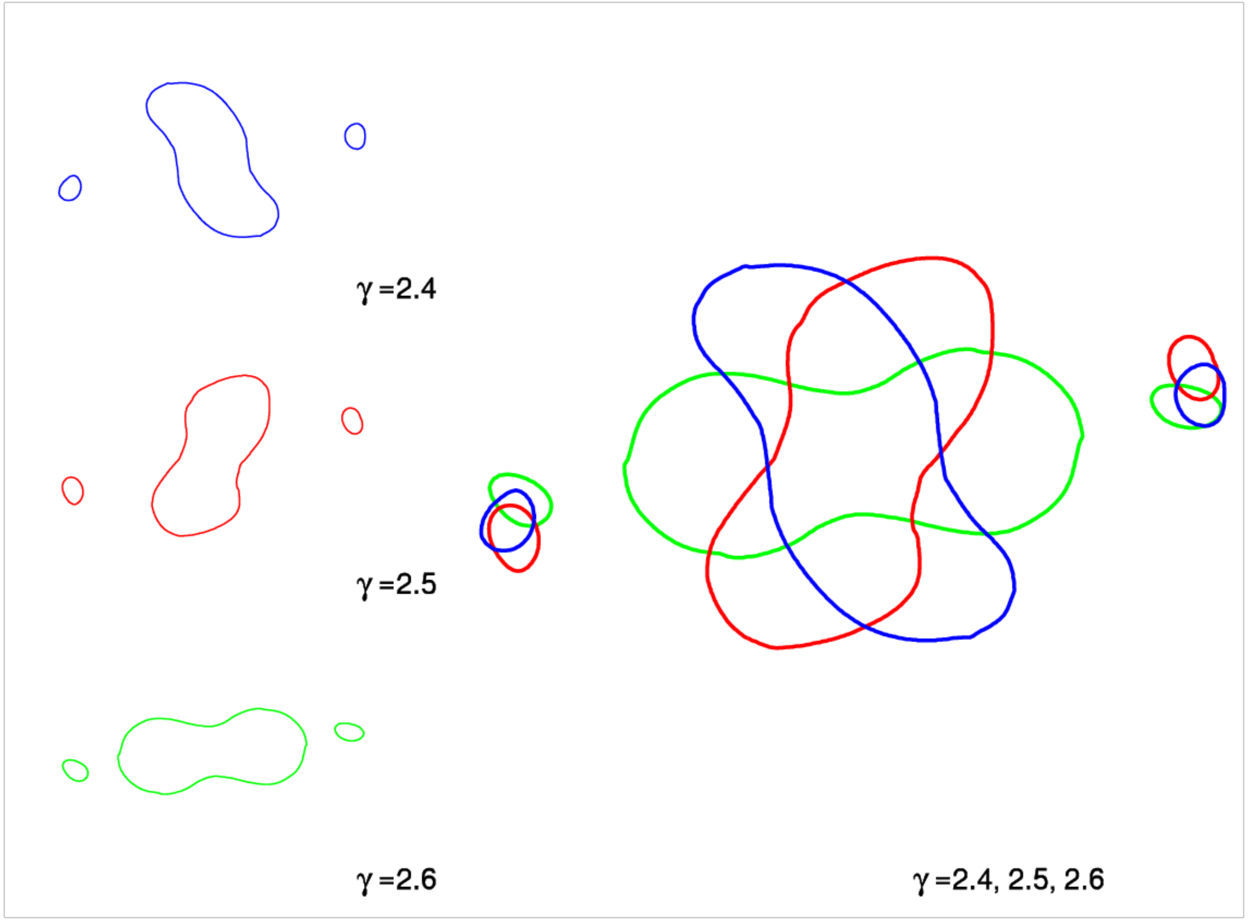

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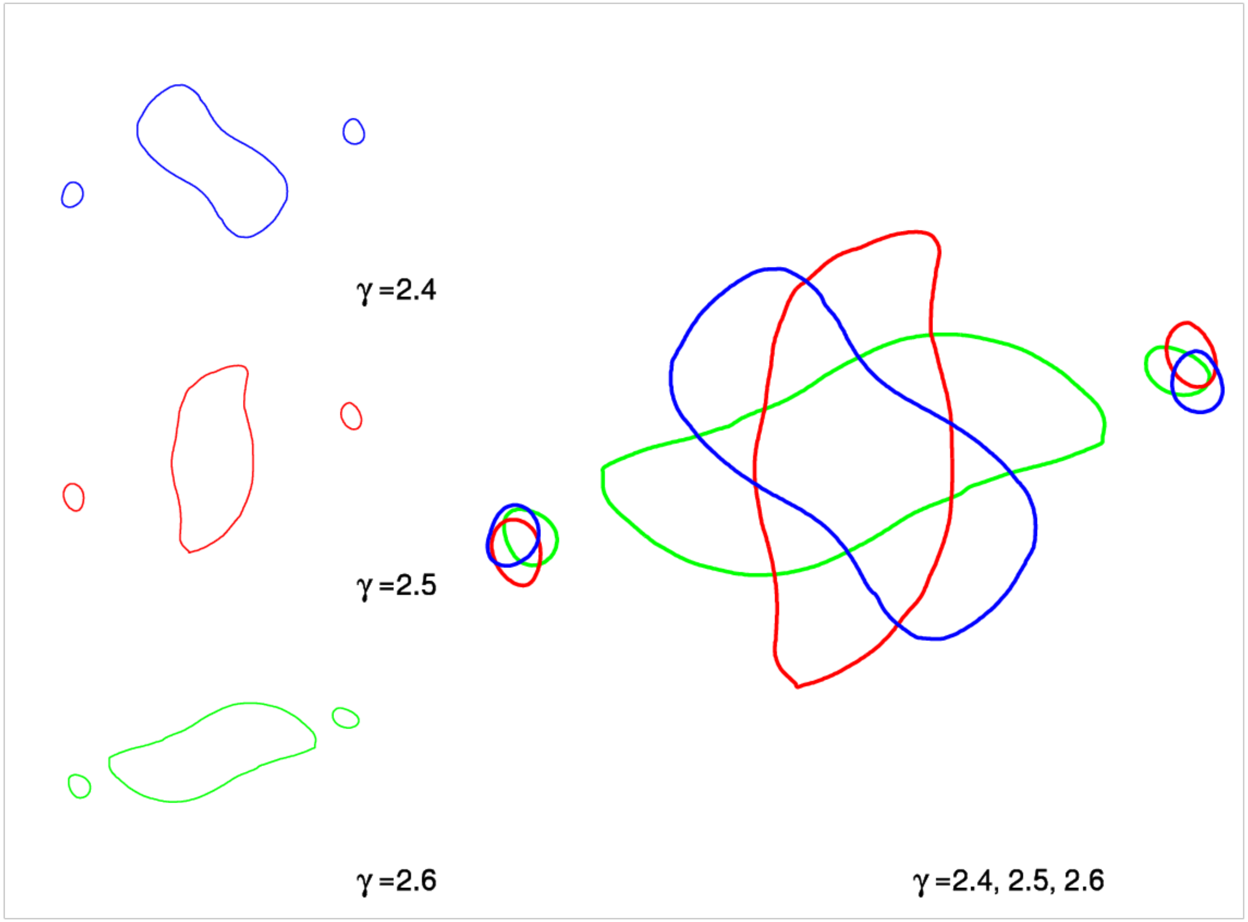

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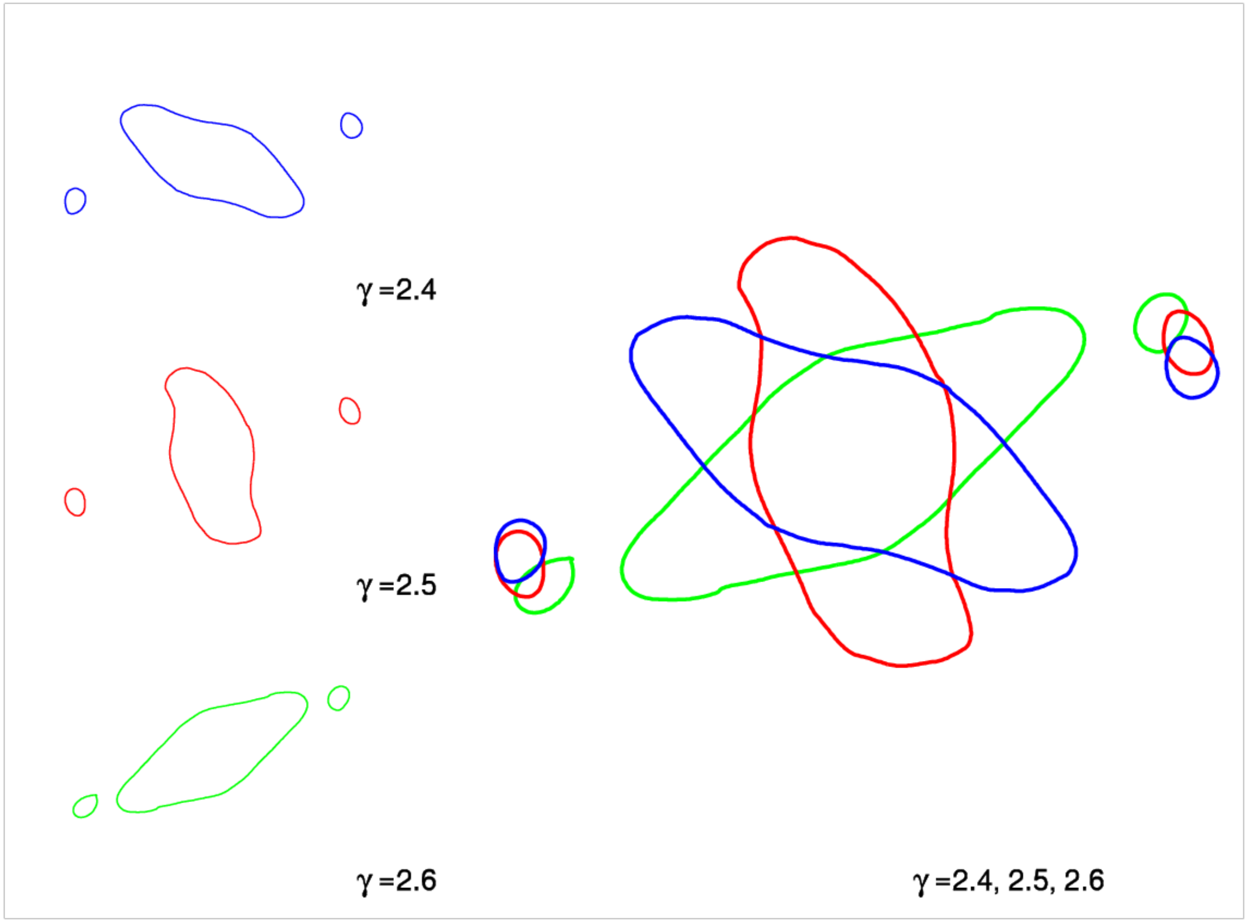

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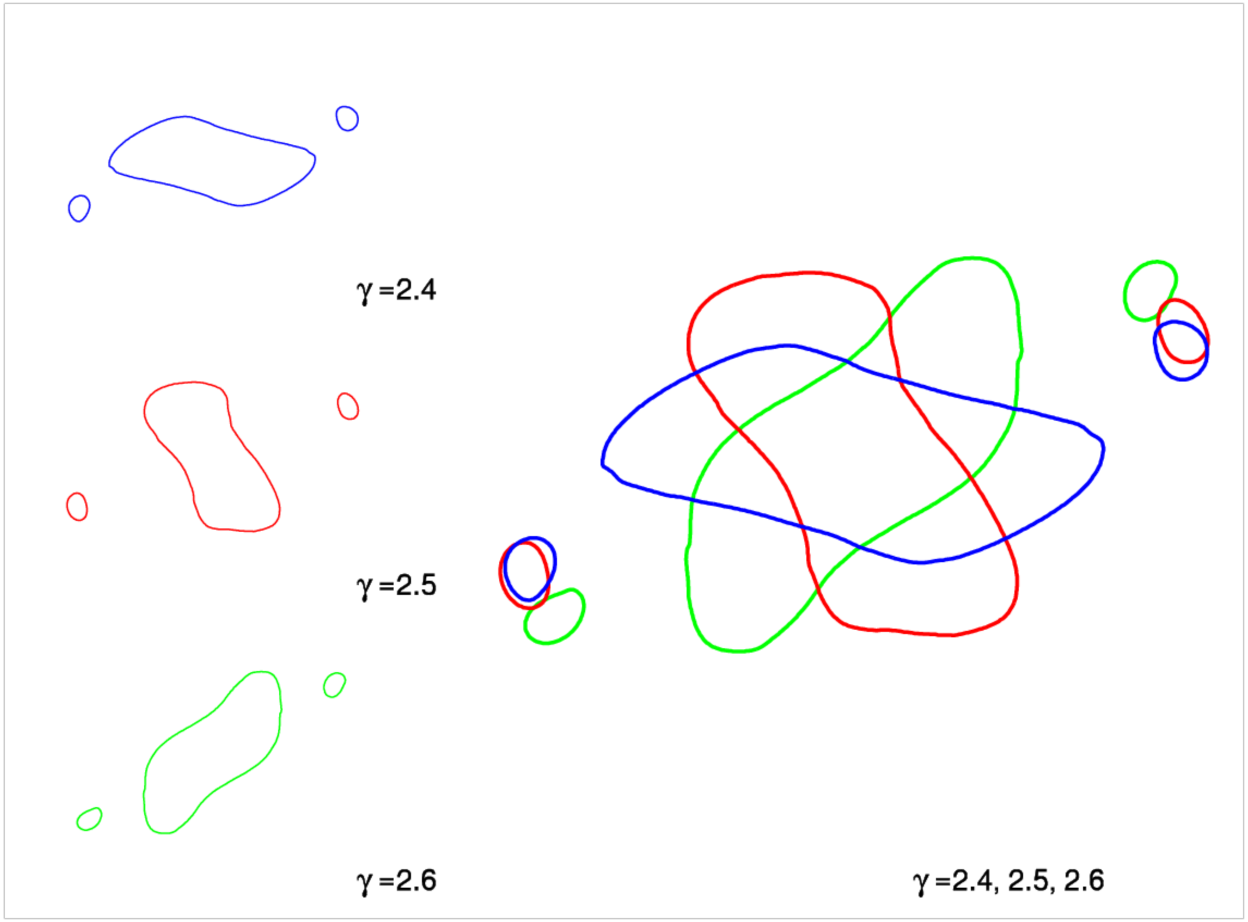

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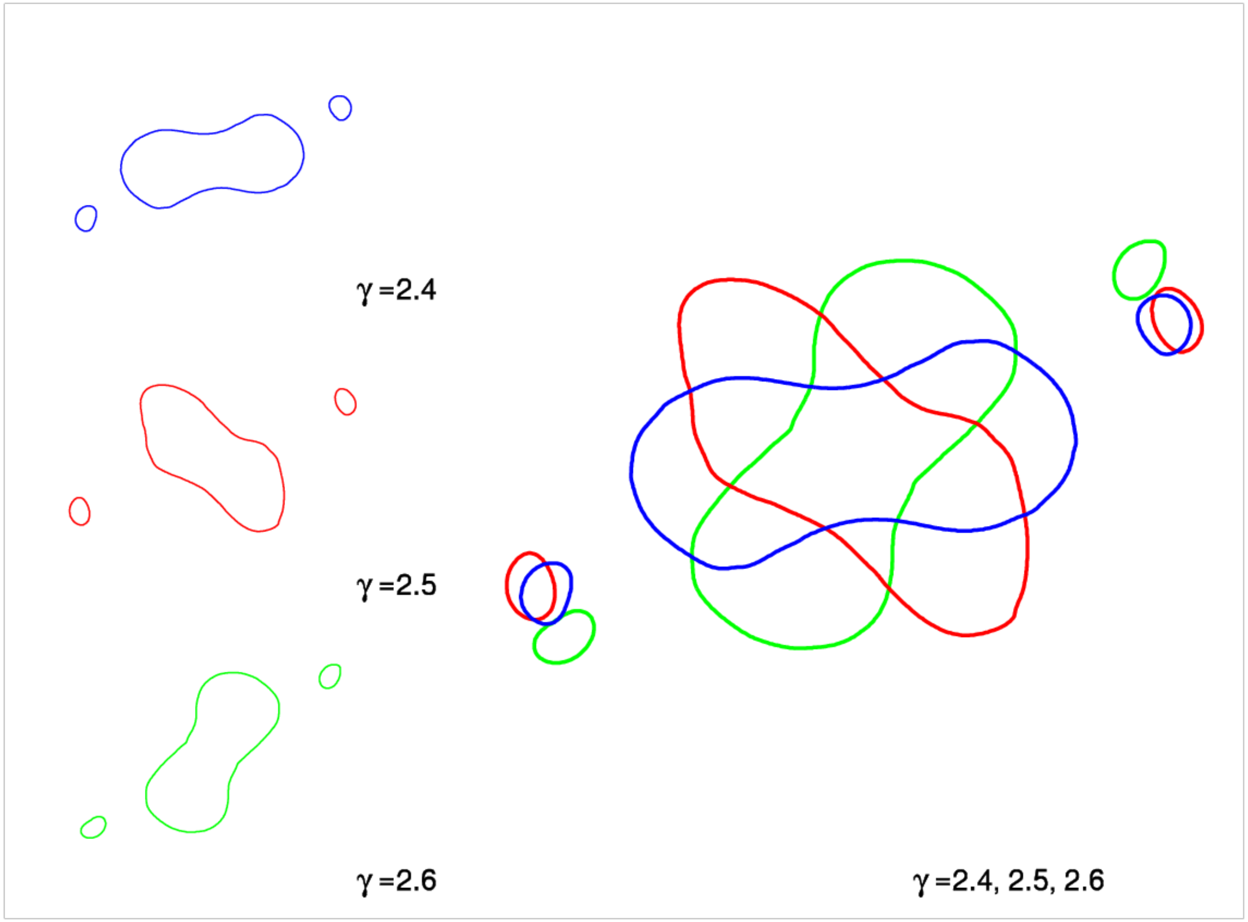

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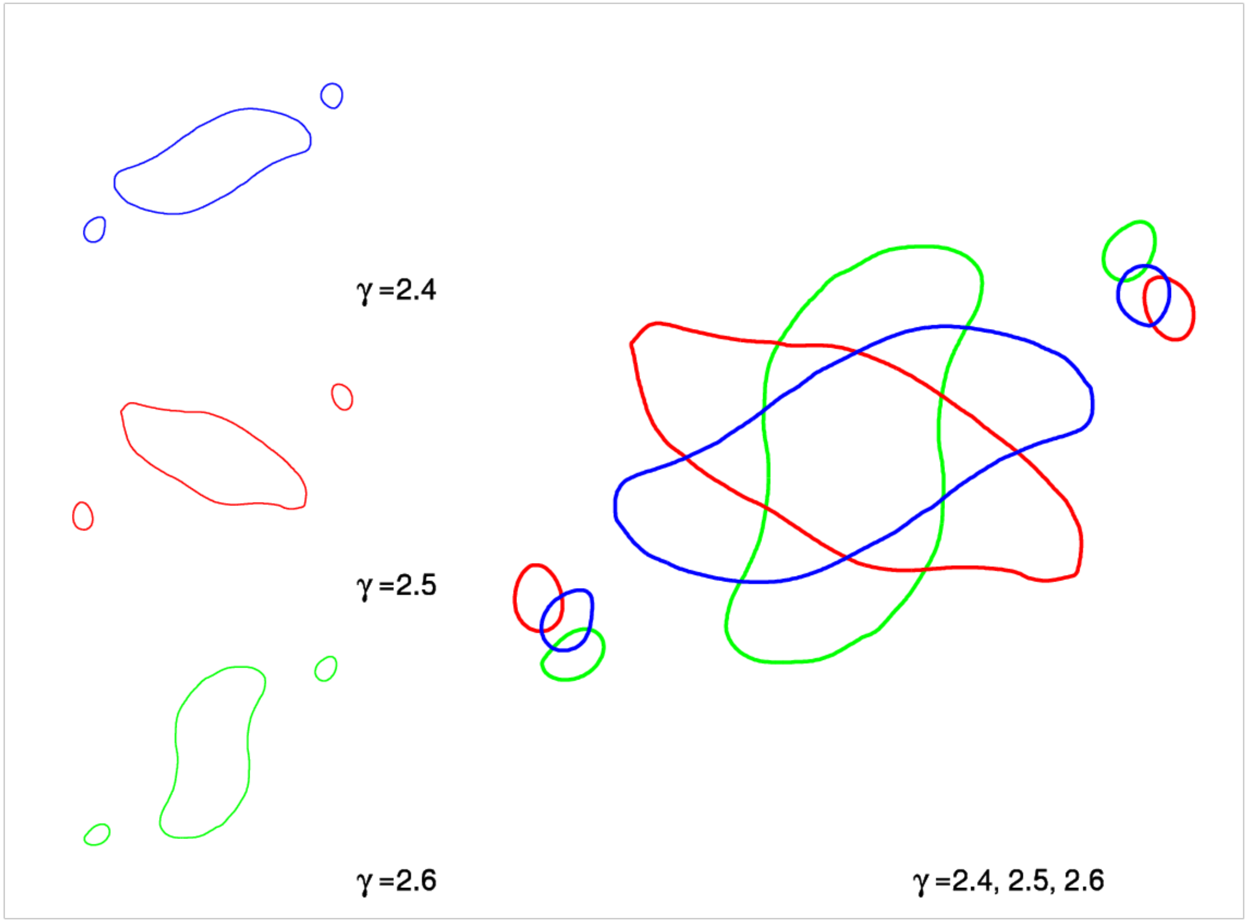
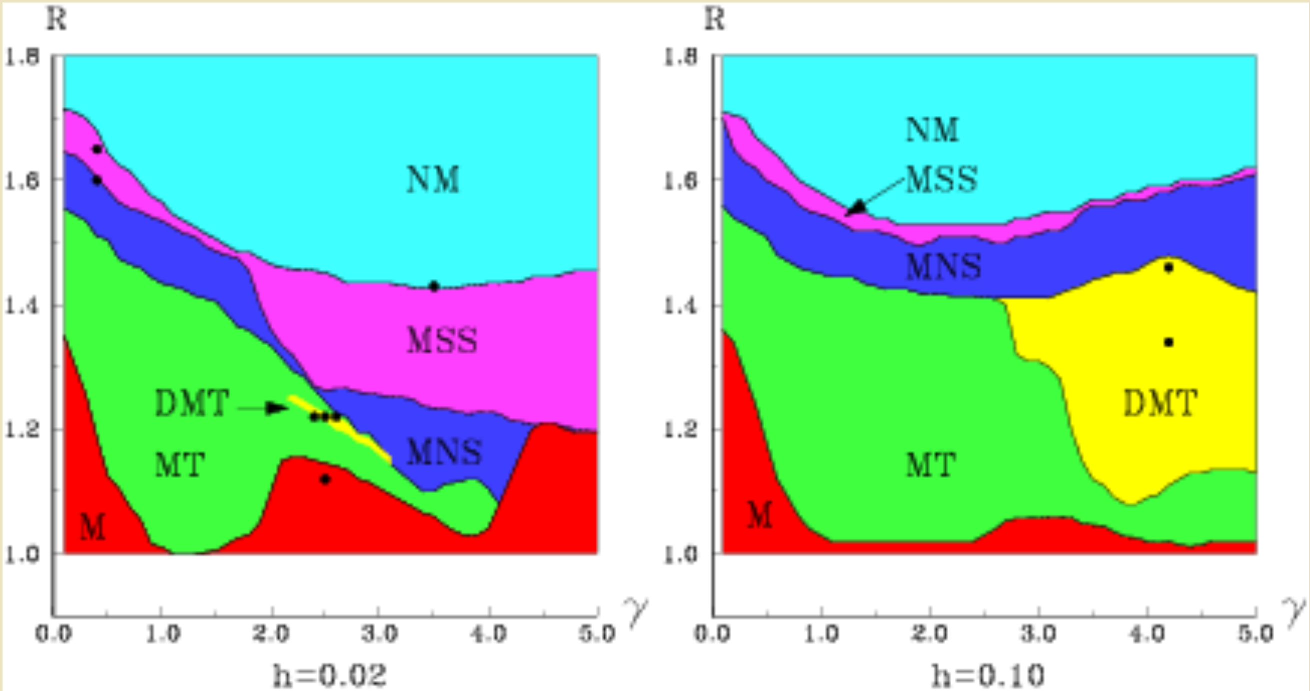


CDM-modeling of interaction of two cyclones of upper layer in two-layer rotating fluid: diagrams of states



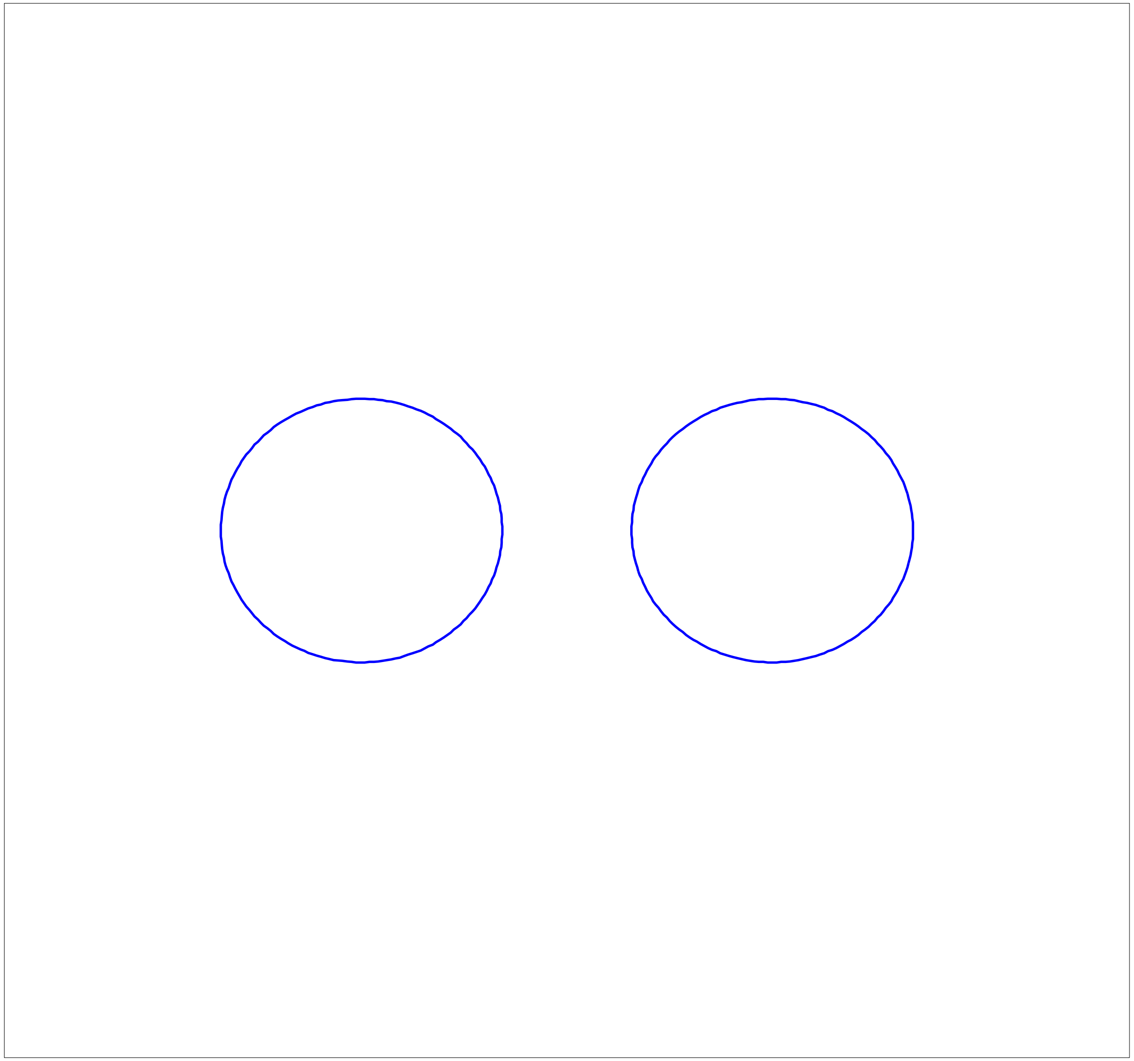
Diagrams in the rectangular domain of plane (γ, R) of possible states of two circular vortices of upper layer with the specified values of the upper-layer thickness: M (merger) - a state, when after the merging of the vortex patches and a short intermediate stage of the thin vortex-line formation, there remains one compact vortex of larger scale. MT (merger/triplet) - merging of vortex patches, and the subsequent formation of a triplet composed of a large central vortex and two peripheral smaller like signed vortices. DMT (double merger/triplet) - the first stage of the evolution is similar to that of MT but later, a new vortex merger occurs leading to the birth of a new triplet. MNS (merger/non-symmetric separation) - a merging, followed by separation into unequal vortex patches. MSS (merger/symmetric separation) - the division is symmetrical, i.e. after a temporary merging, two identical vortex patches are formed again. NM (no merger) - vortex patches, pulsating, rotate around a common center of vorticity without merging.

γ=4.2, h_1=0.1:

(a) R=1.46, (b) R=1.34

Case (a):
evolution of vortex patches
S_2=0.257, S_3=0.325

t=0



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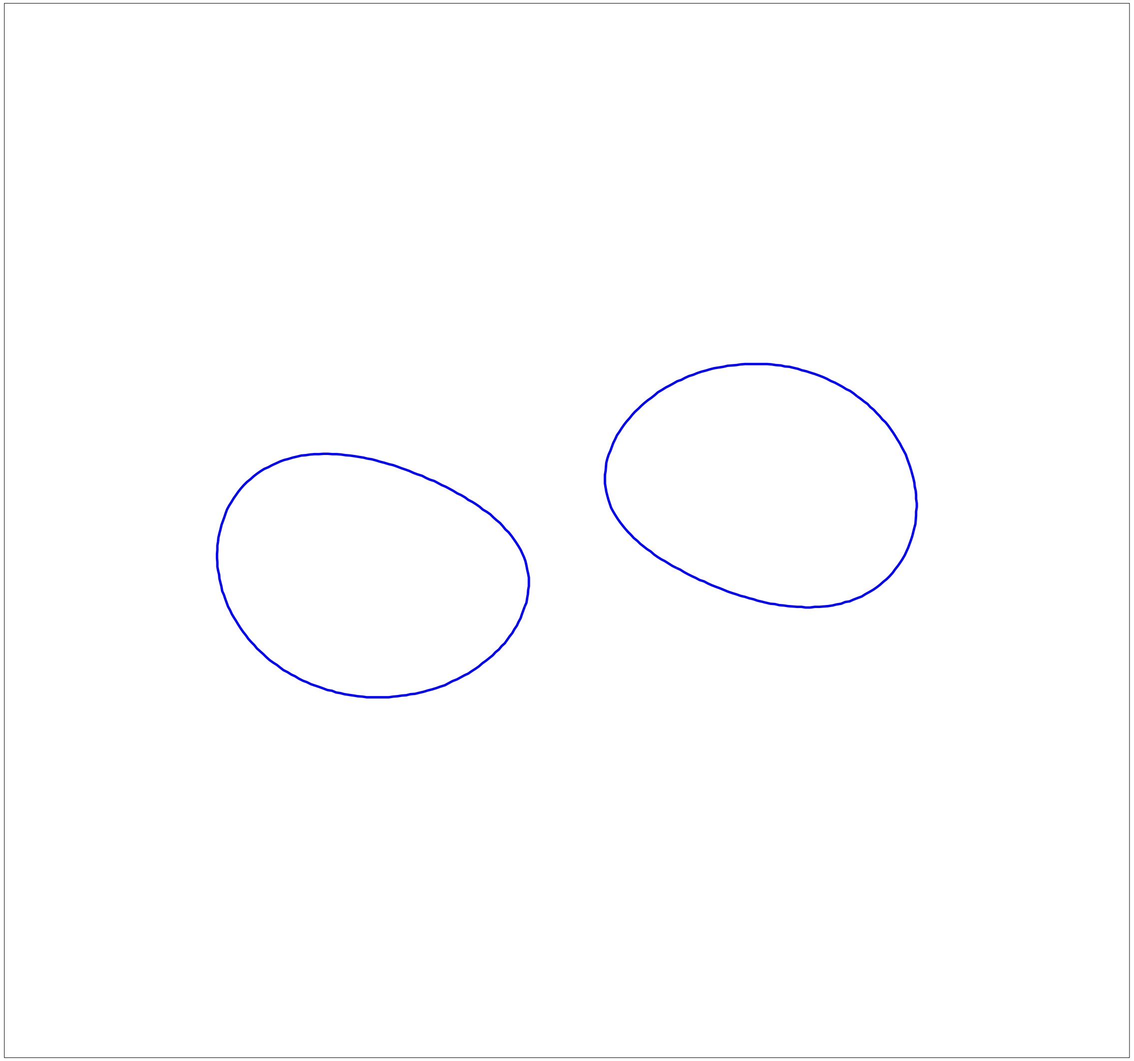

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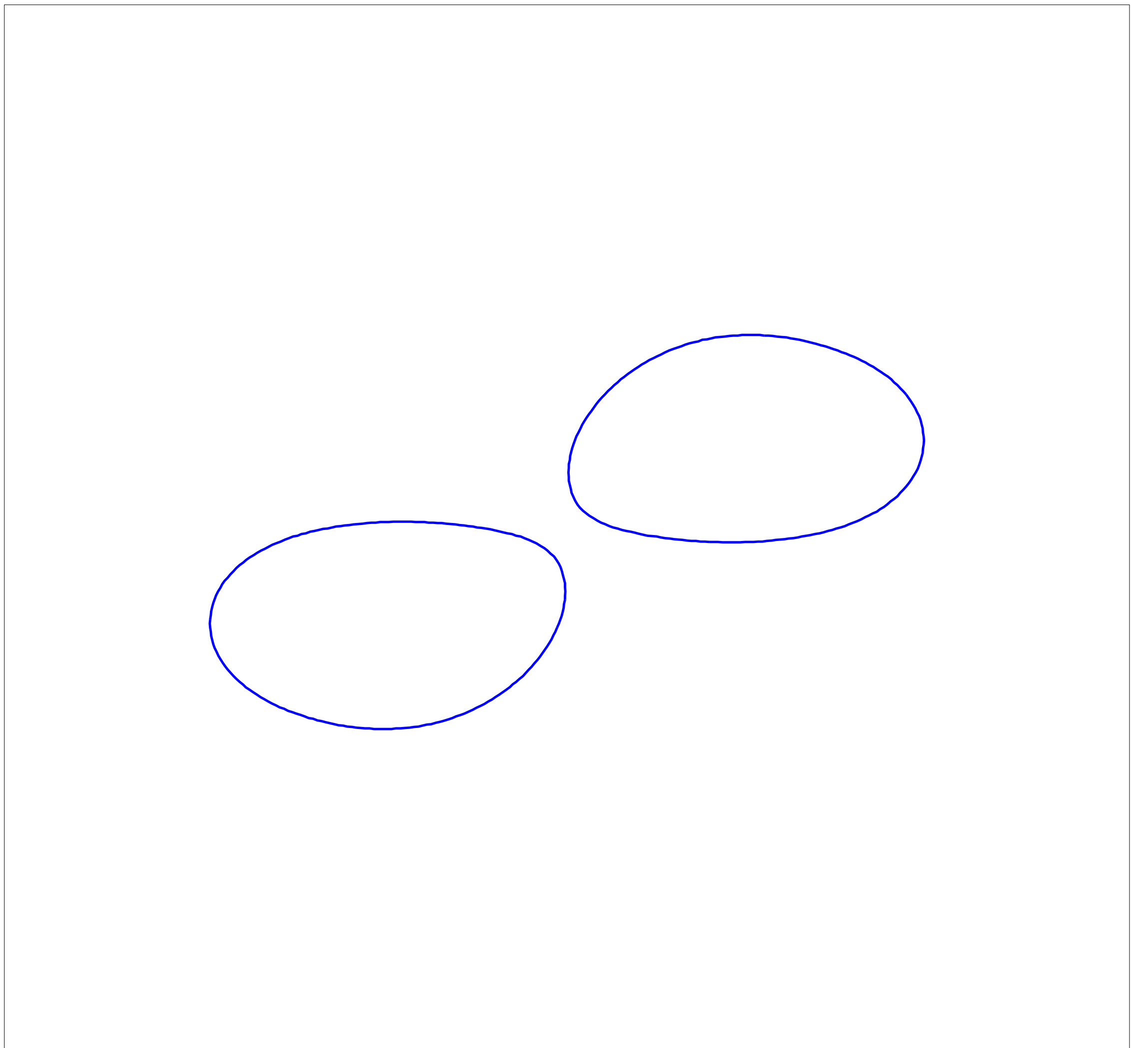

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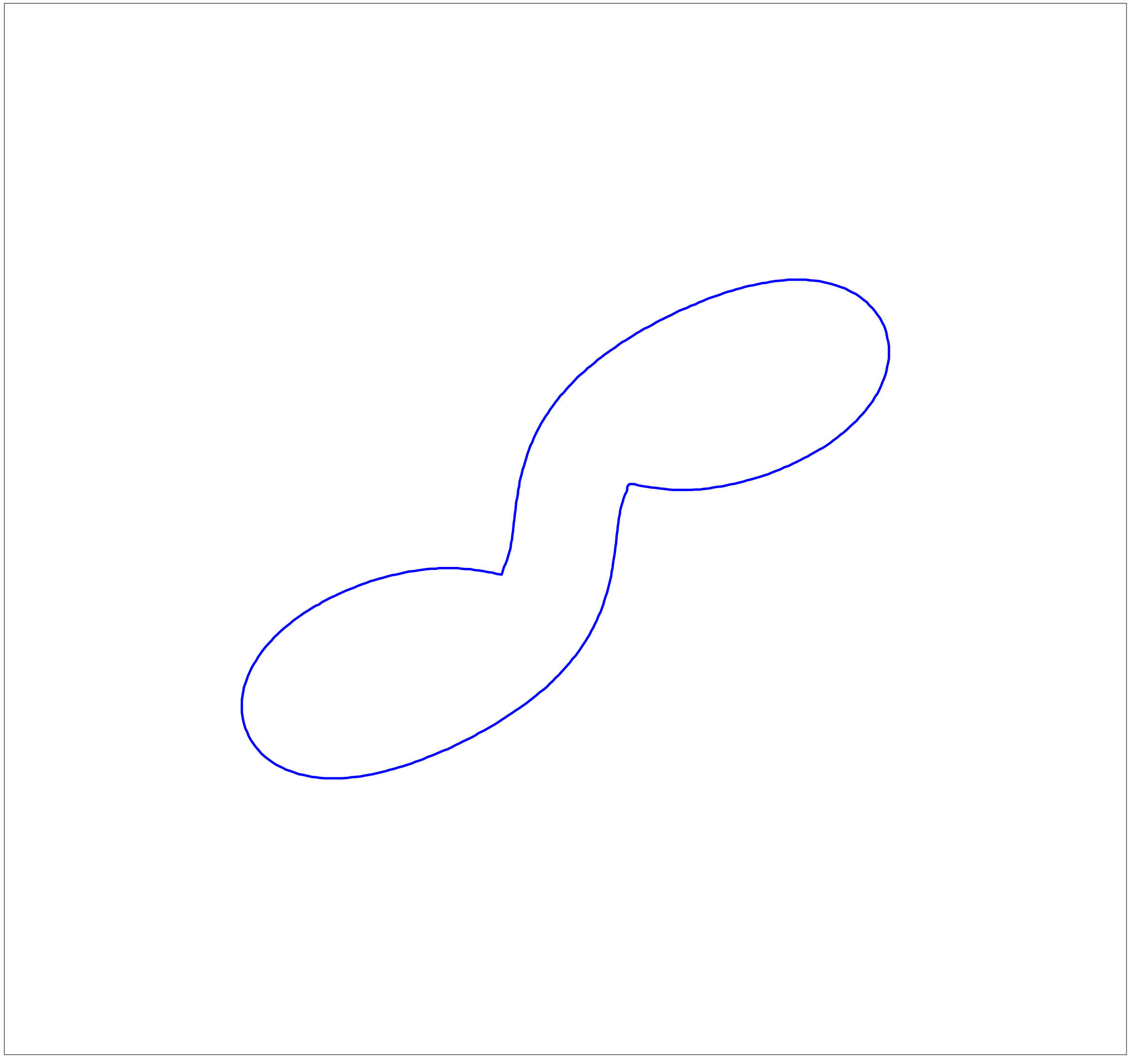

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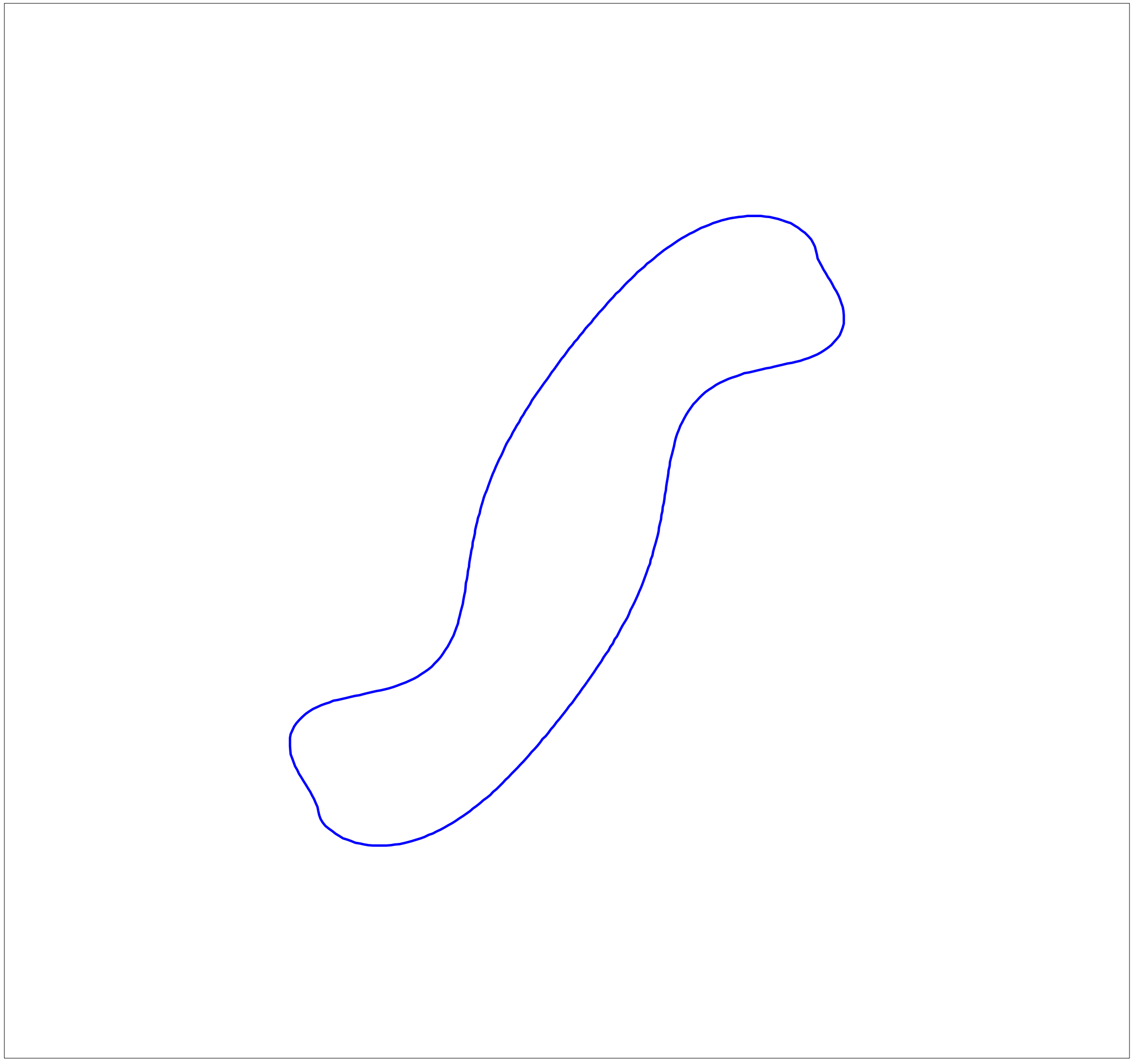

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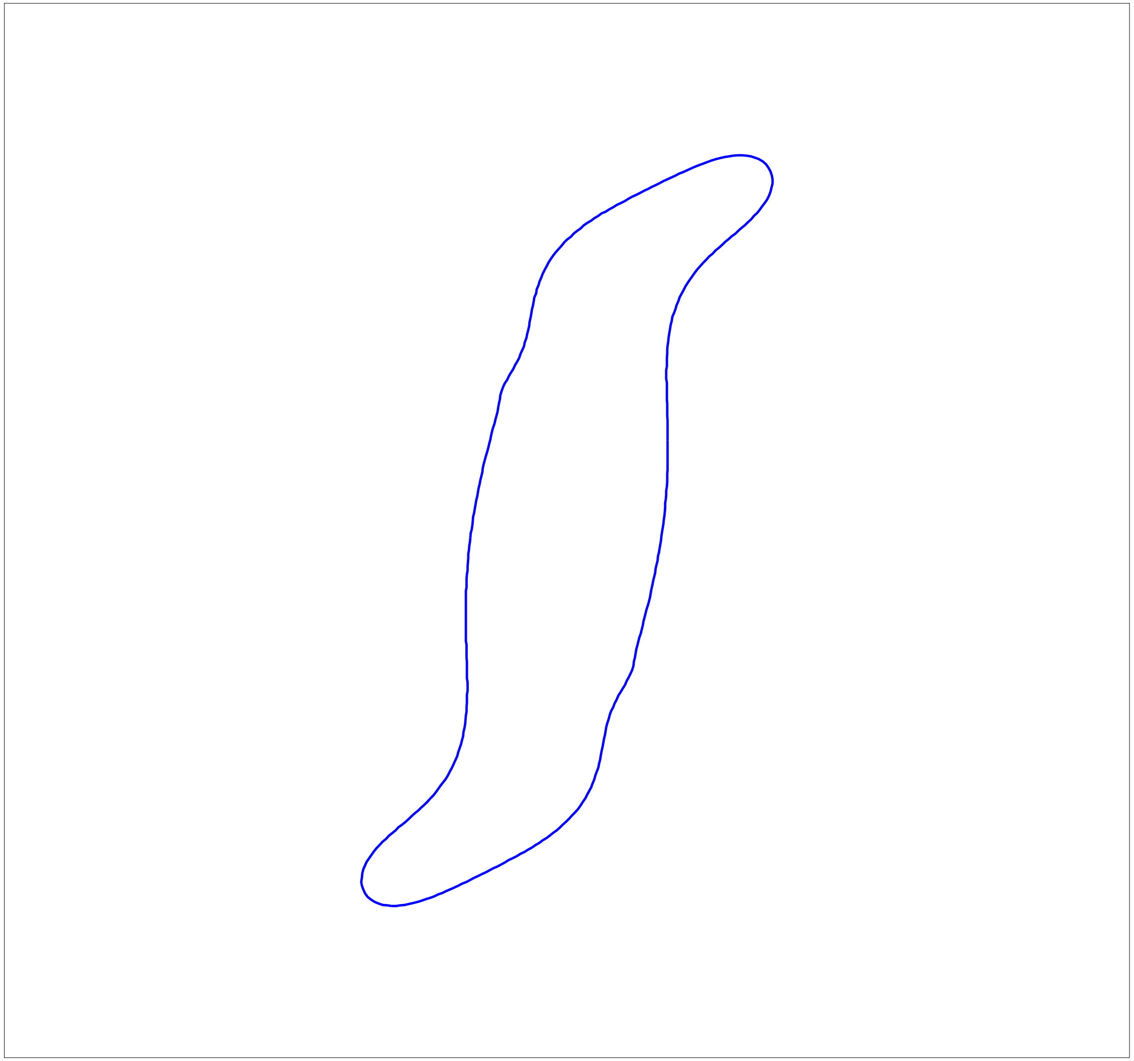

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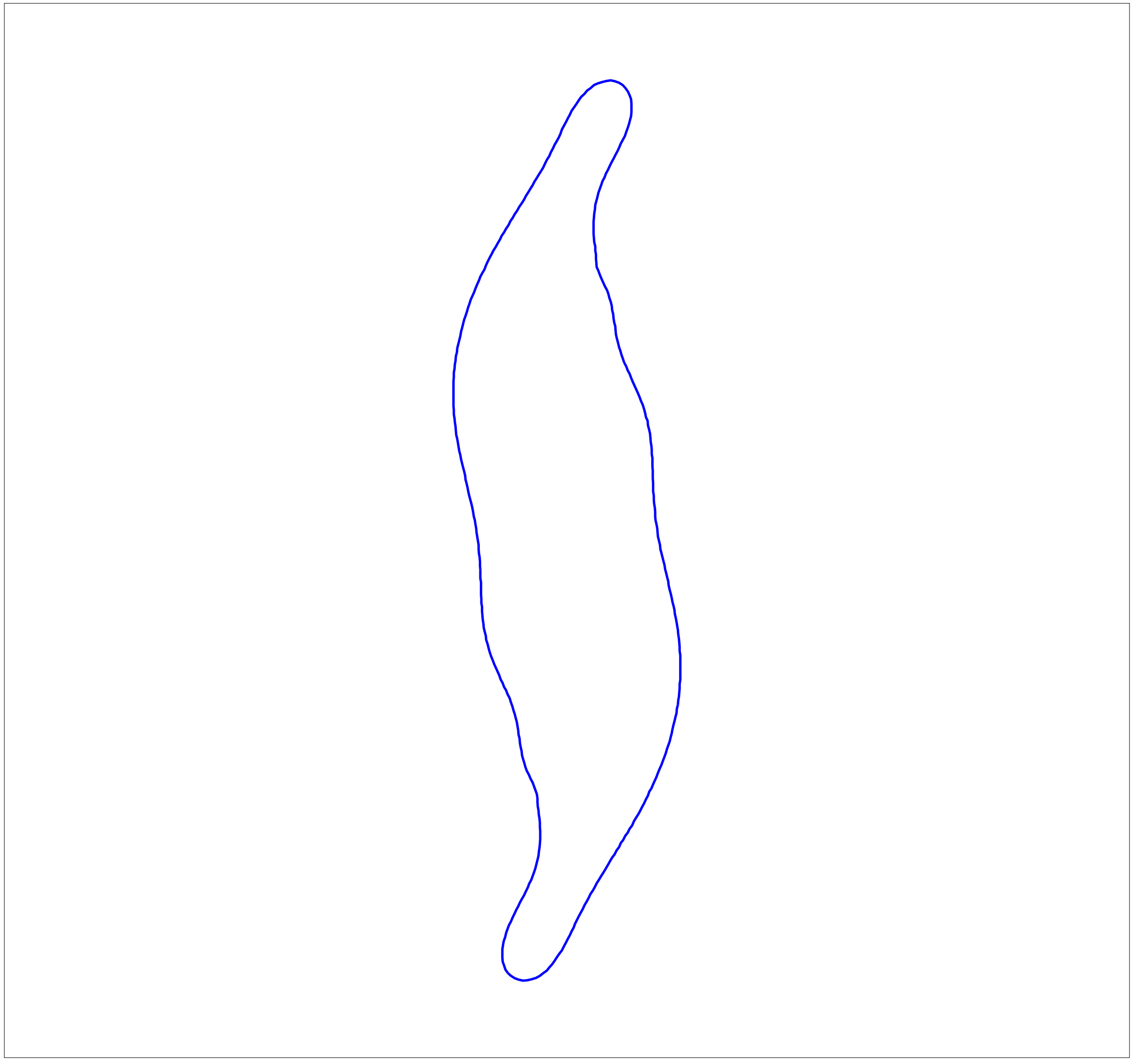

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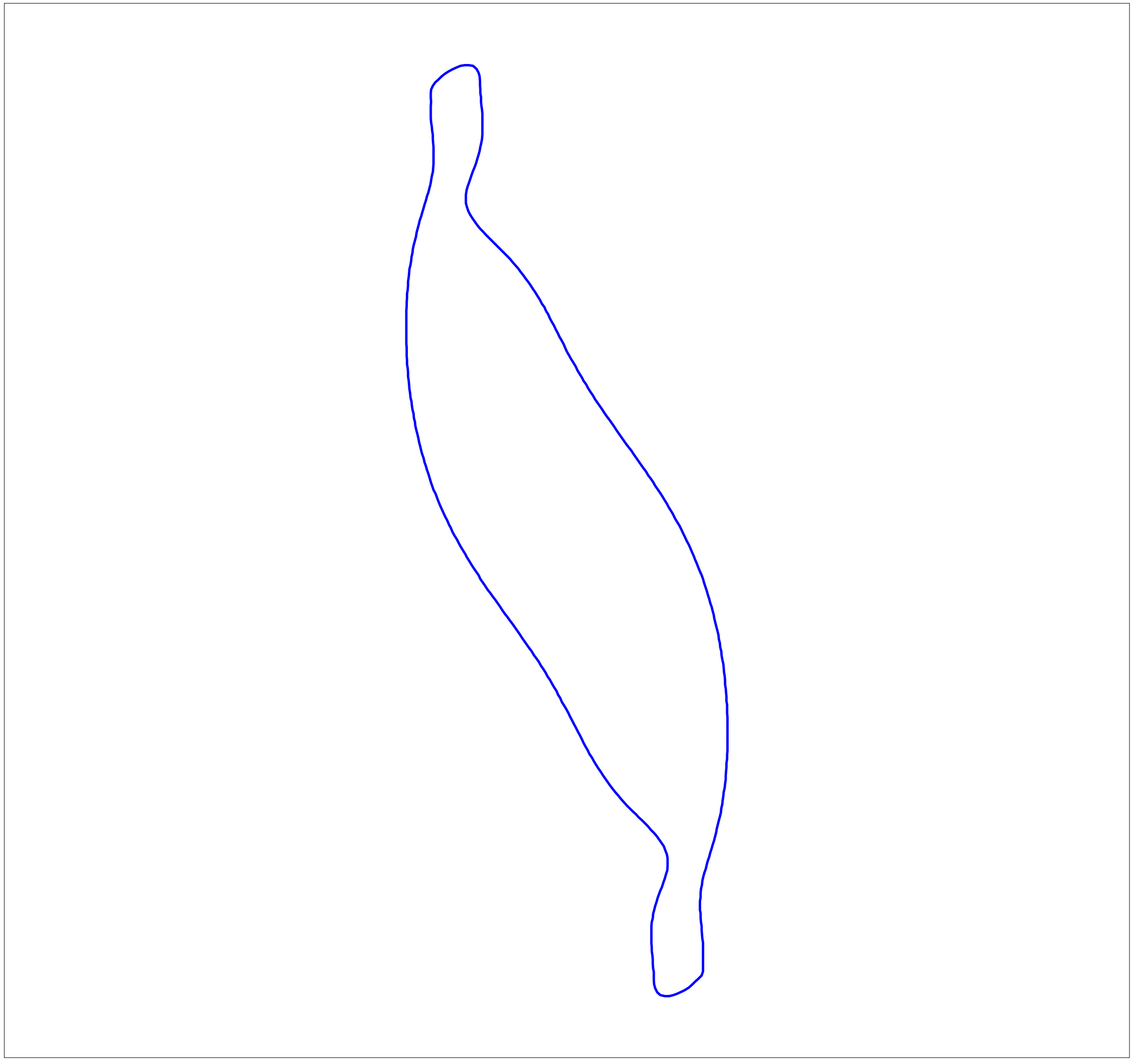

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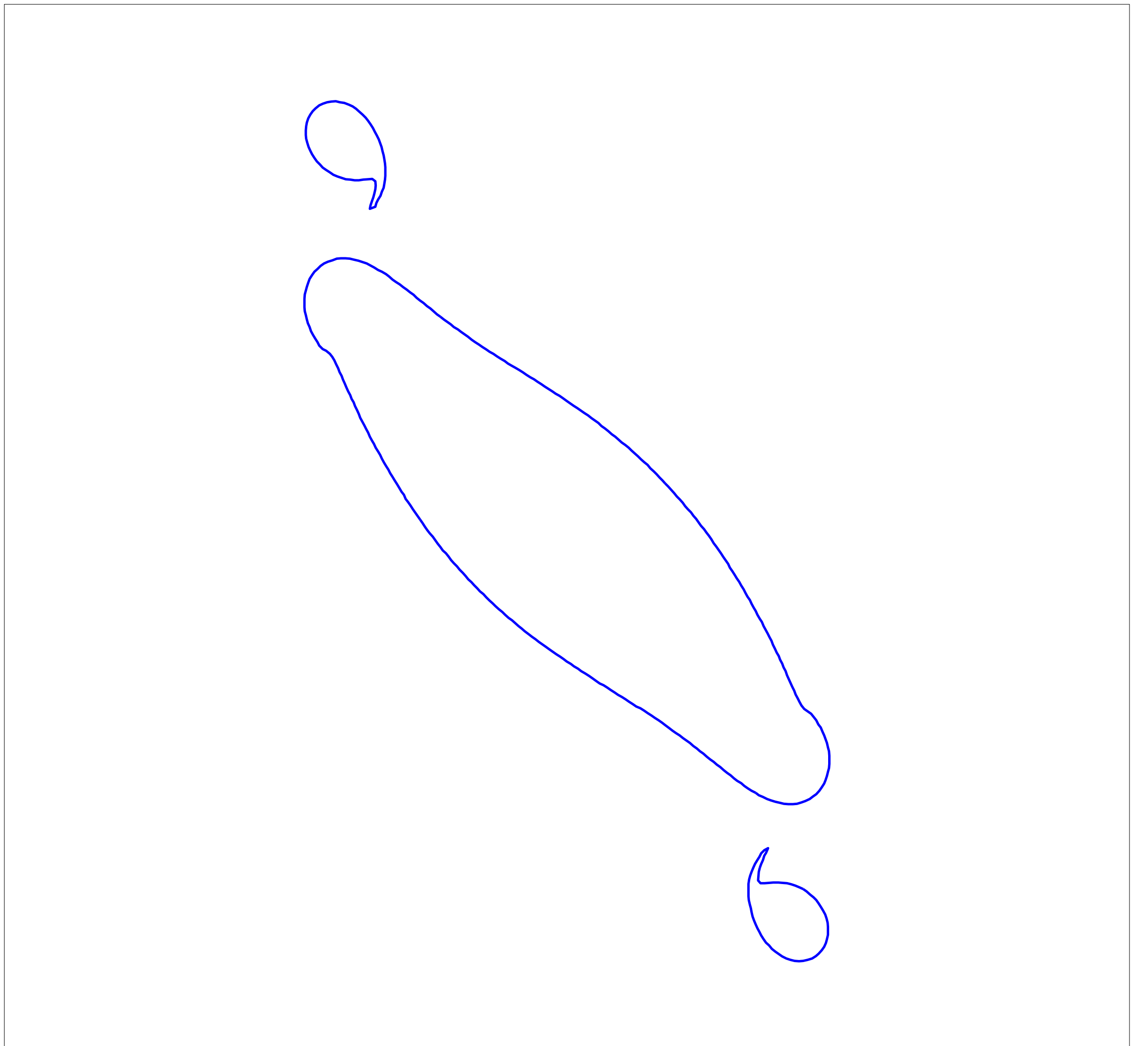

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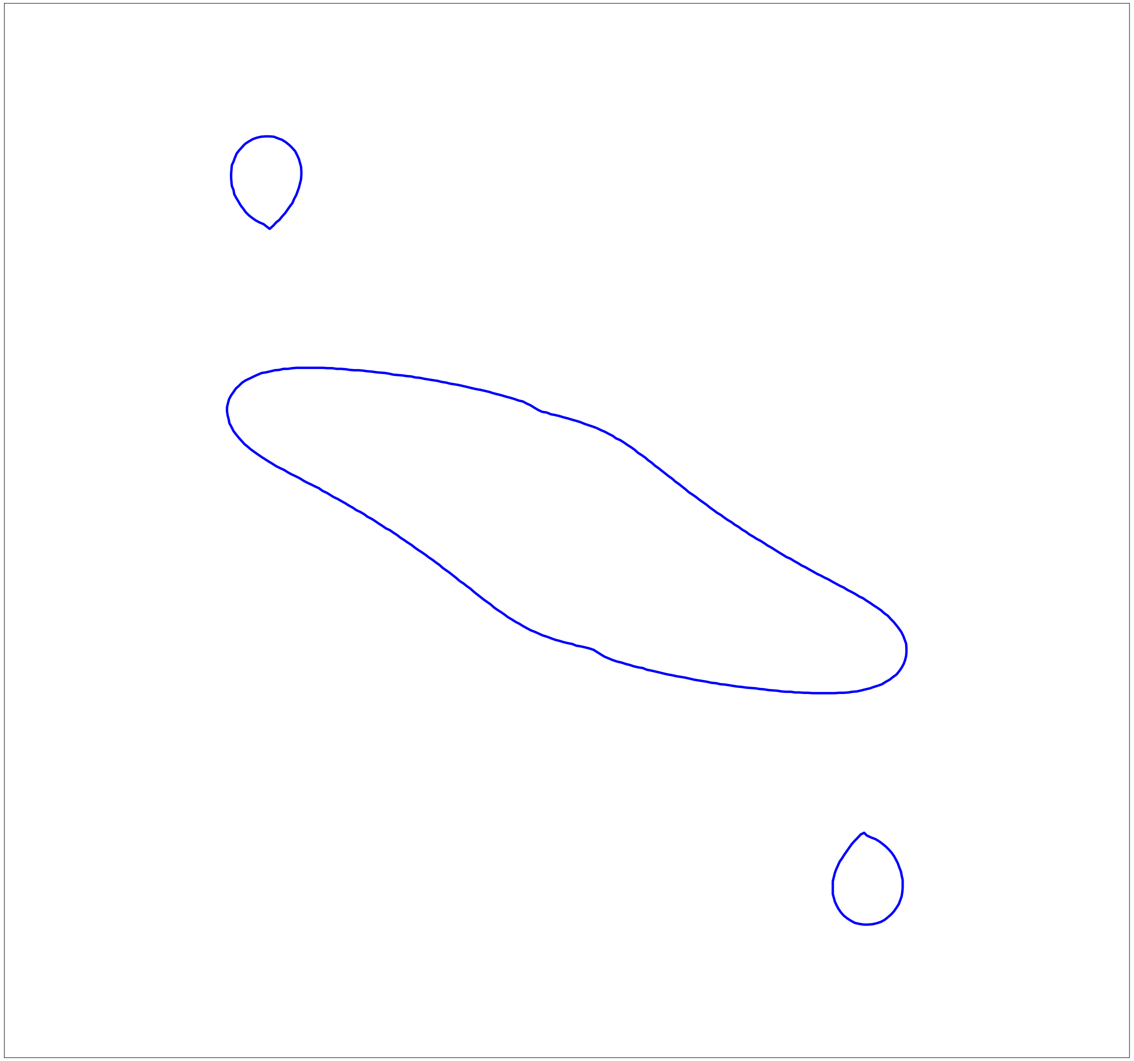

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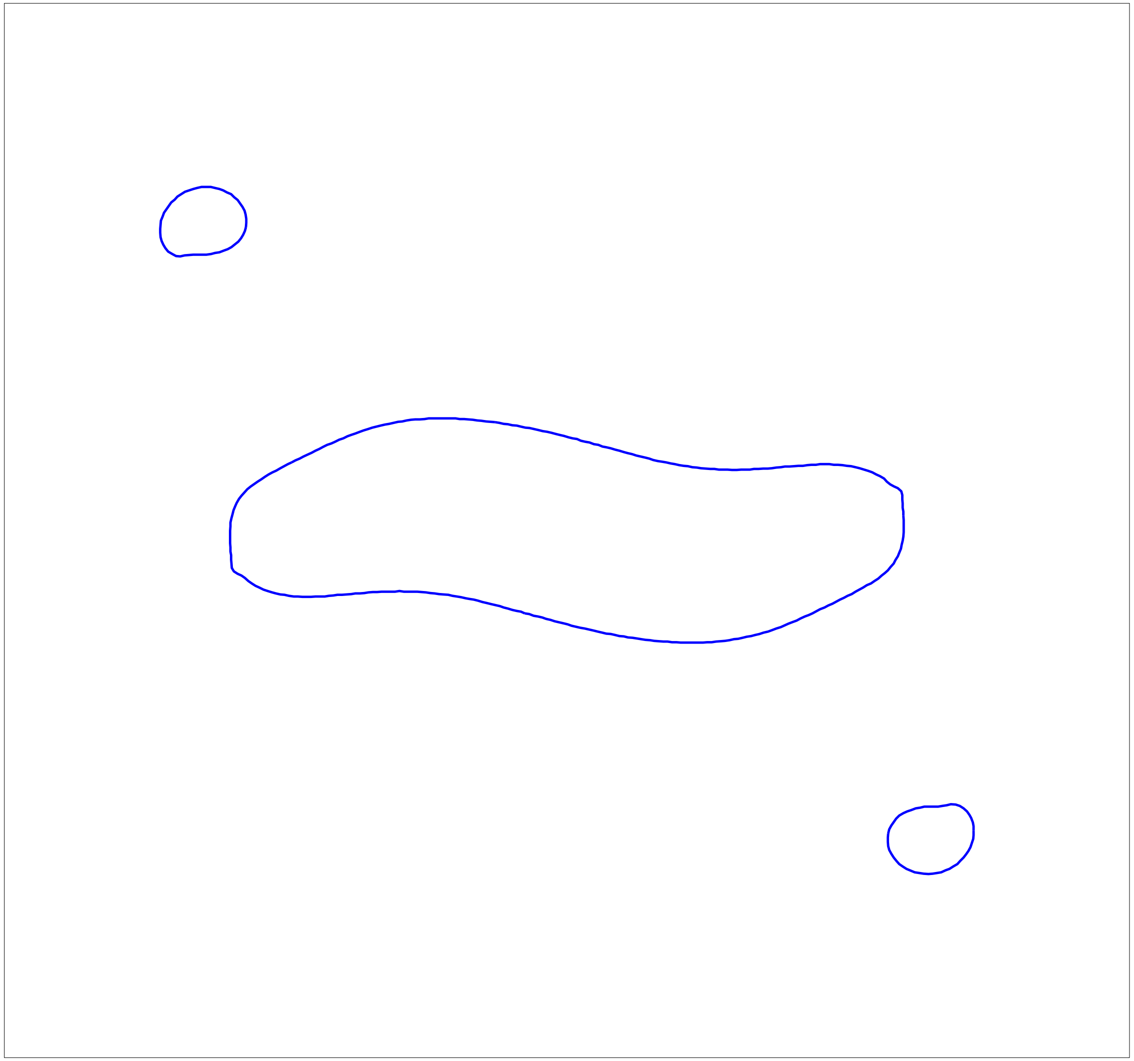

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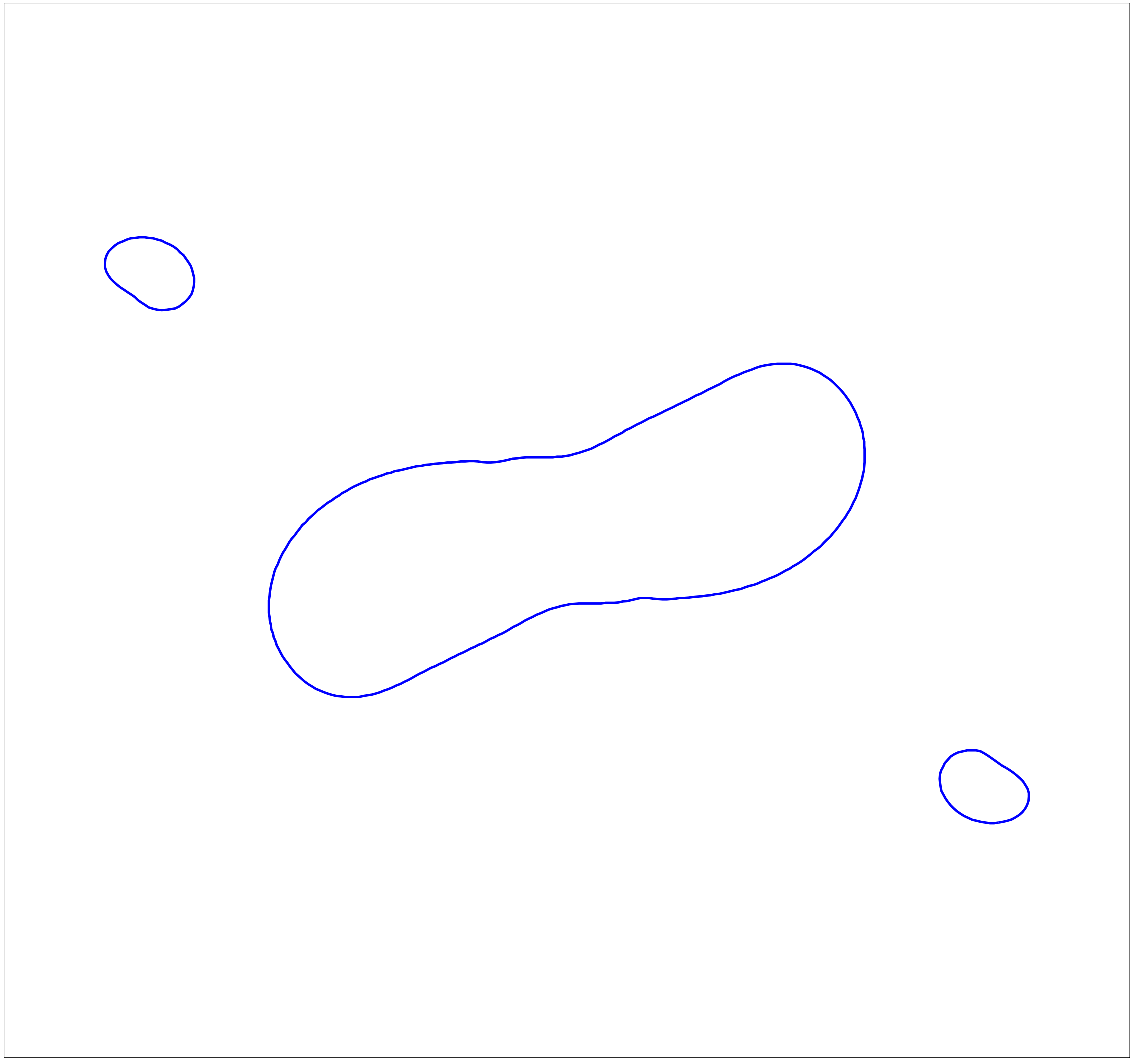

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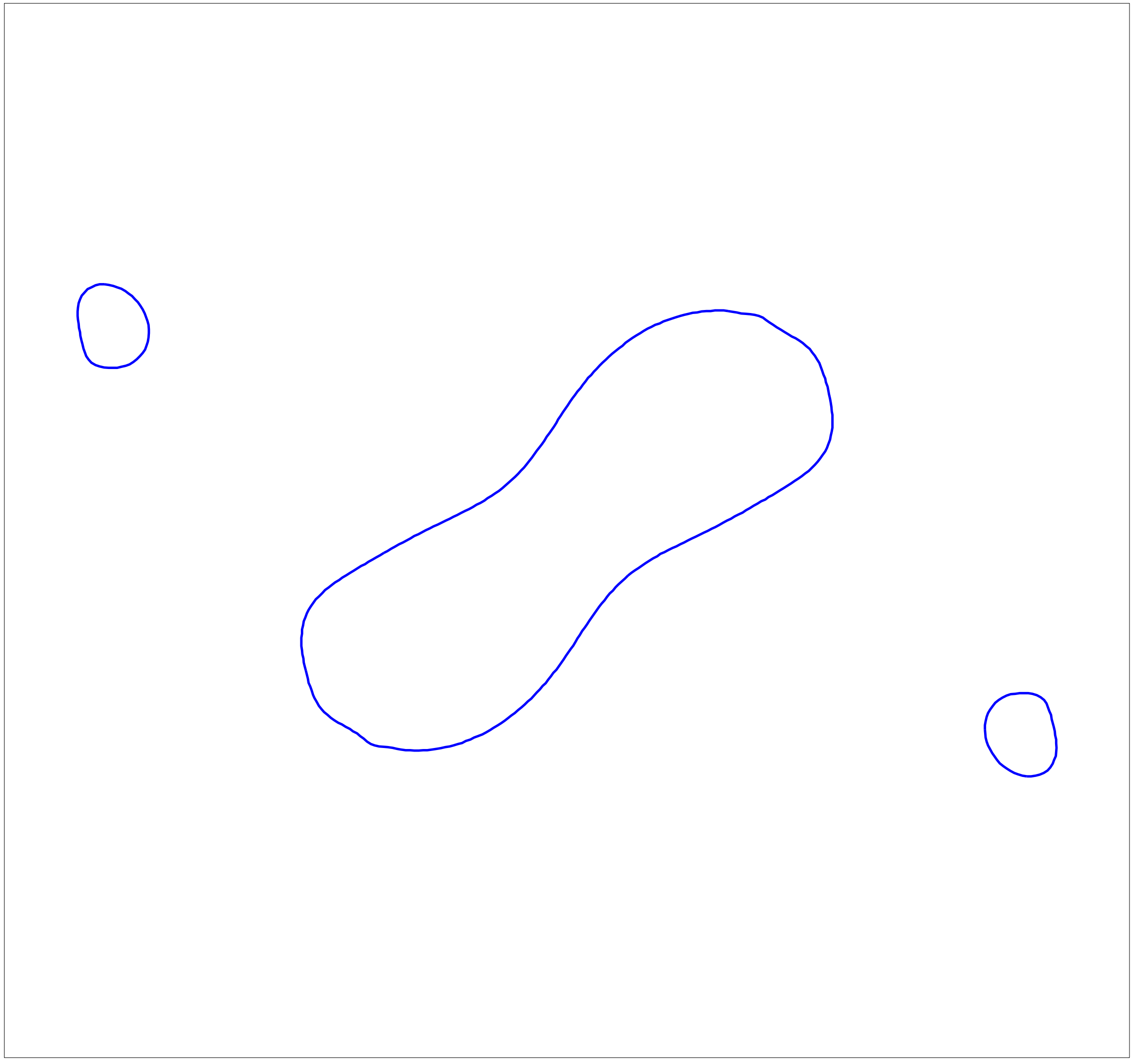

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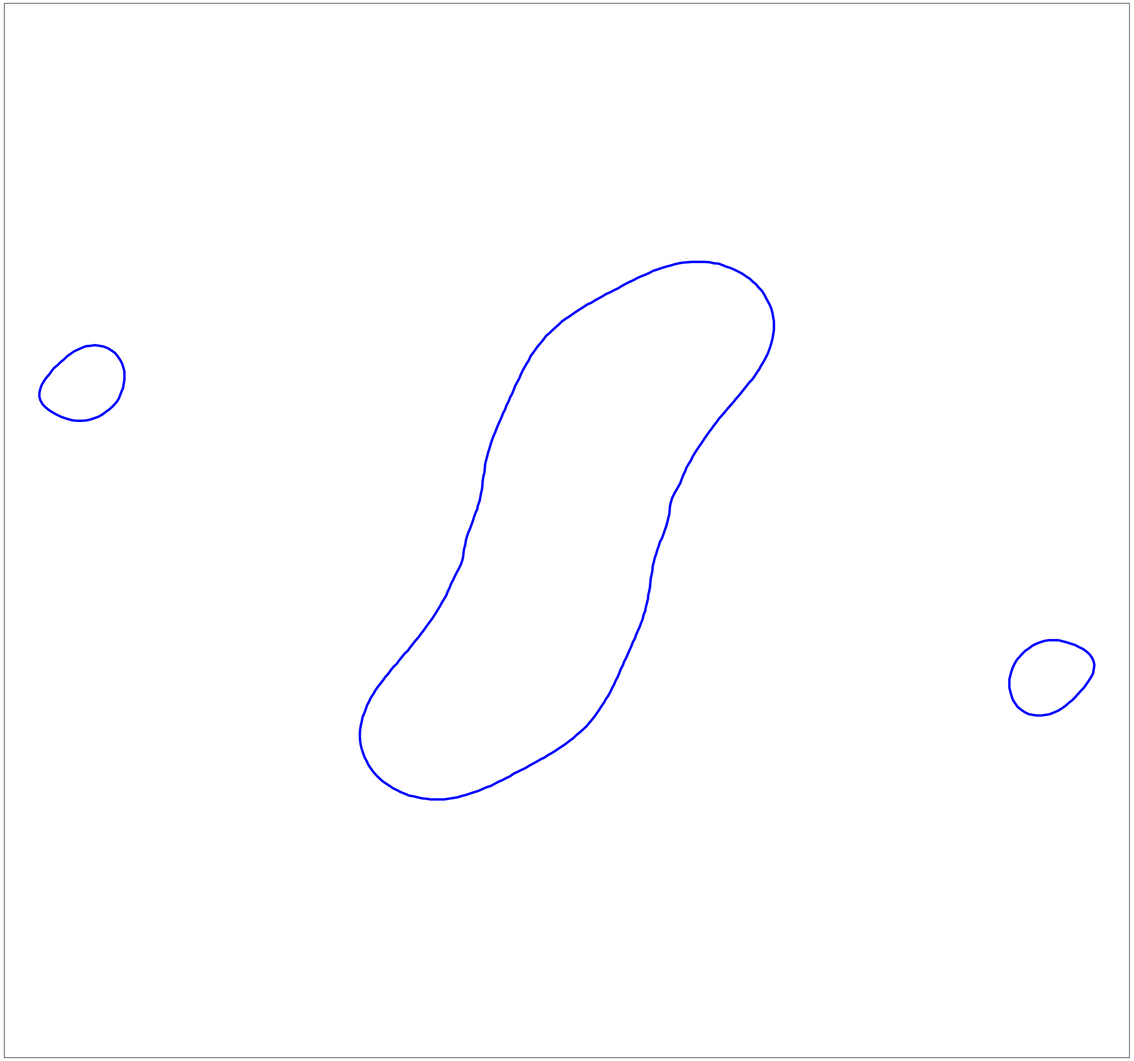

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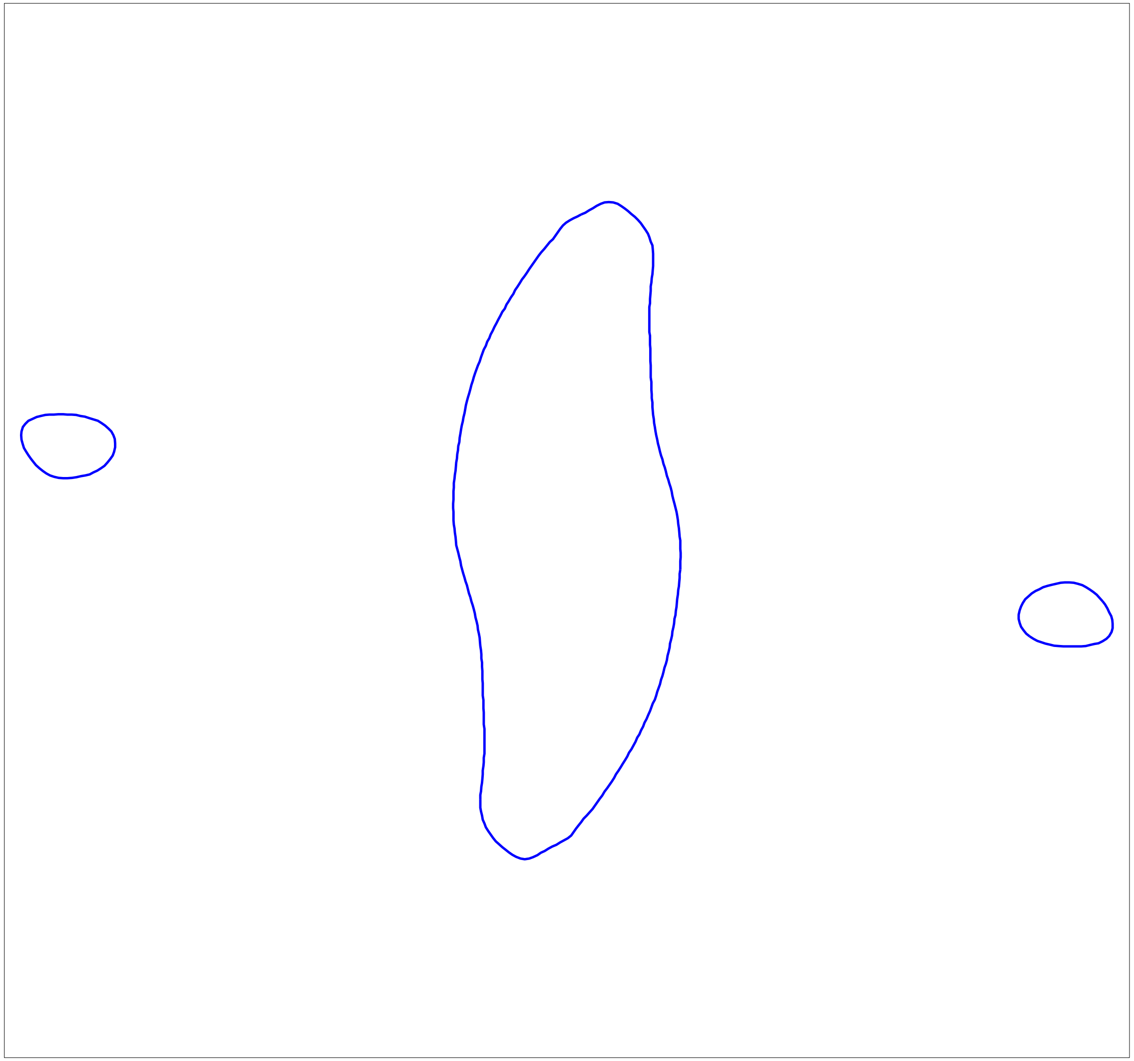

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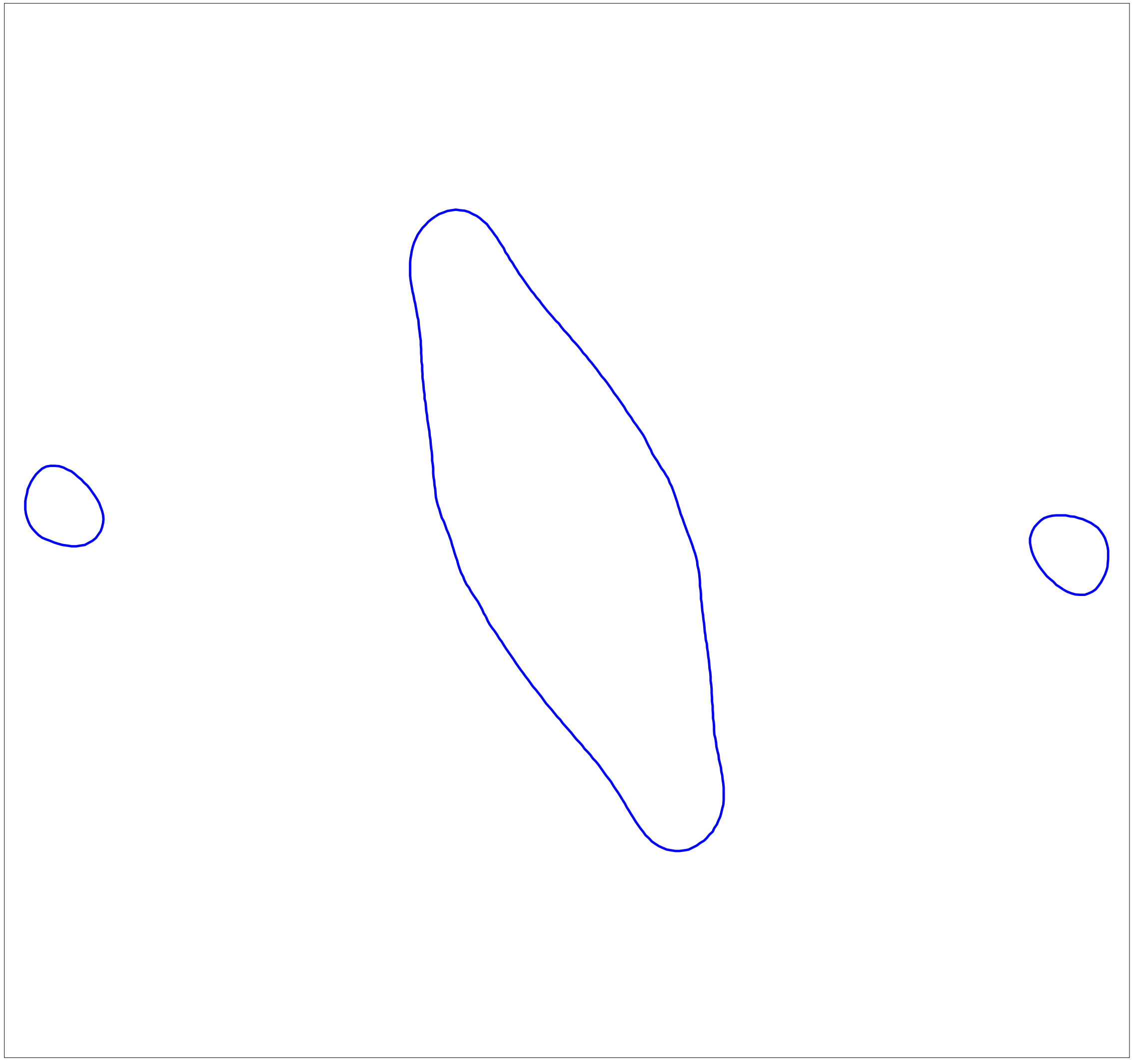

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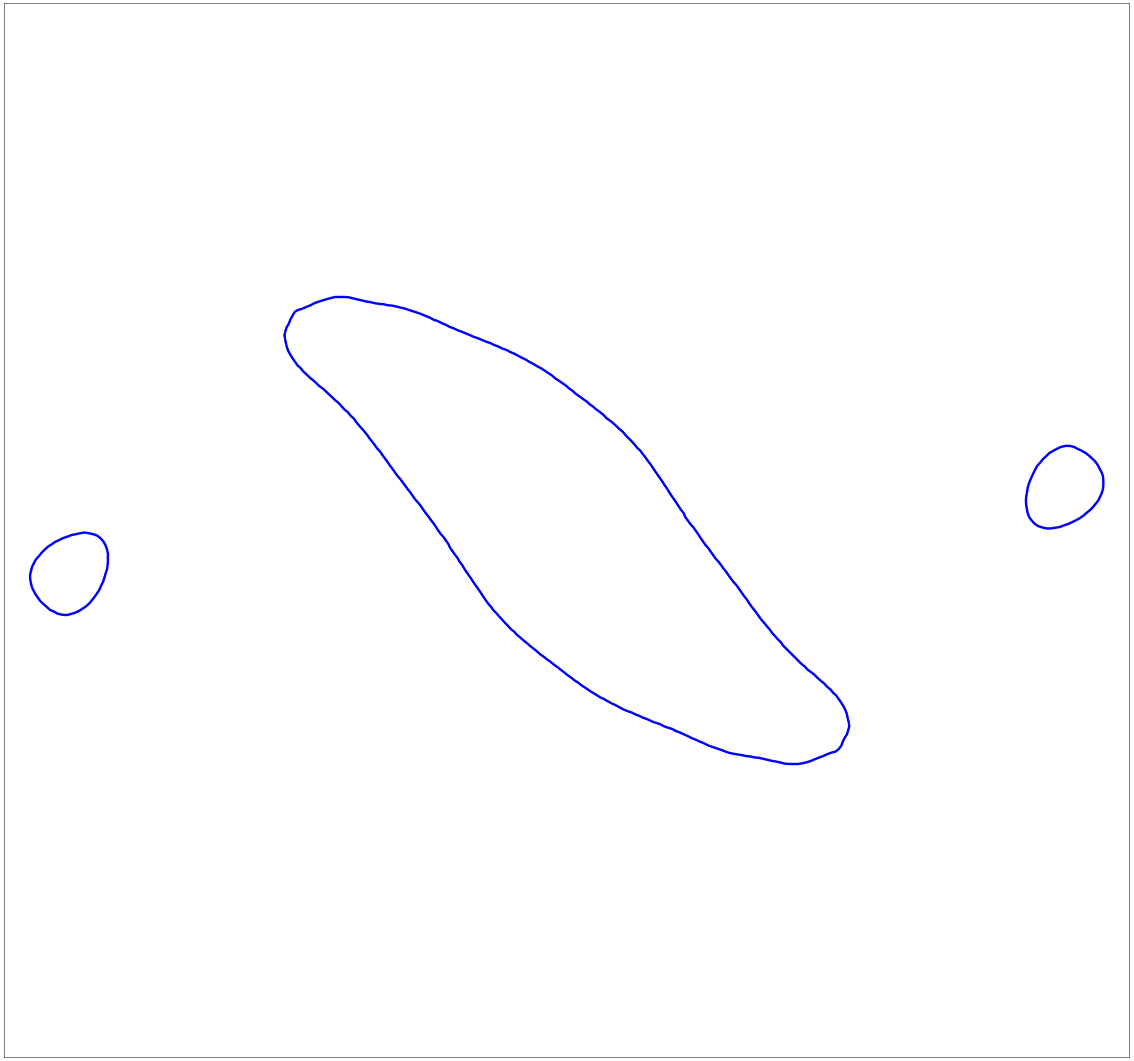

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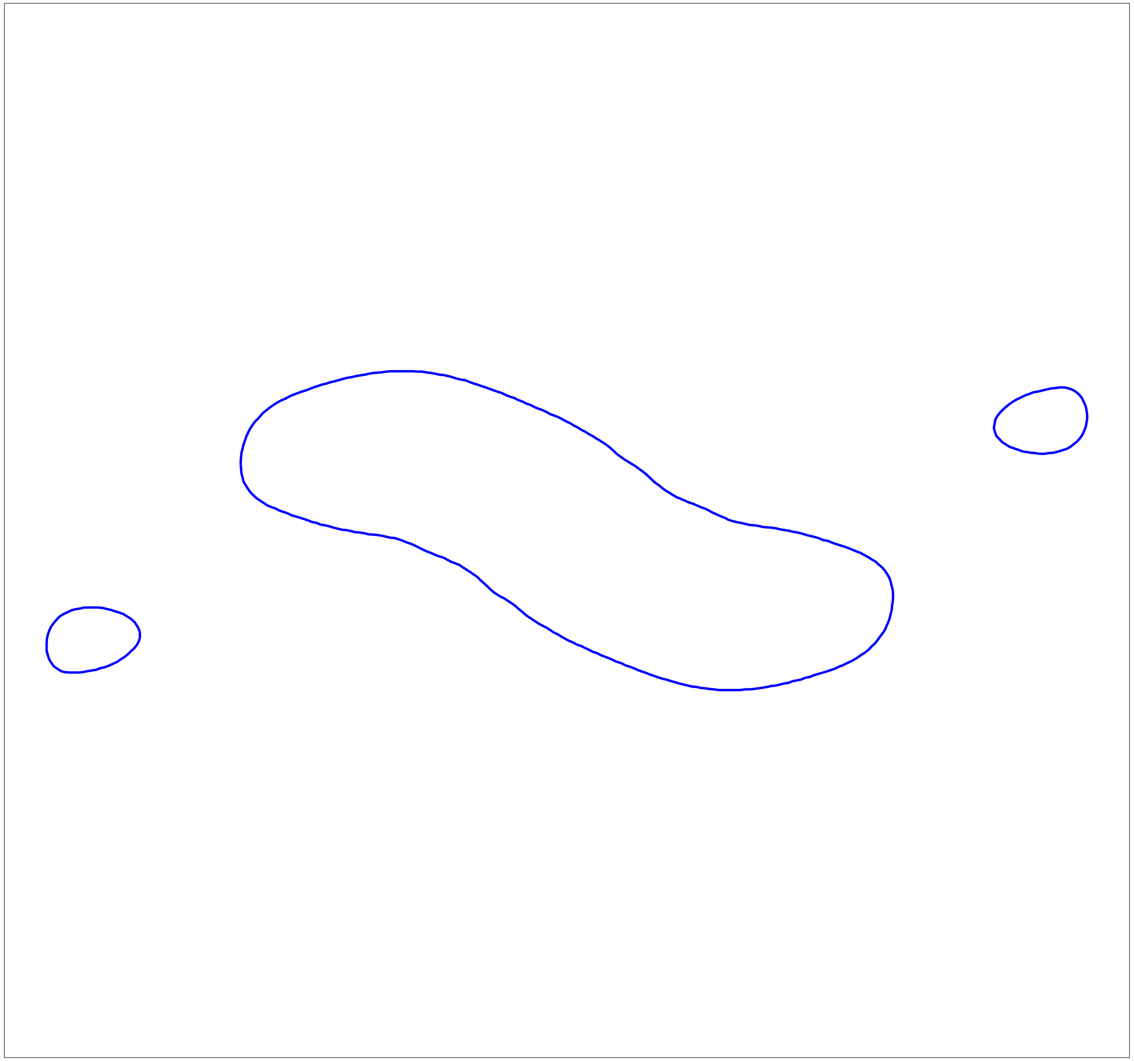

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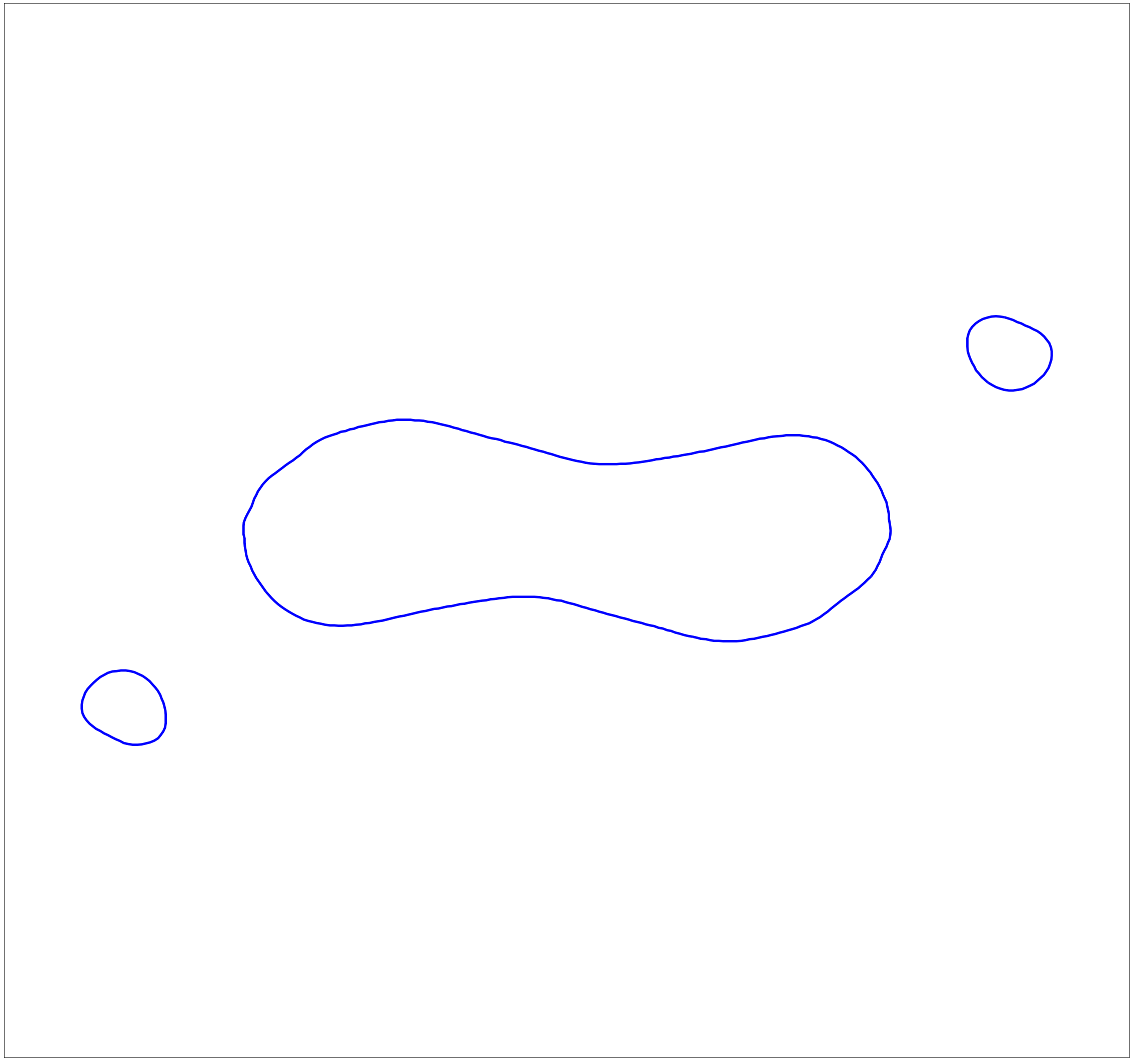

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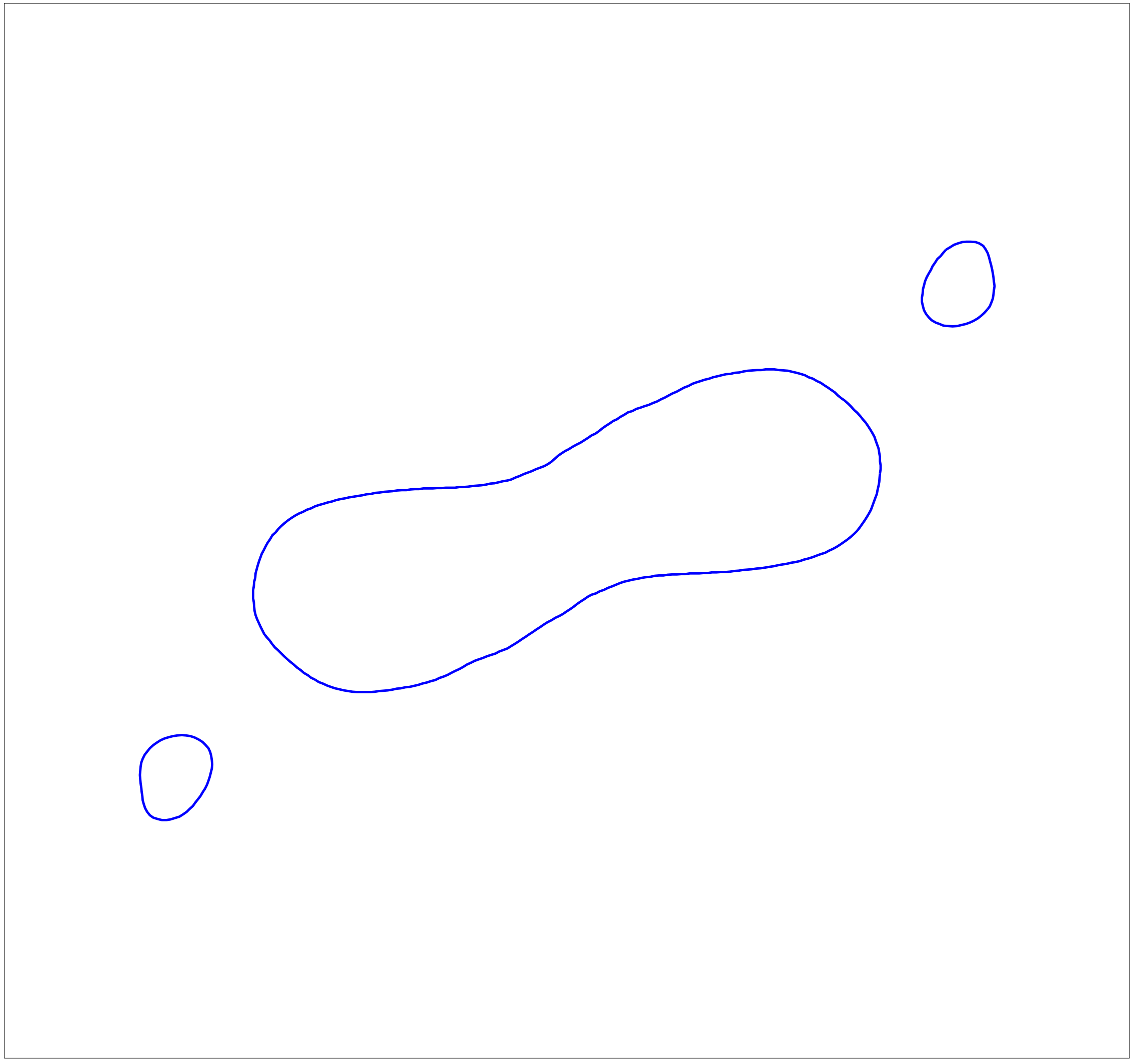

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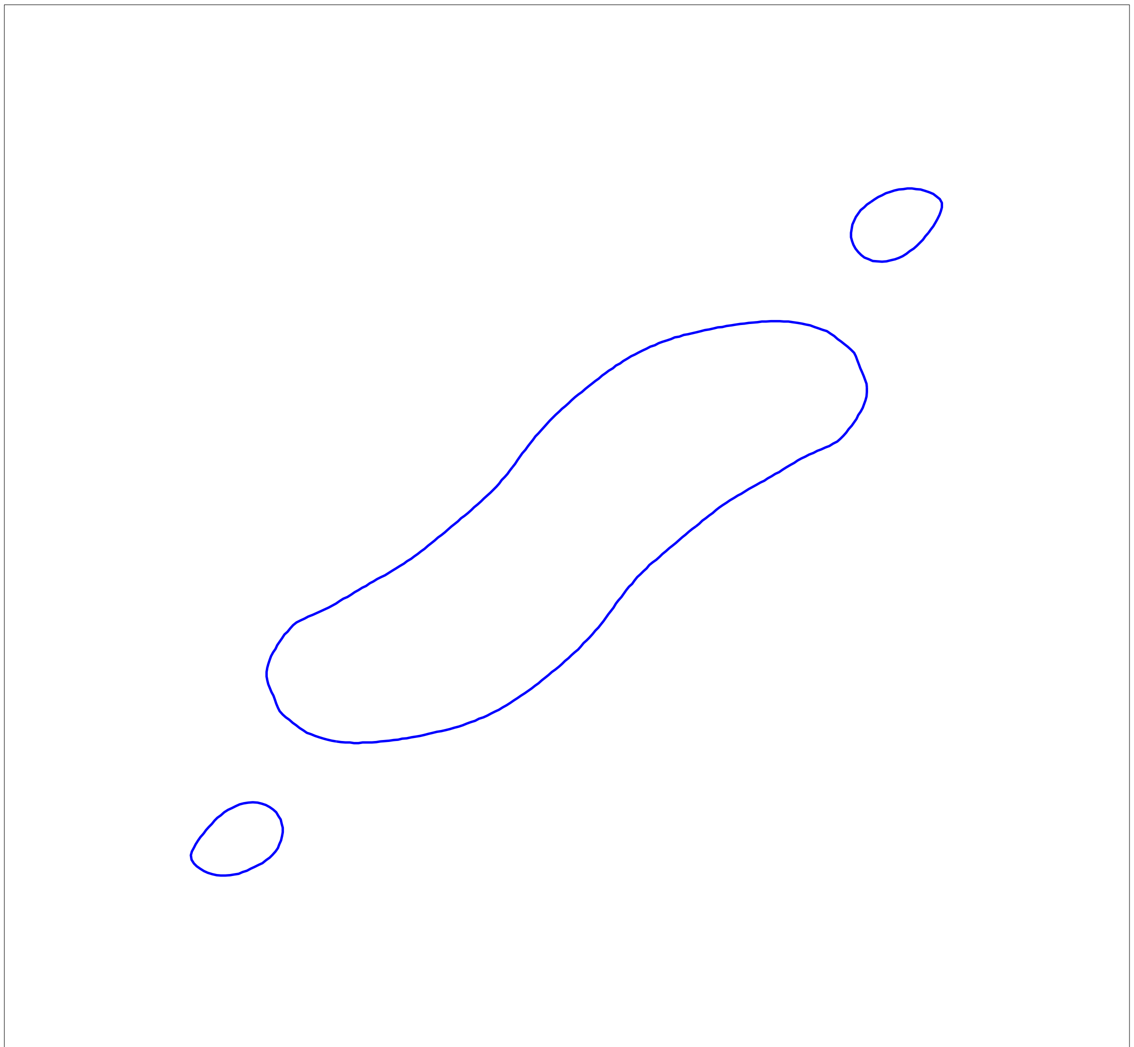

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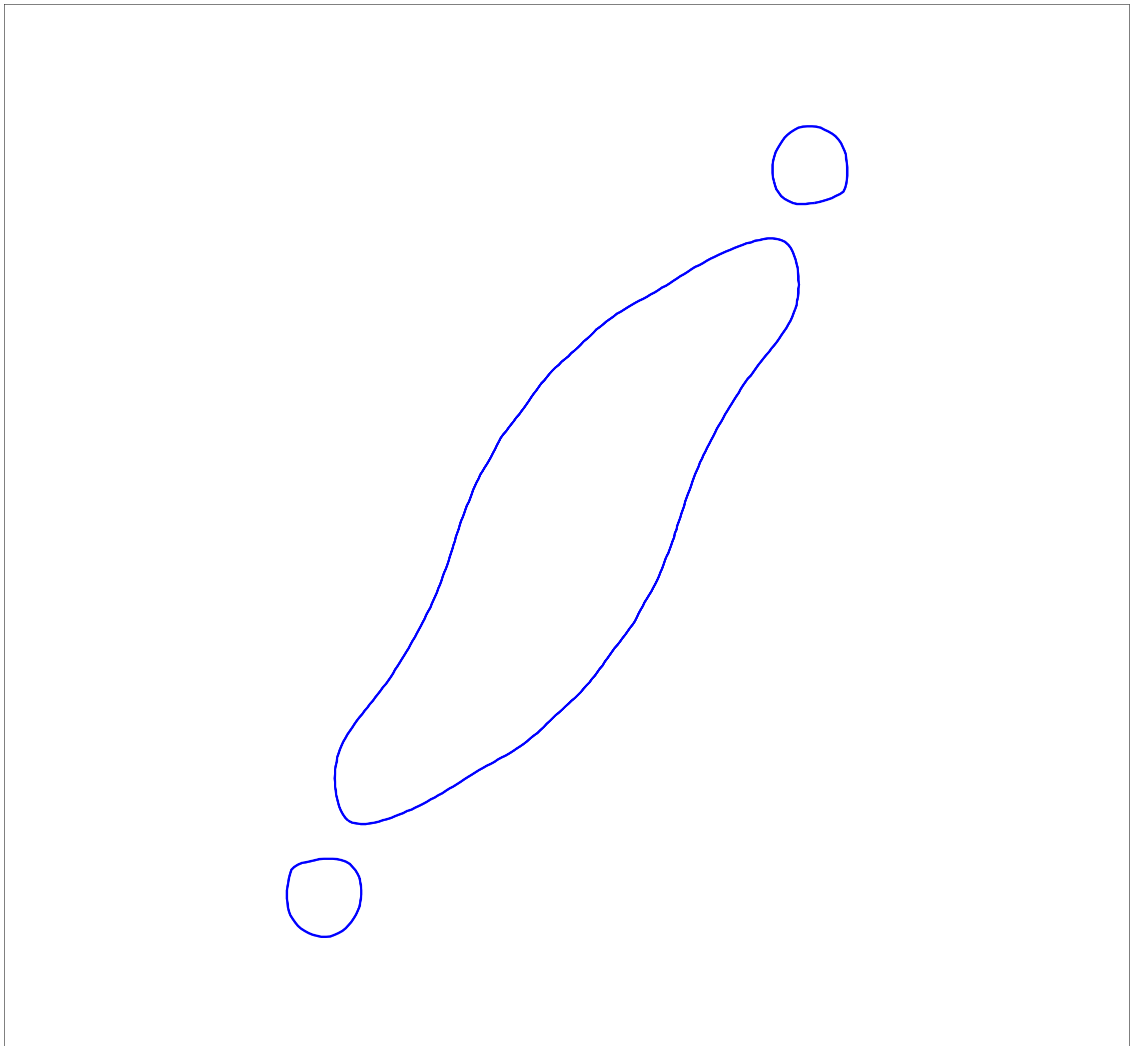

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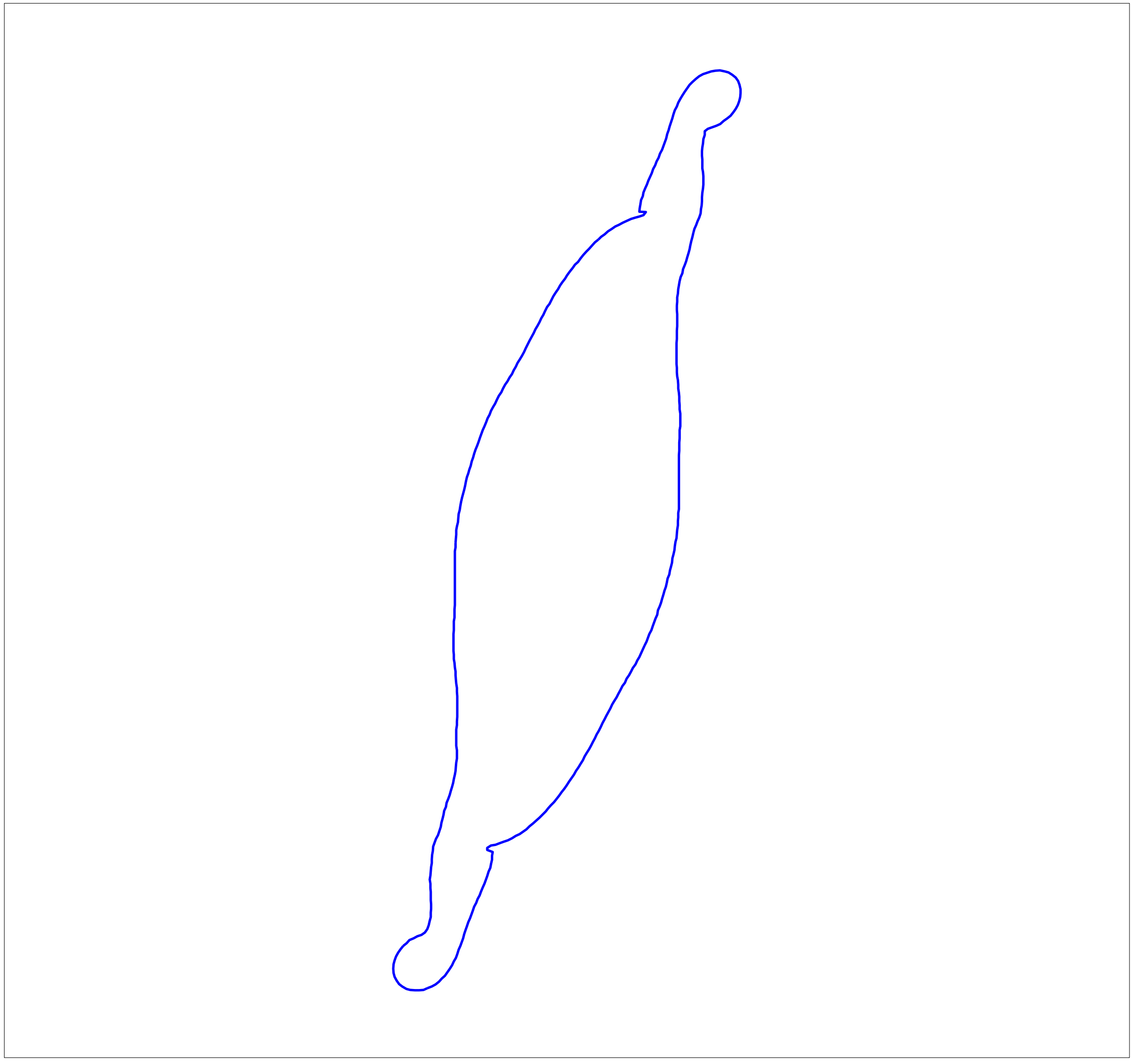

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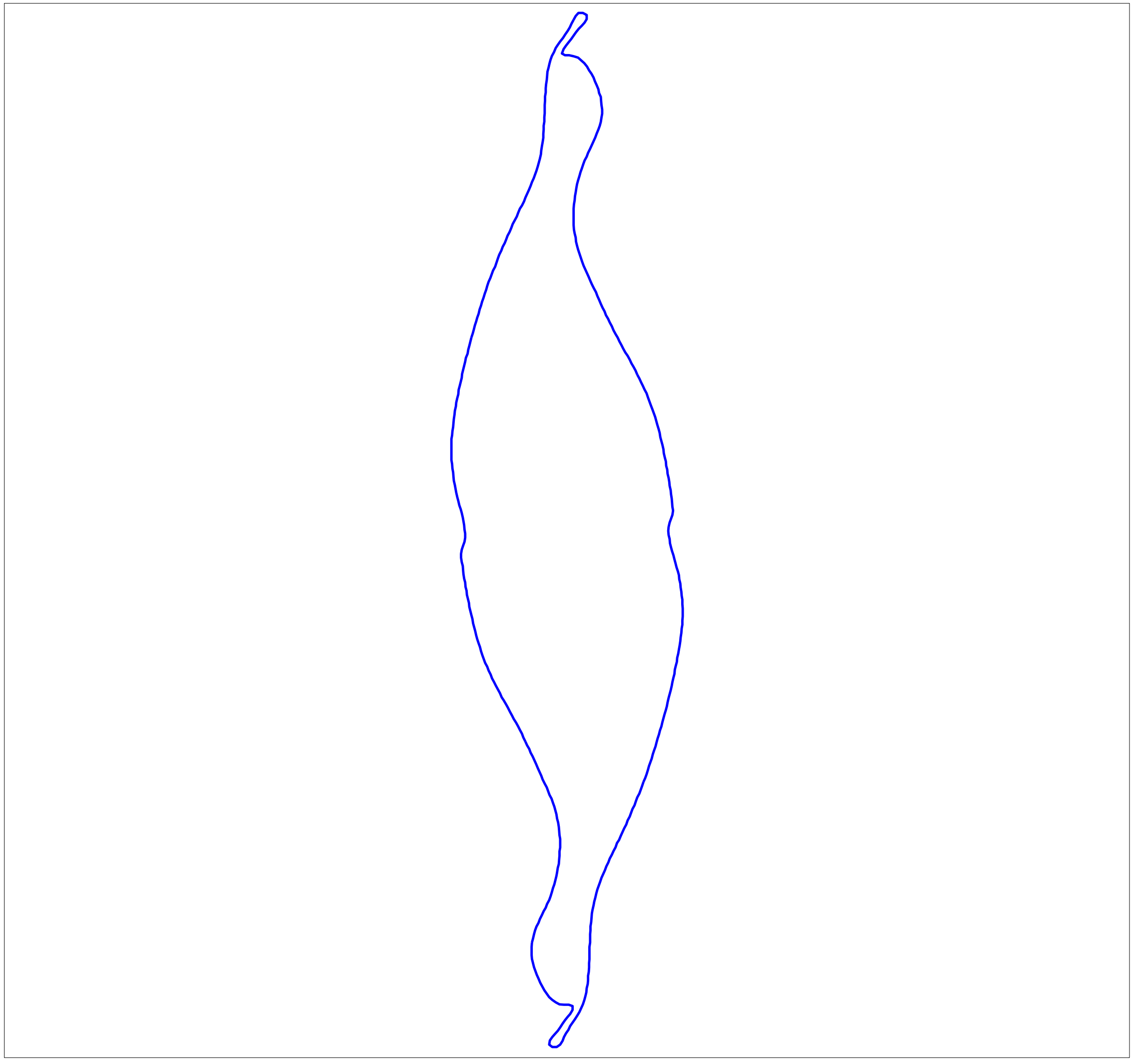

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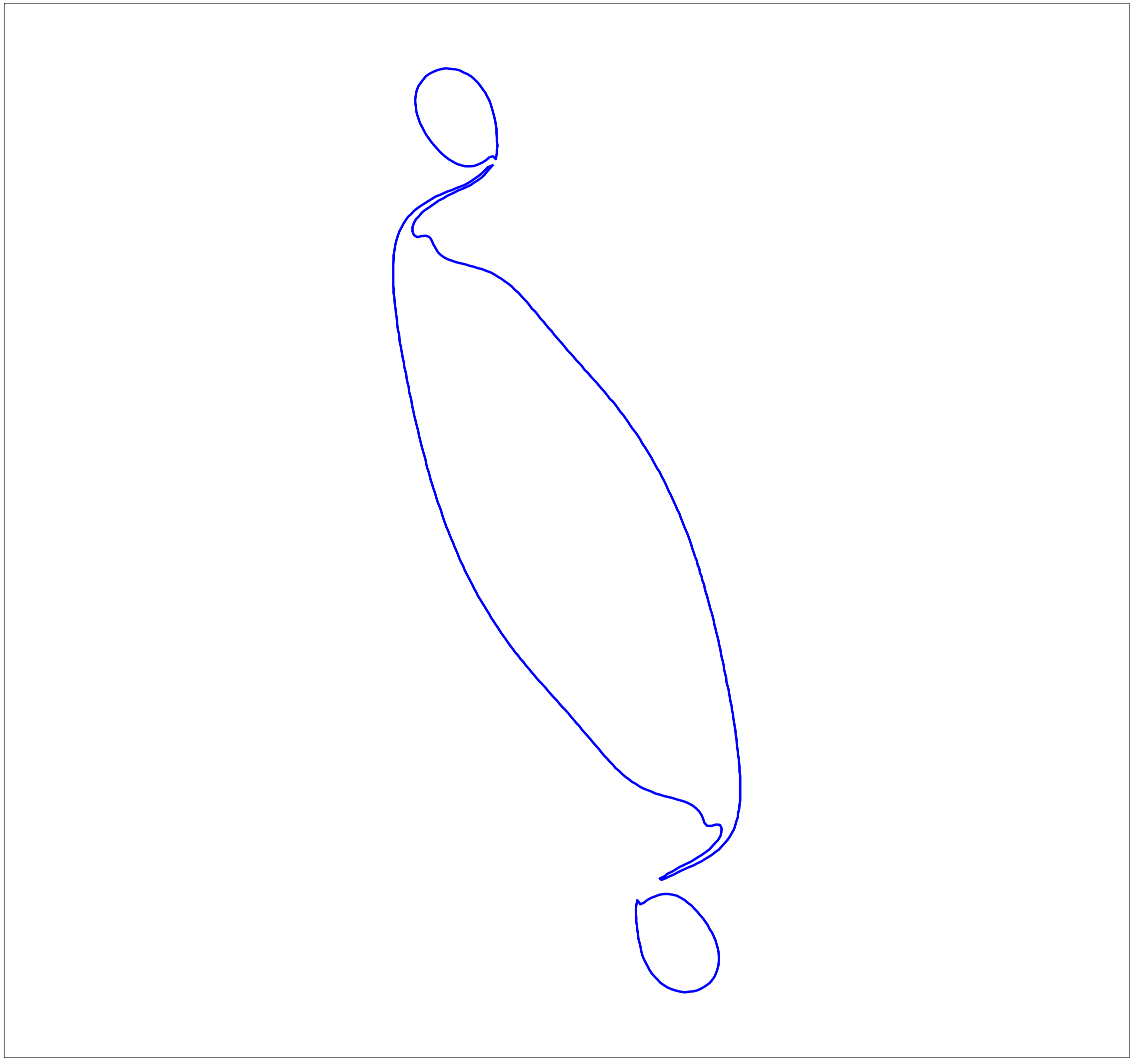

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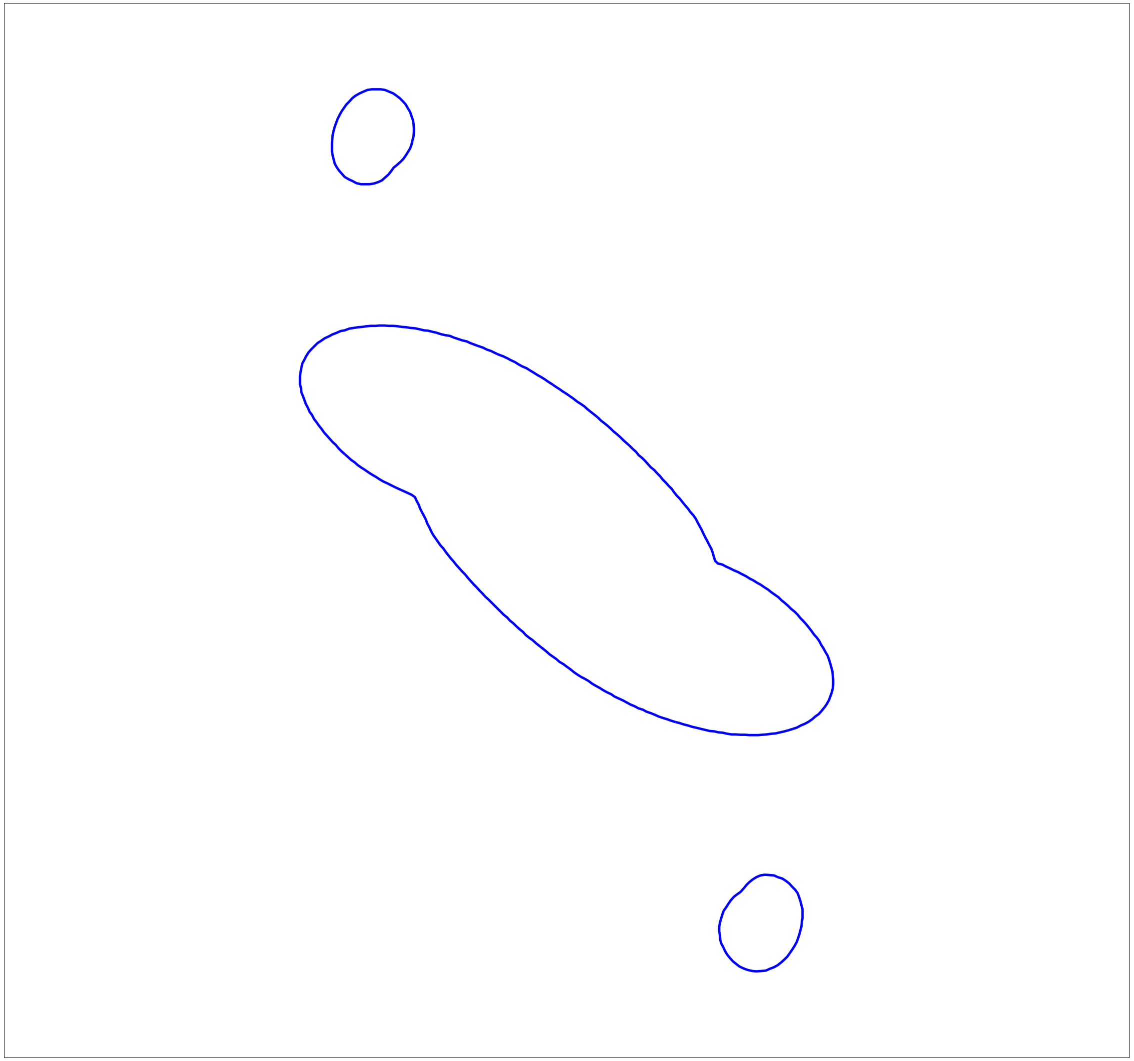

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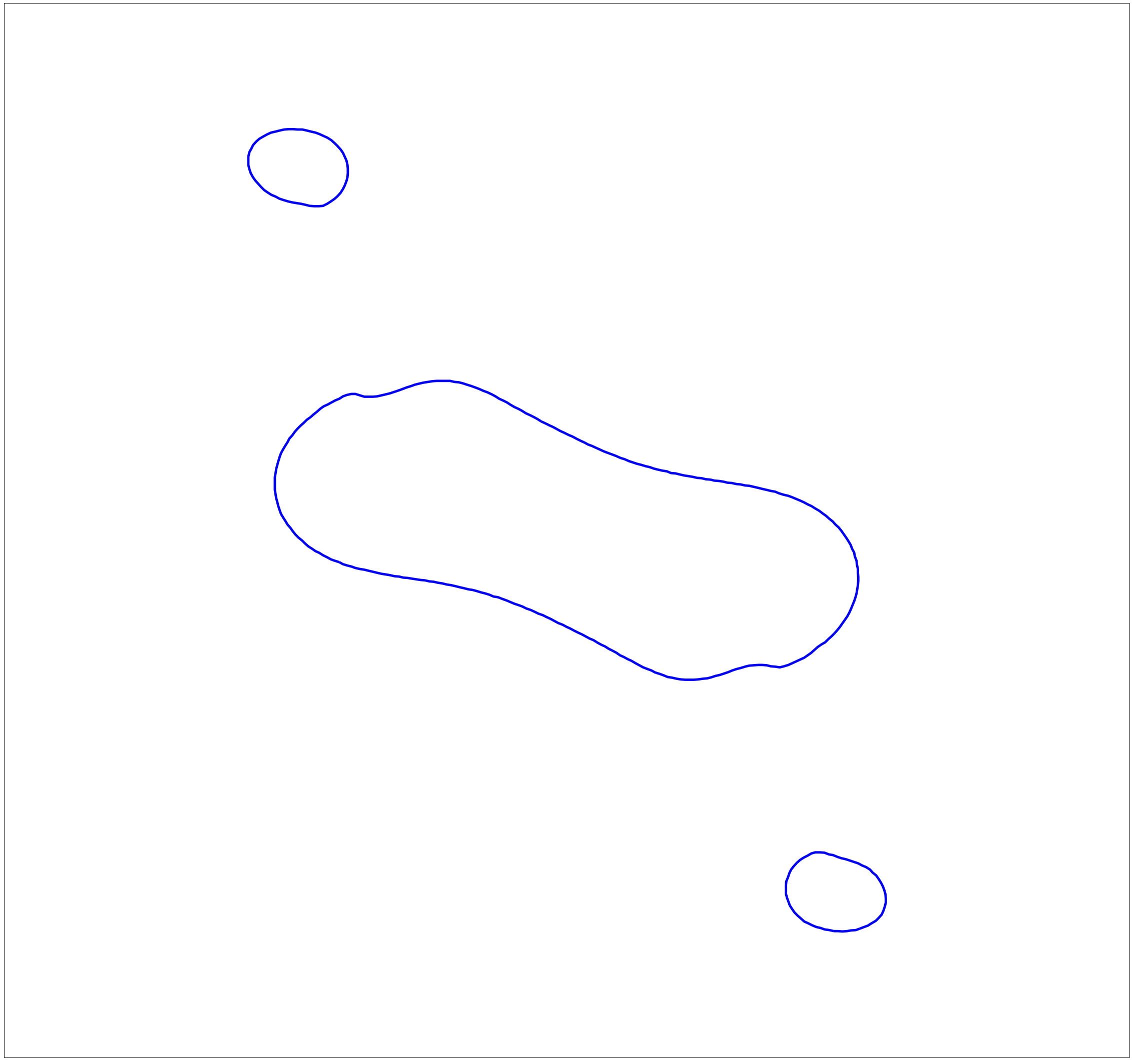

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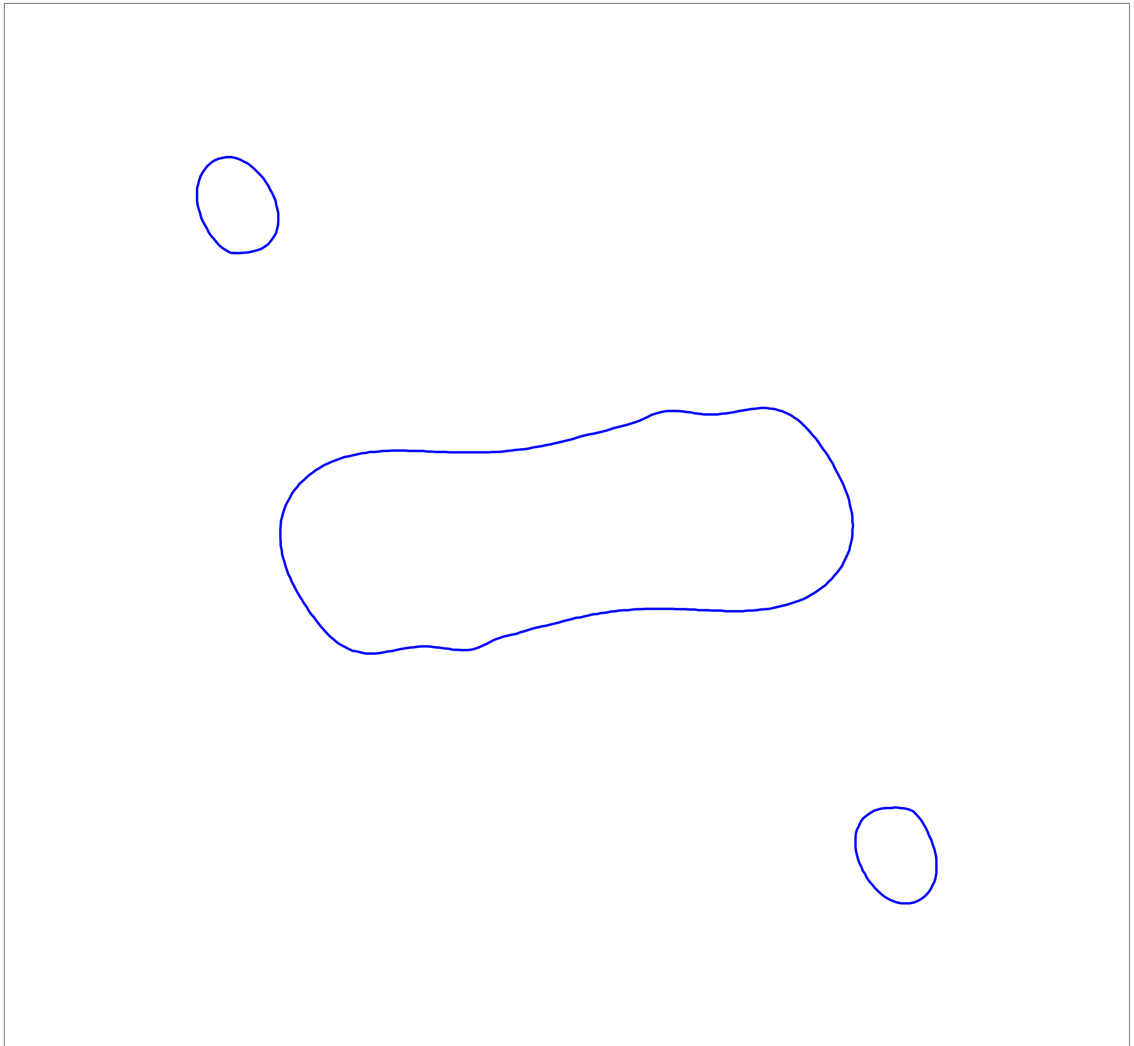

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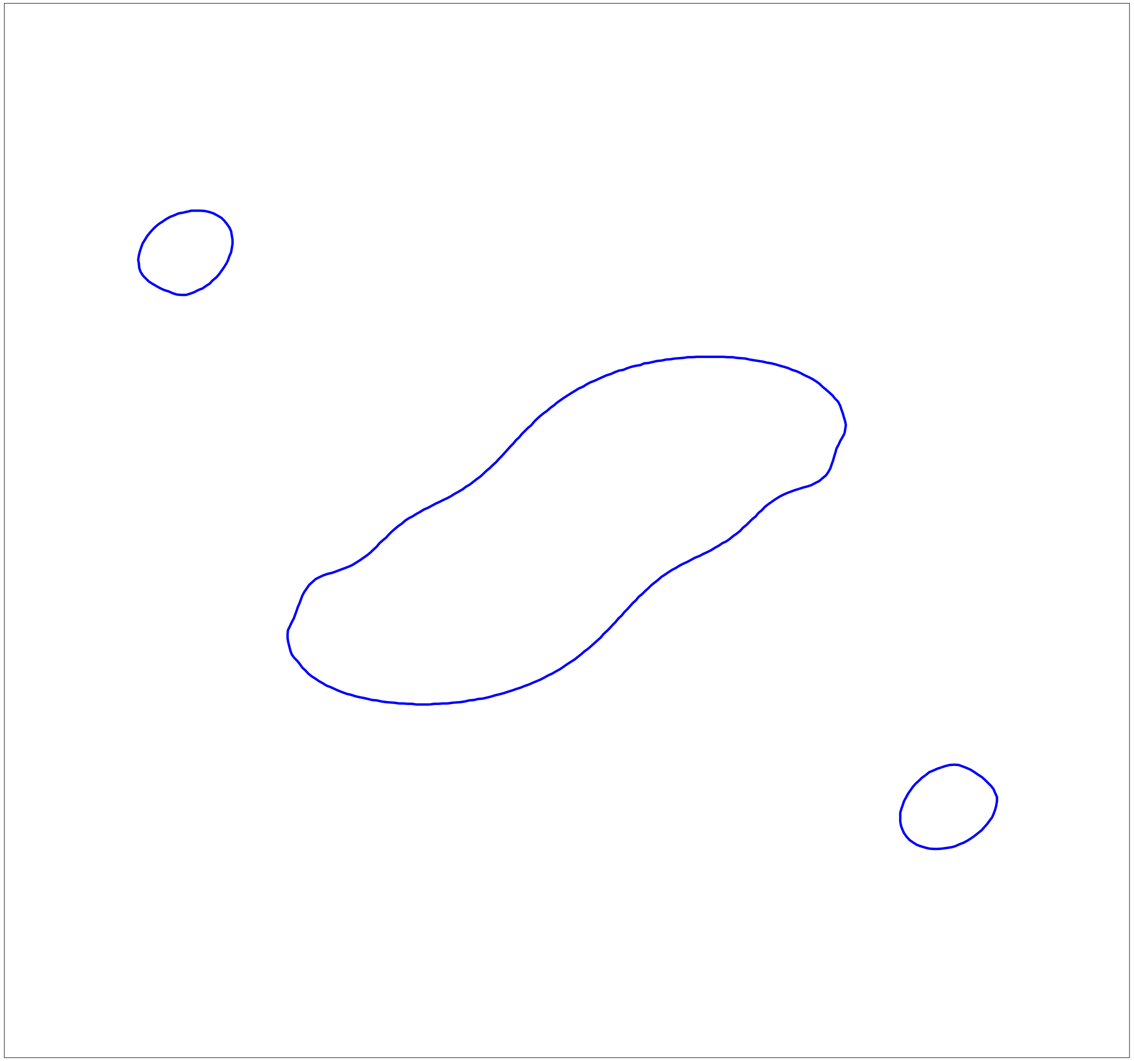

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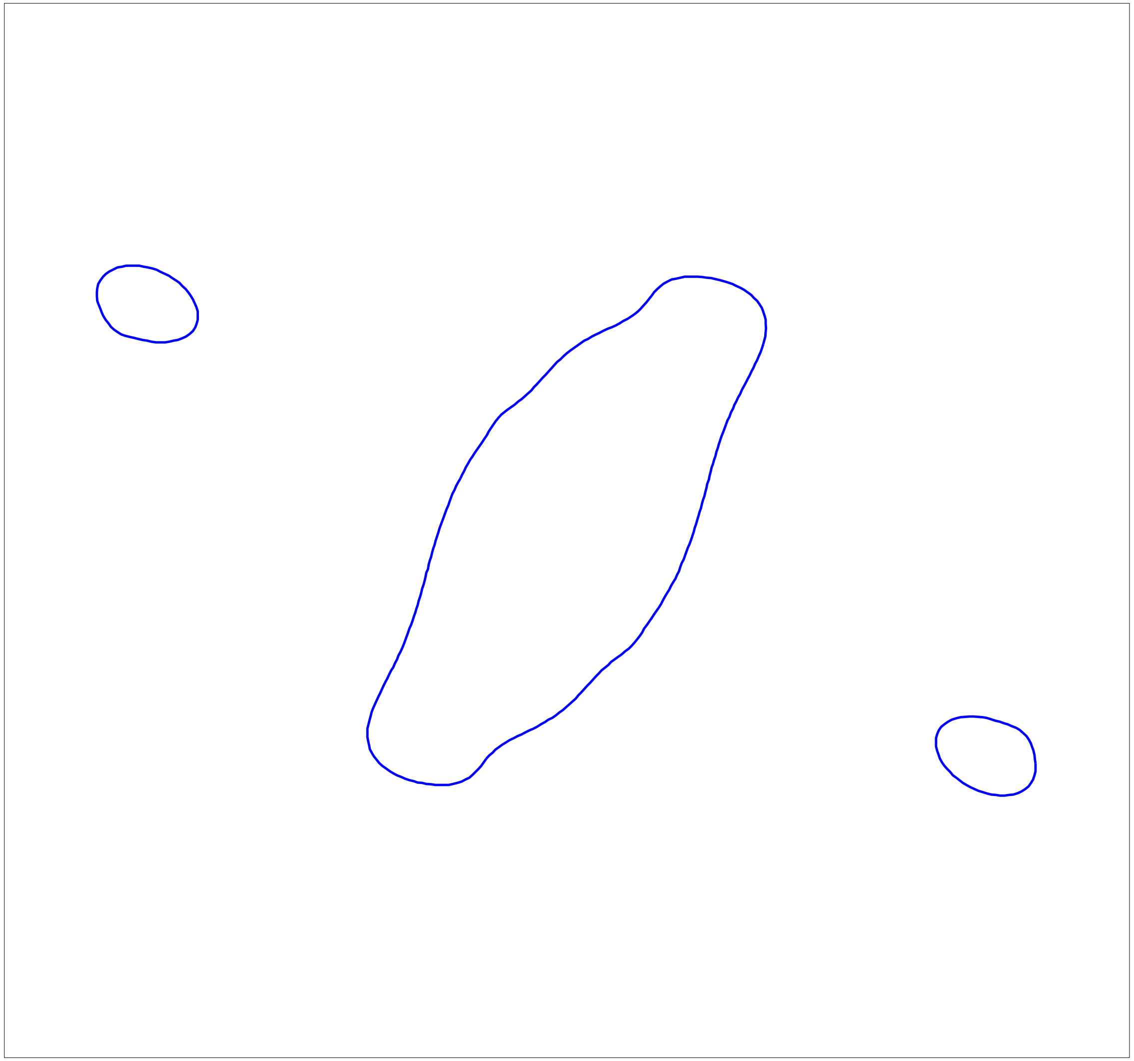

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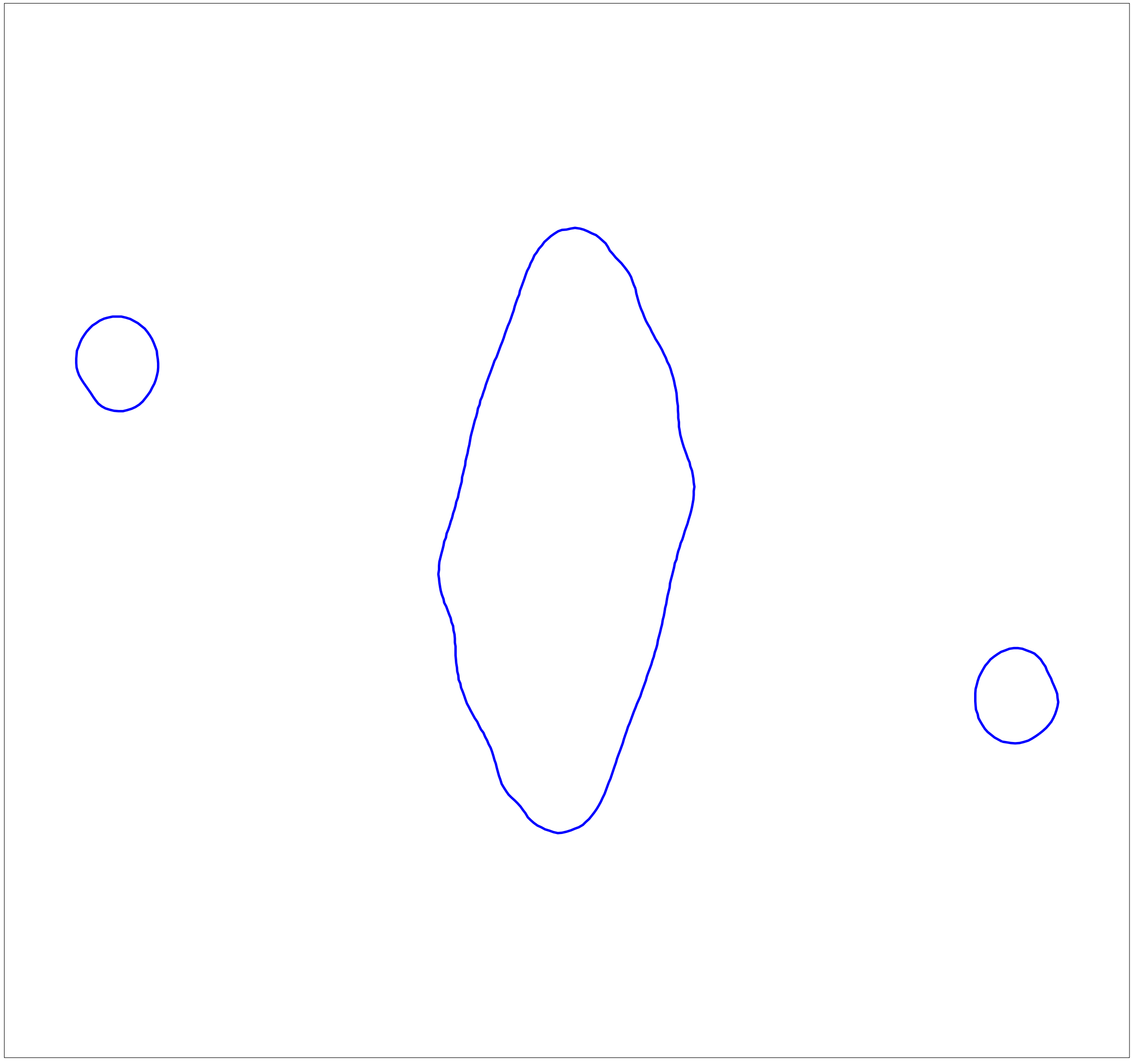

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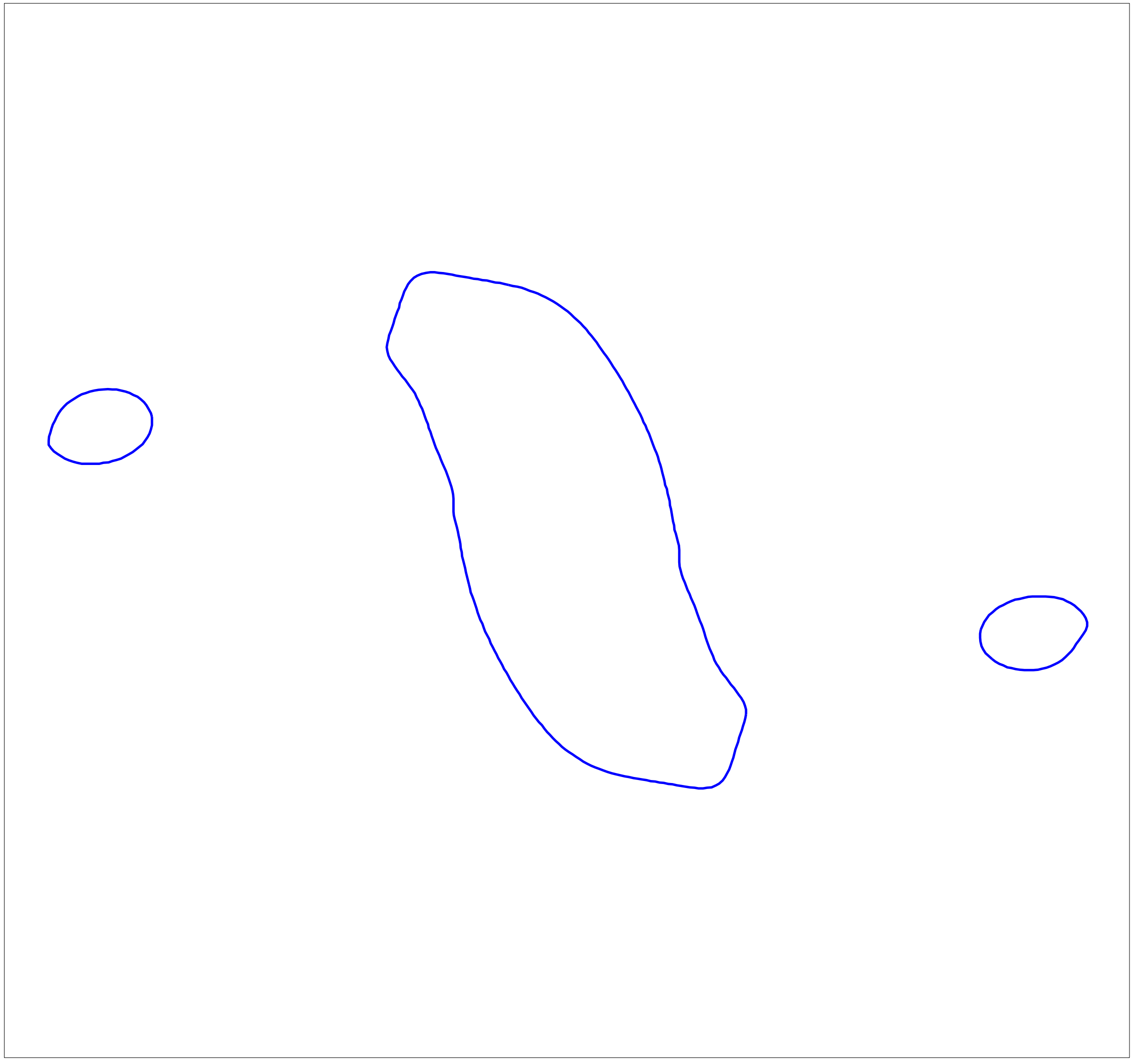
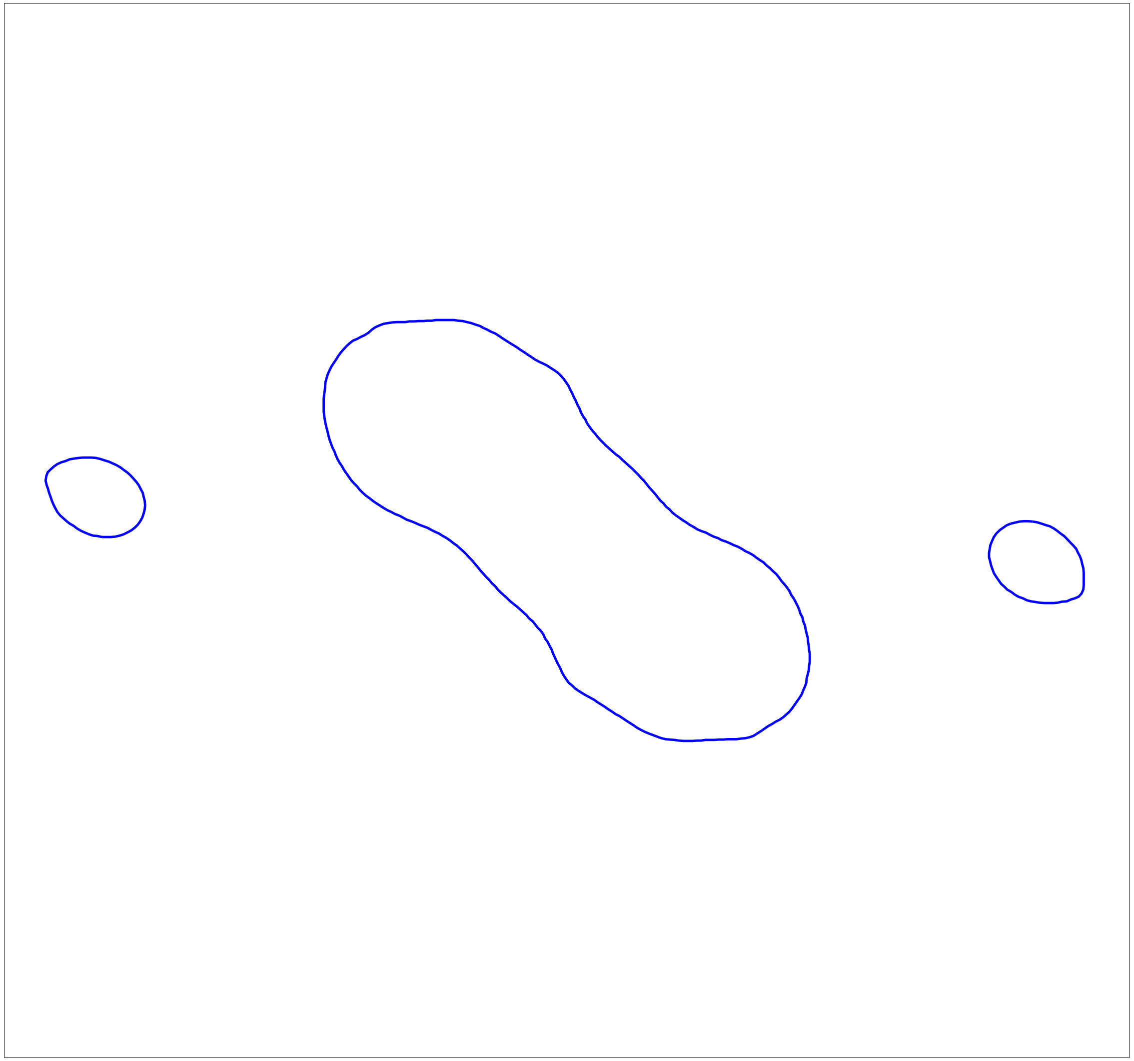
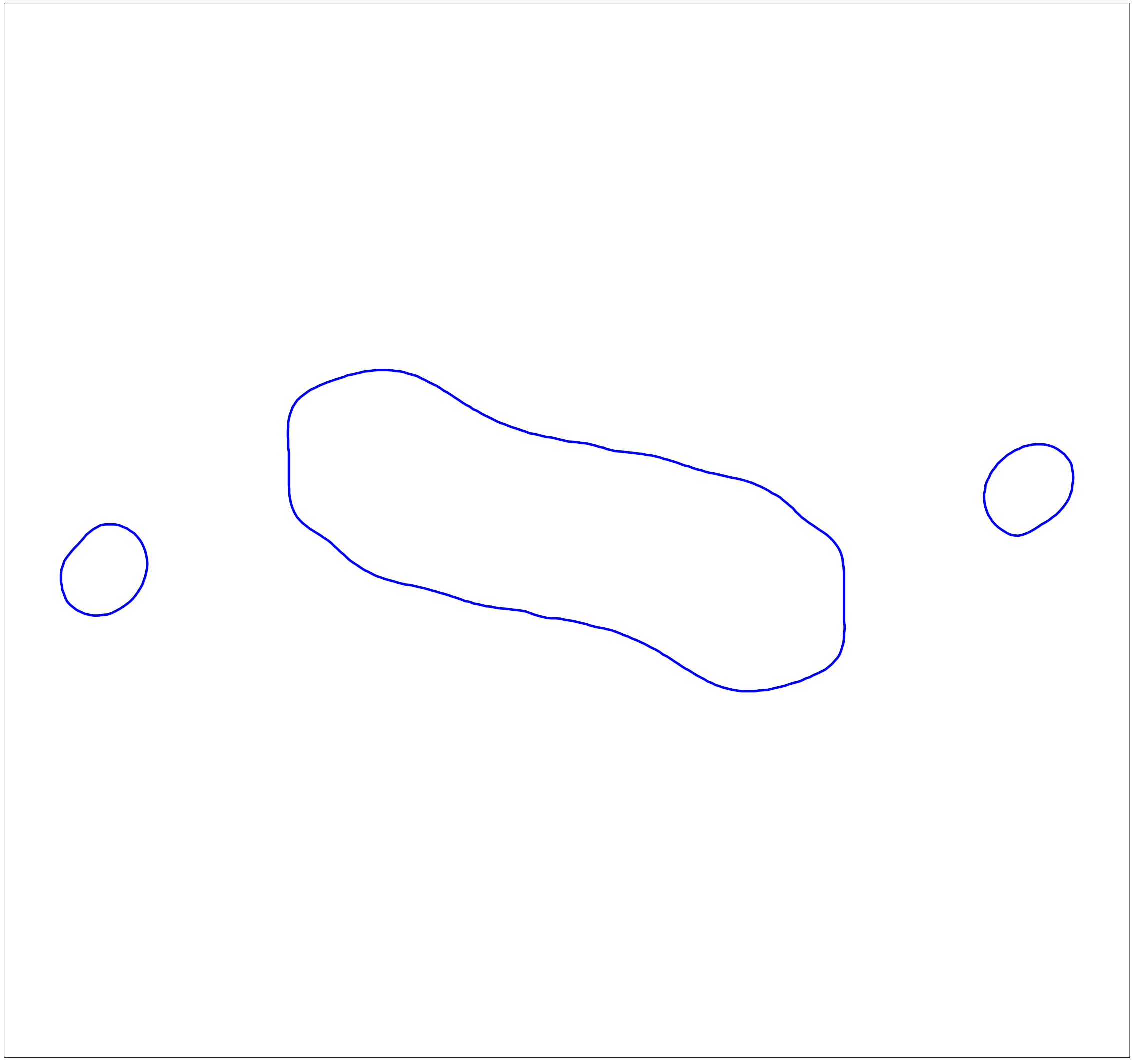


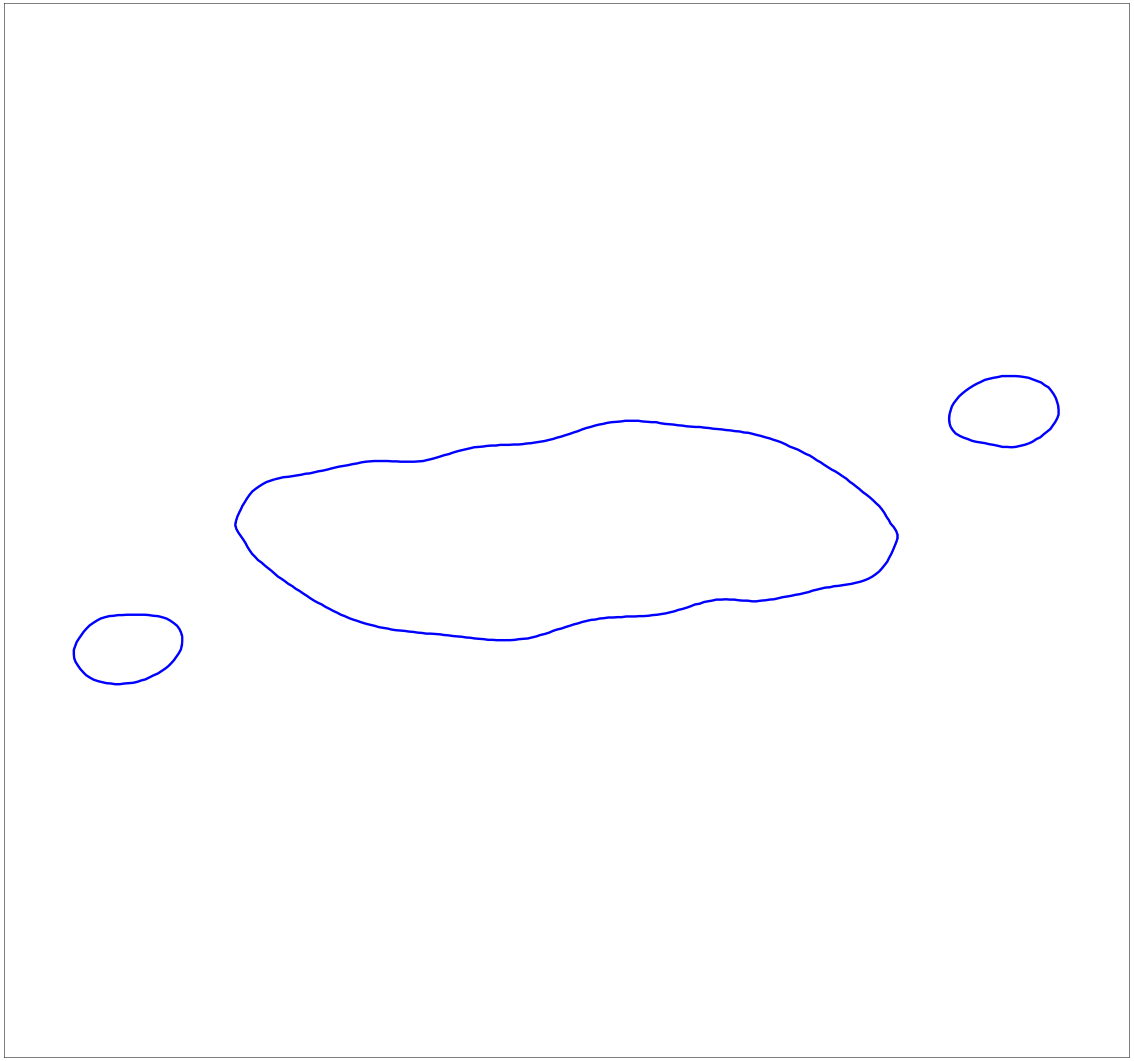
t=64



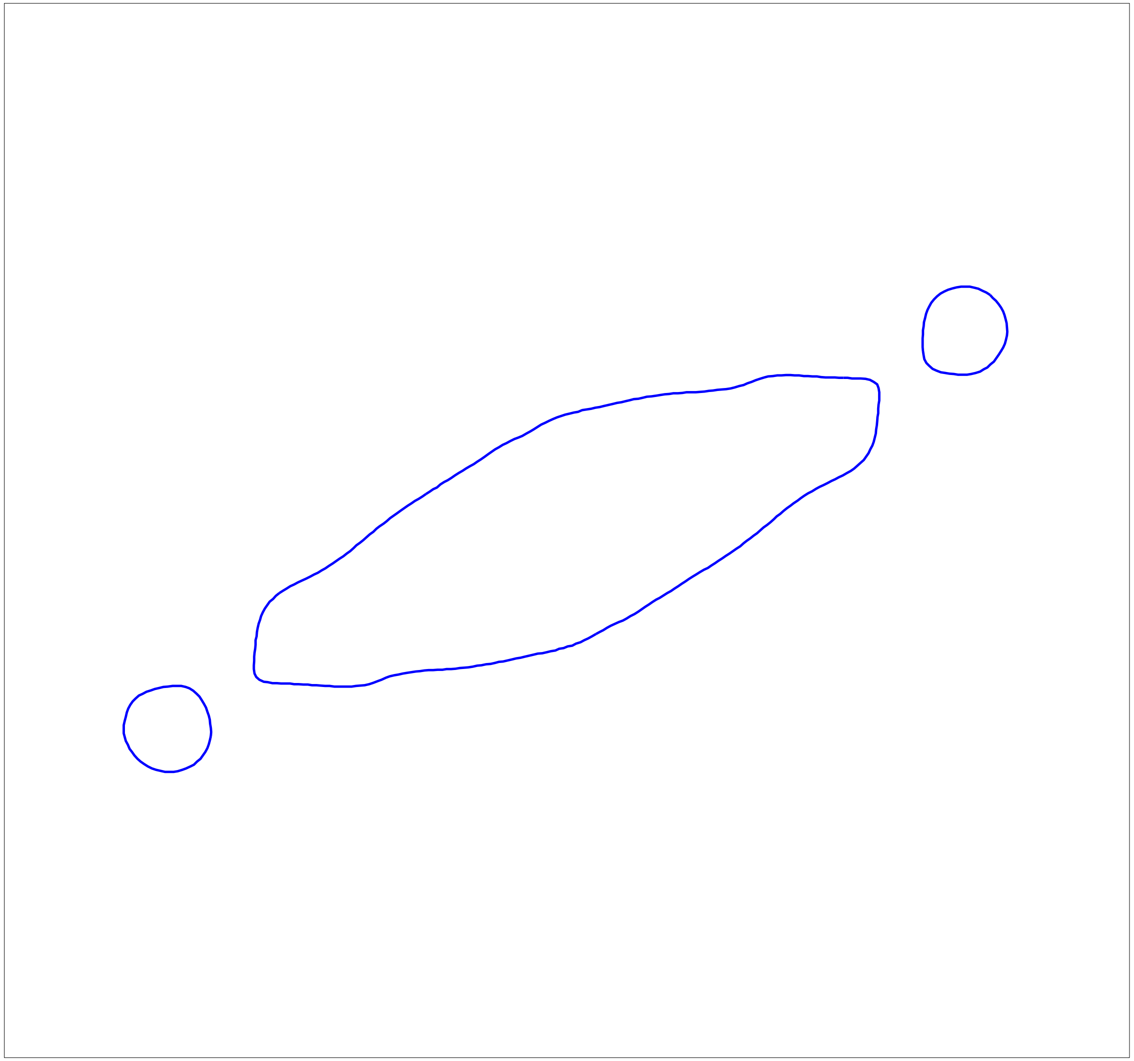
t=66



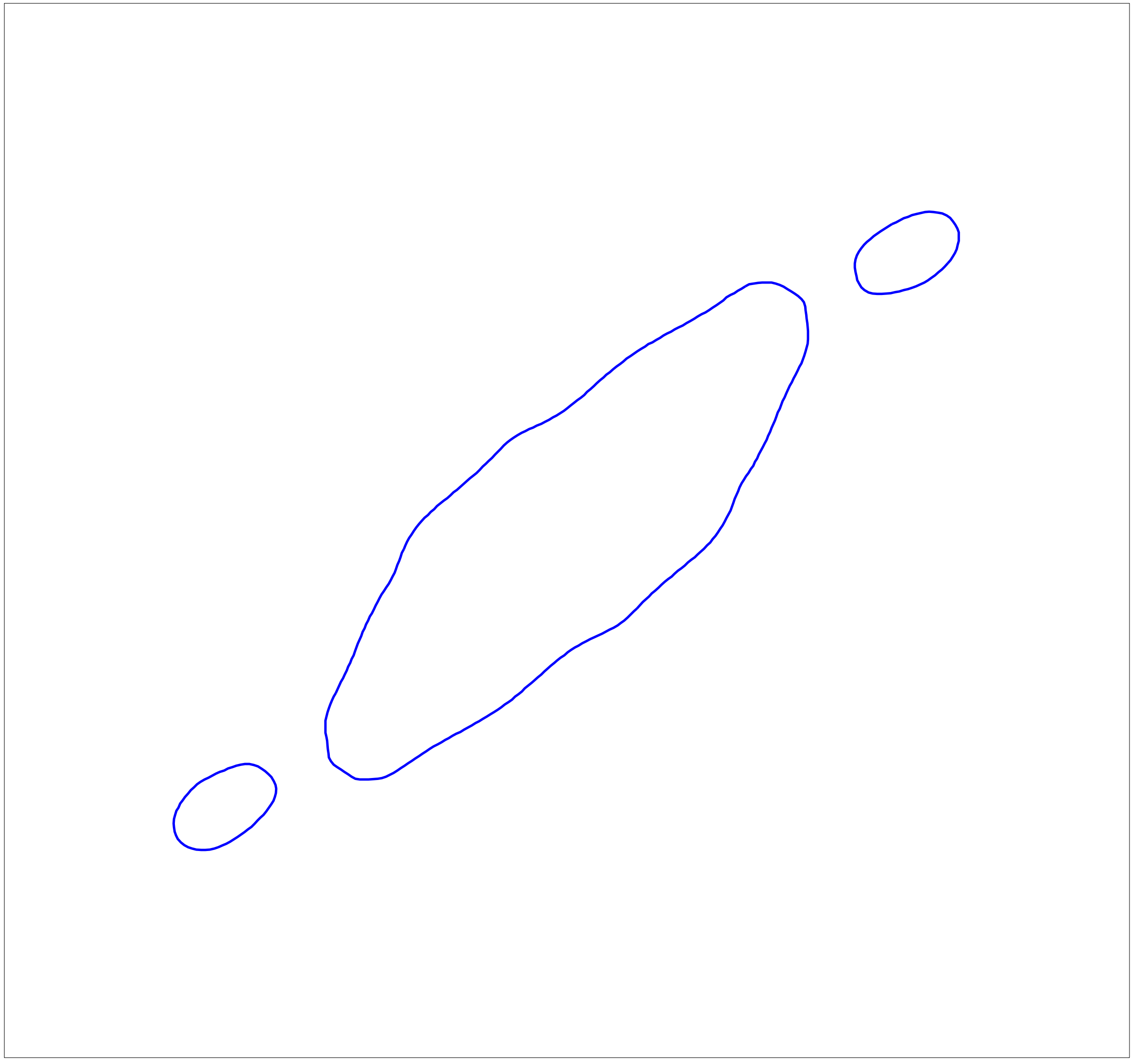
t=68



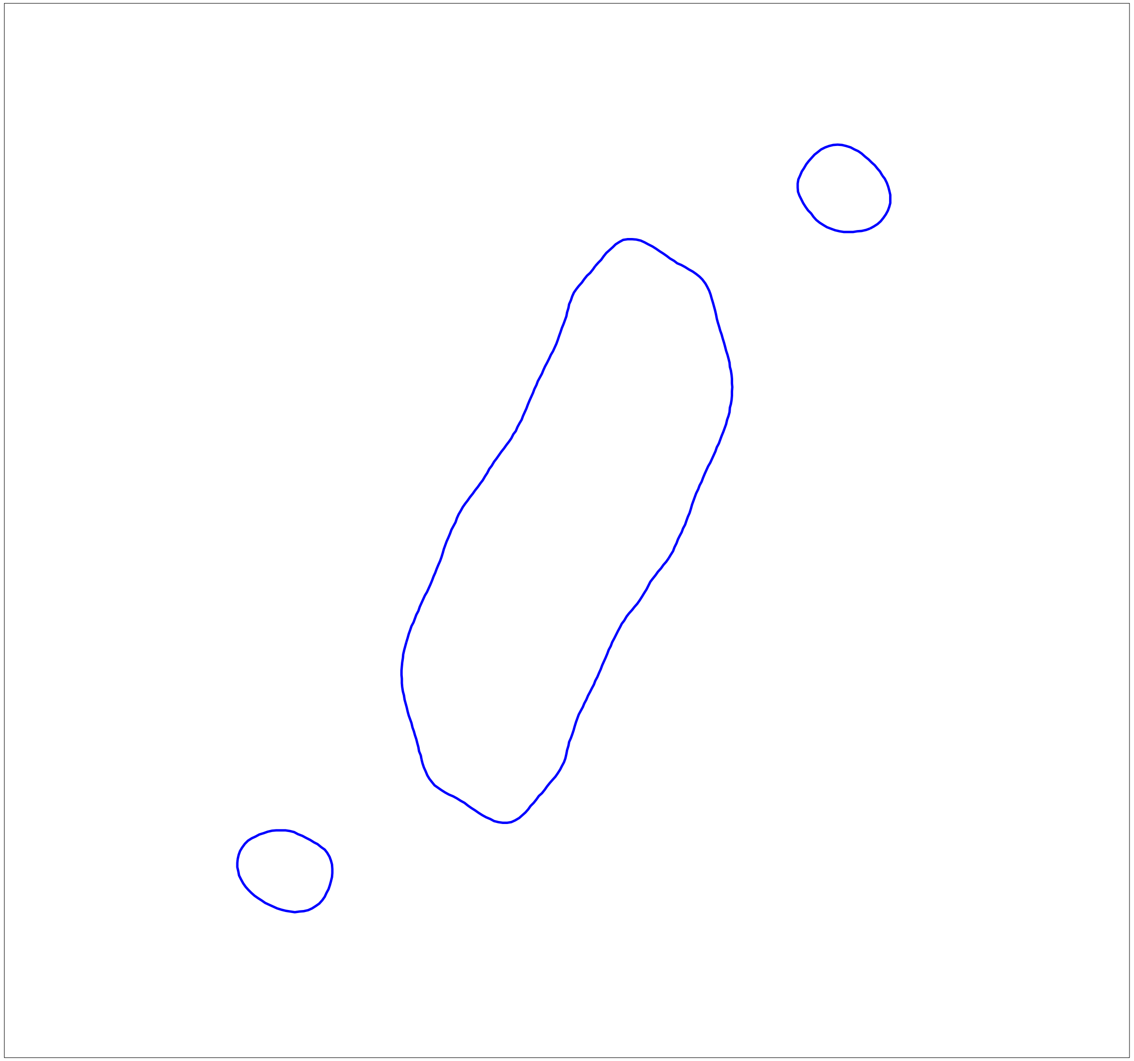
t=70



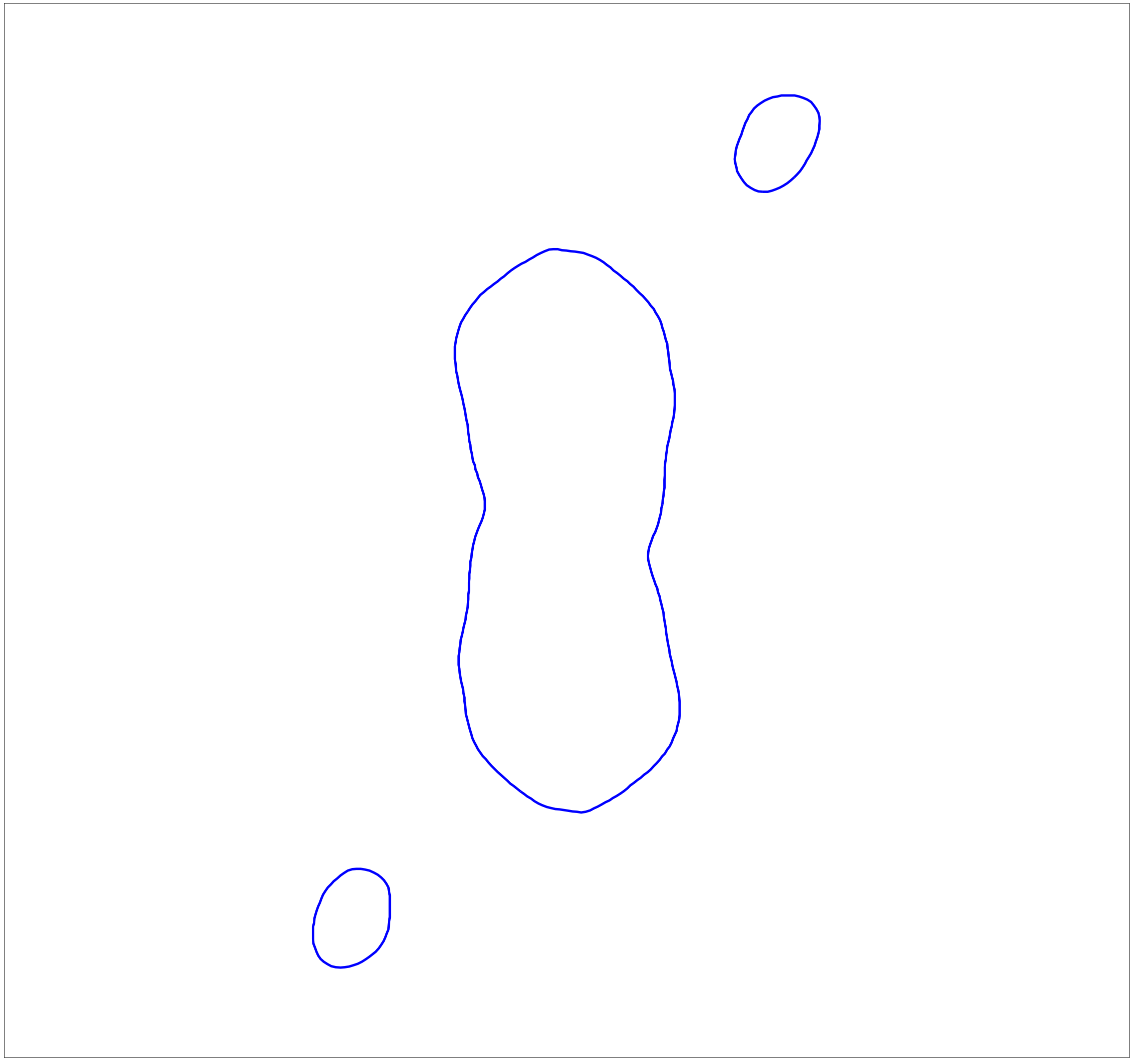
t=72



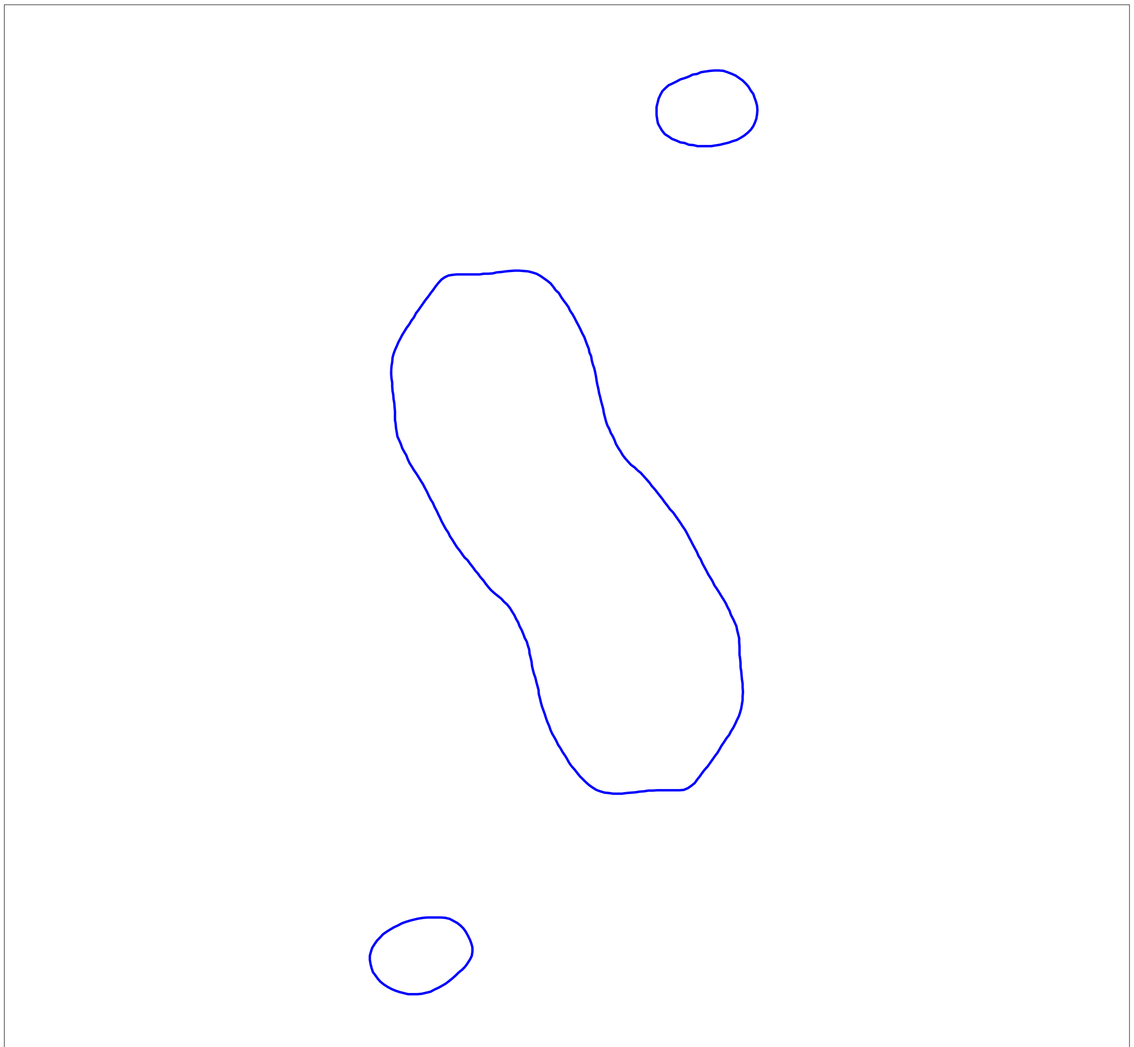
t=74



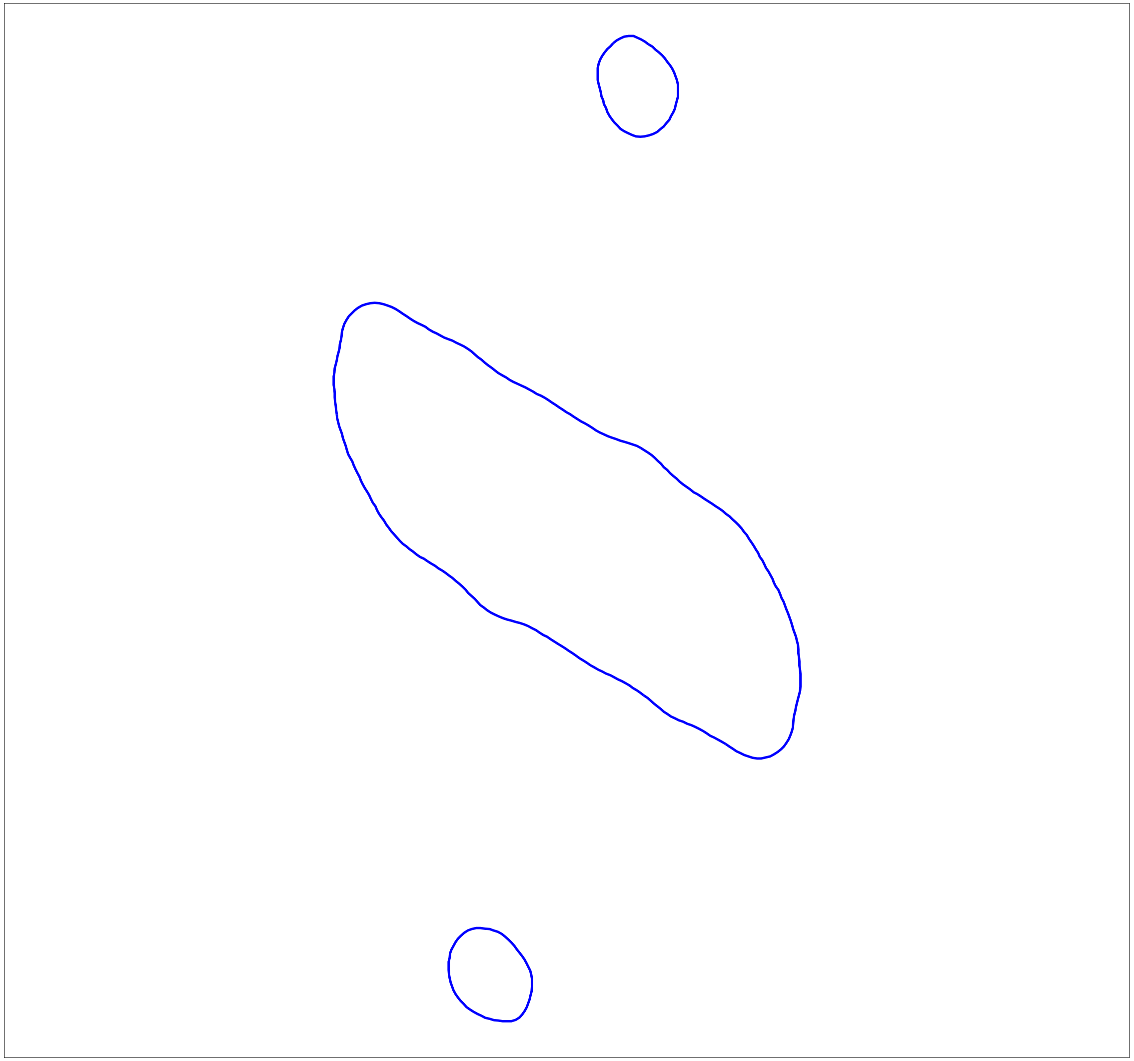
t=76



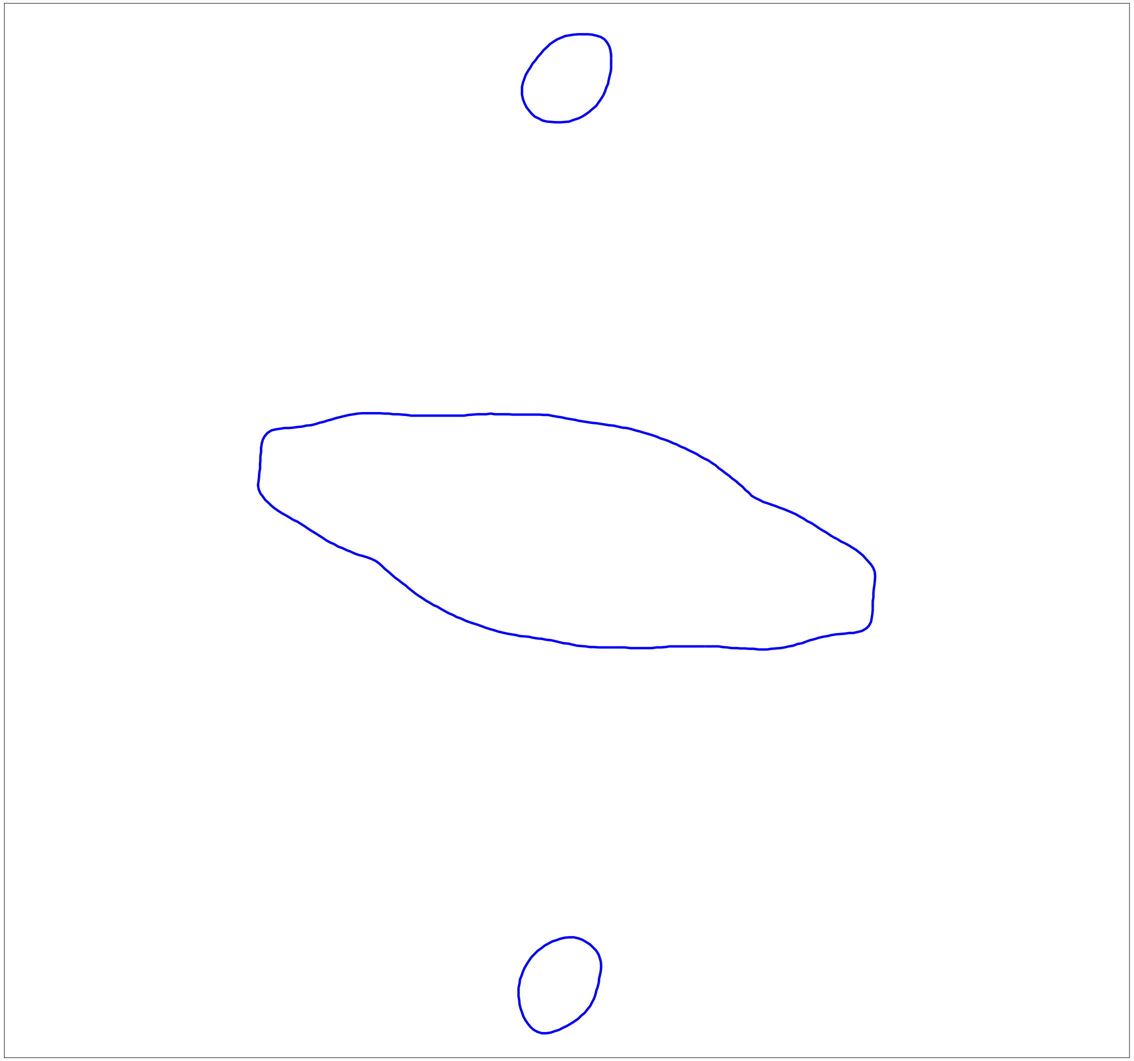
t=78



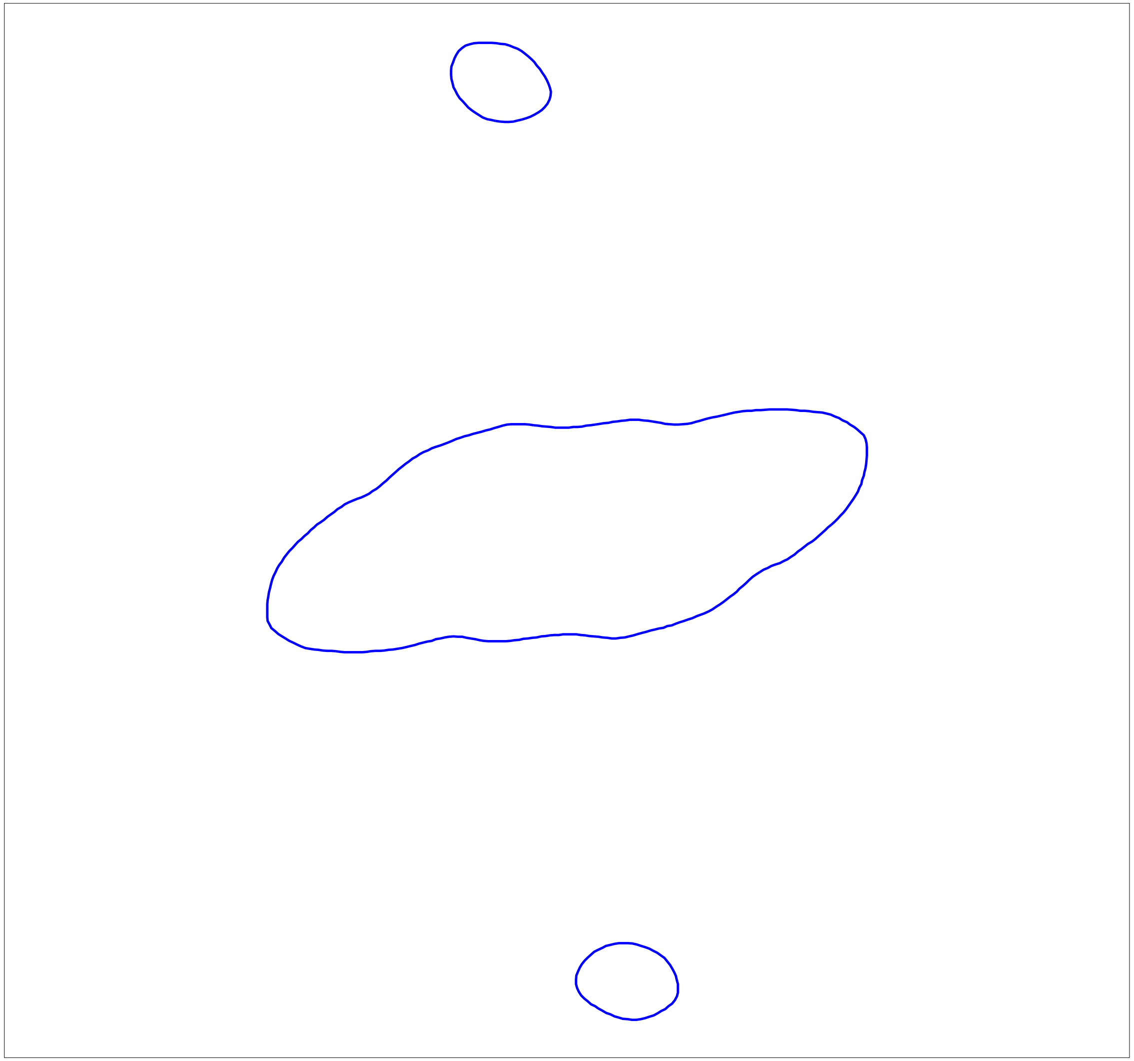
t=80



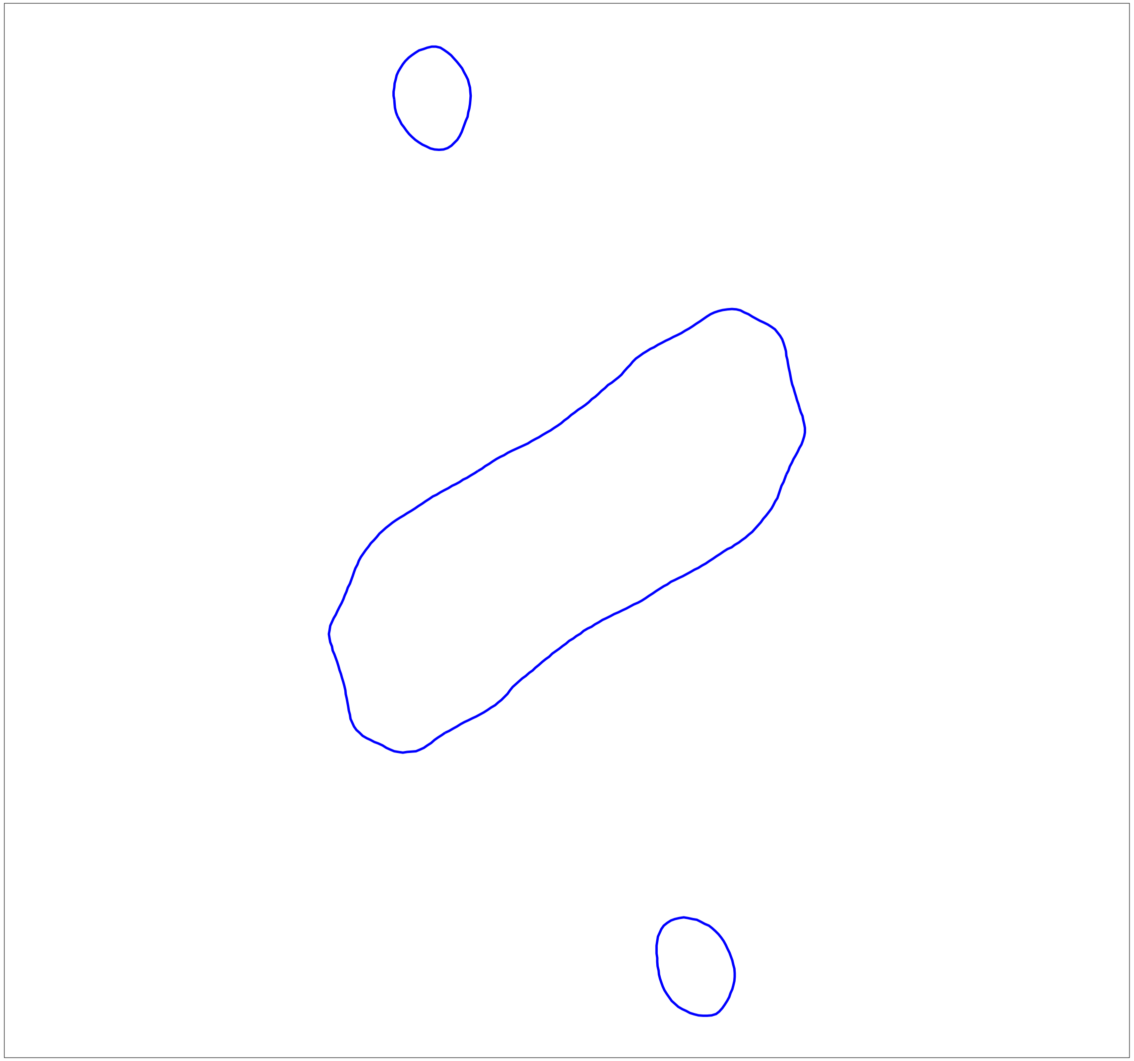
t=82



t=84



t=86



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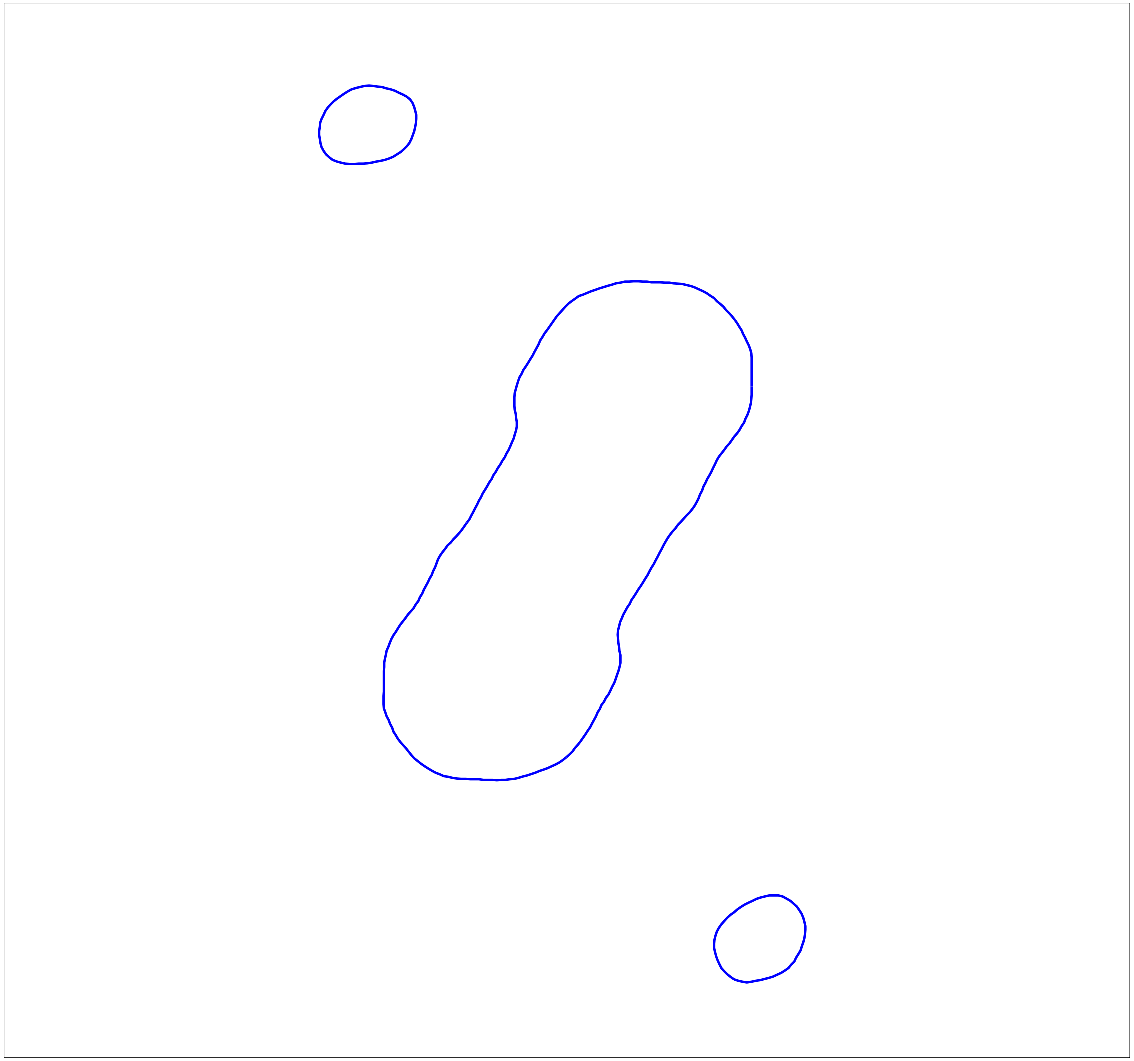

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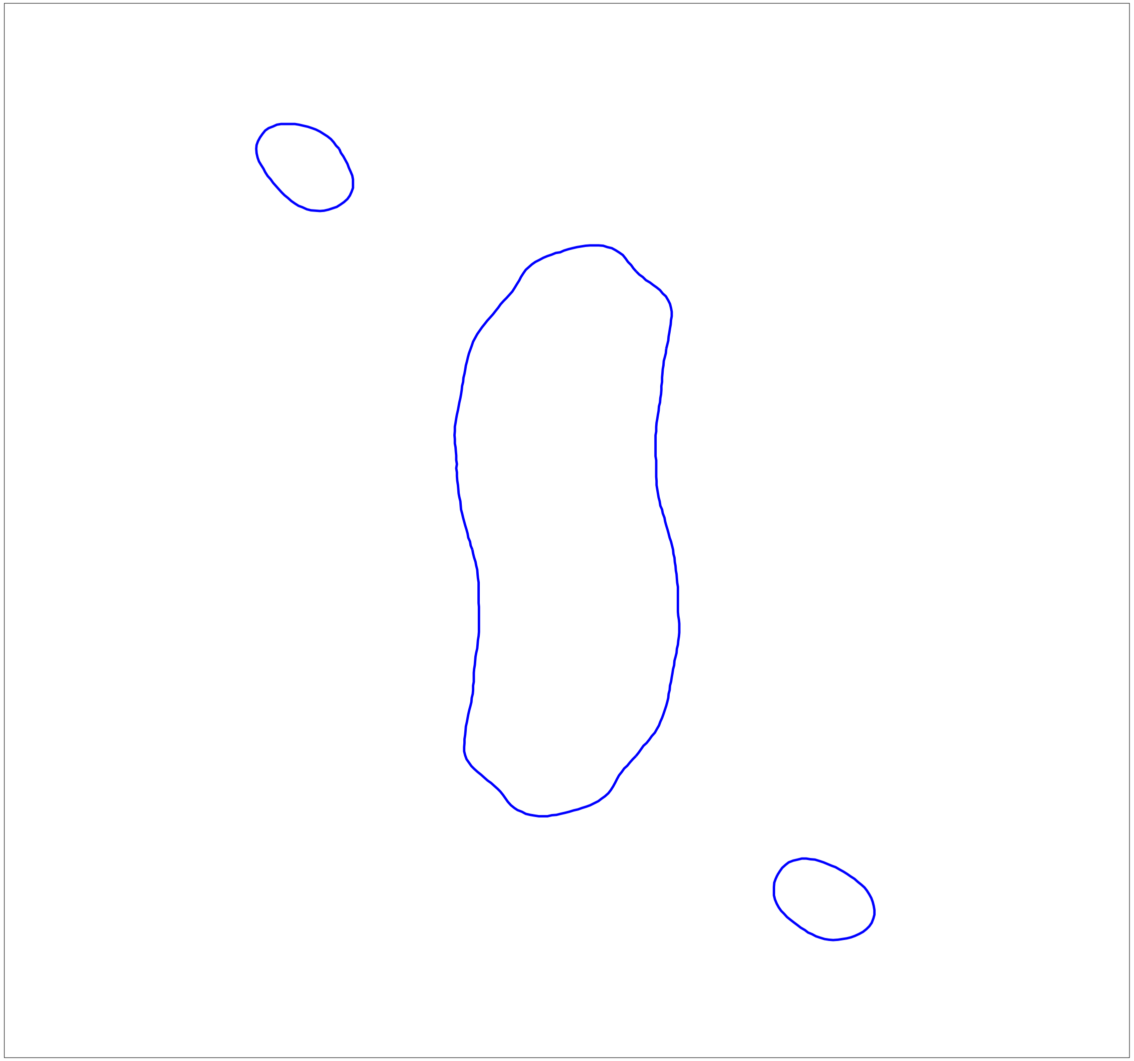
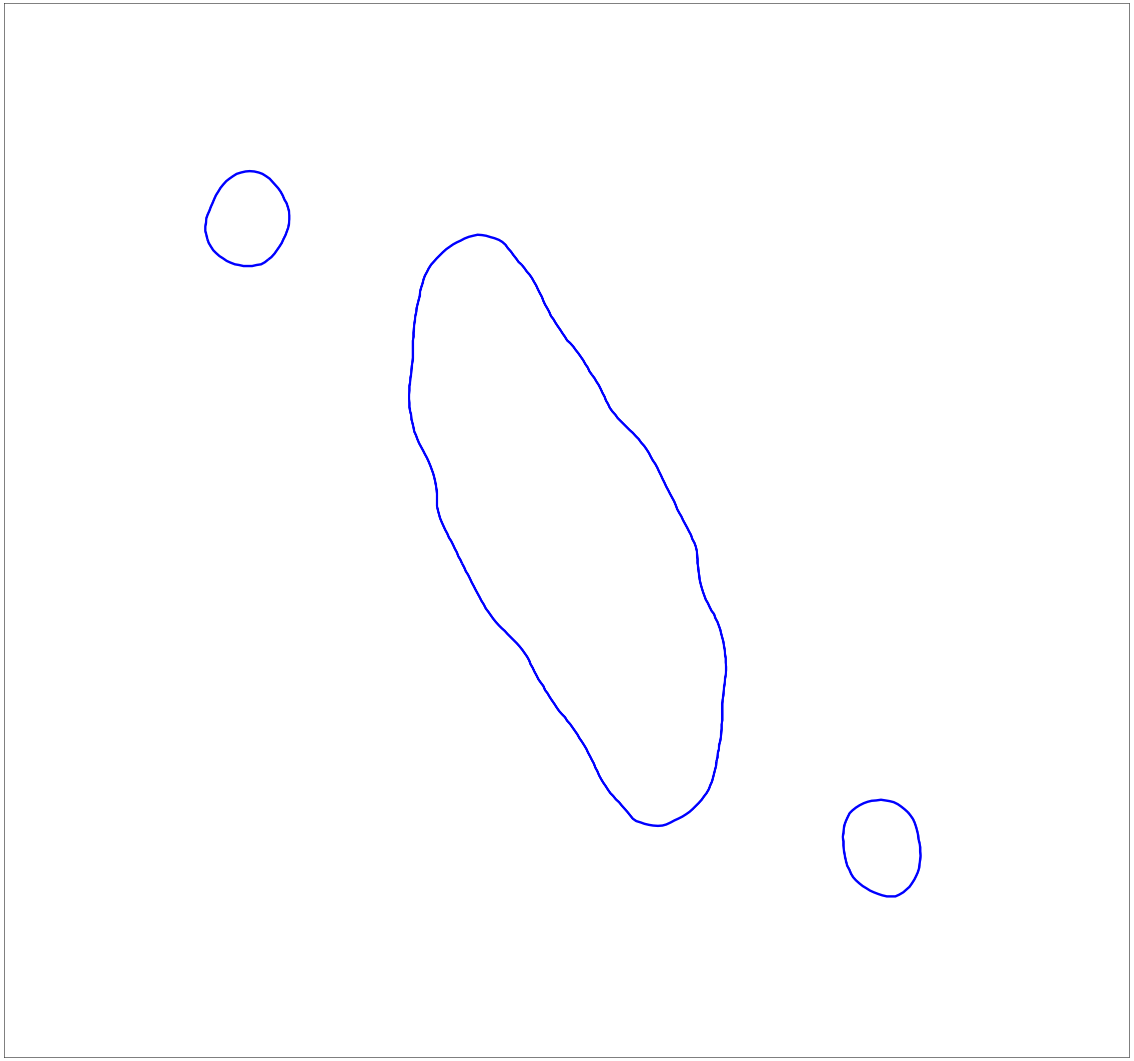
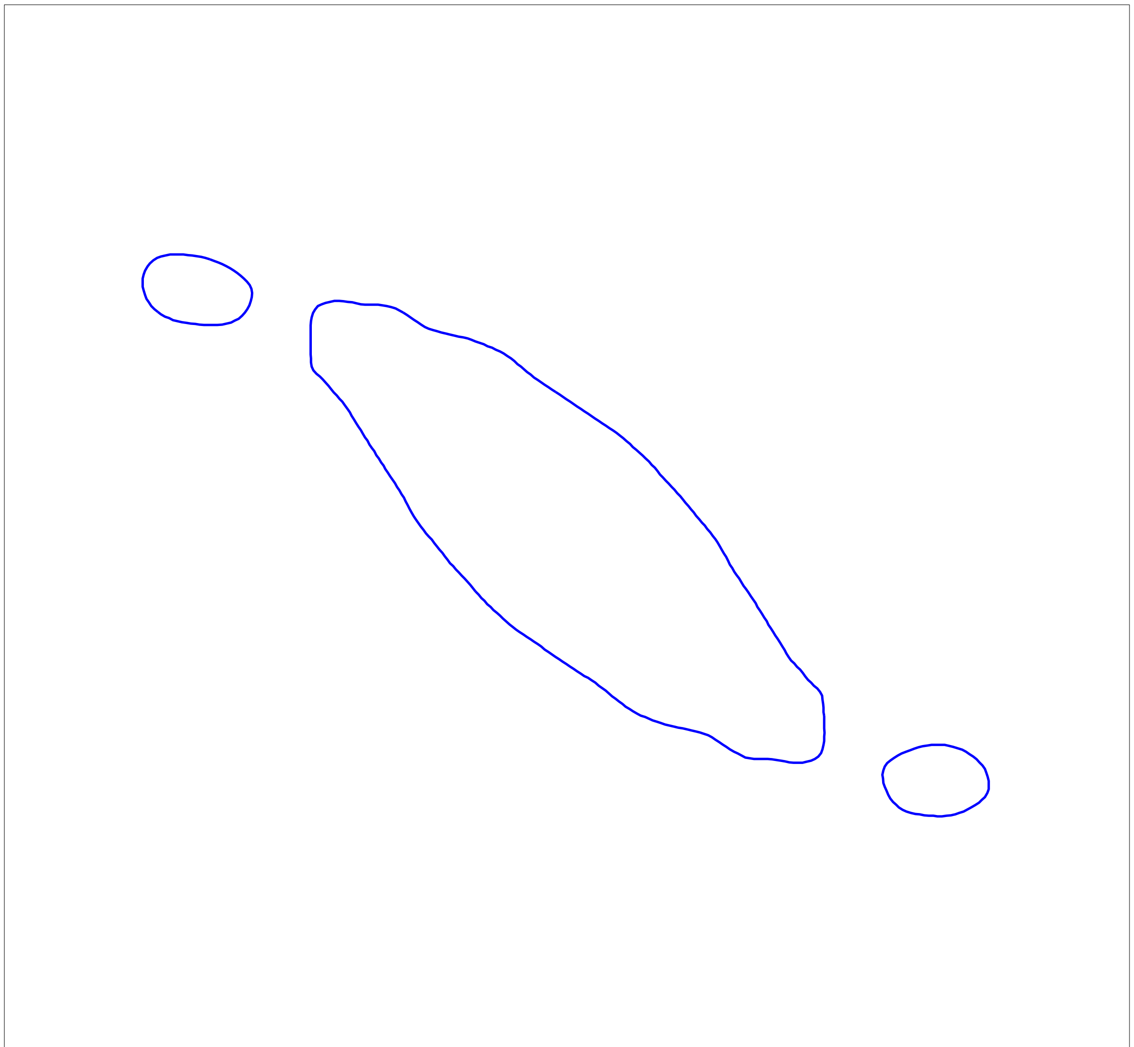


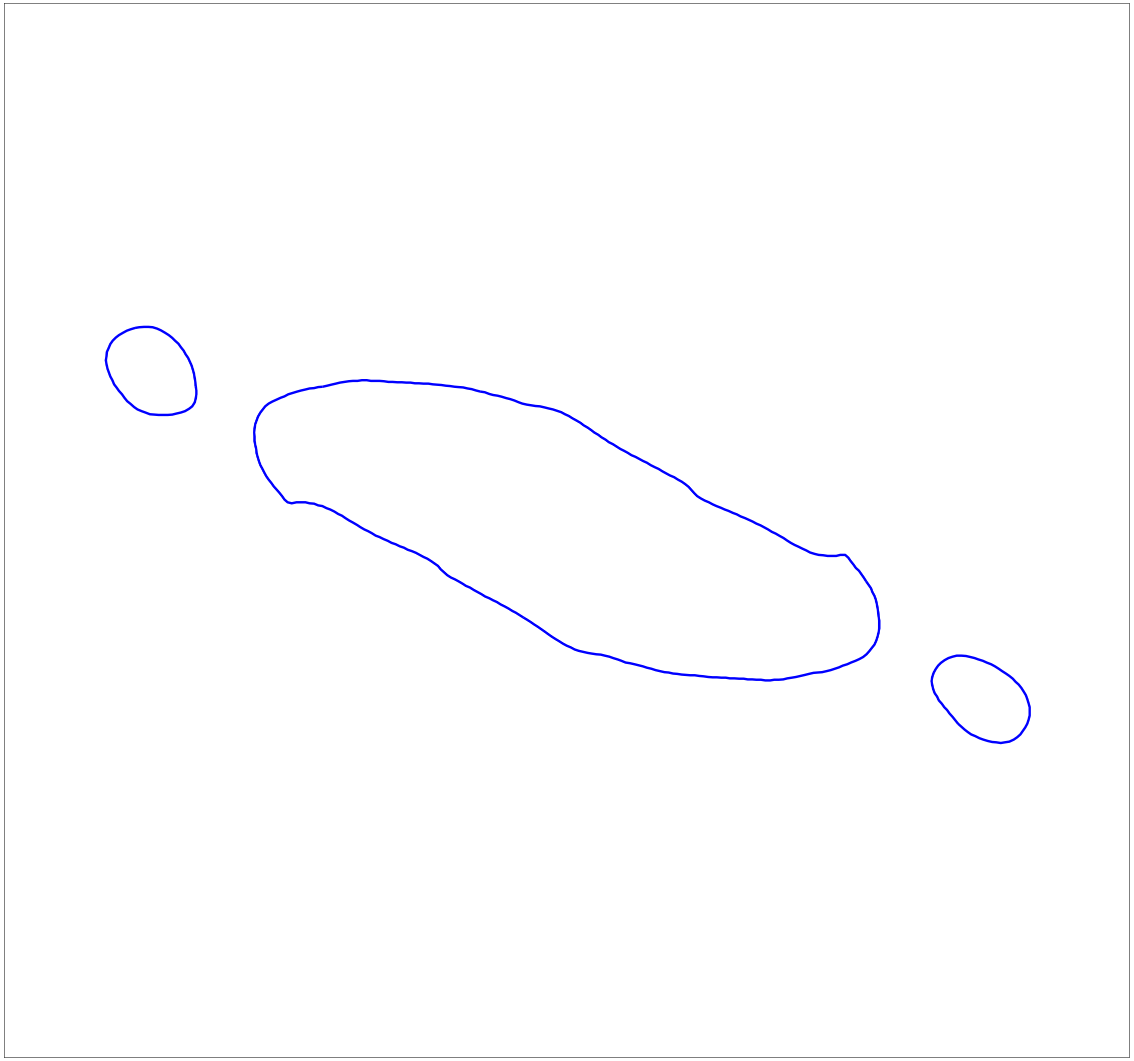
t=92



t=94



t=96



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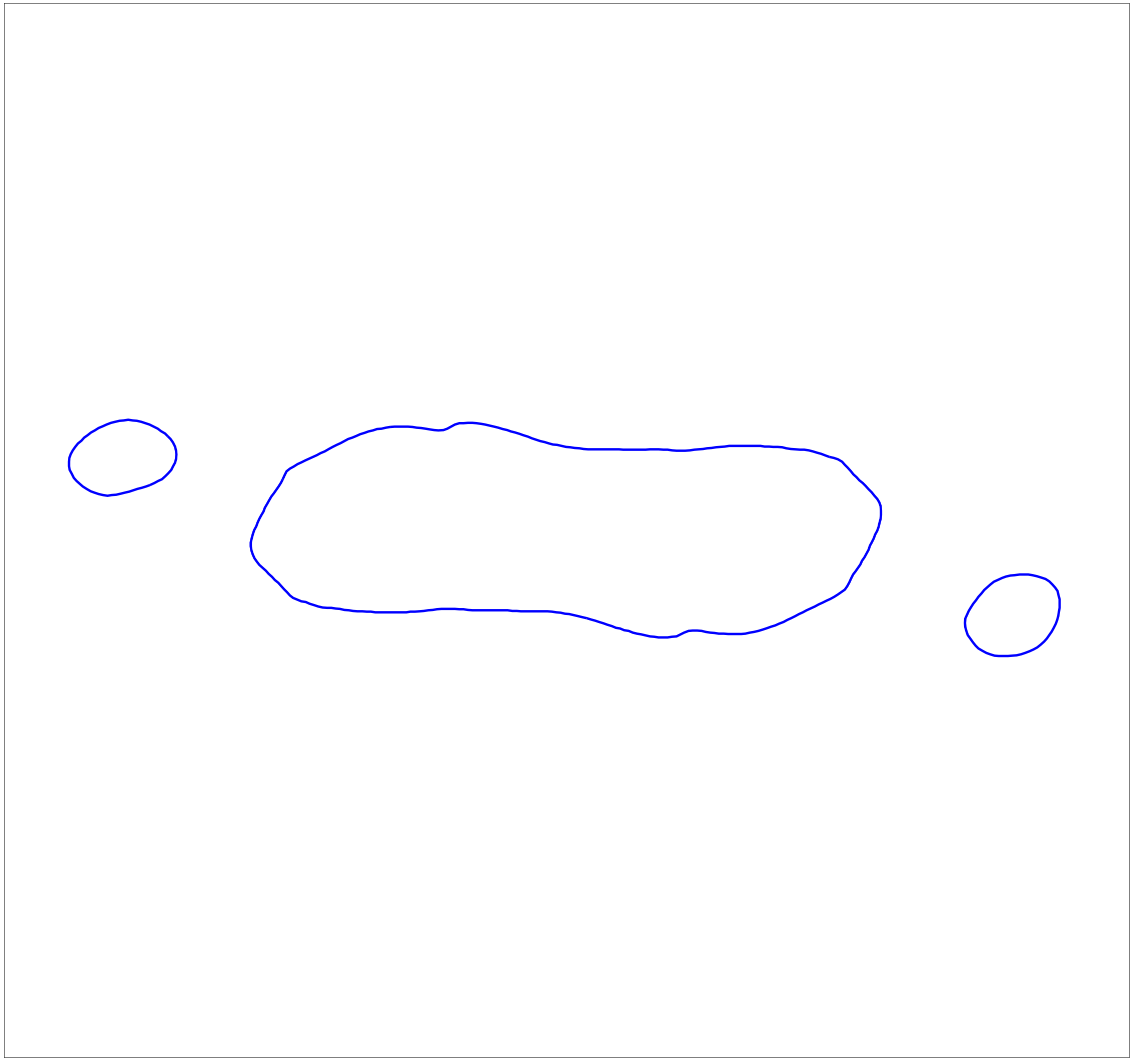

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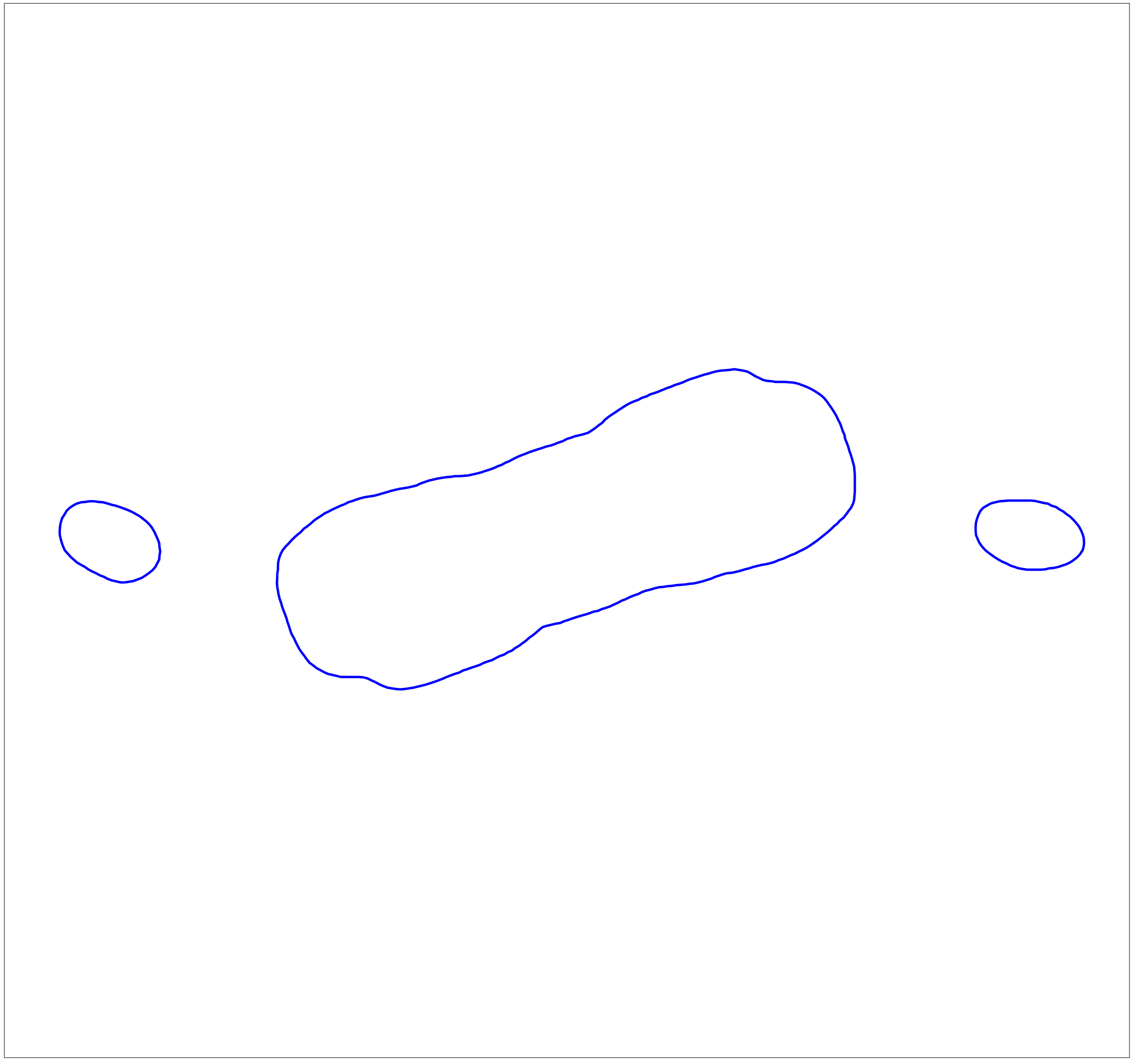
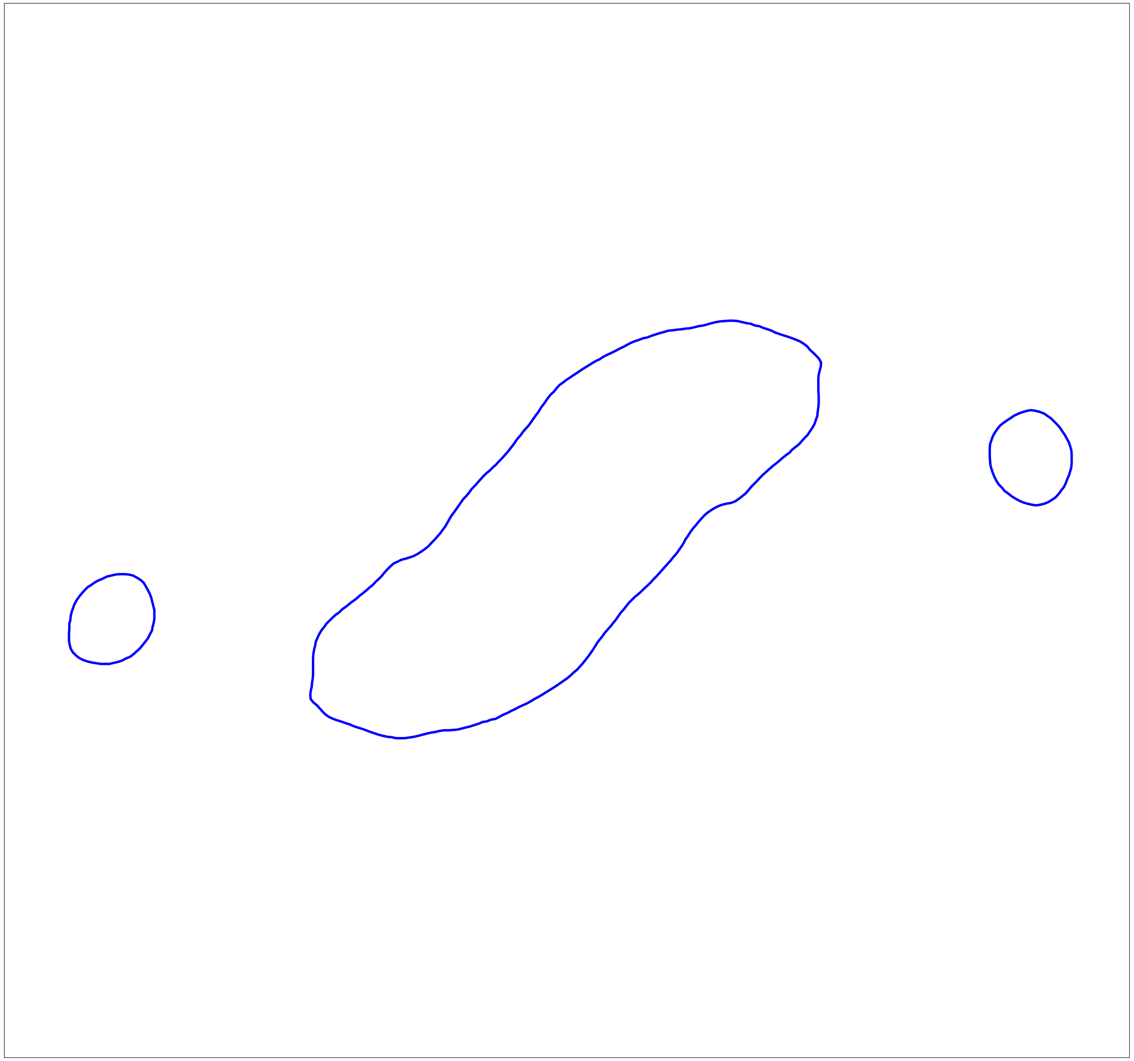
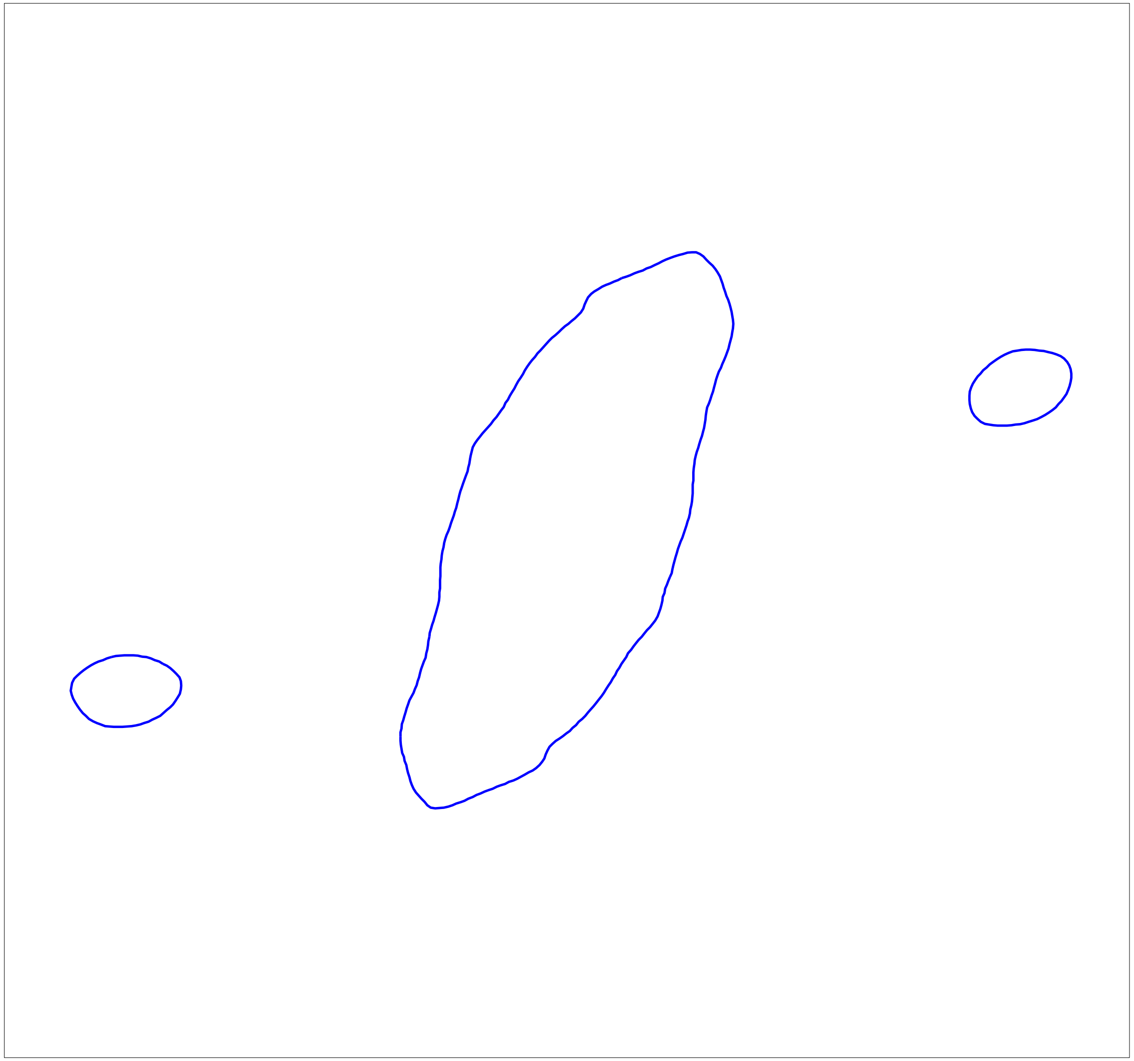


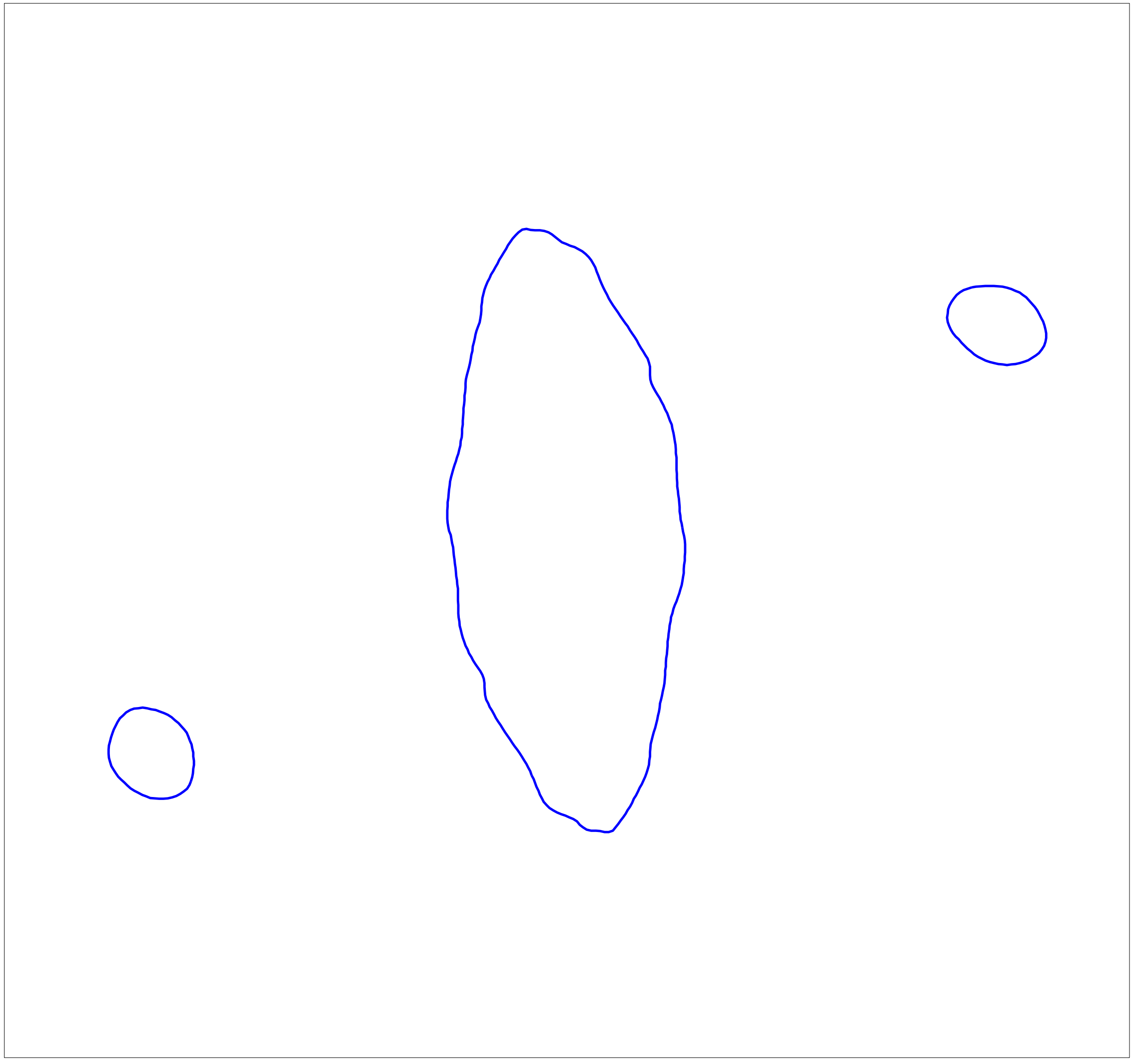
t=102



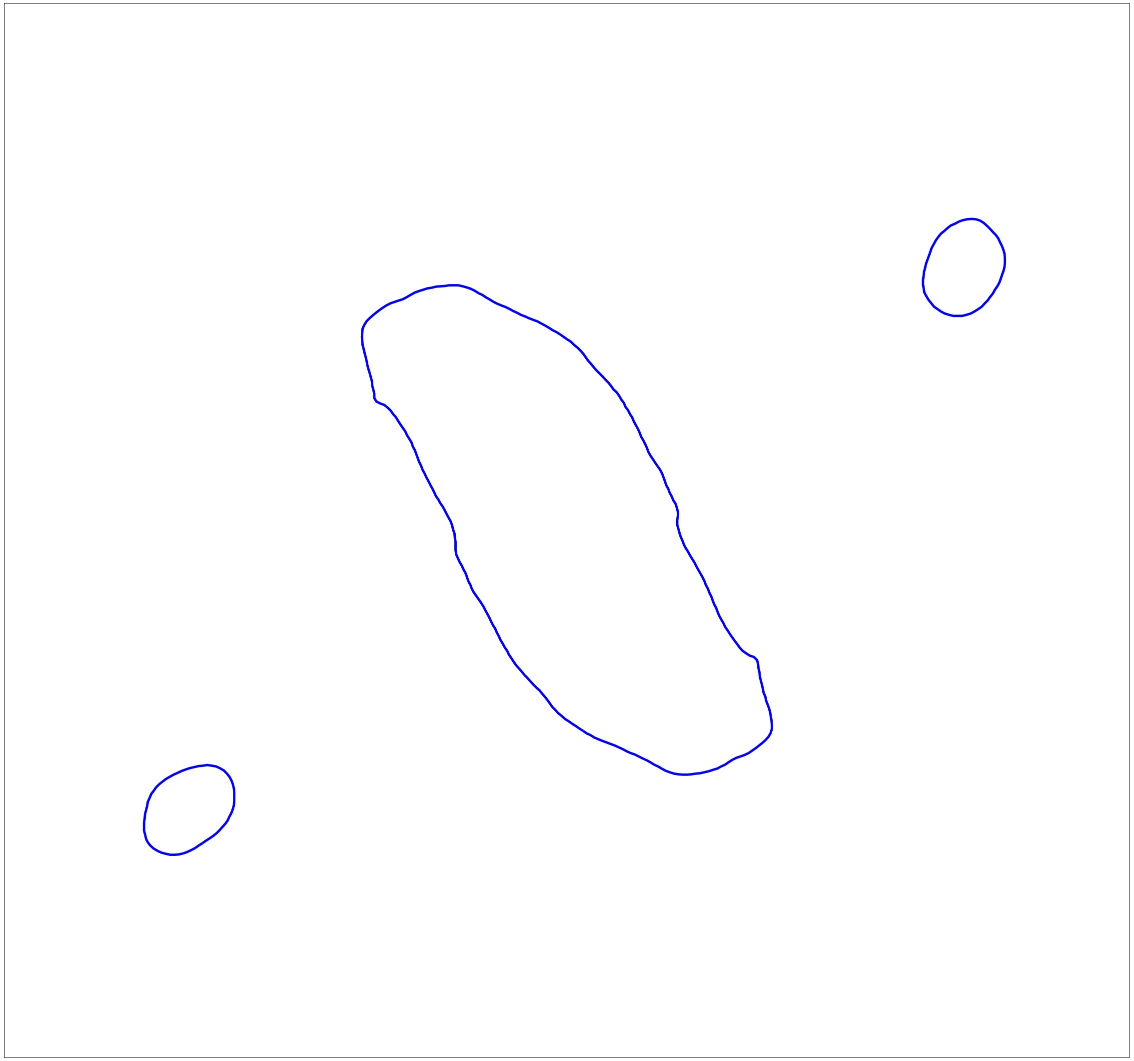
t=104



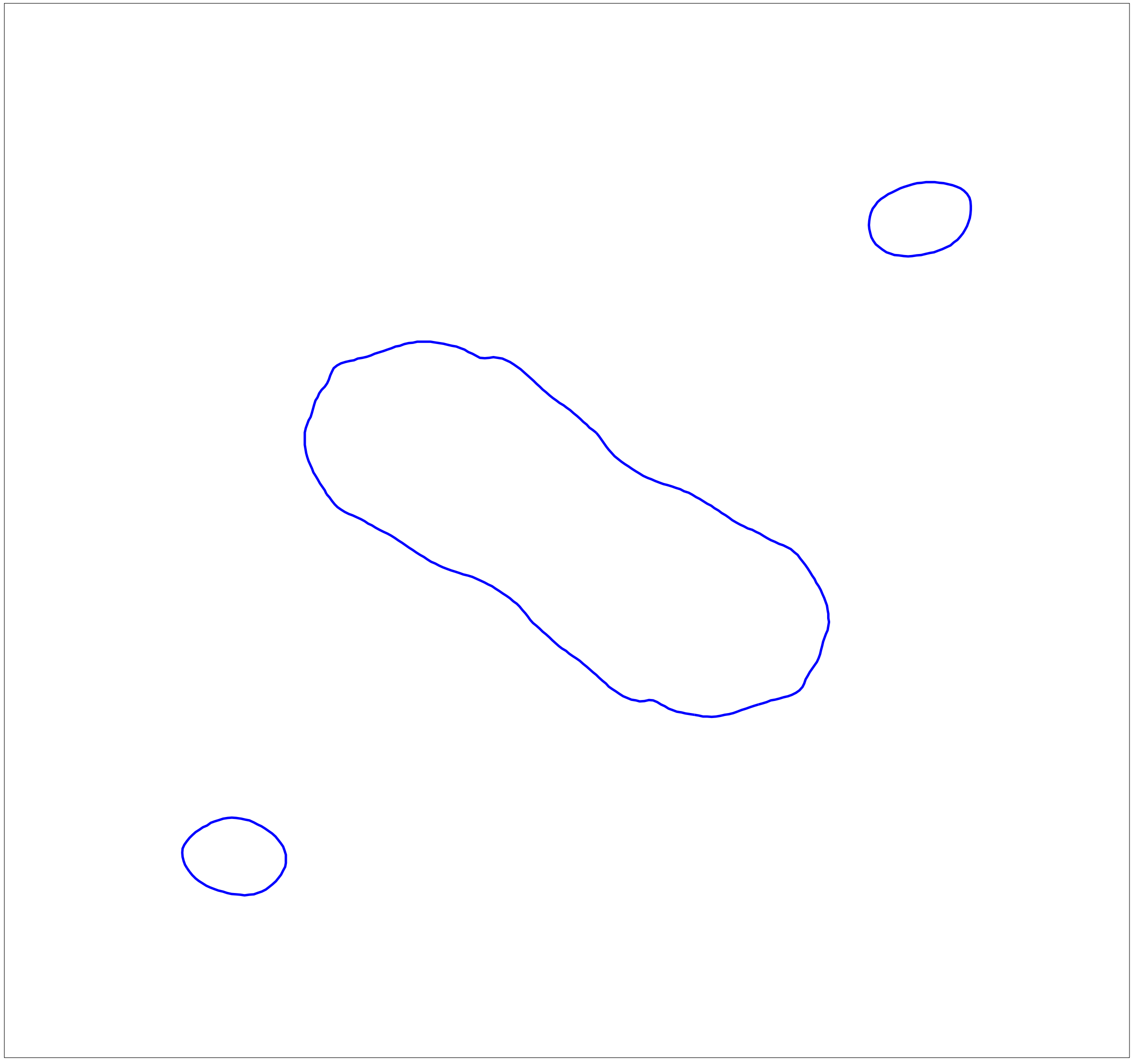
t=106



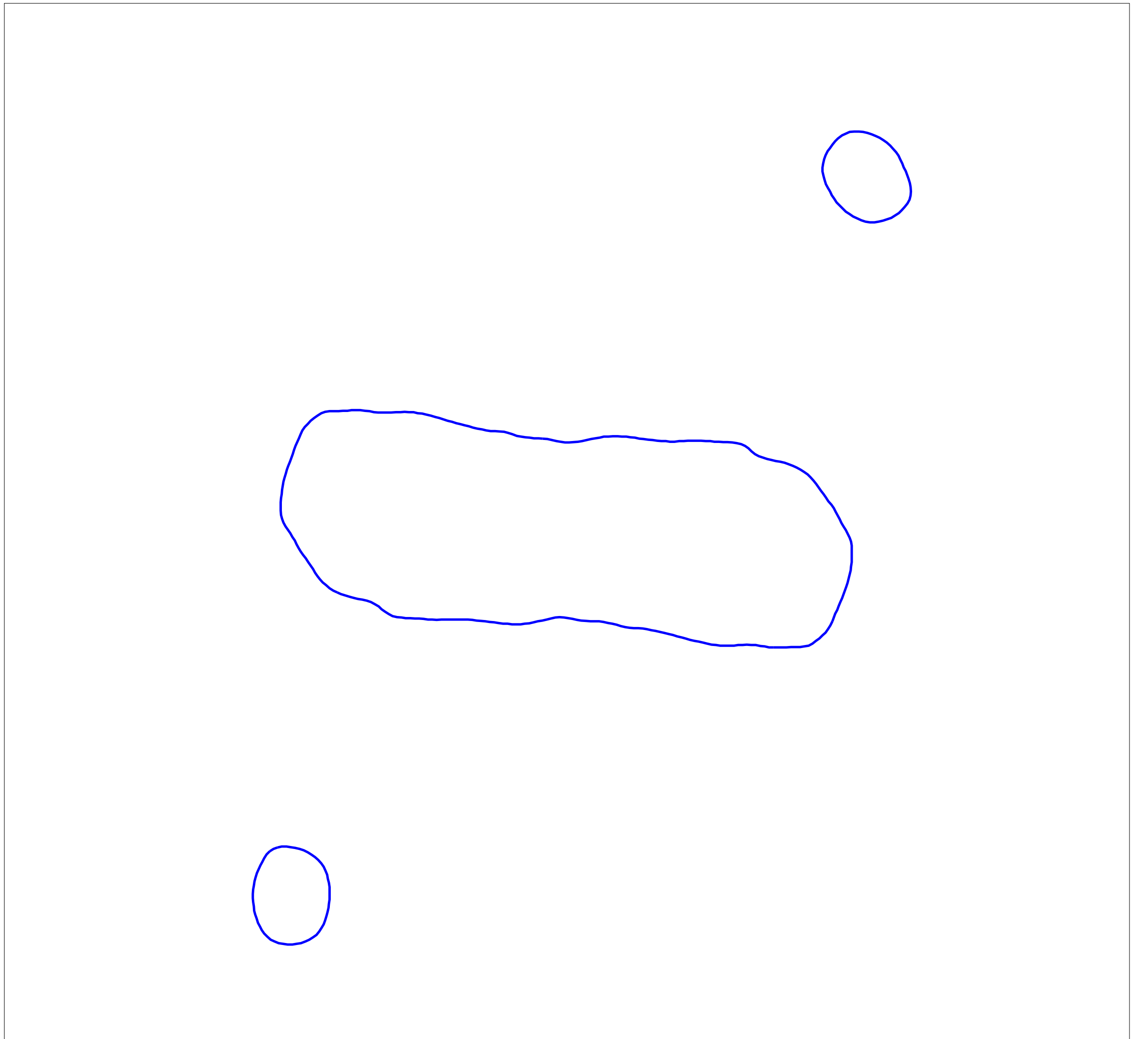
t=108



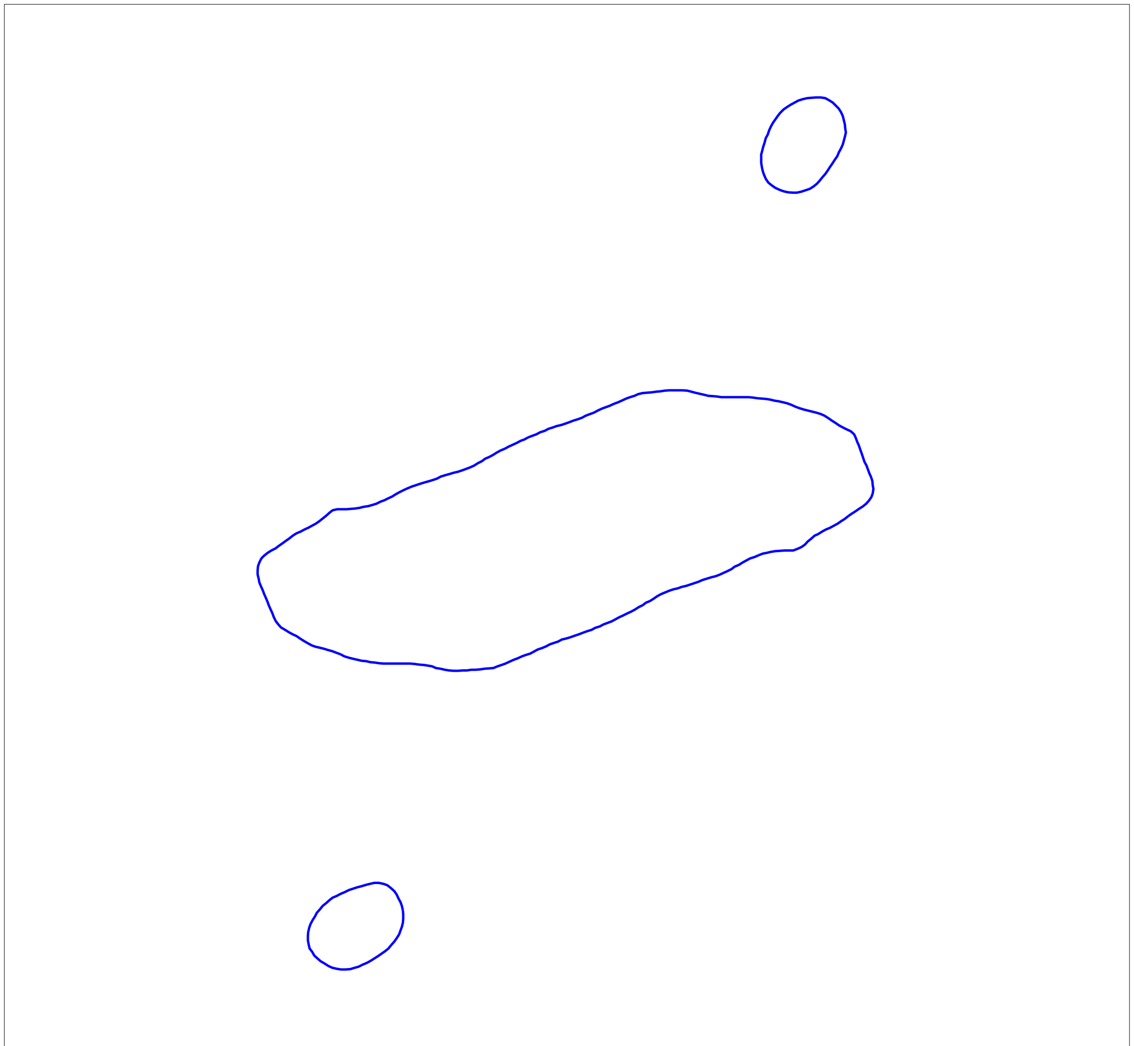
t=110



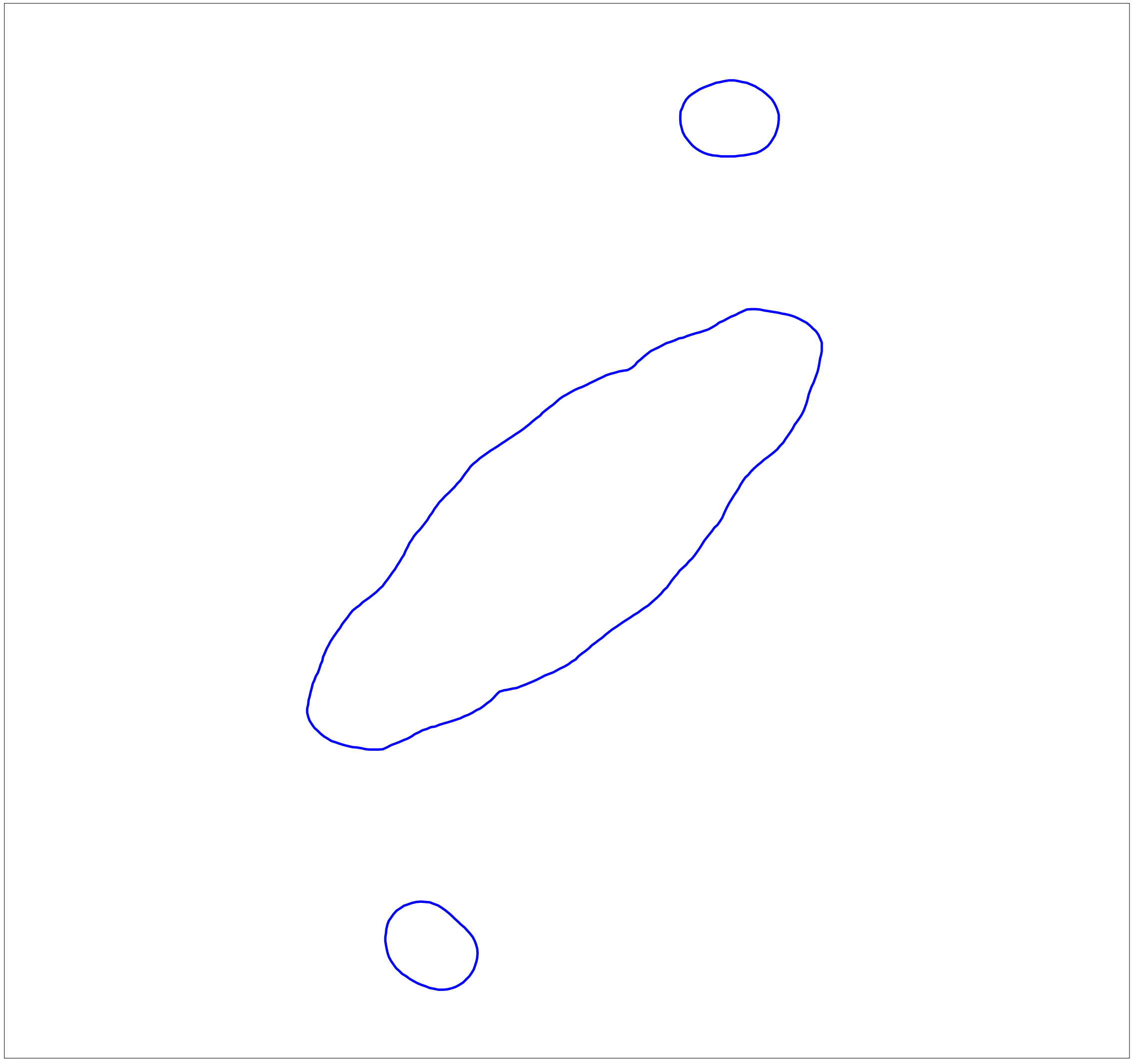
t=112



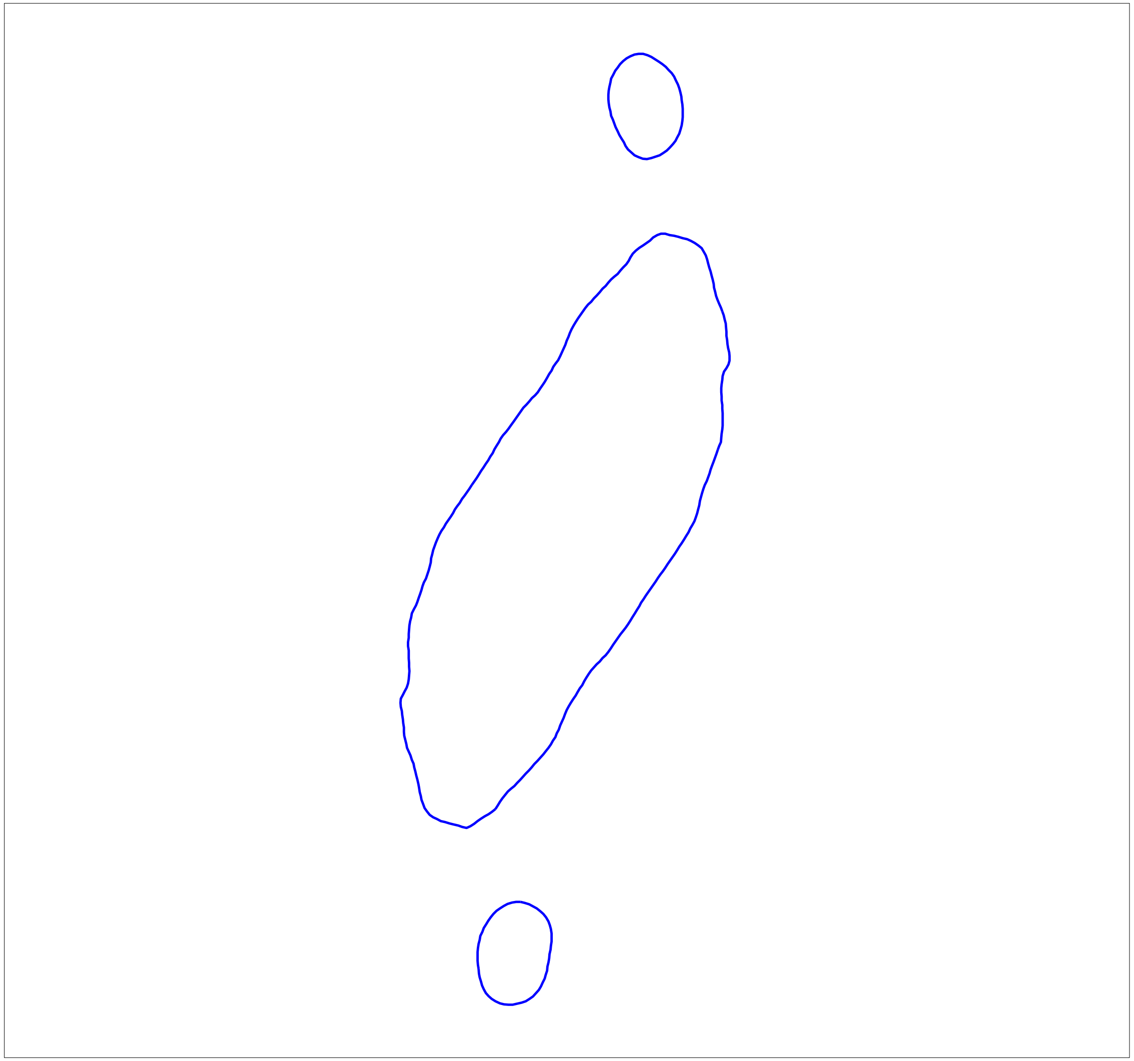
t=114



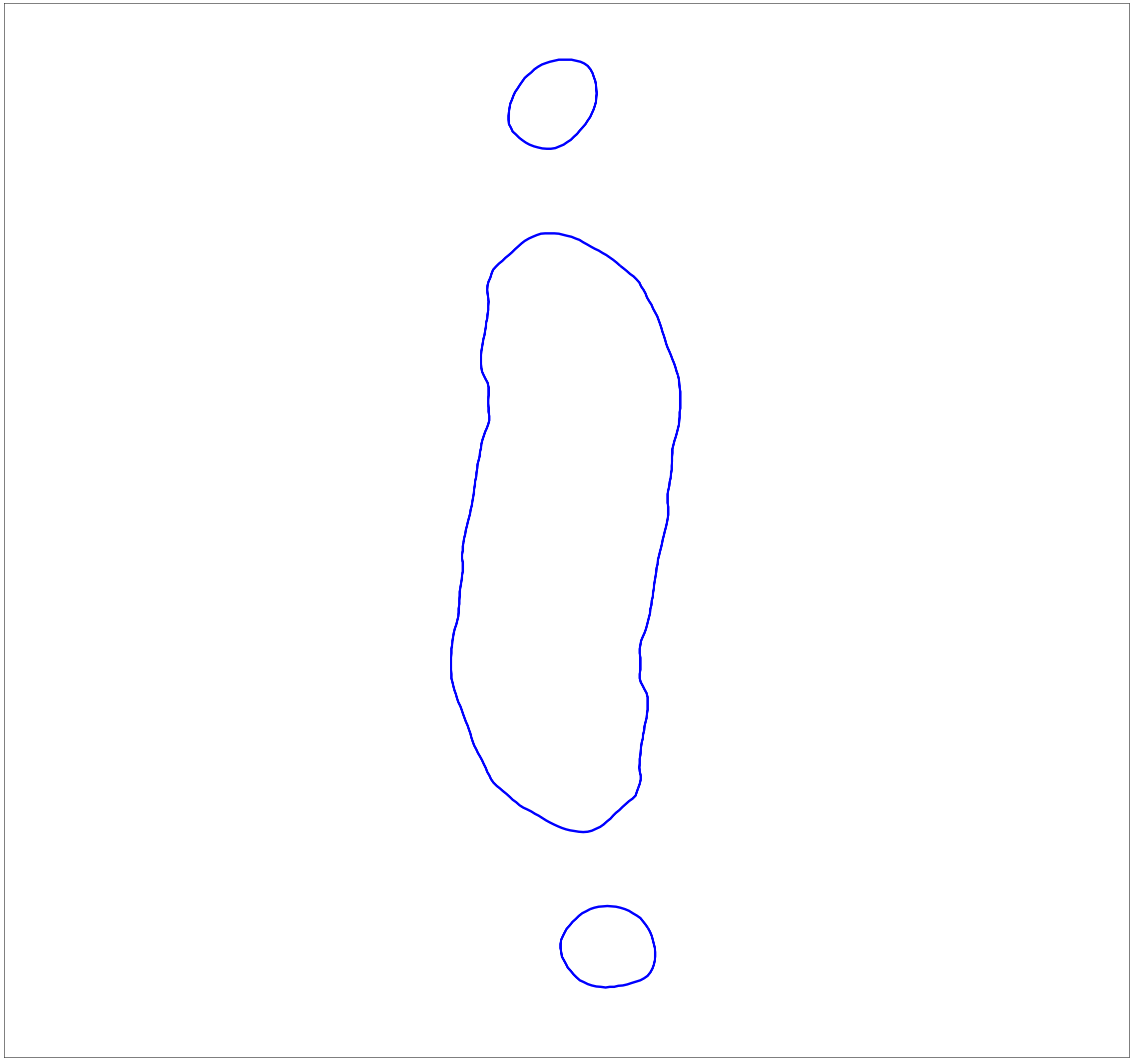
t=116



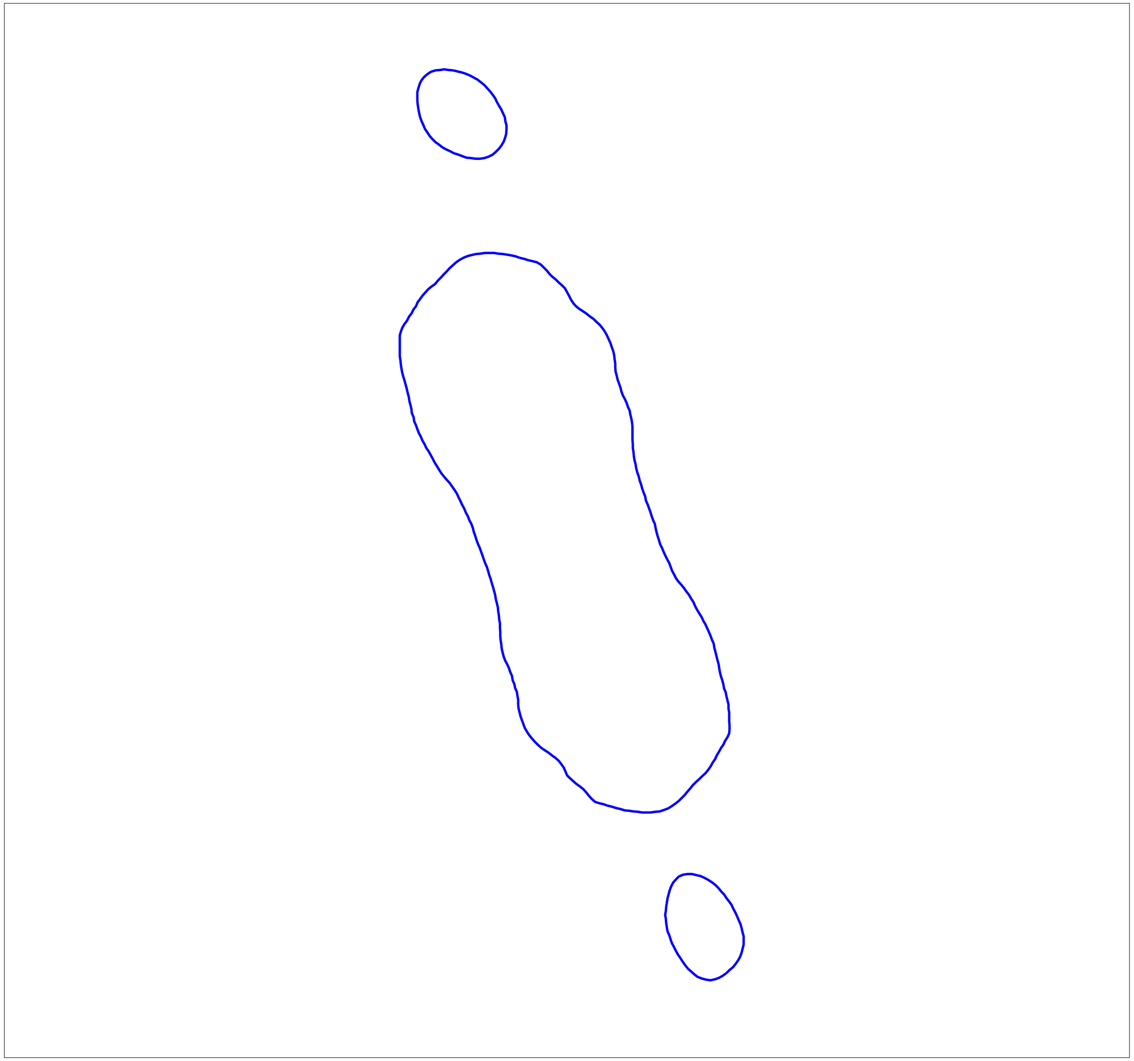
t=118



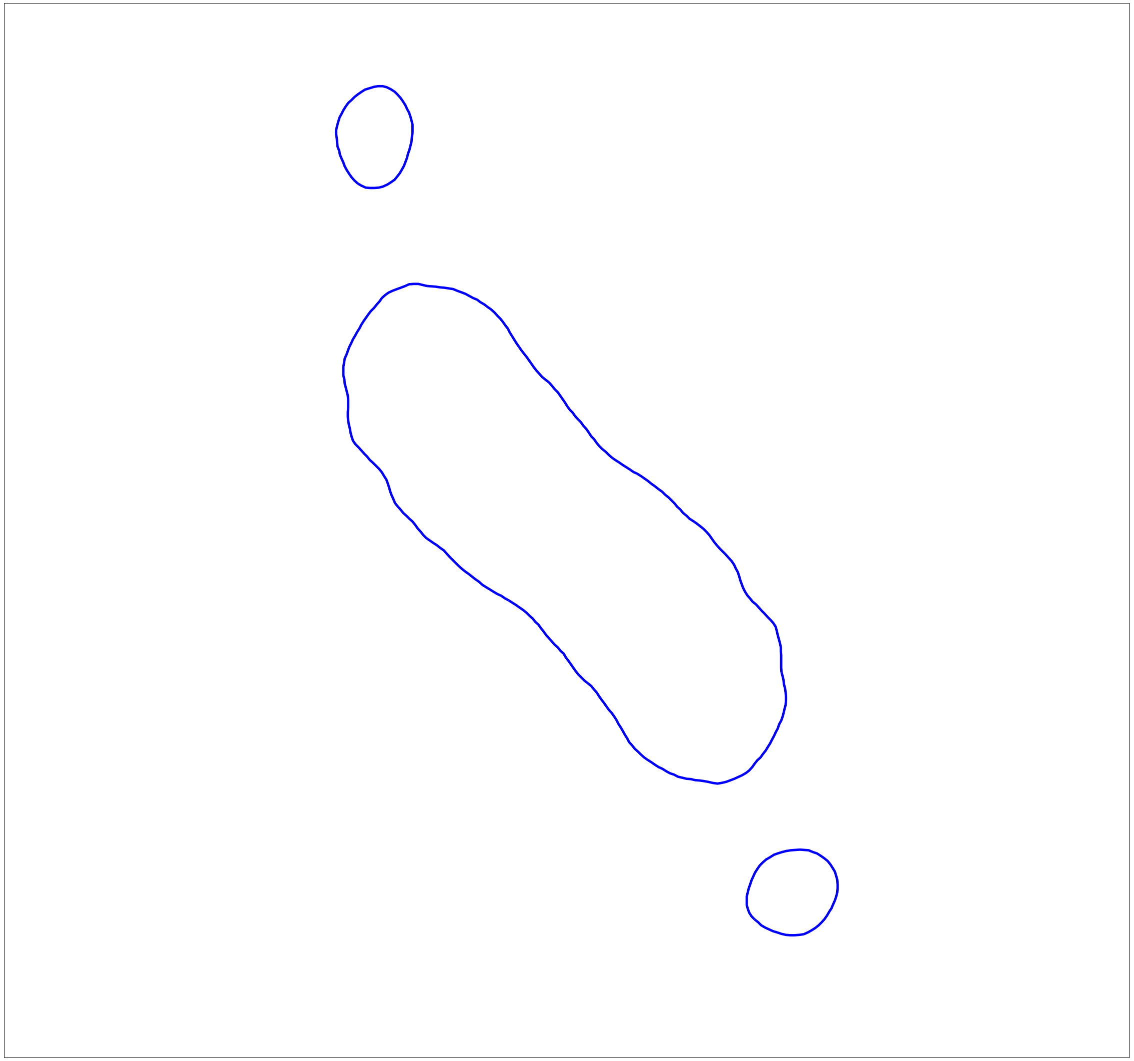
t=120



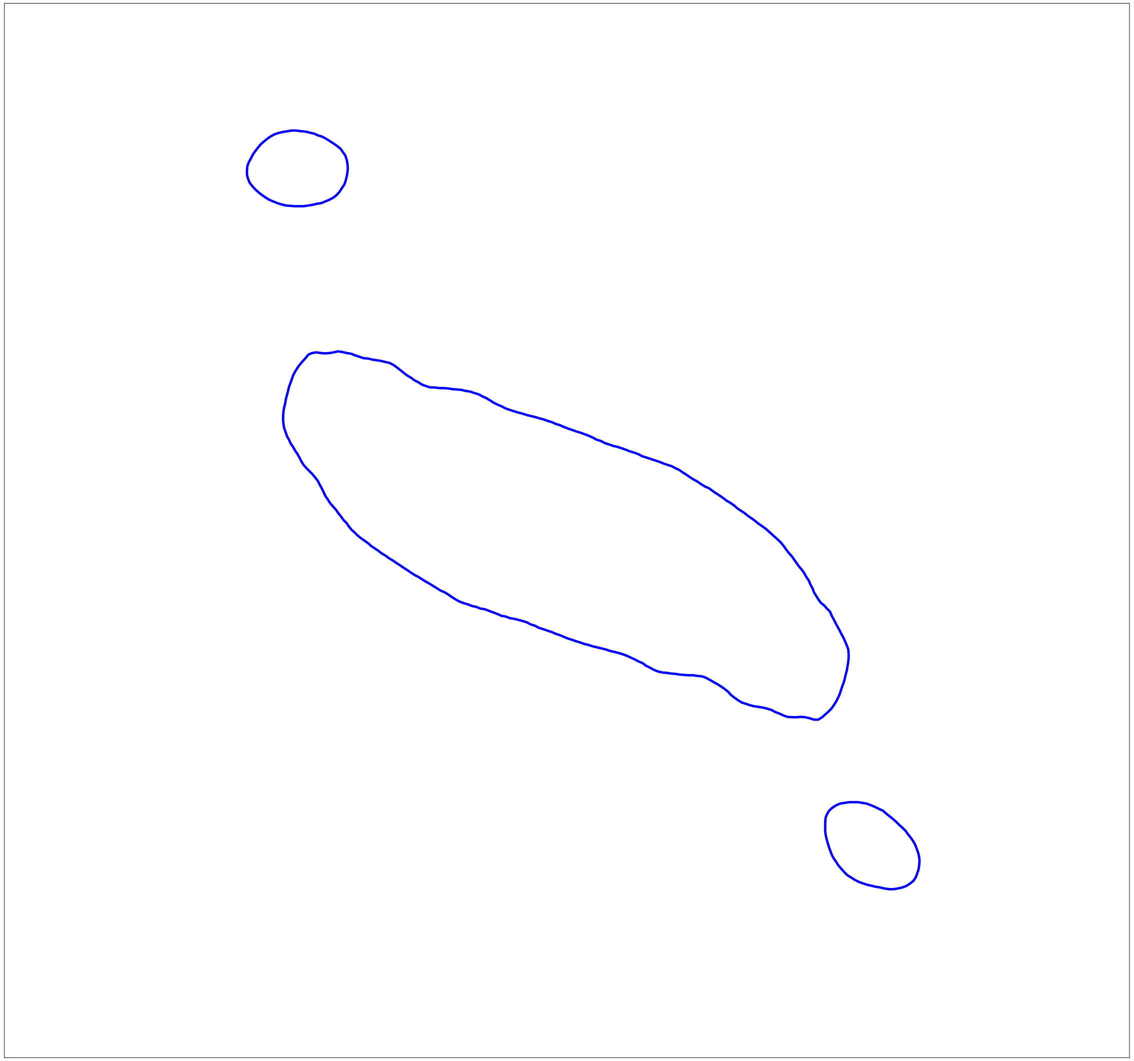
t=122



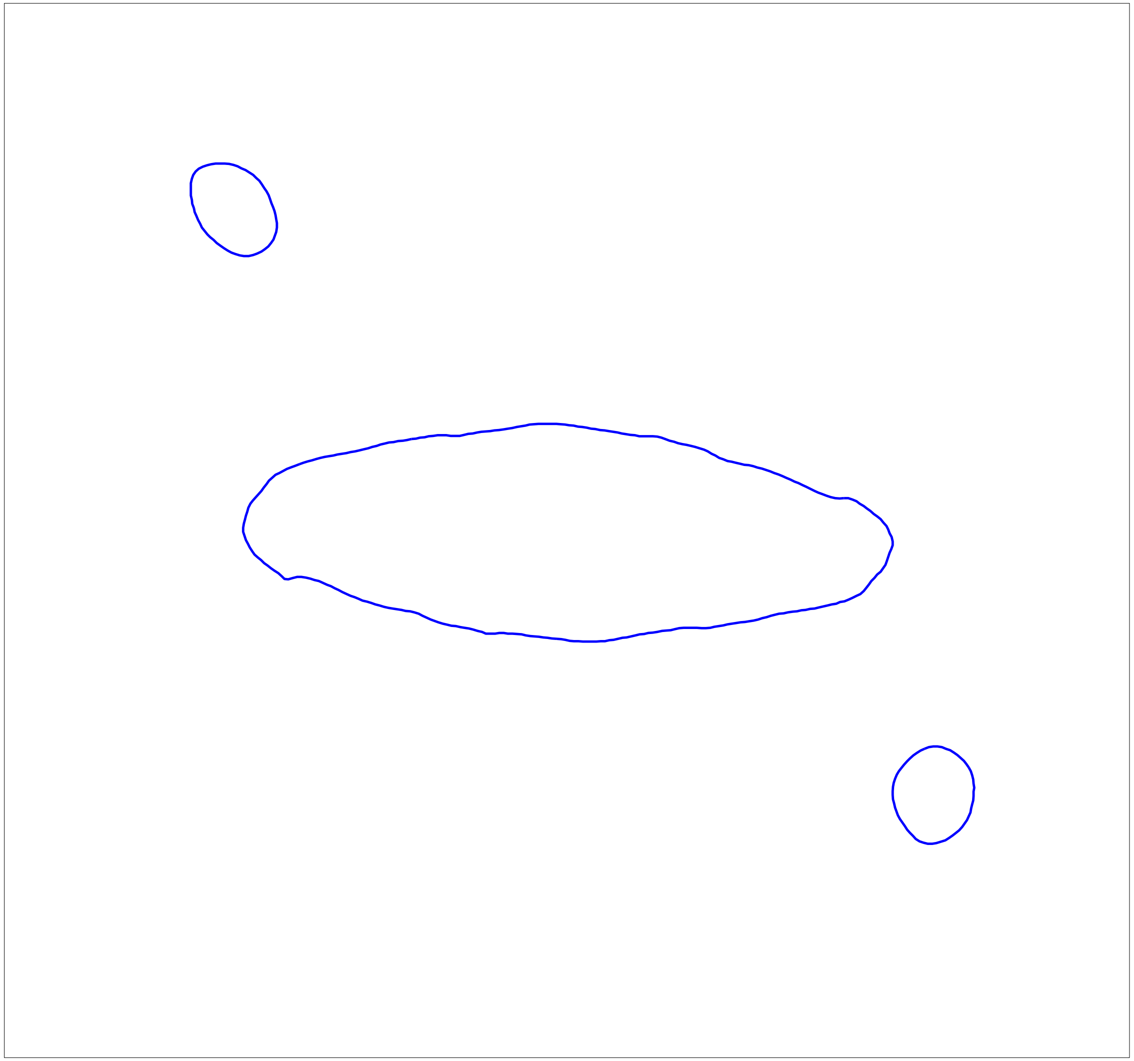
t=124



t=126

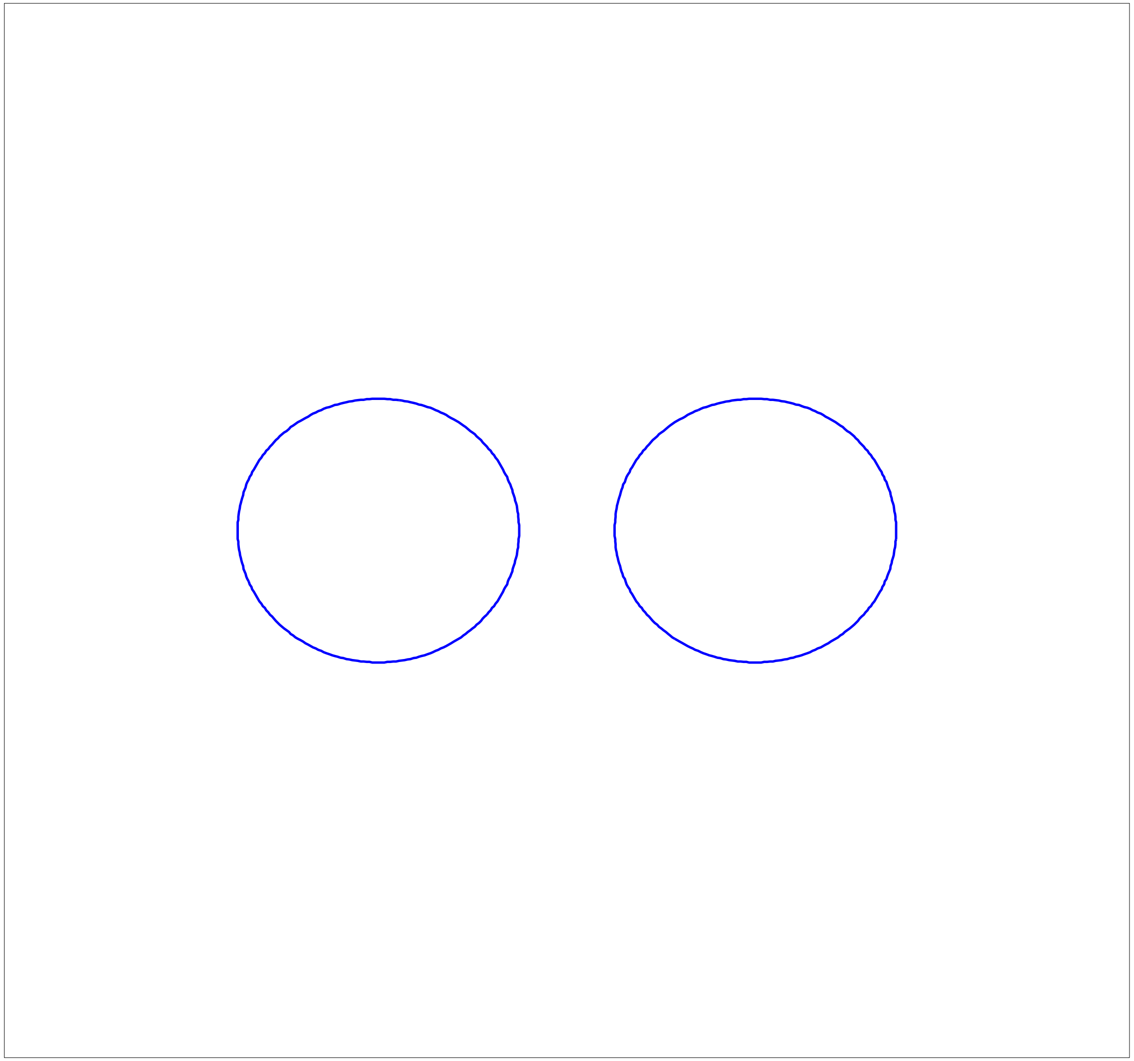


t=128

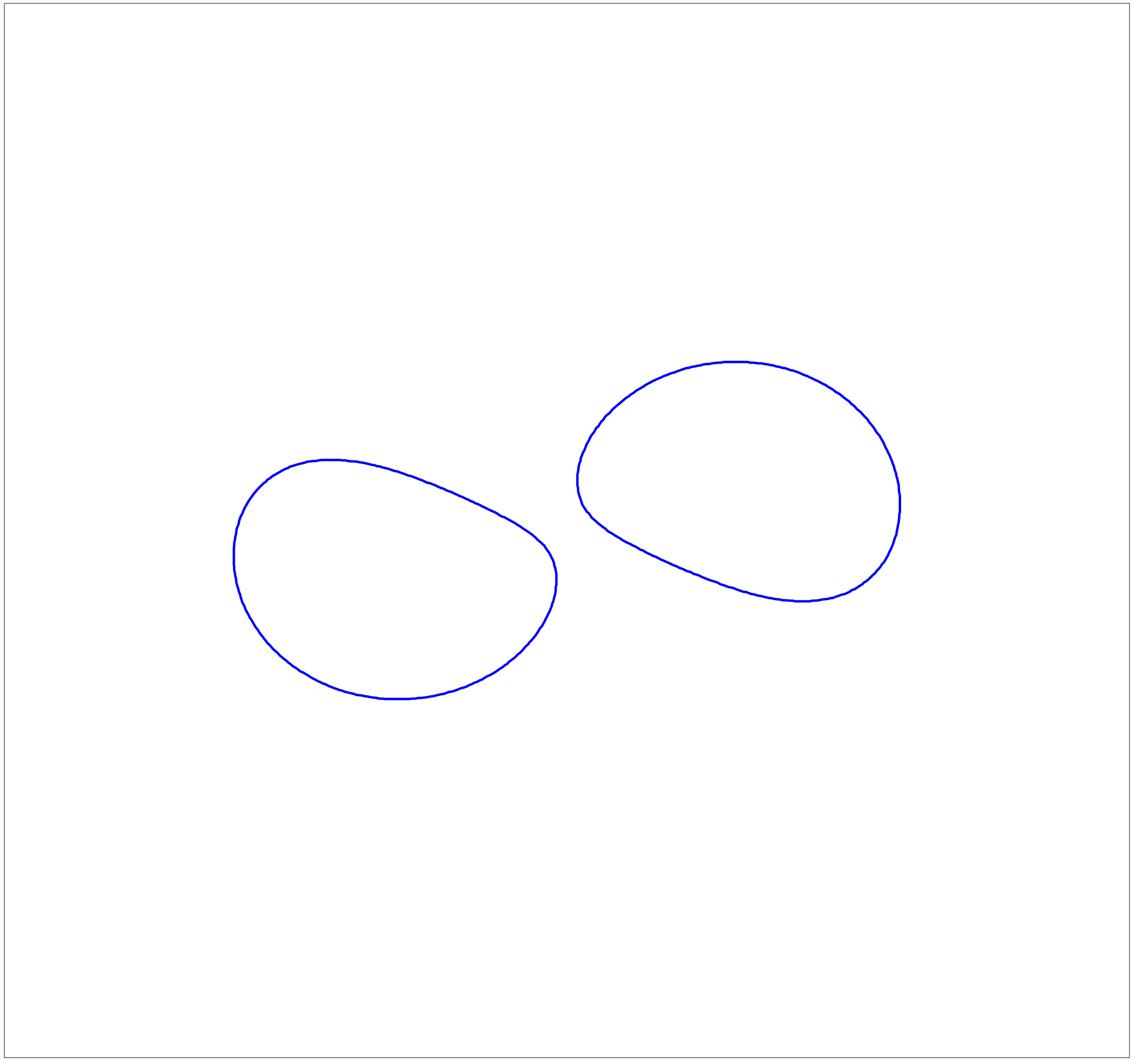


Case (b): evolution of vortex patches $S_2=0.346$, $S_3=0.172$

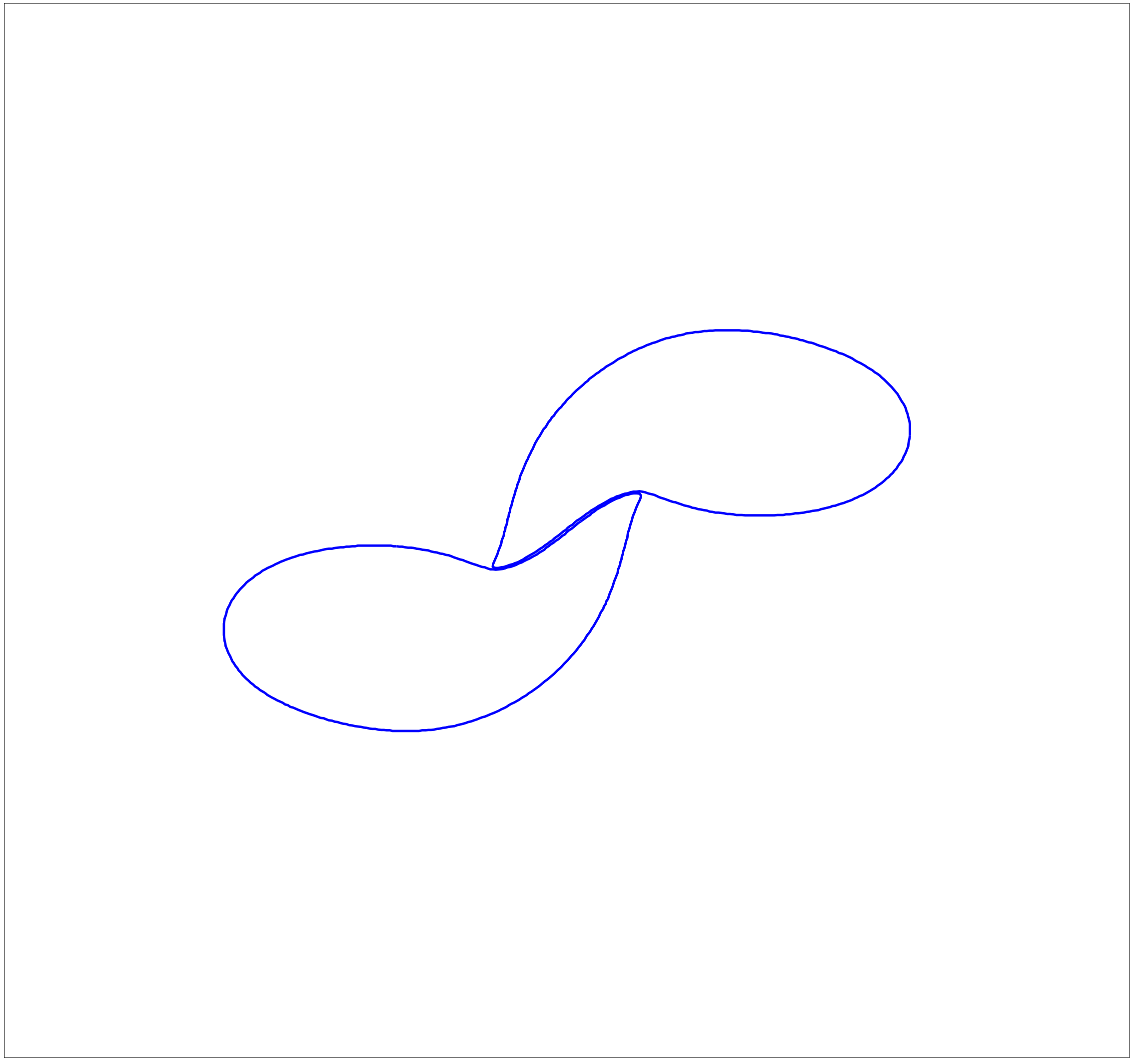
t=0



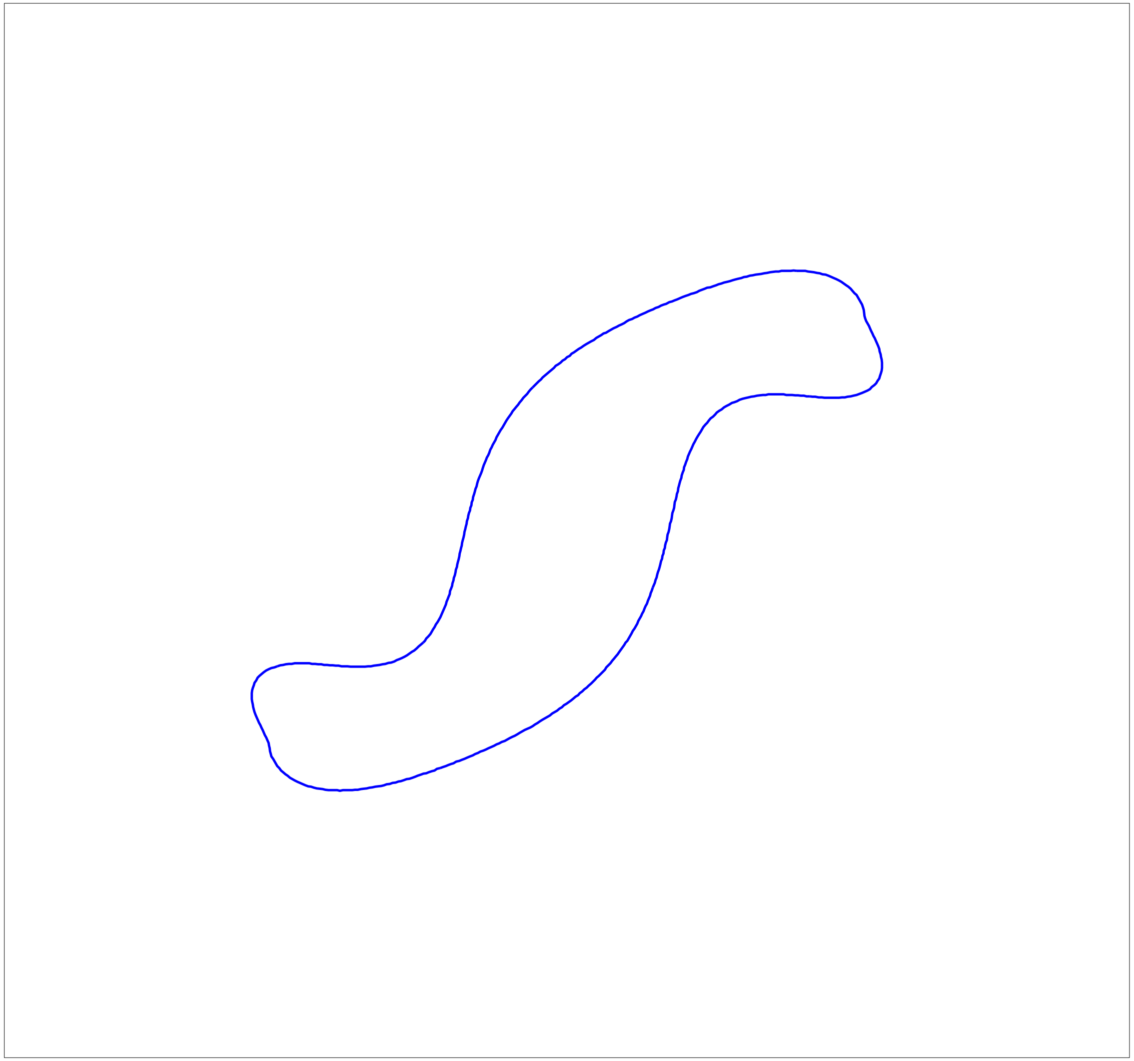
t=2



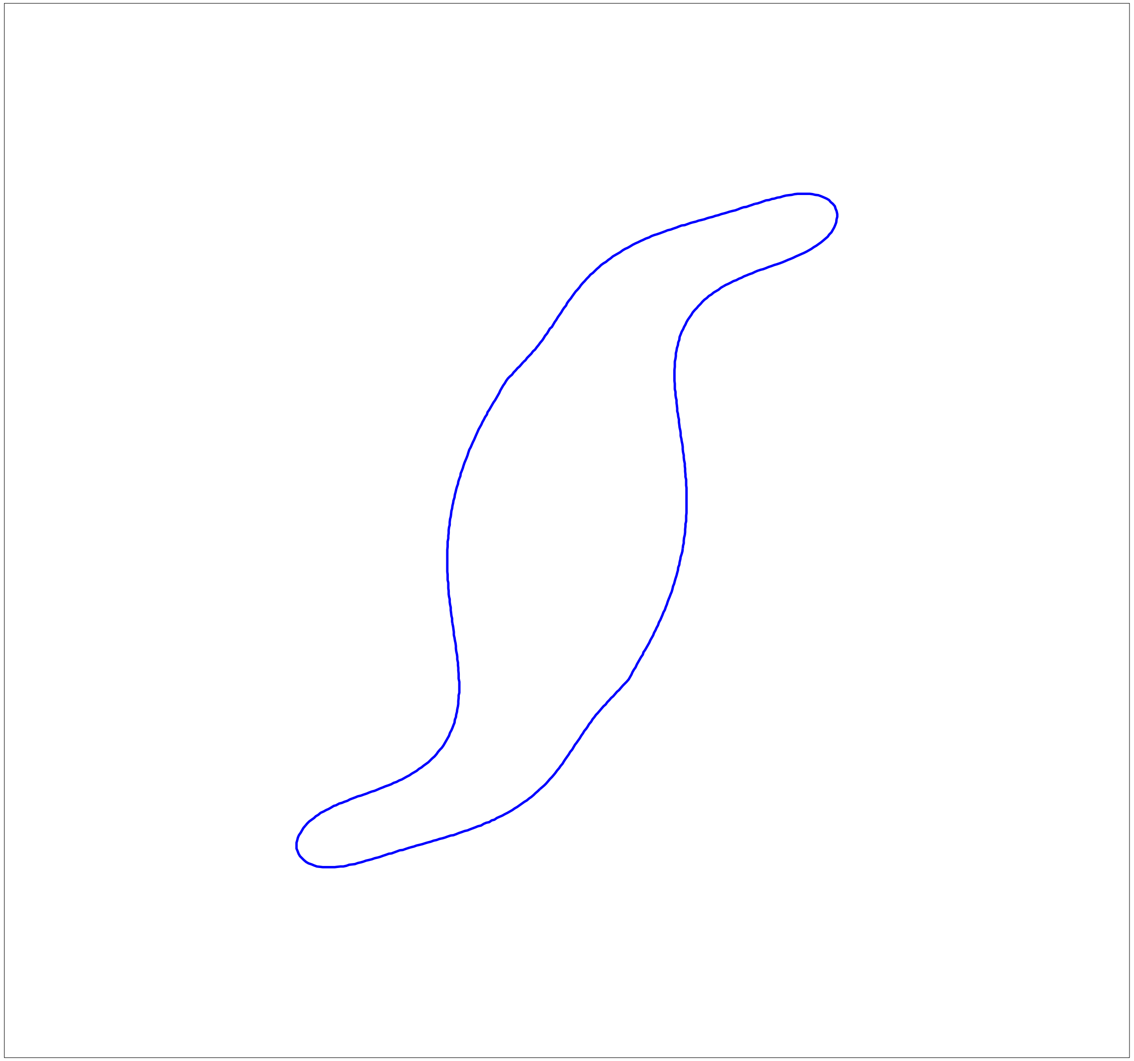
t=4



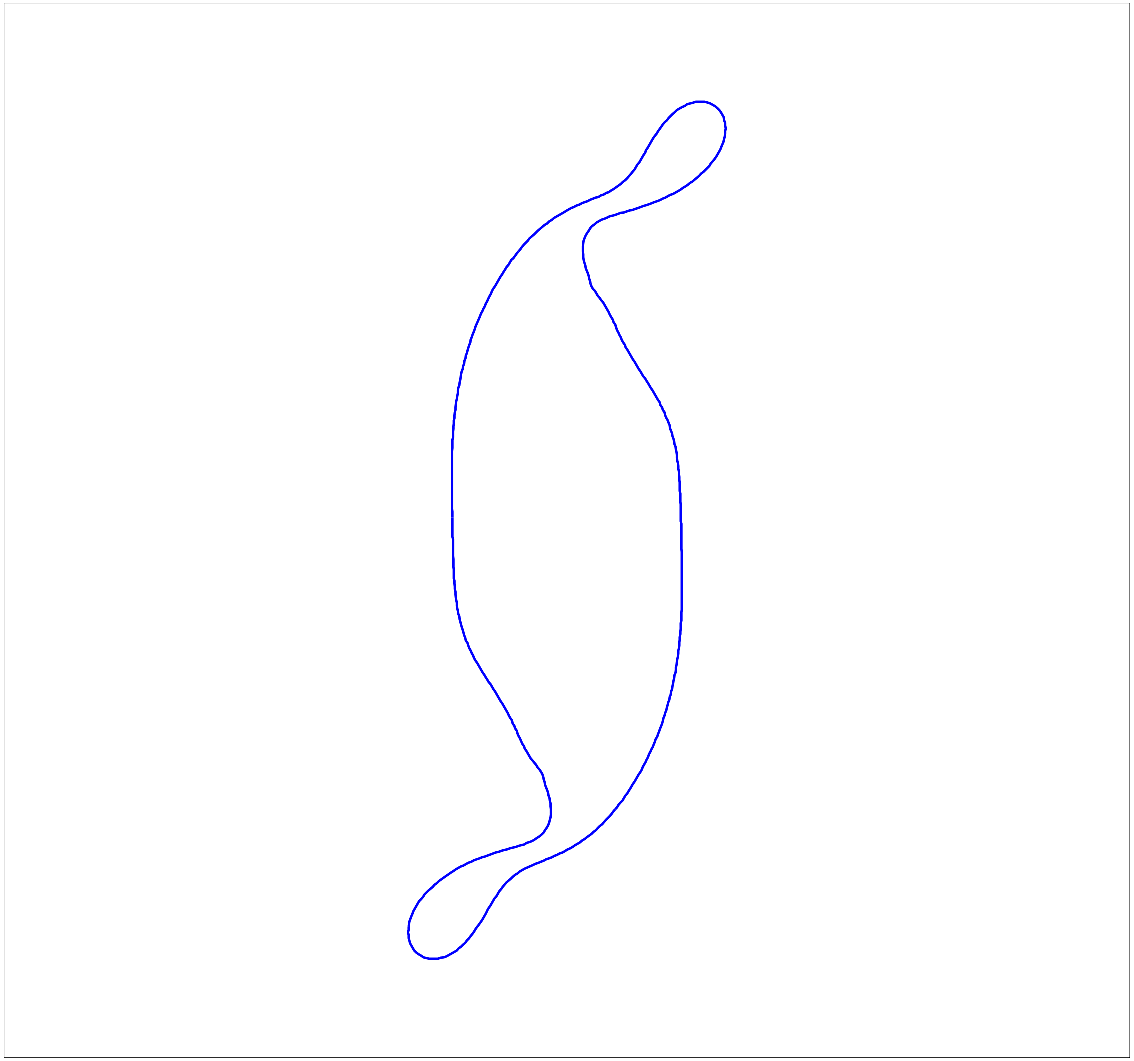
t=6



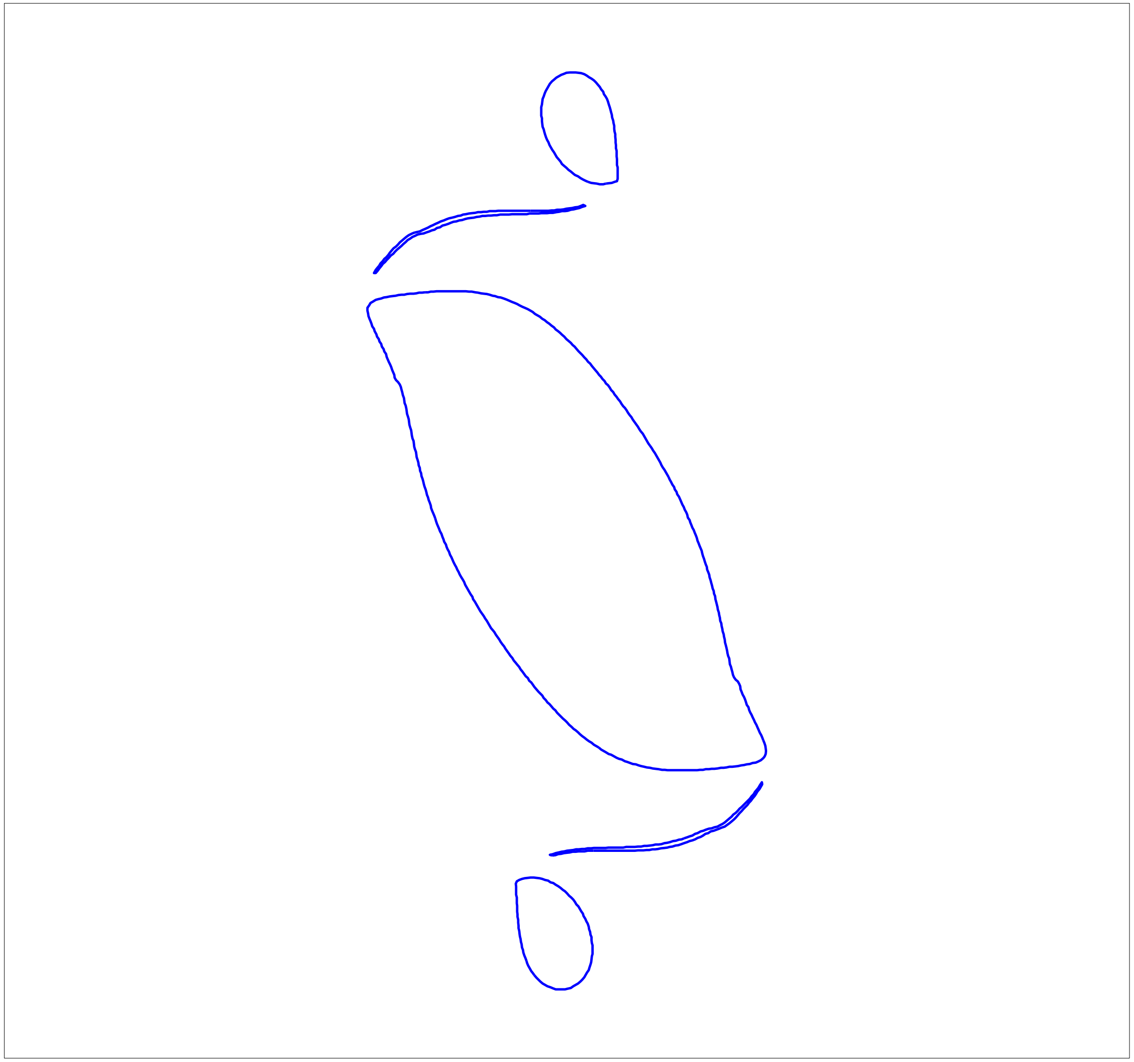
t=8



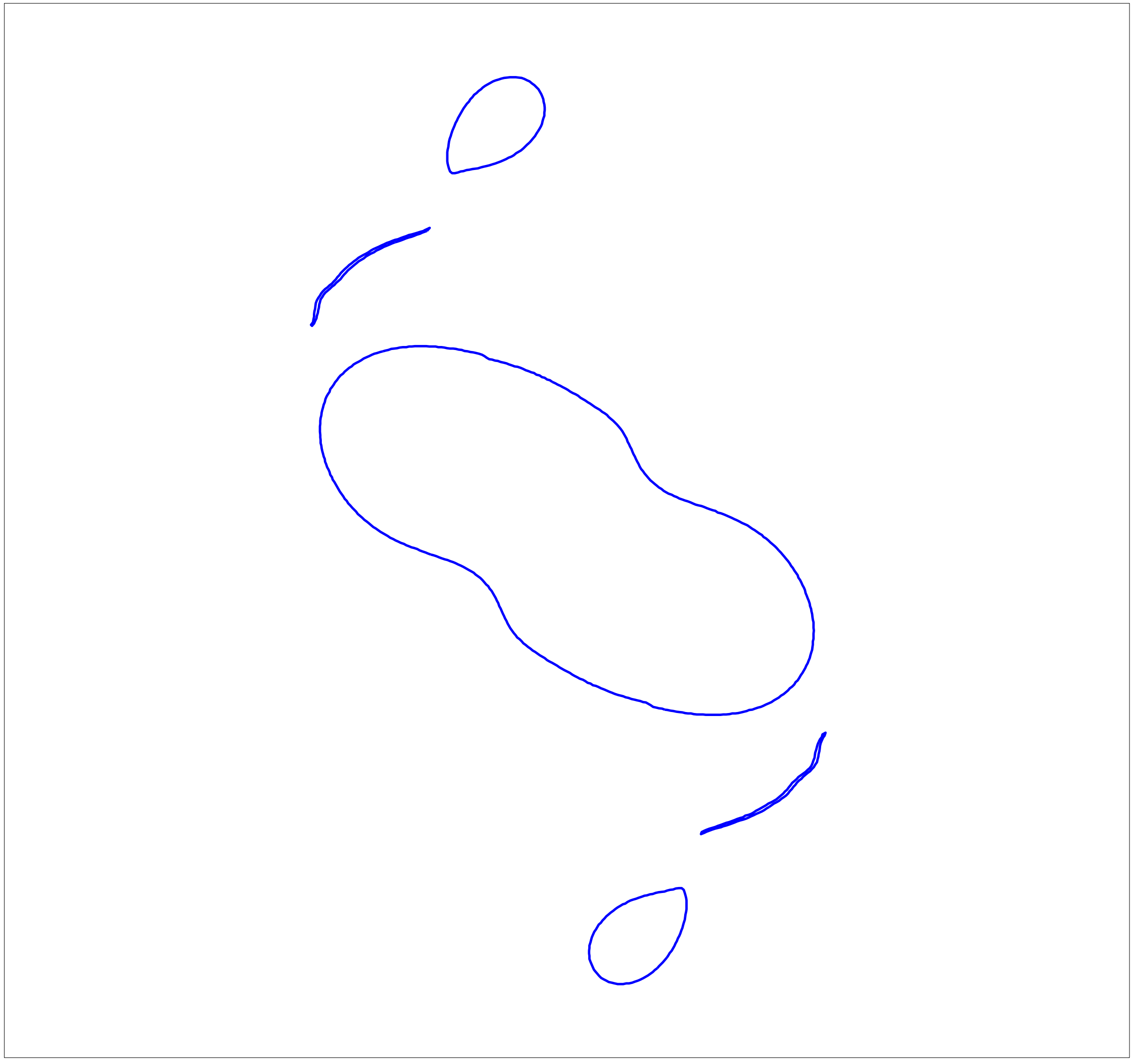
t=10



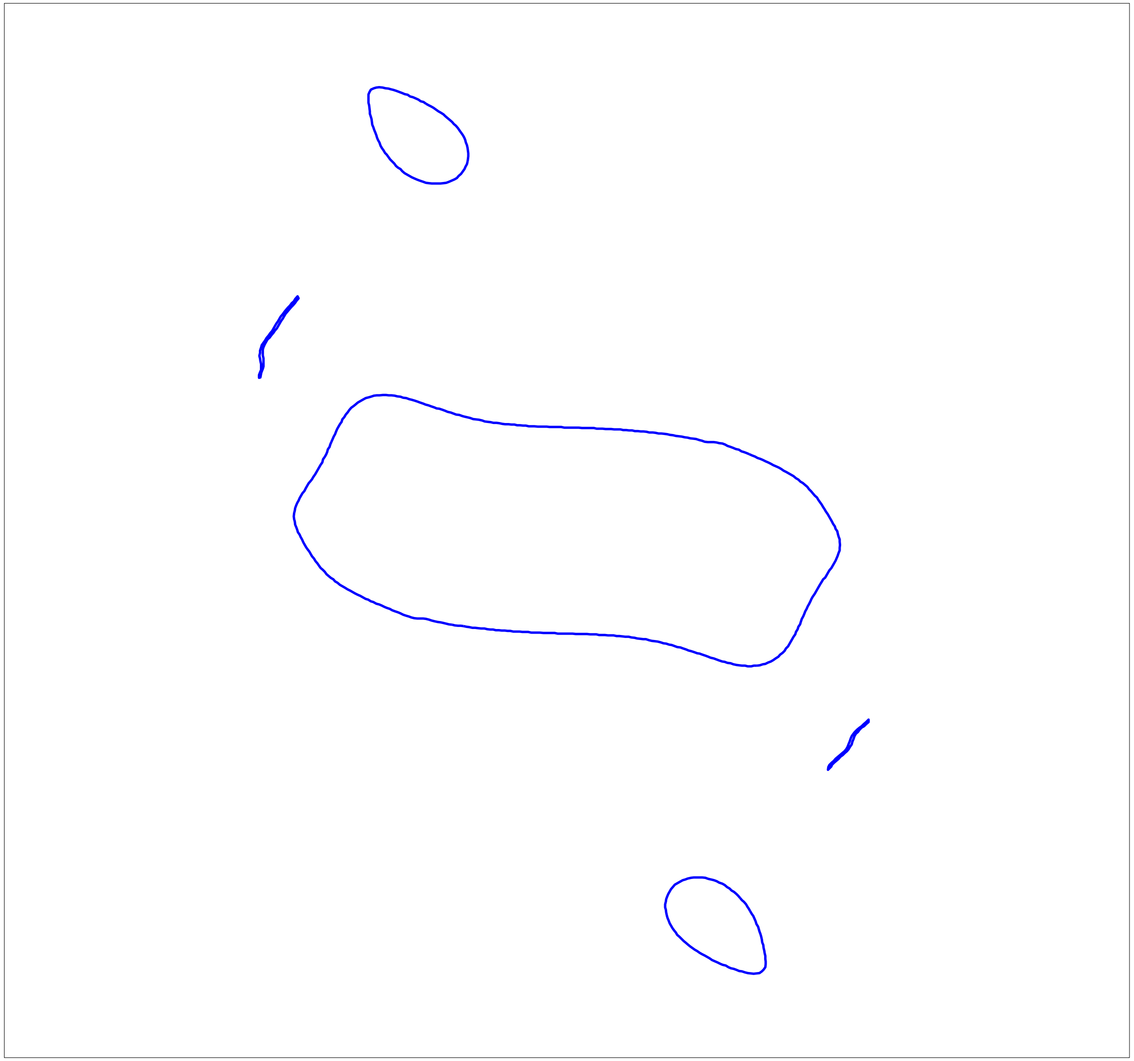
t=12



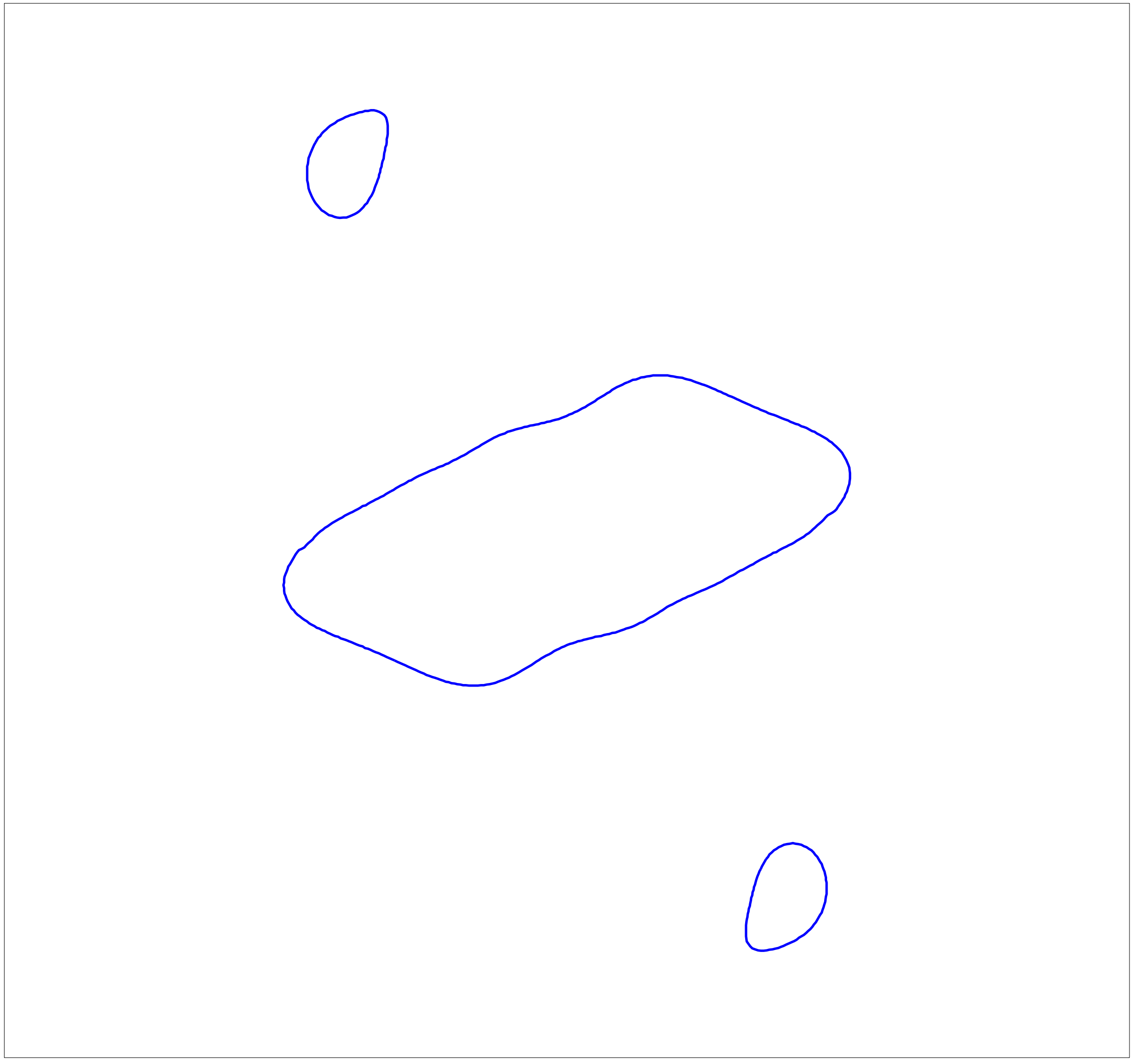
t=14



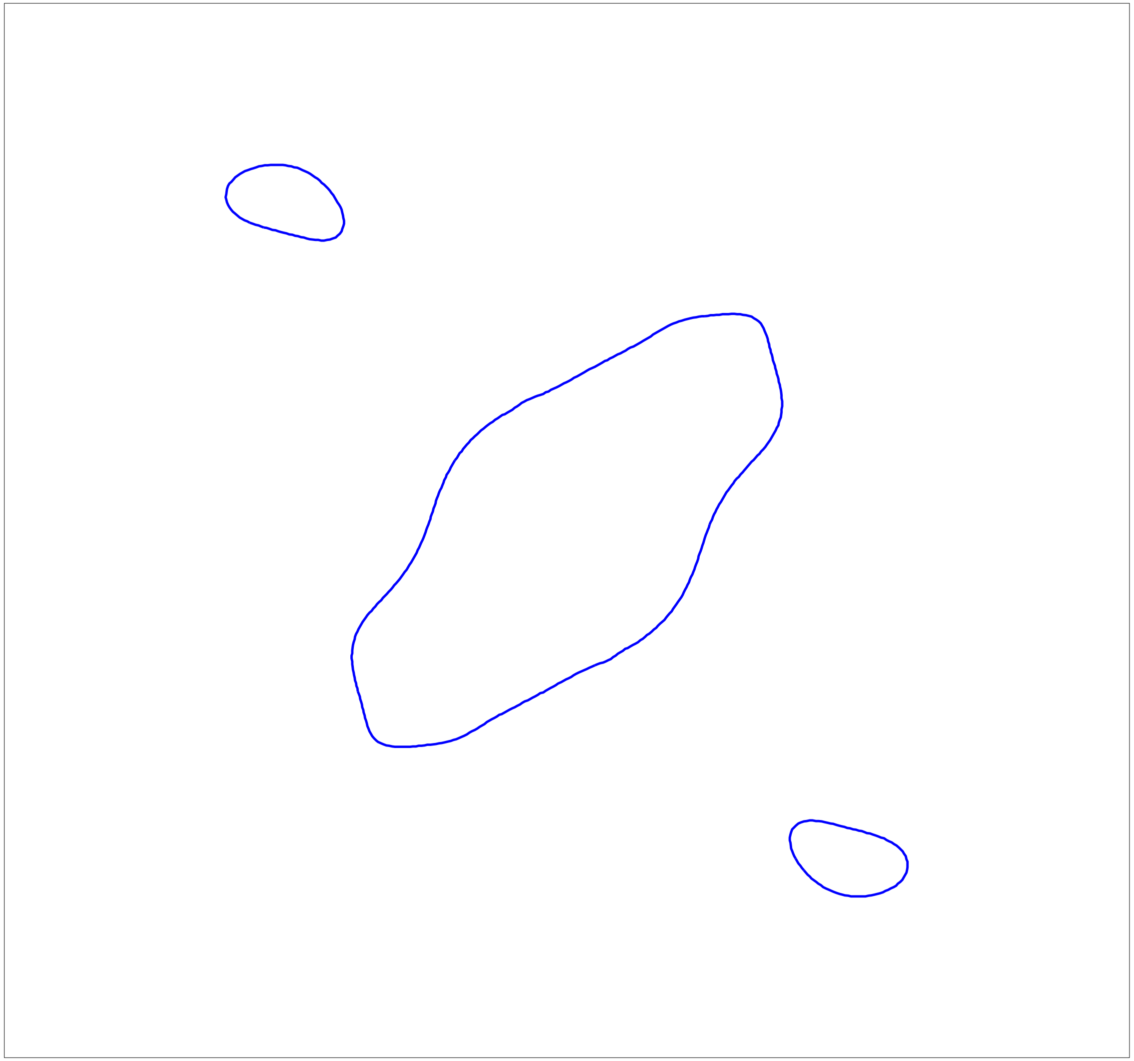
t=16



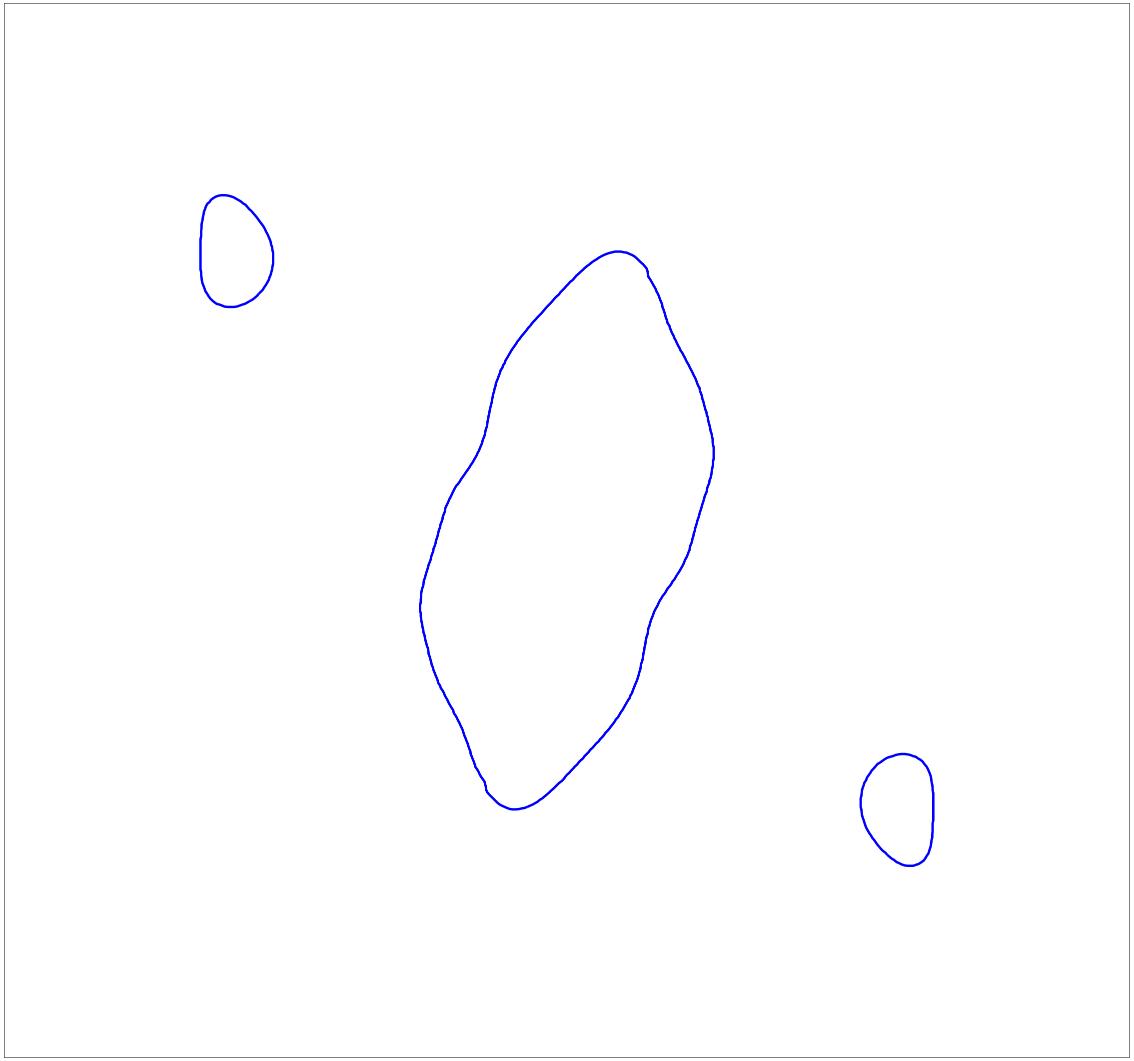
t=18



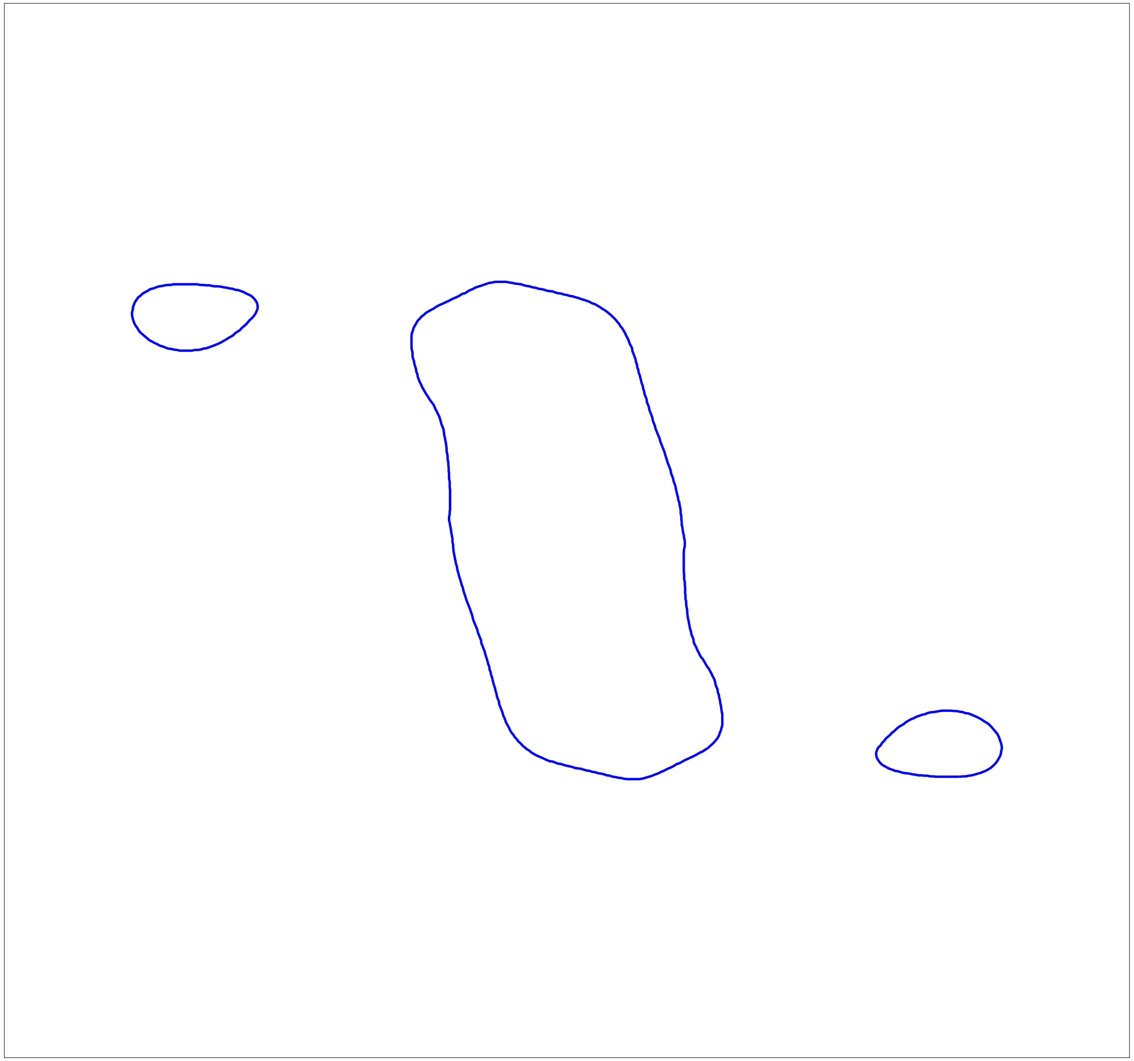
t=20



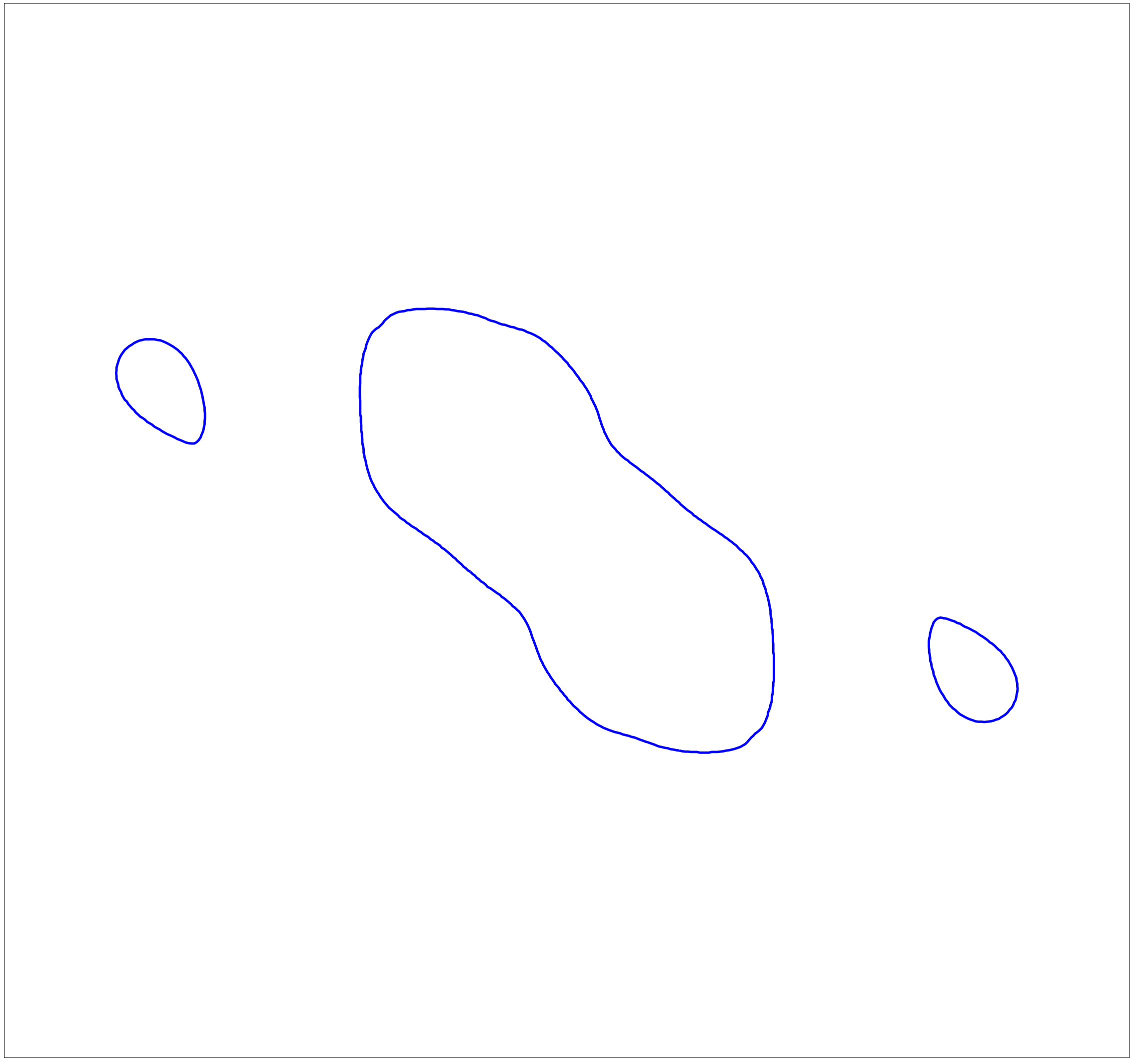
t=22



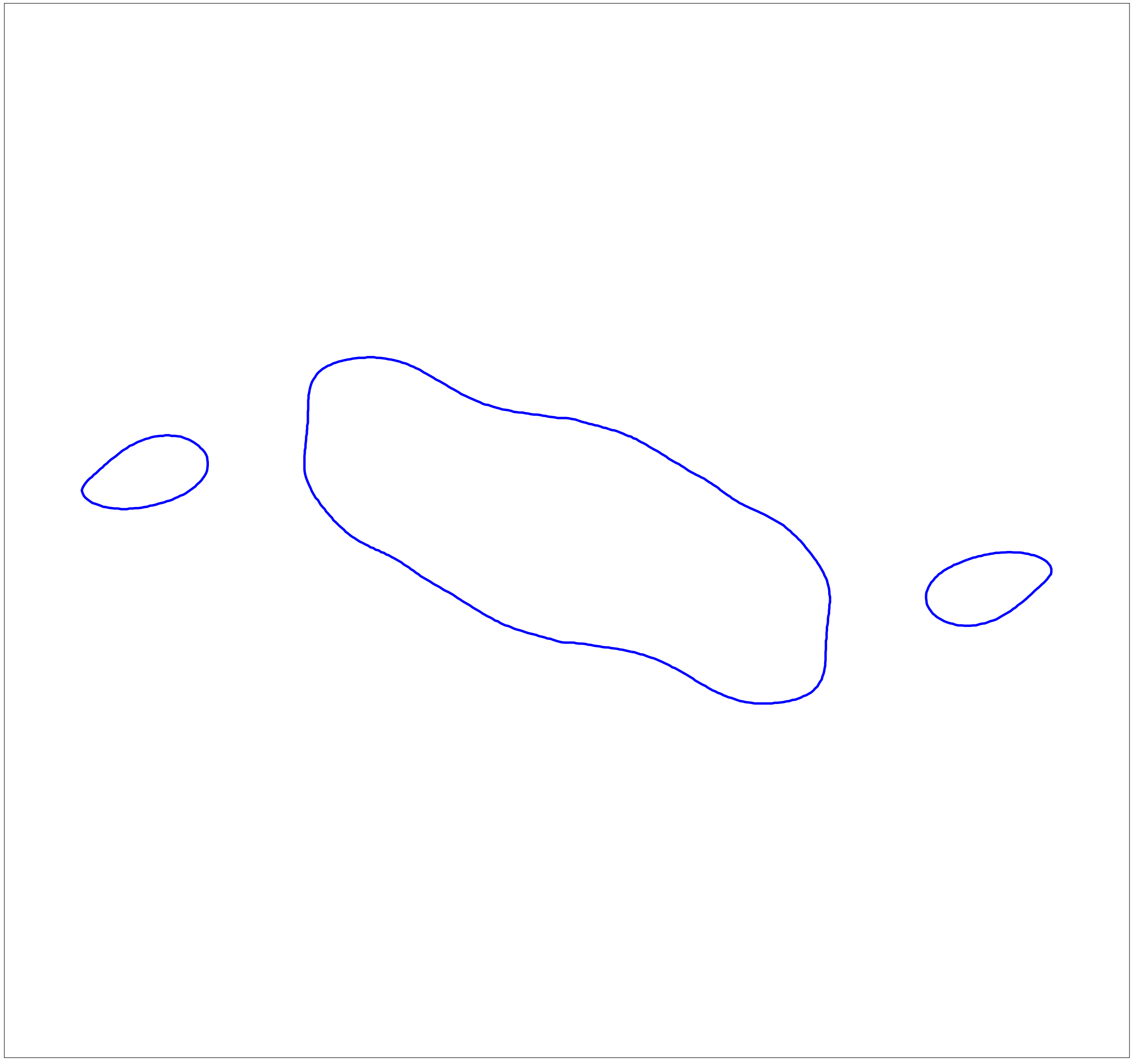
t=24



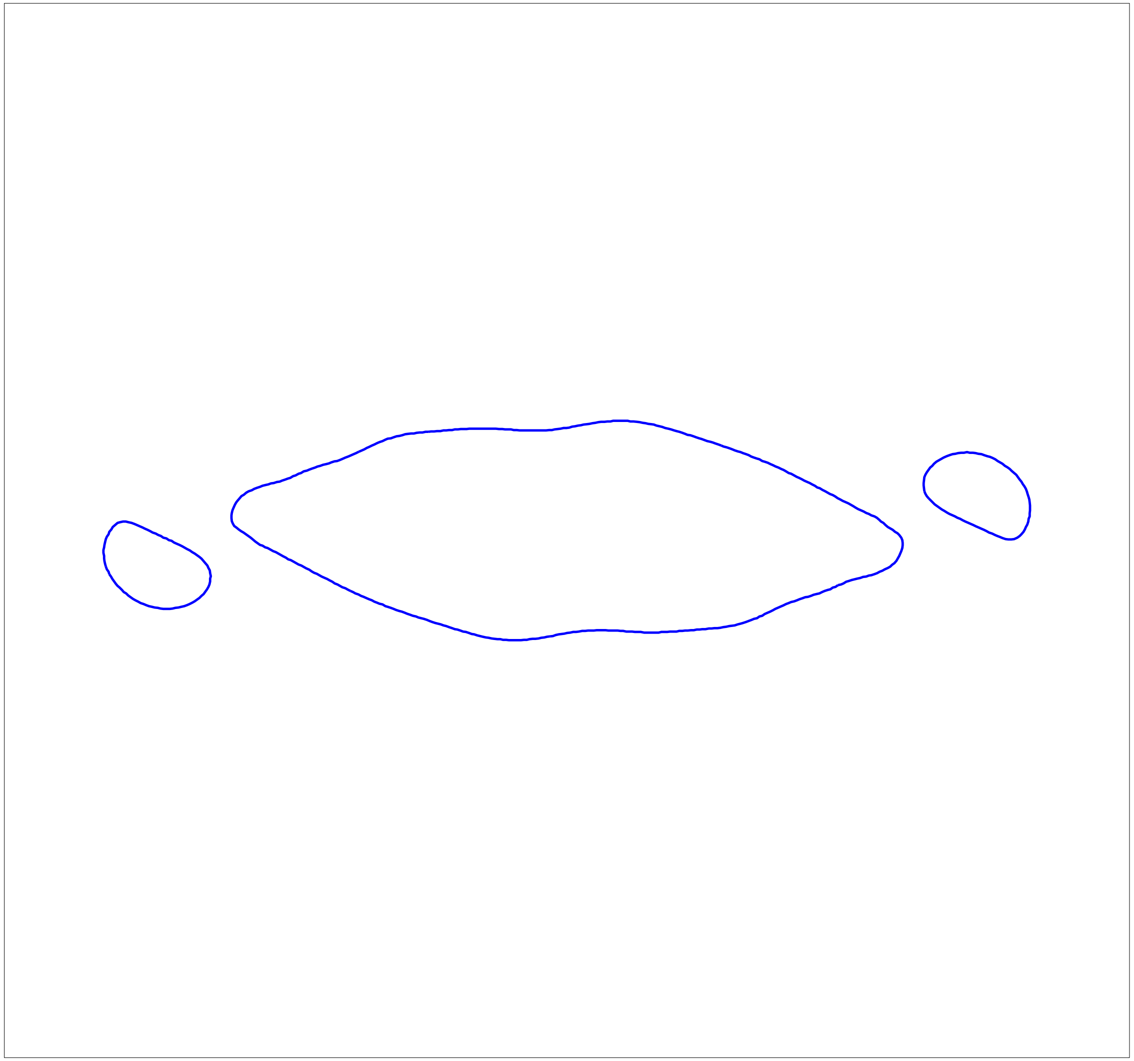
t=26



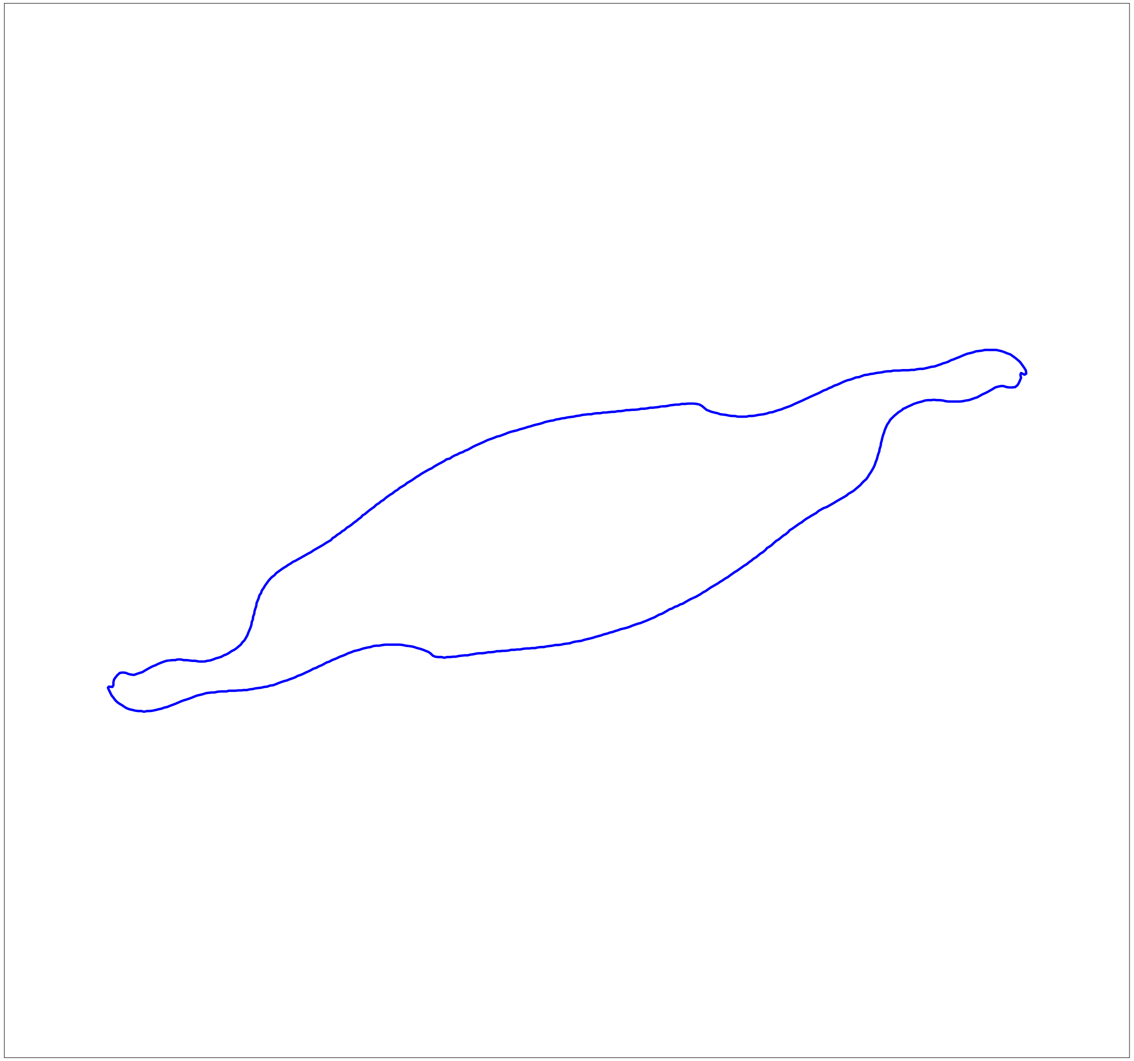
t=28



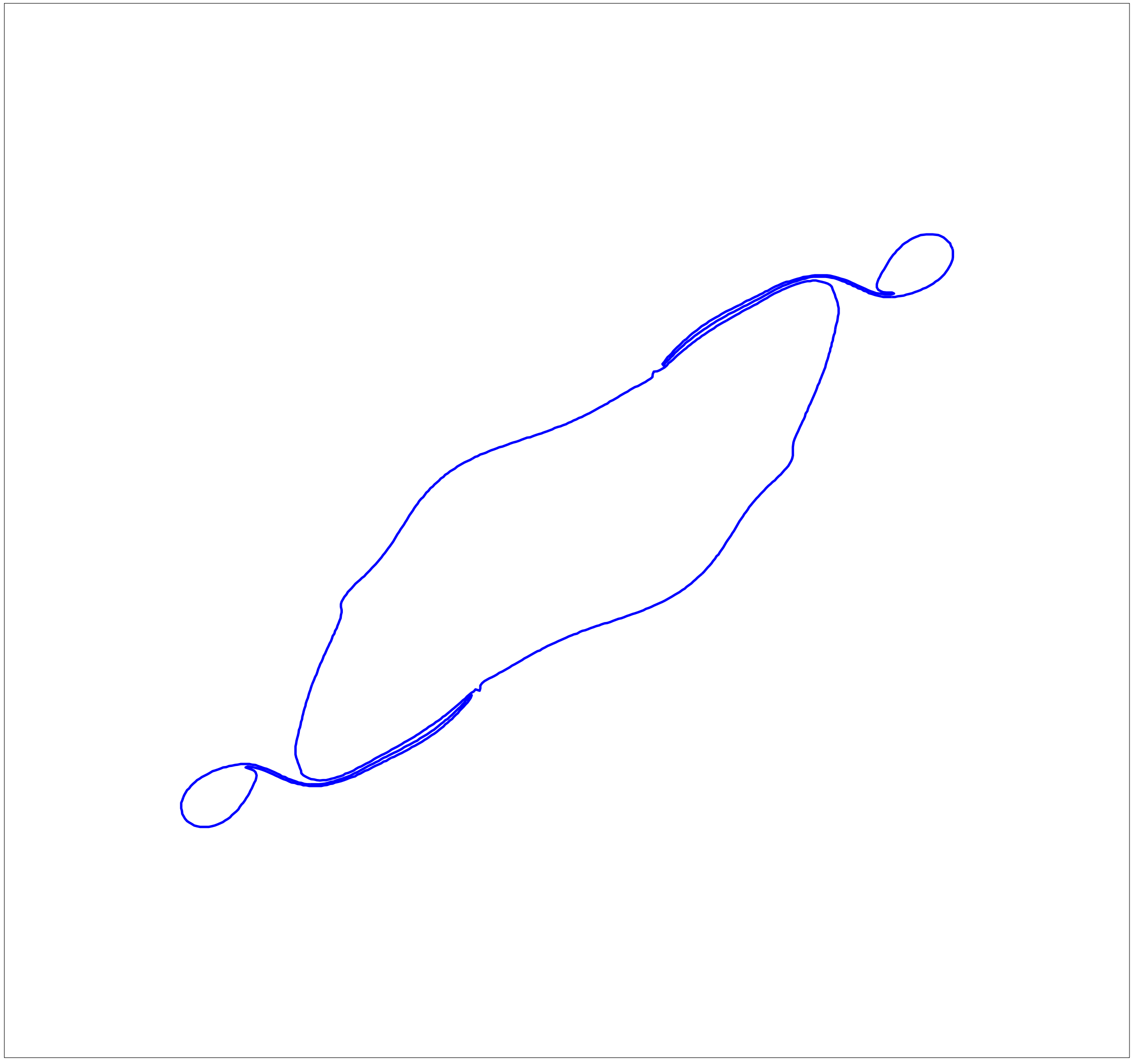
t=30



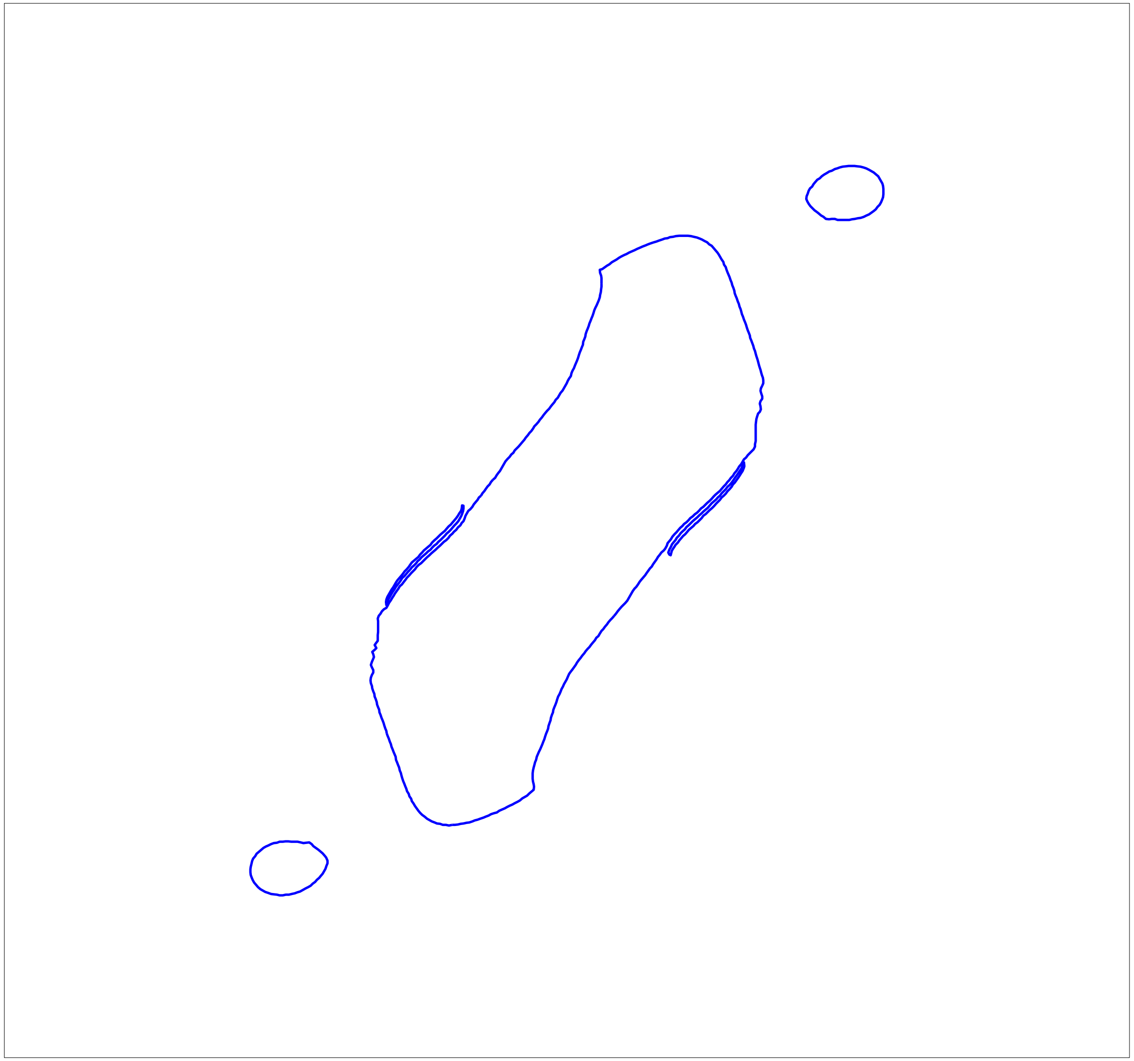
t=32



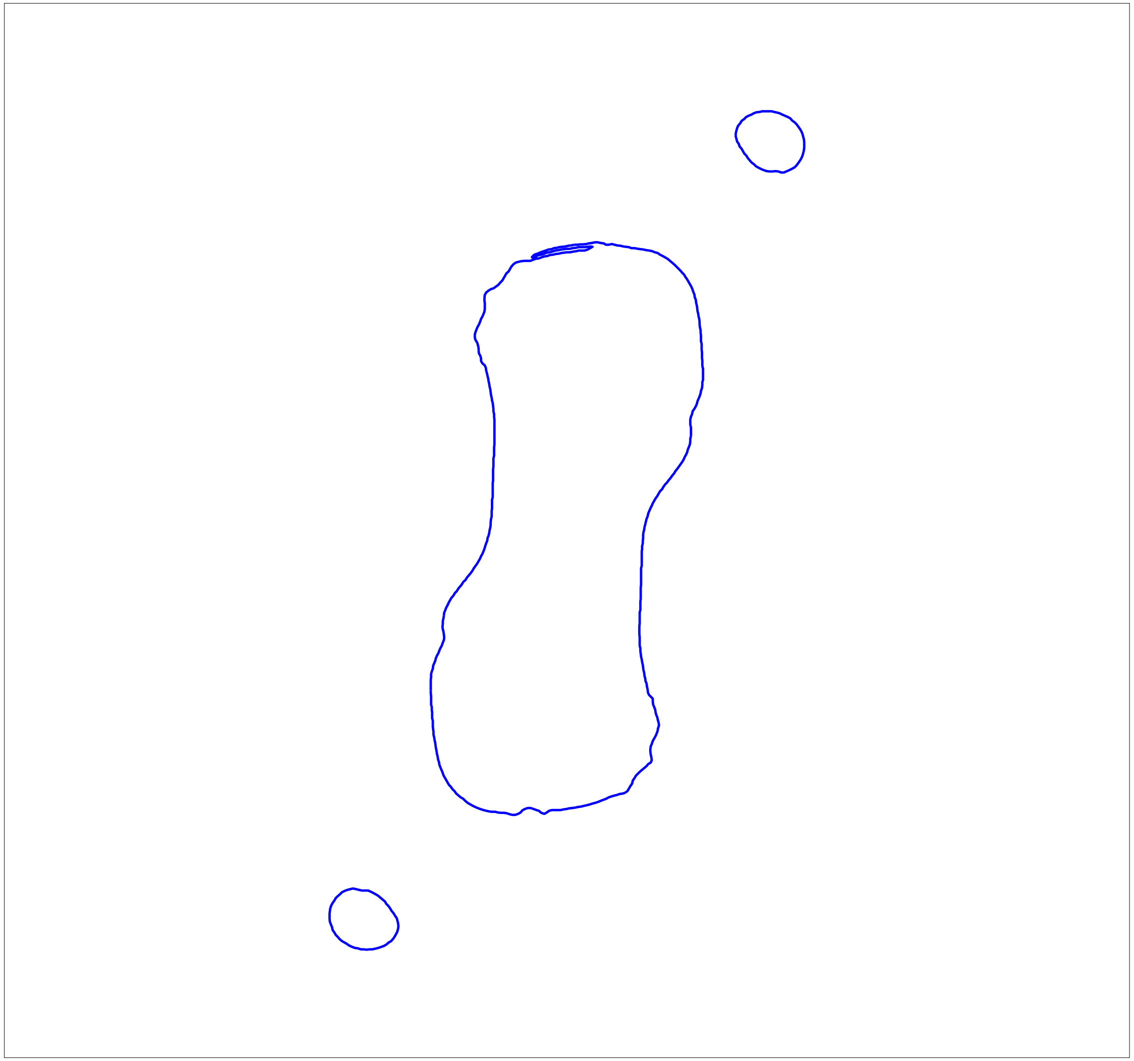
t=34



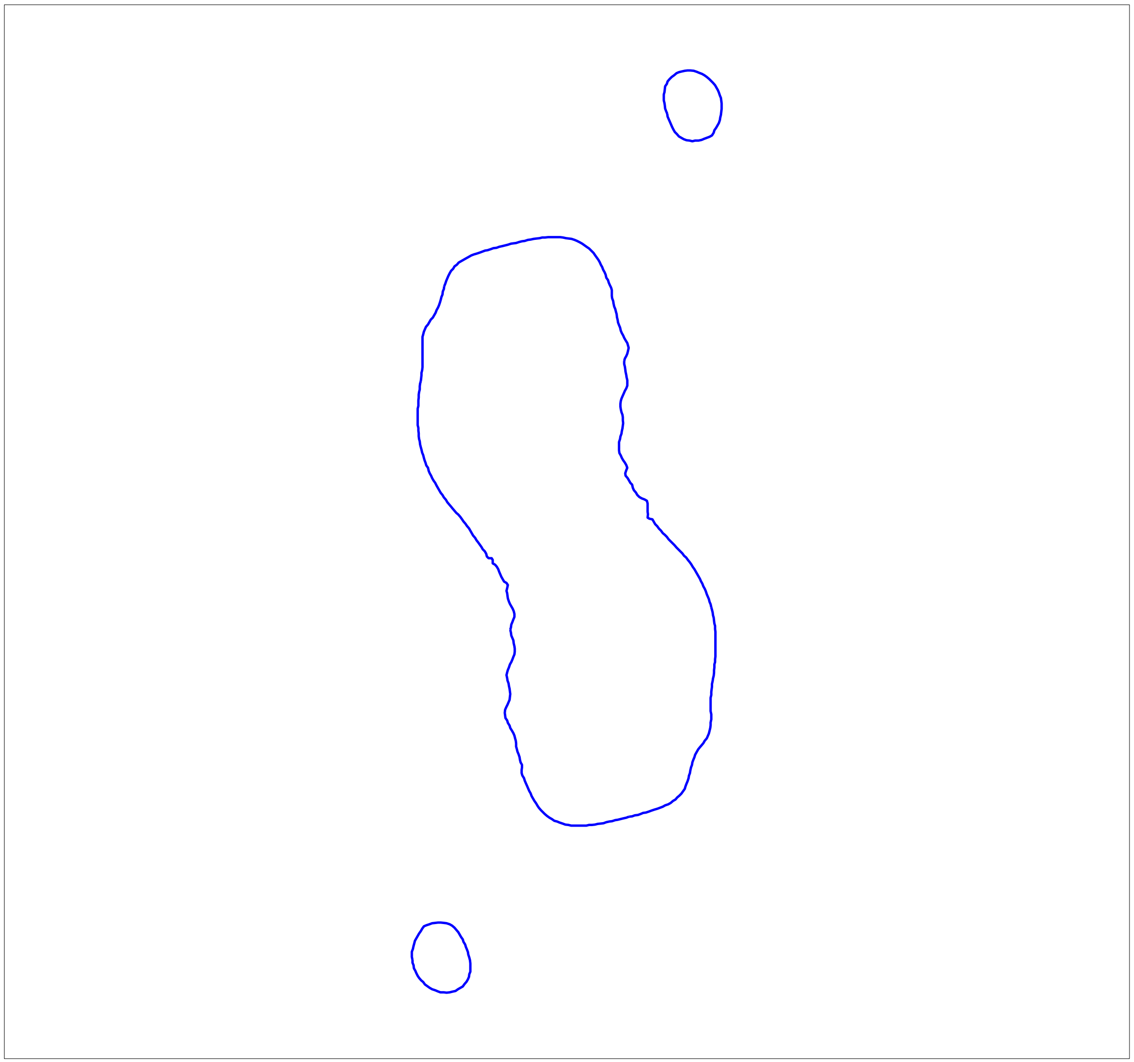
t=36



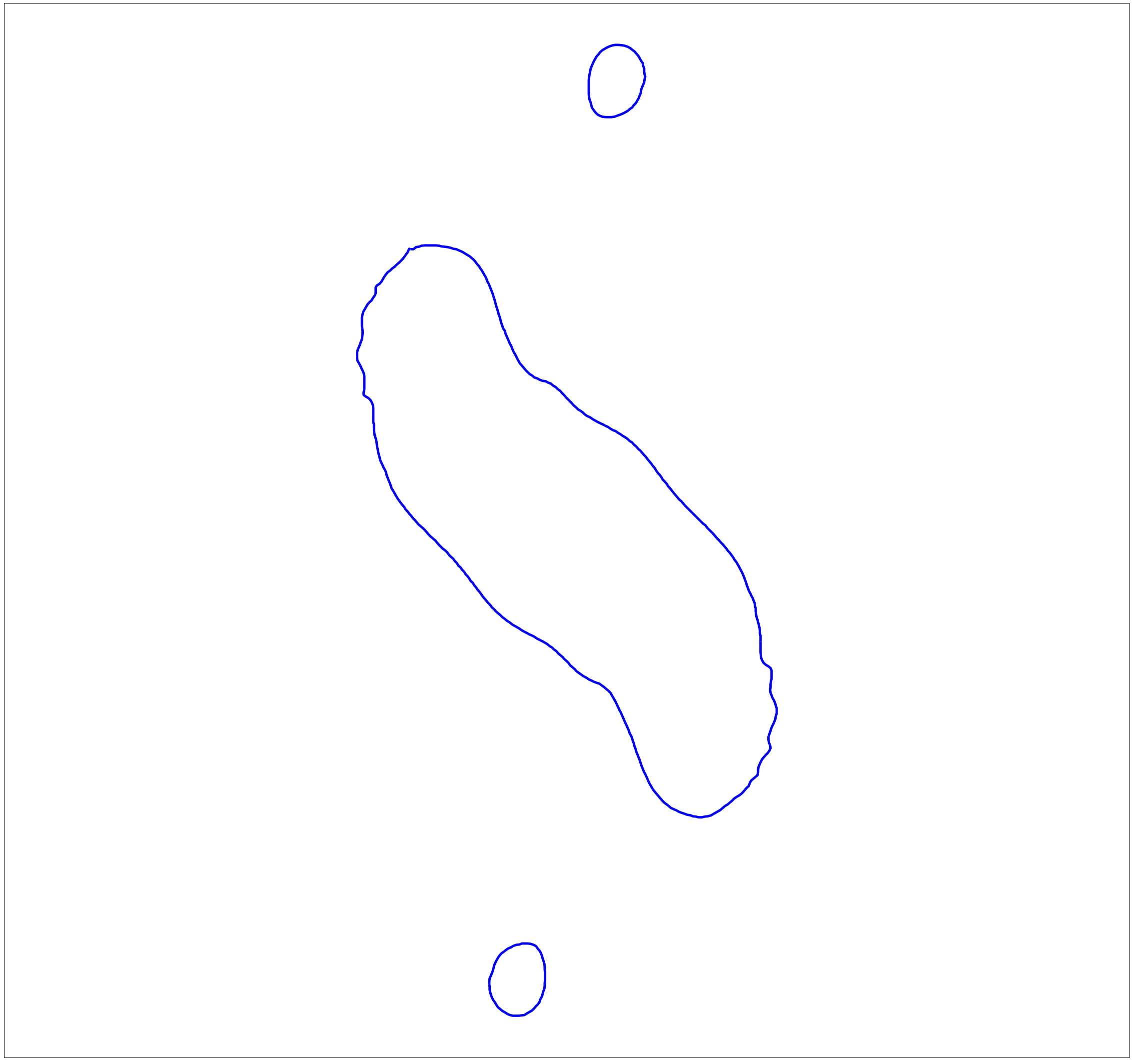
t=38



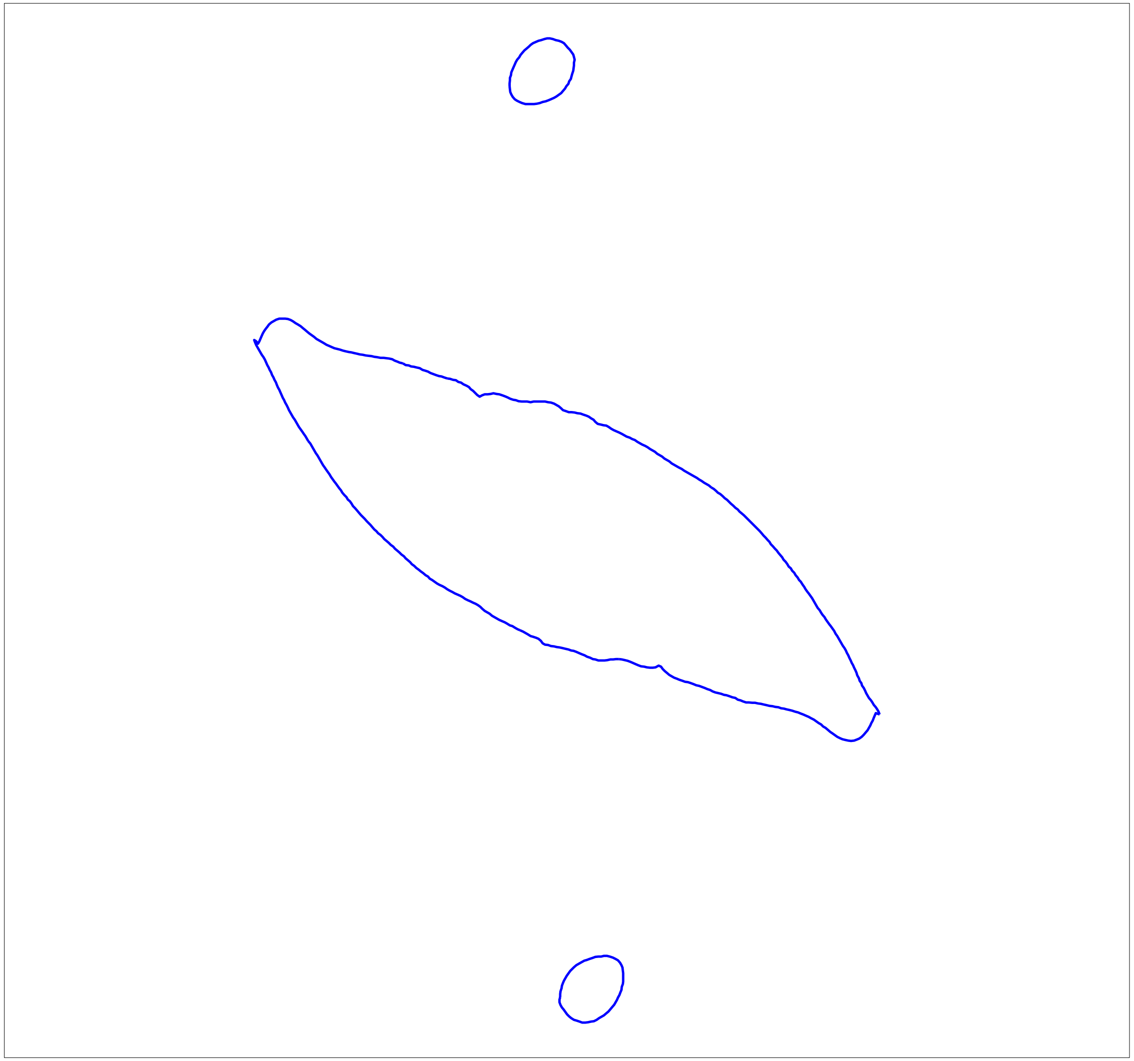
t=40



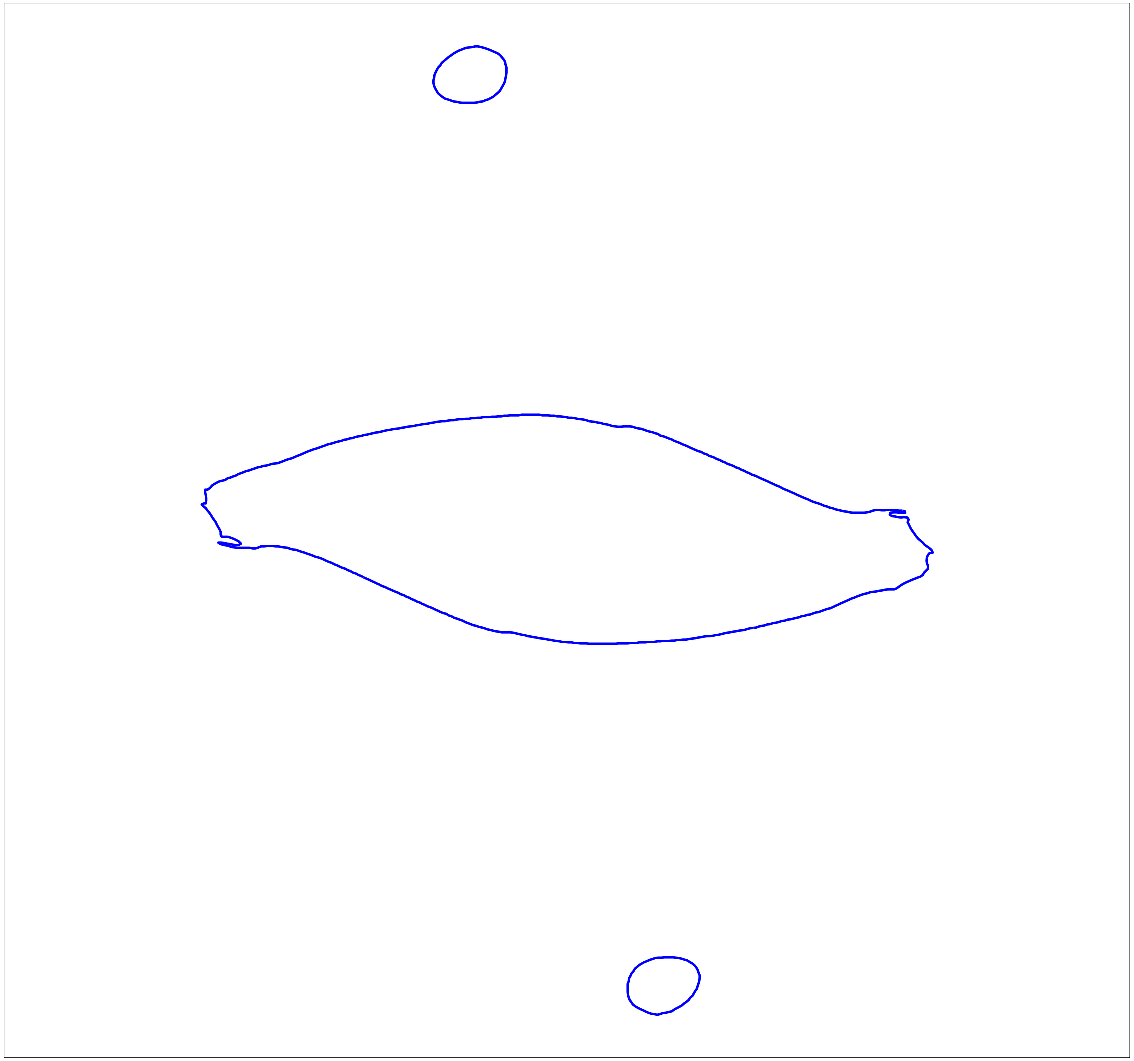
t=42



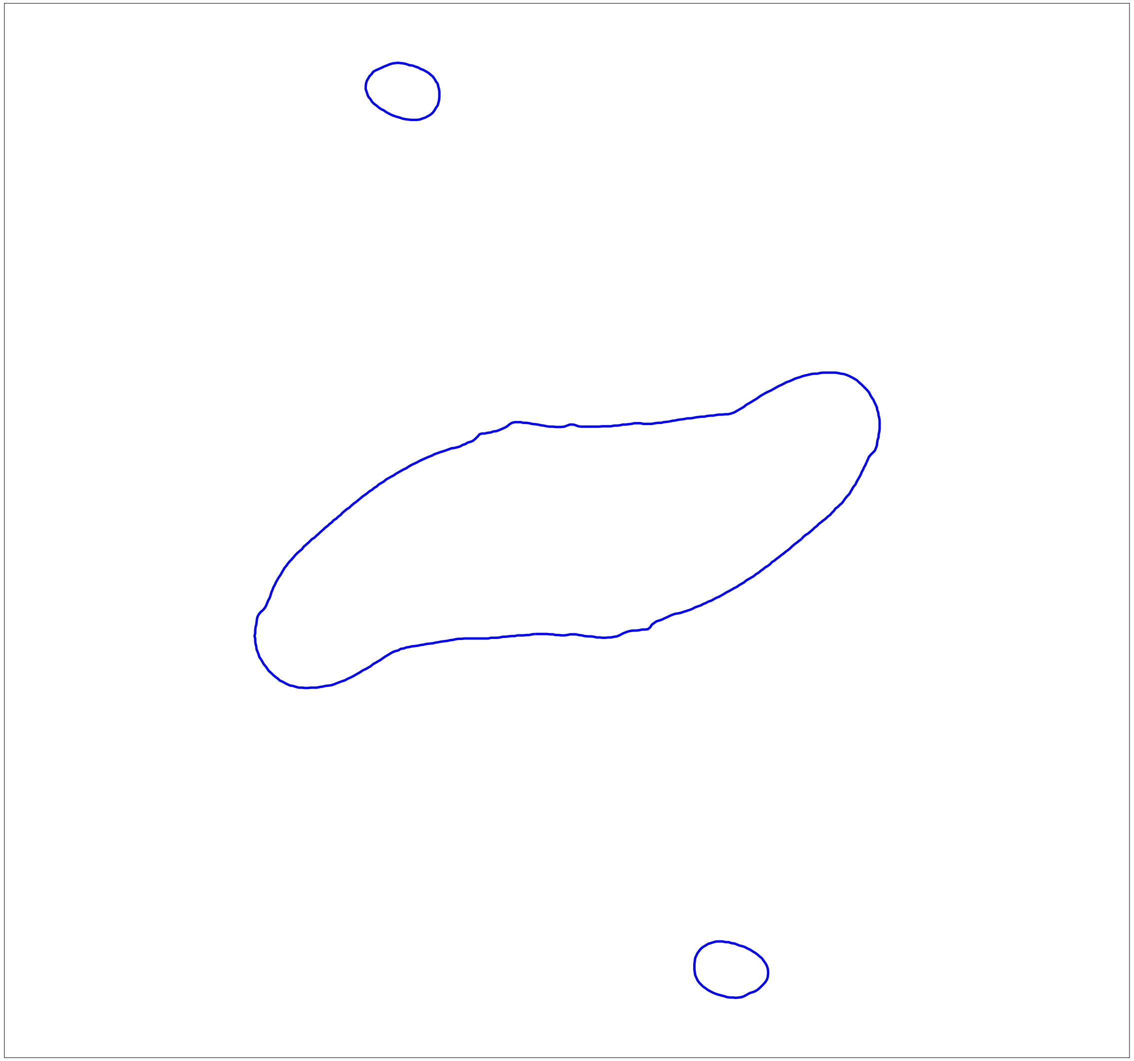
t=44



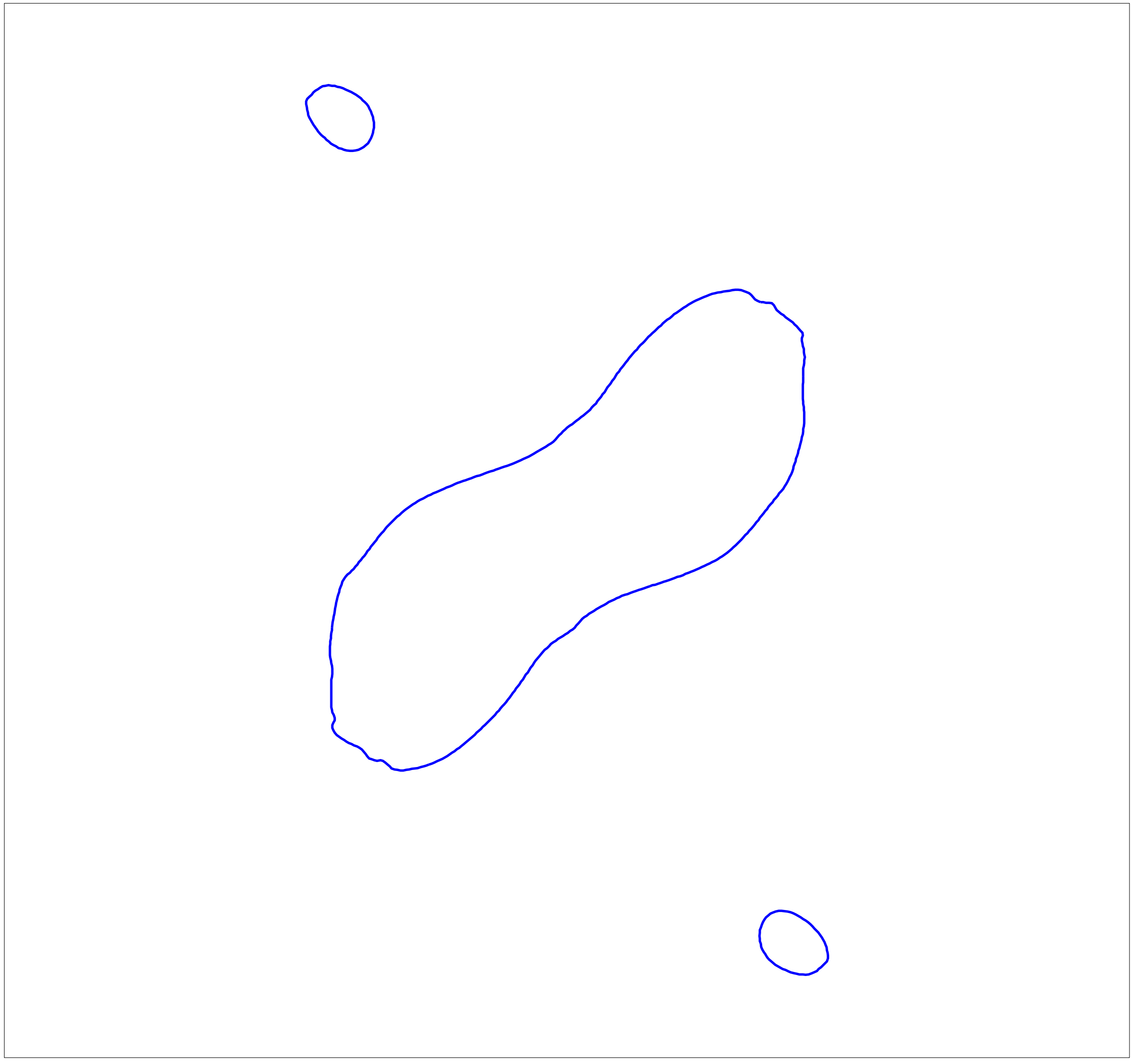
t=46



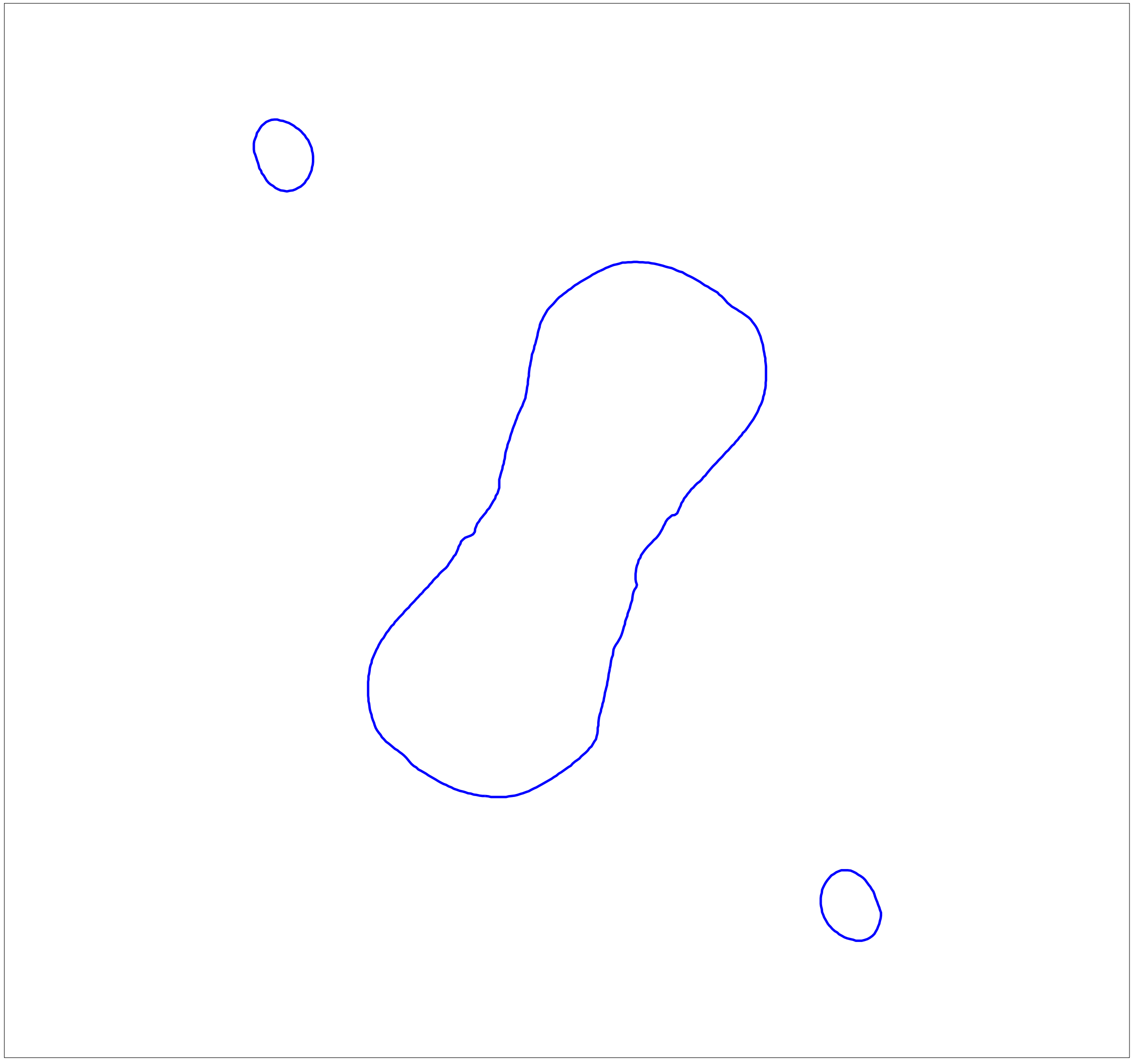
t=48



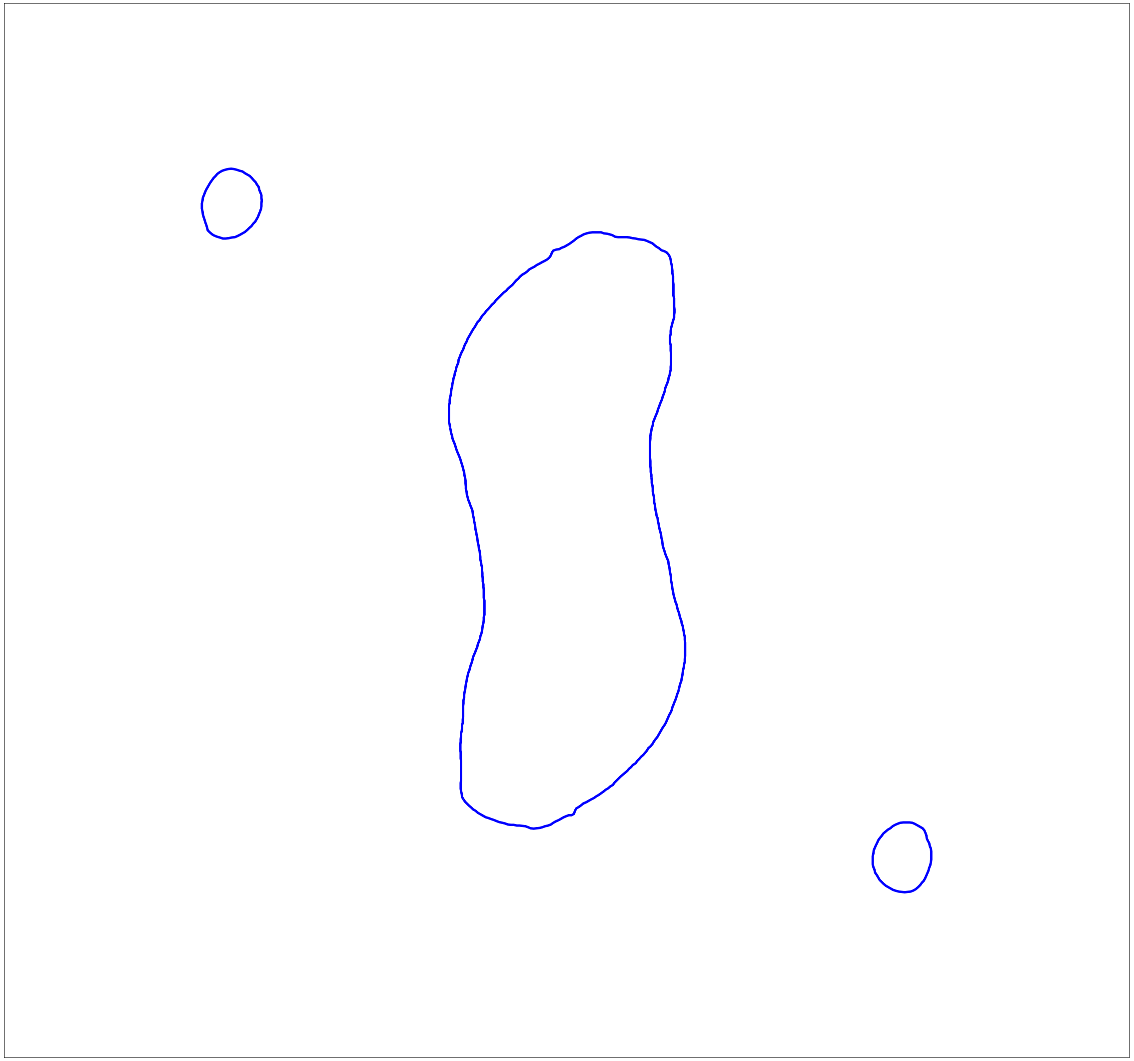
t=50



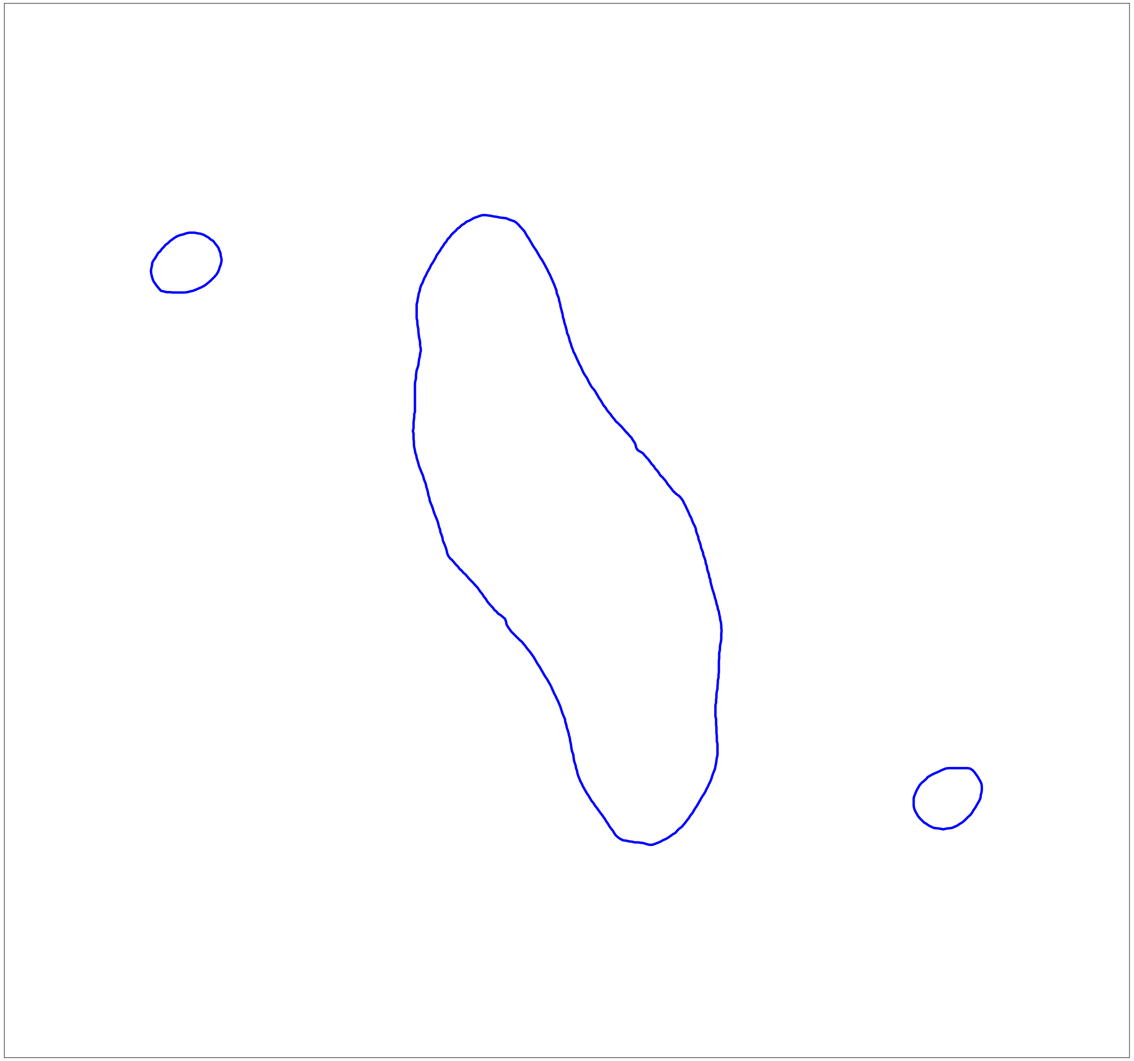
t=52



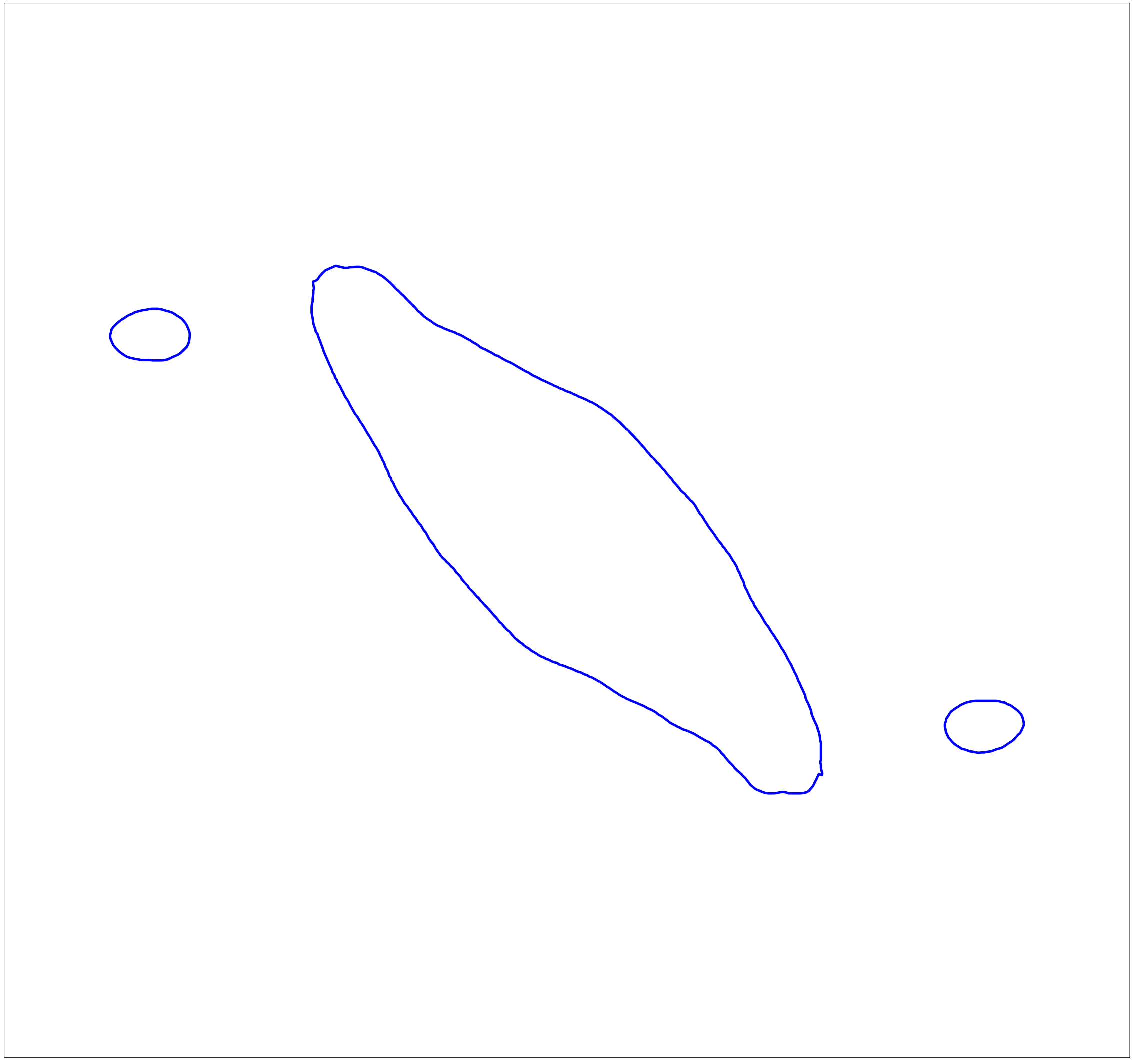
t=54



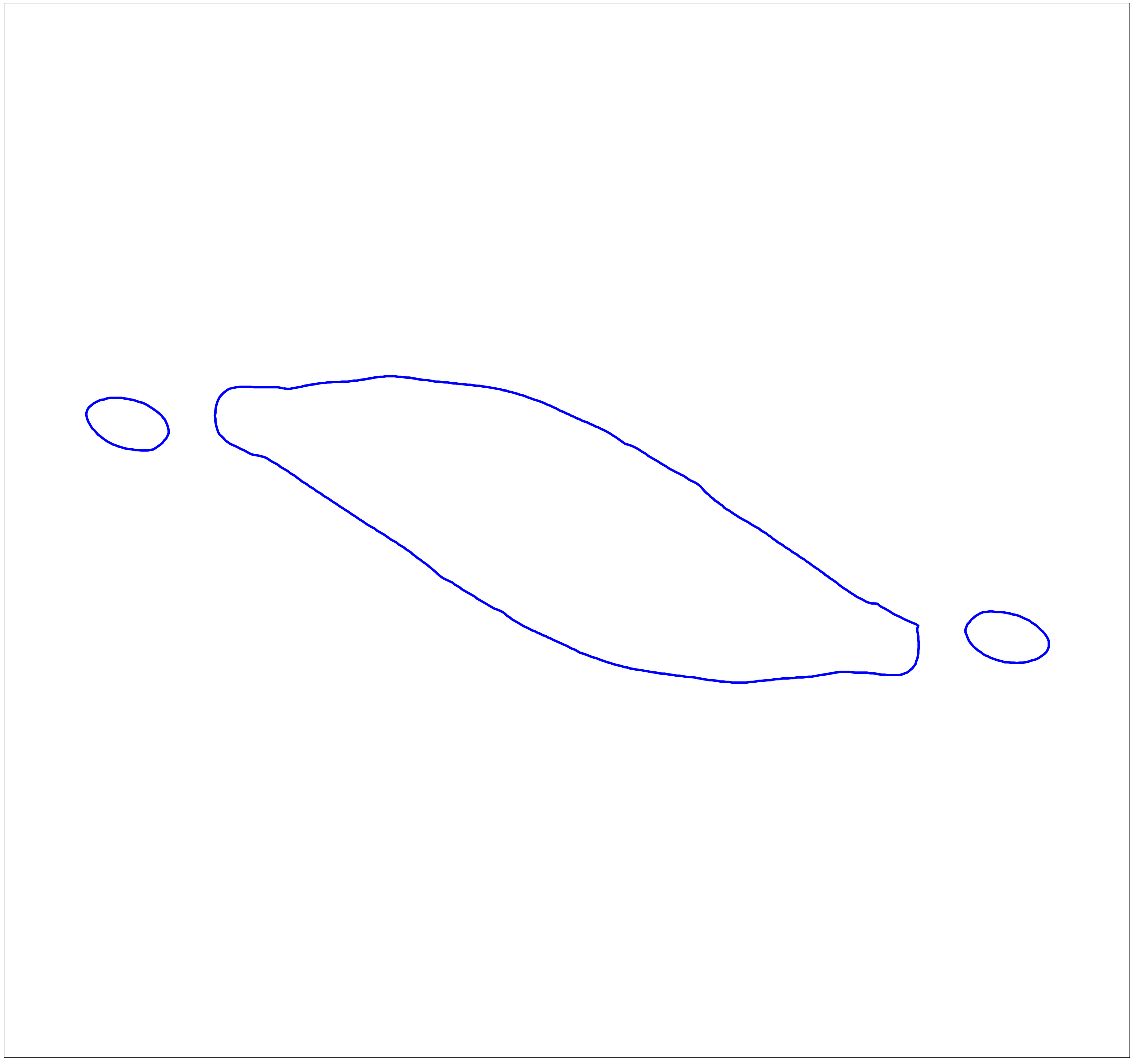
t=56



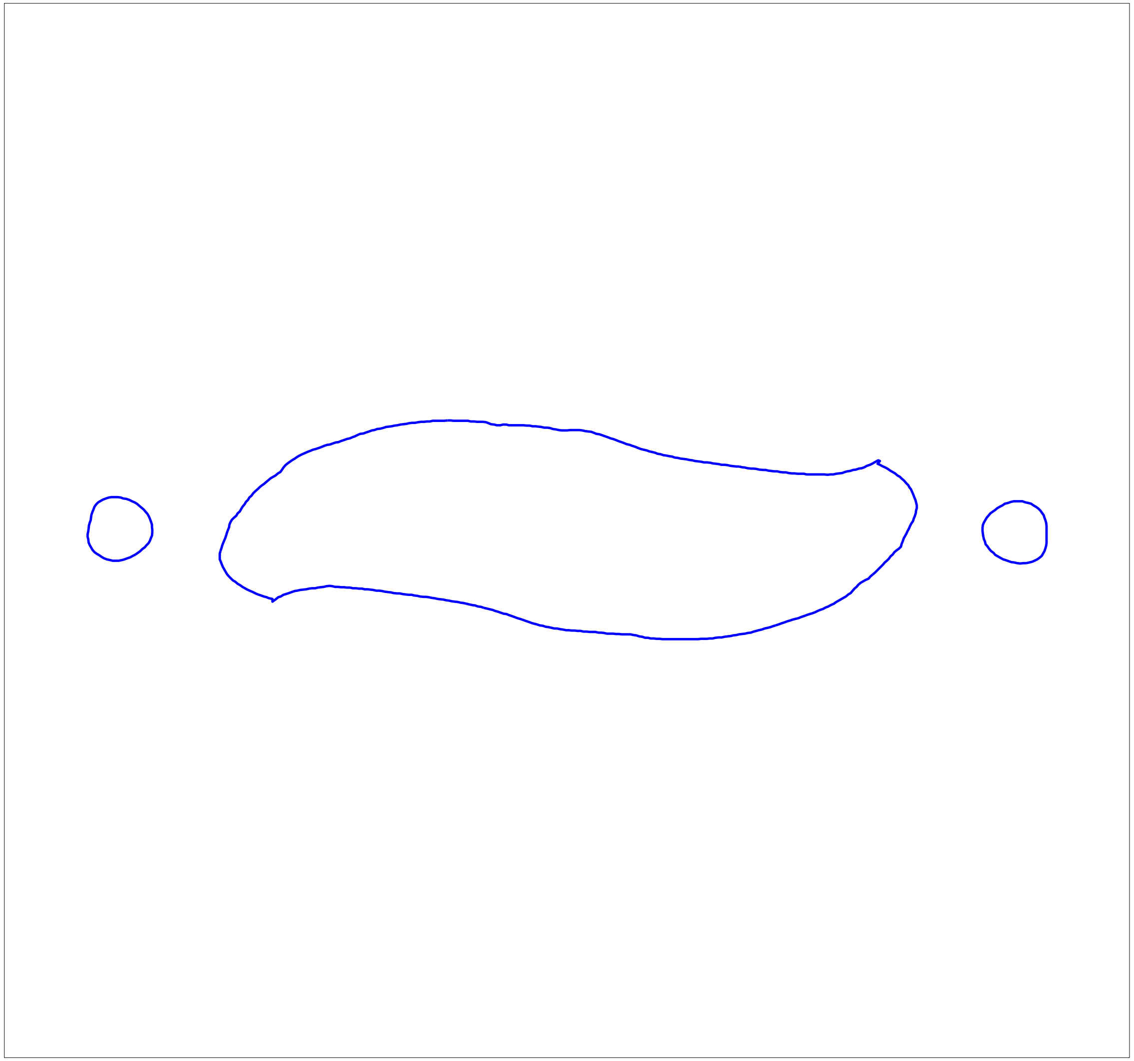
t=58



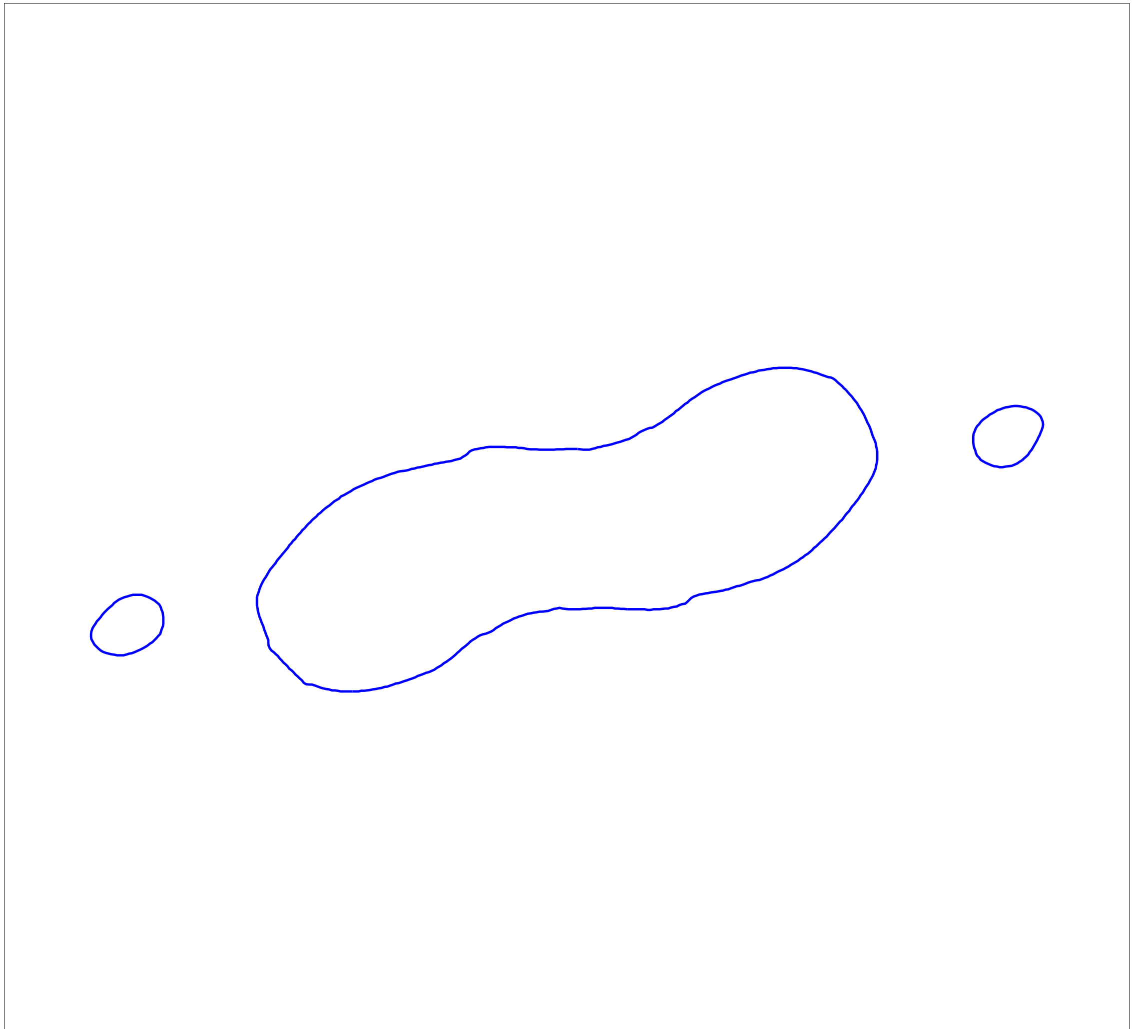
t=60



t=62



t=64



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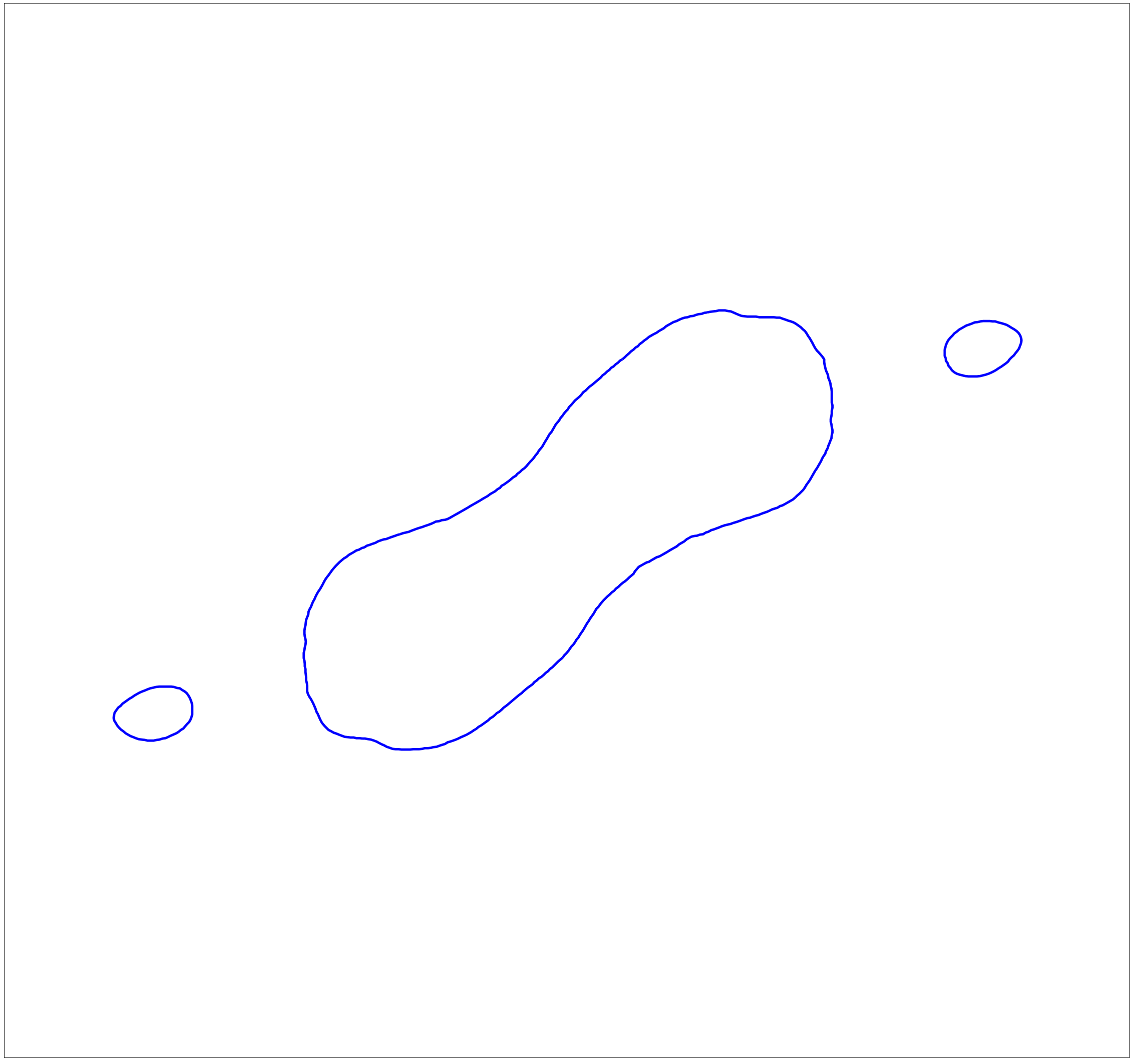

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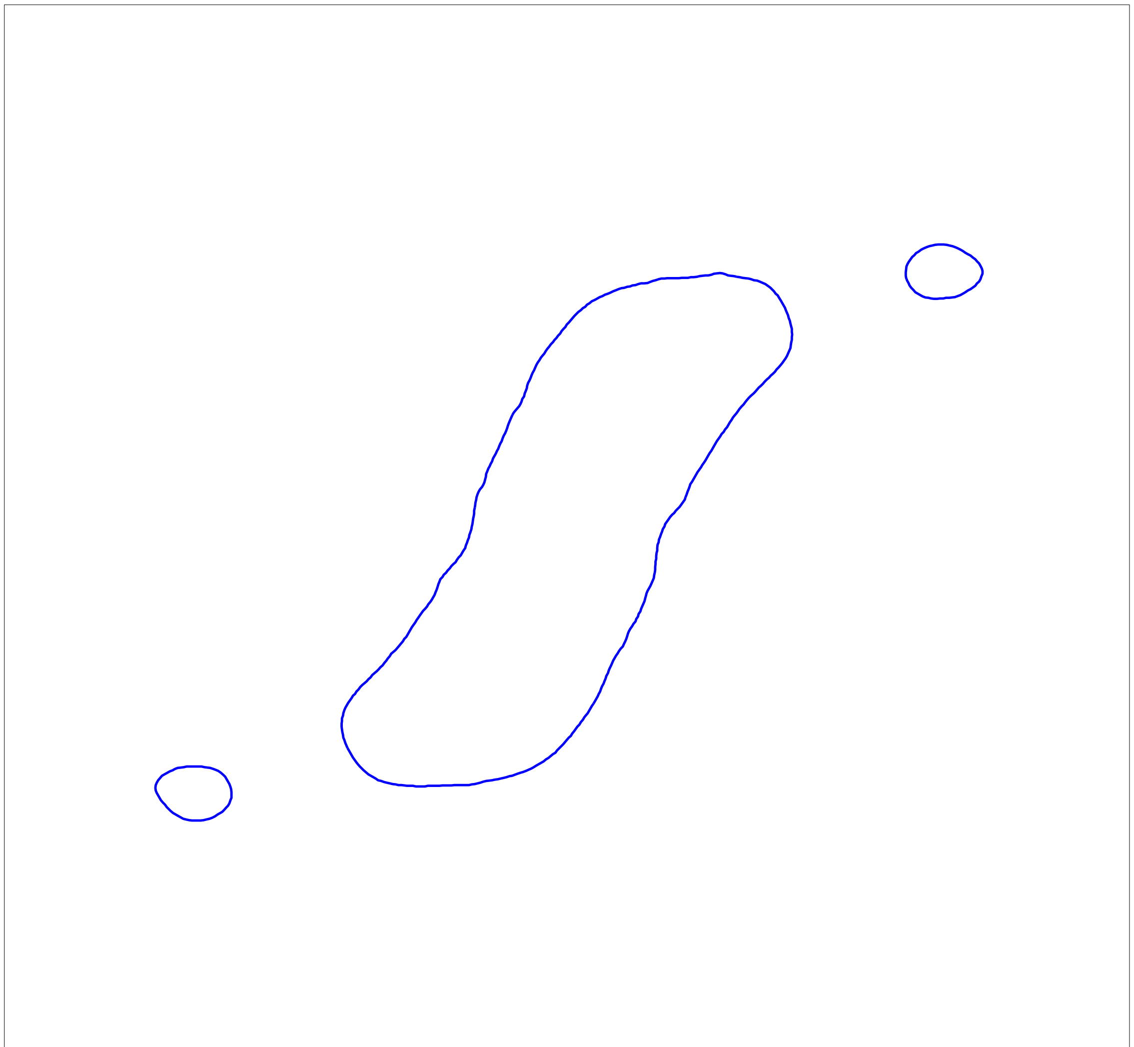
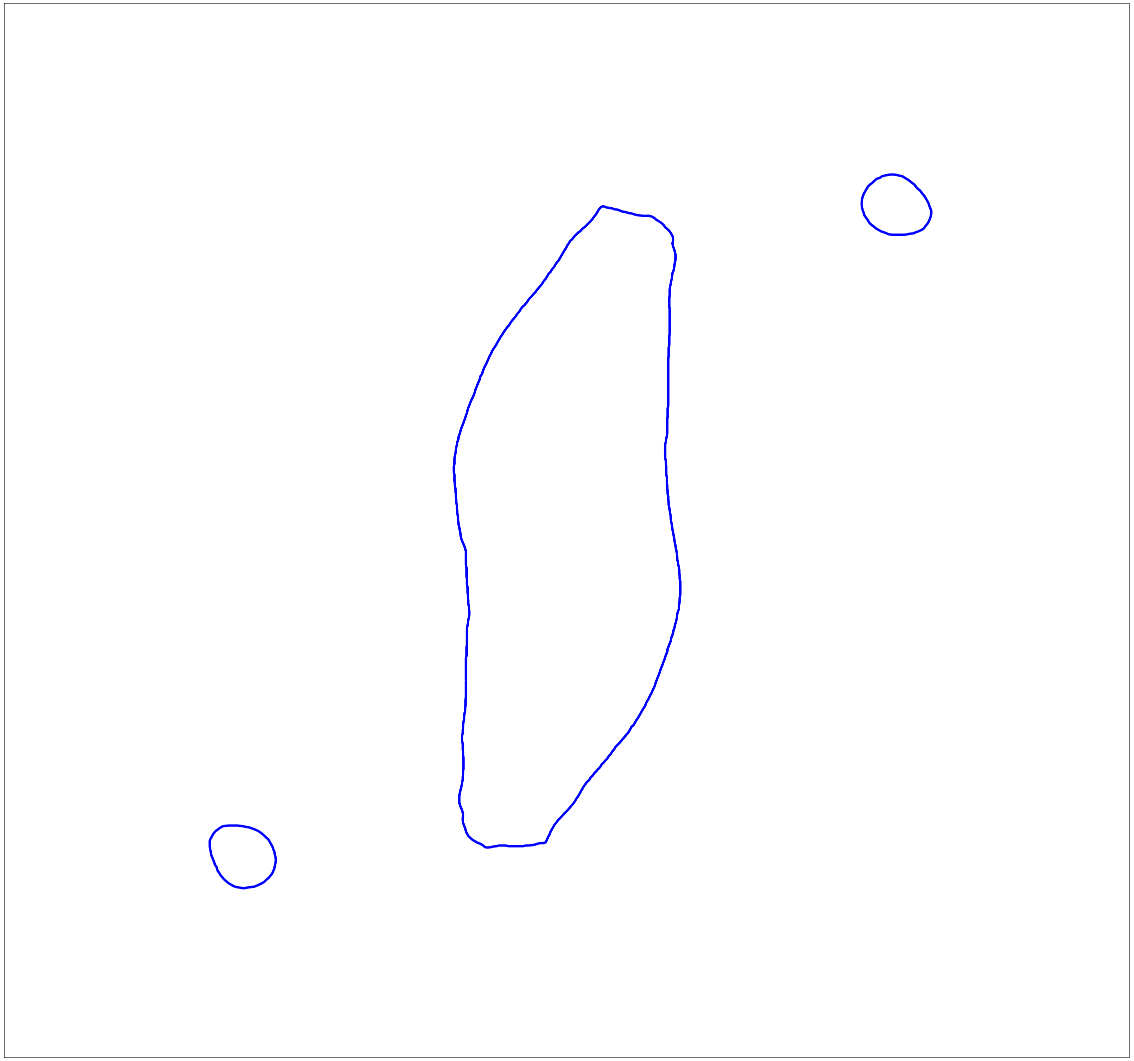
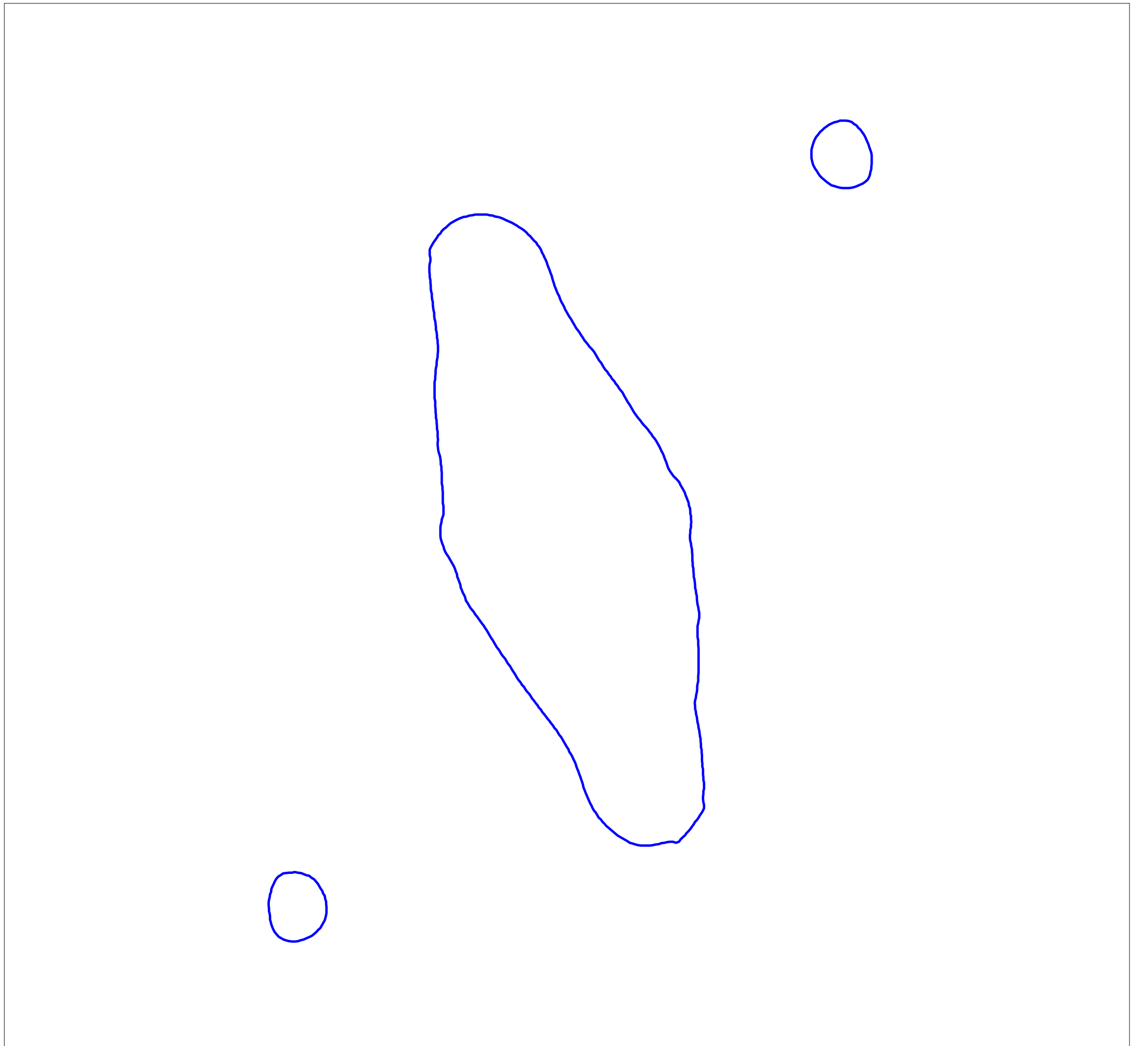


t=70



t=72



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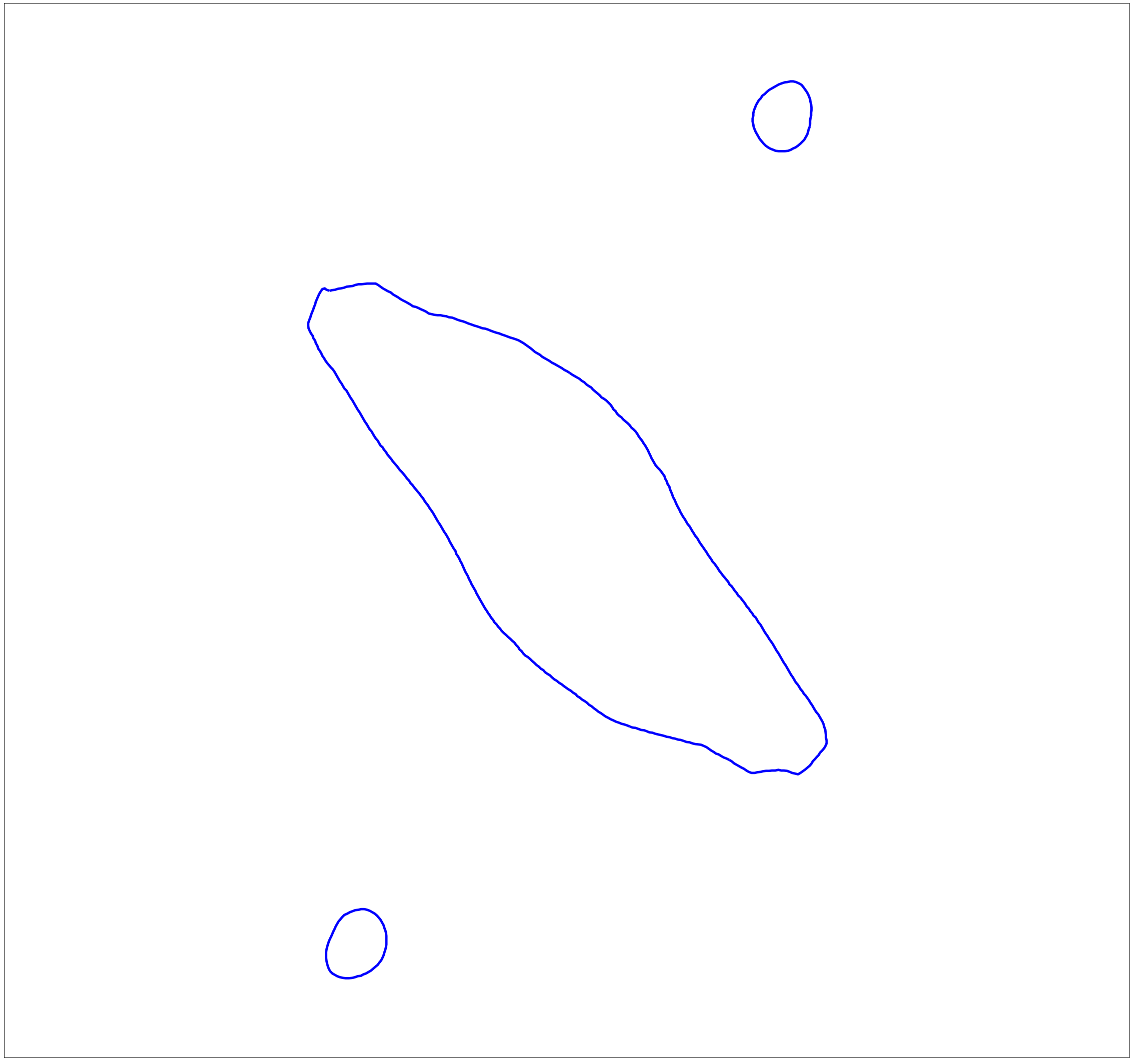

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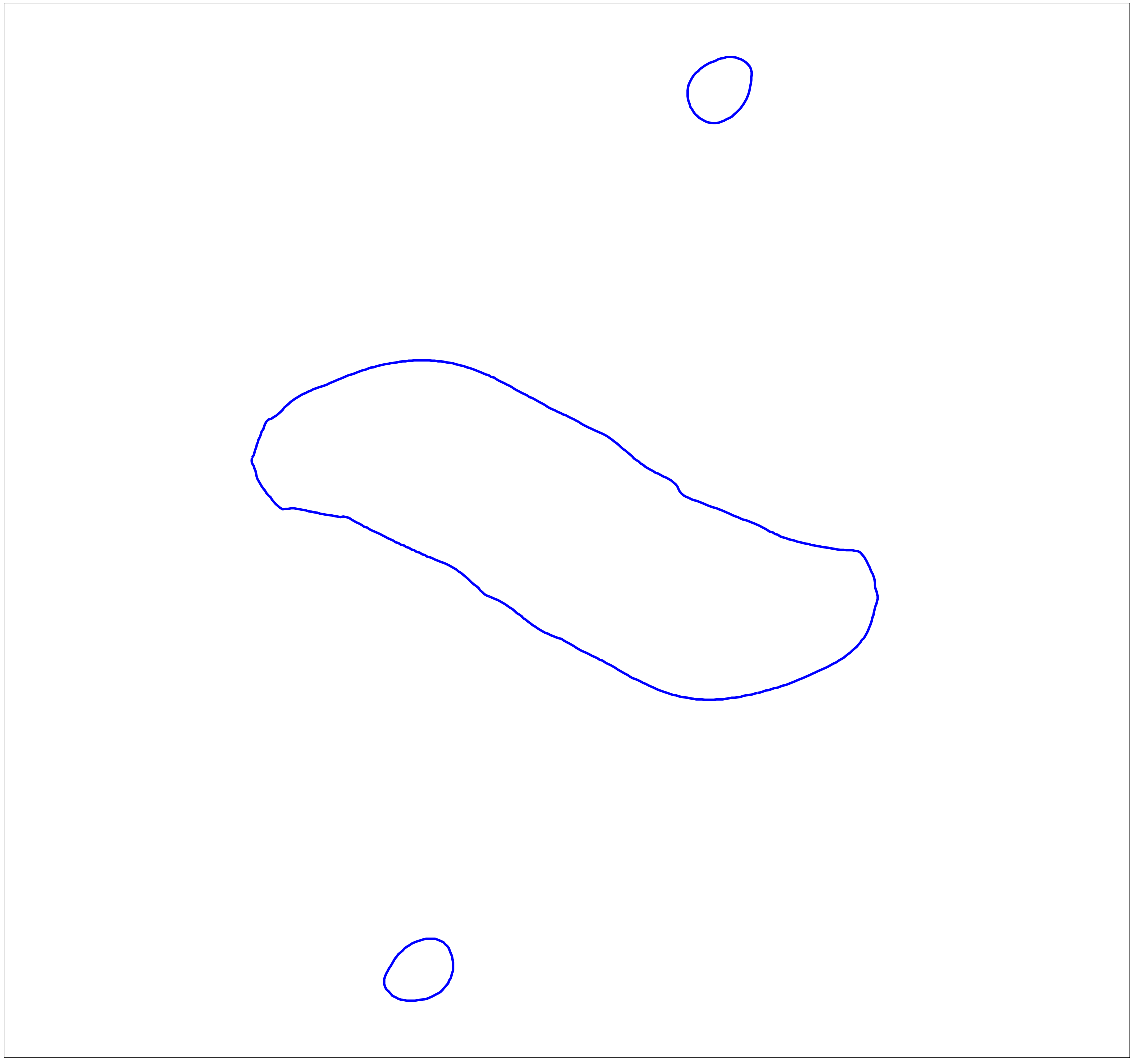
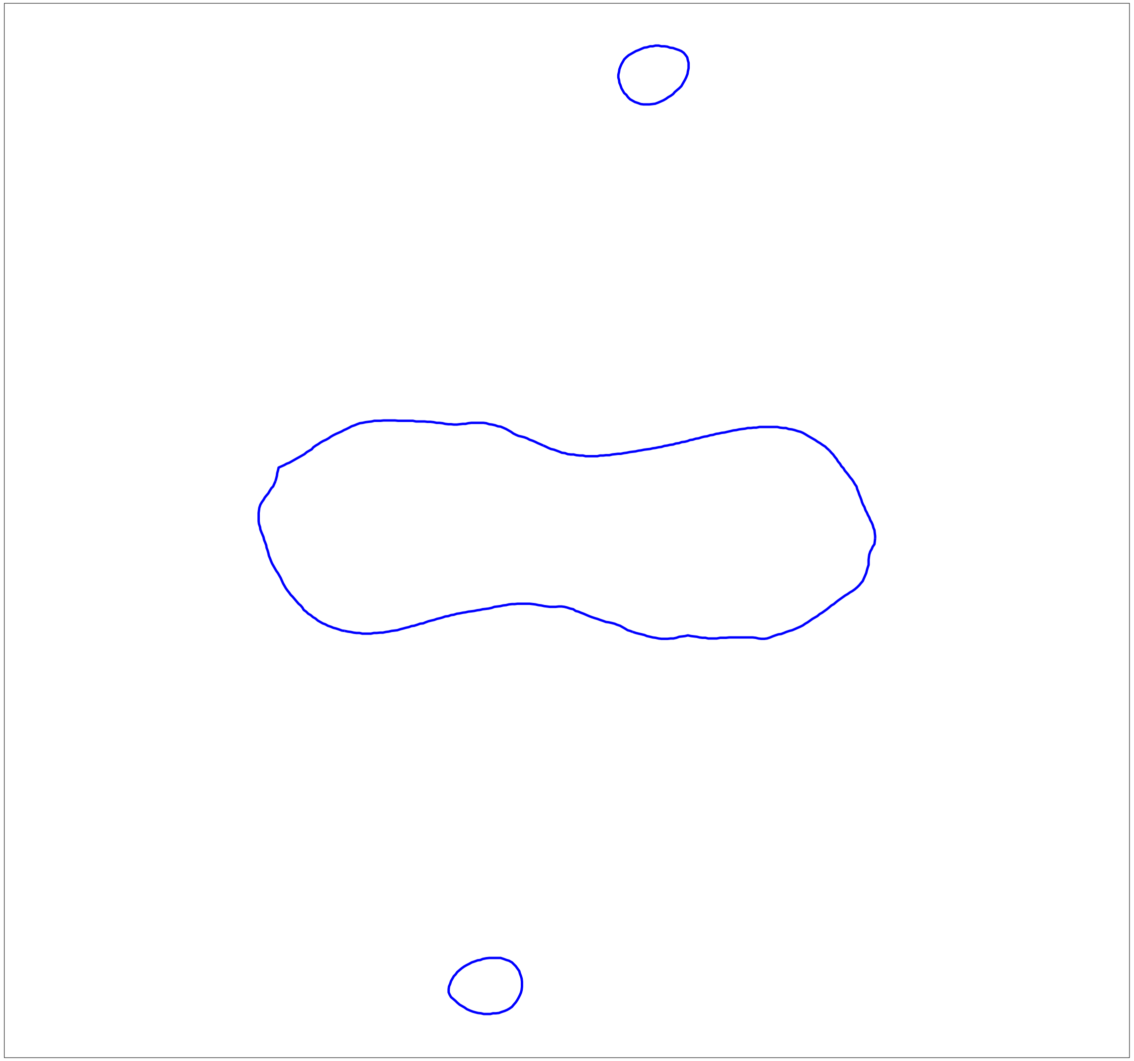
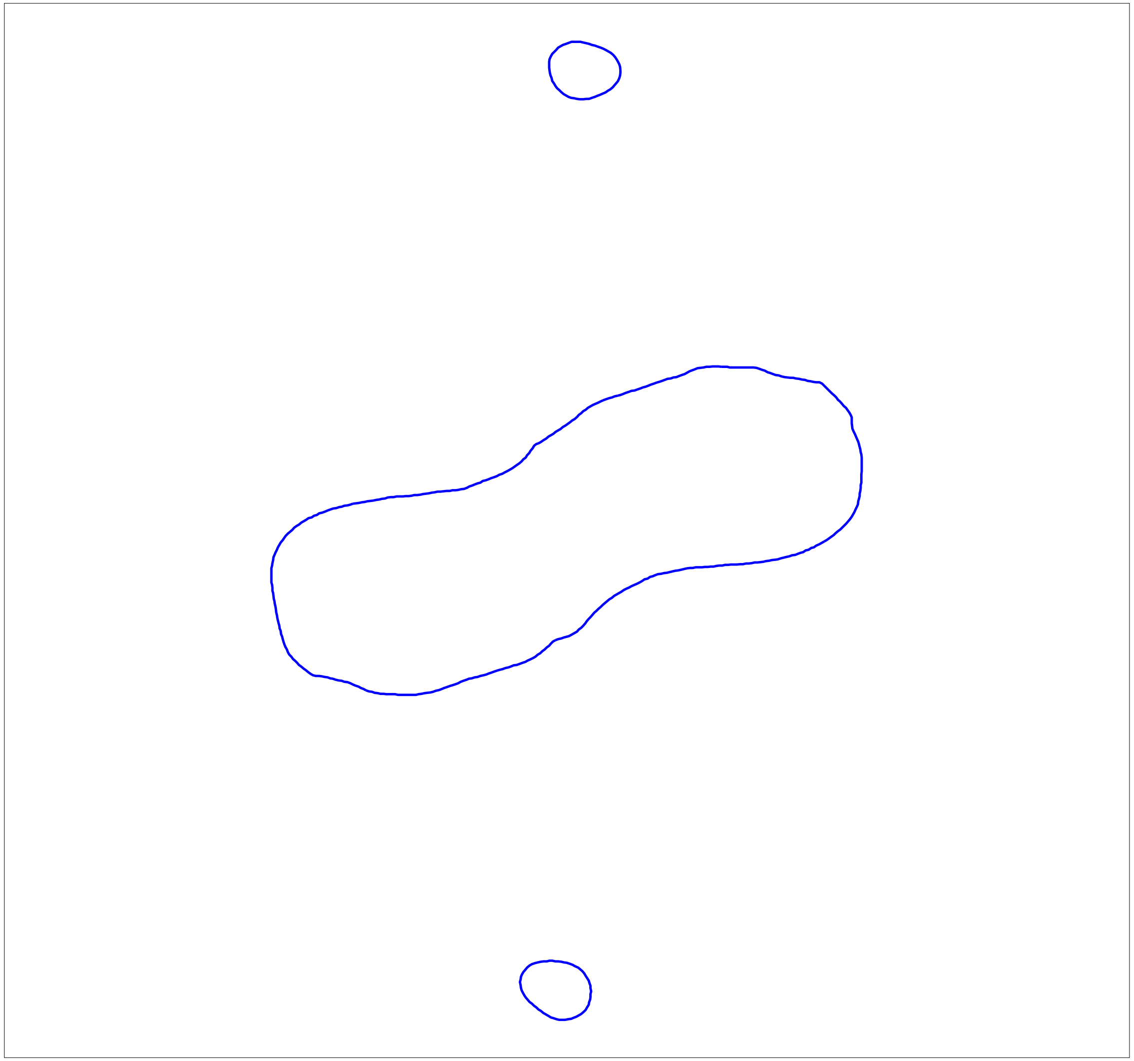


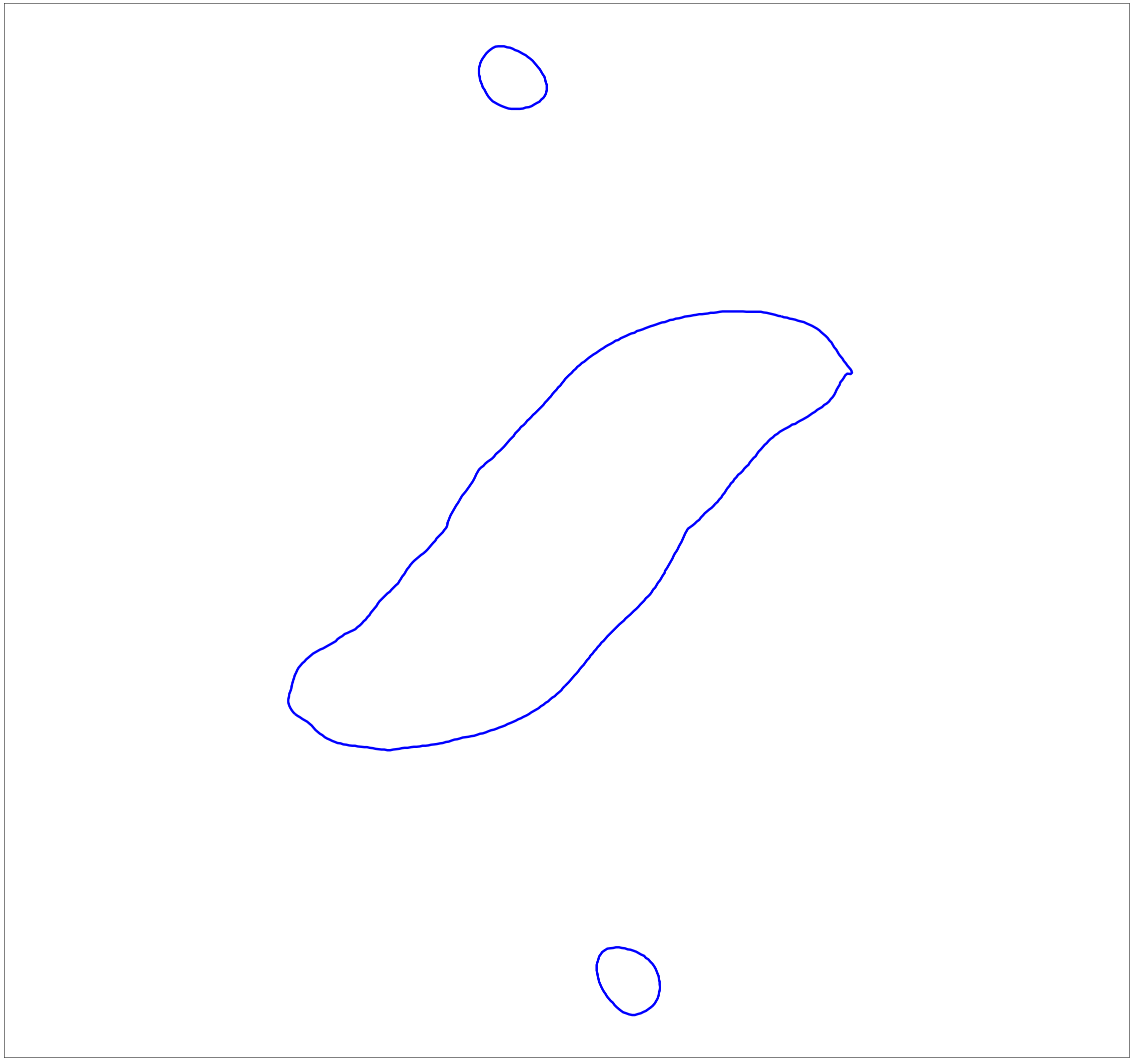
t=78



t=80



t=82



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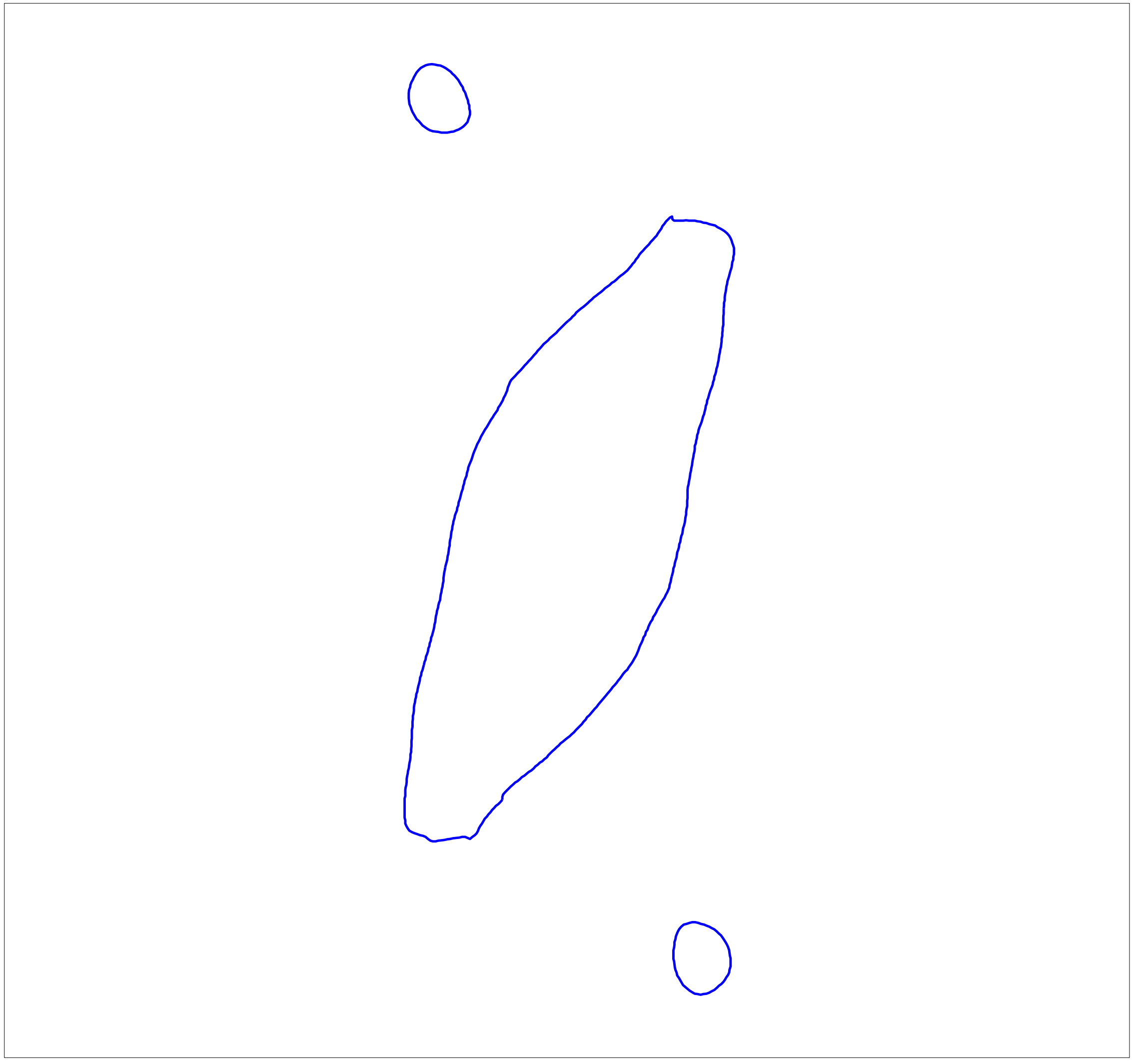

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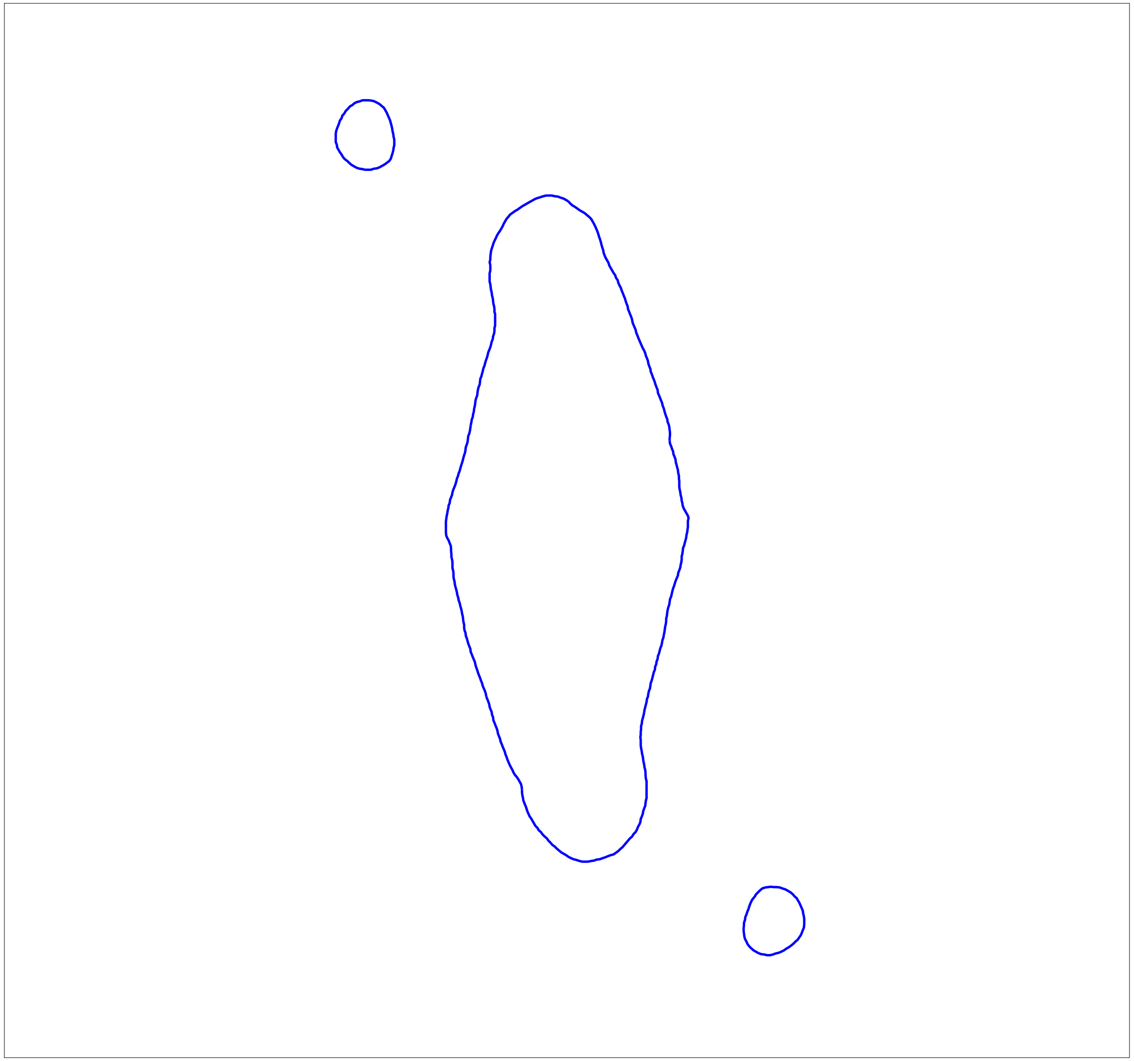

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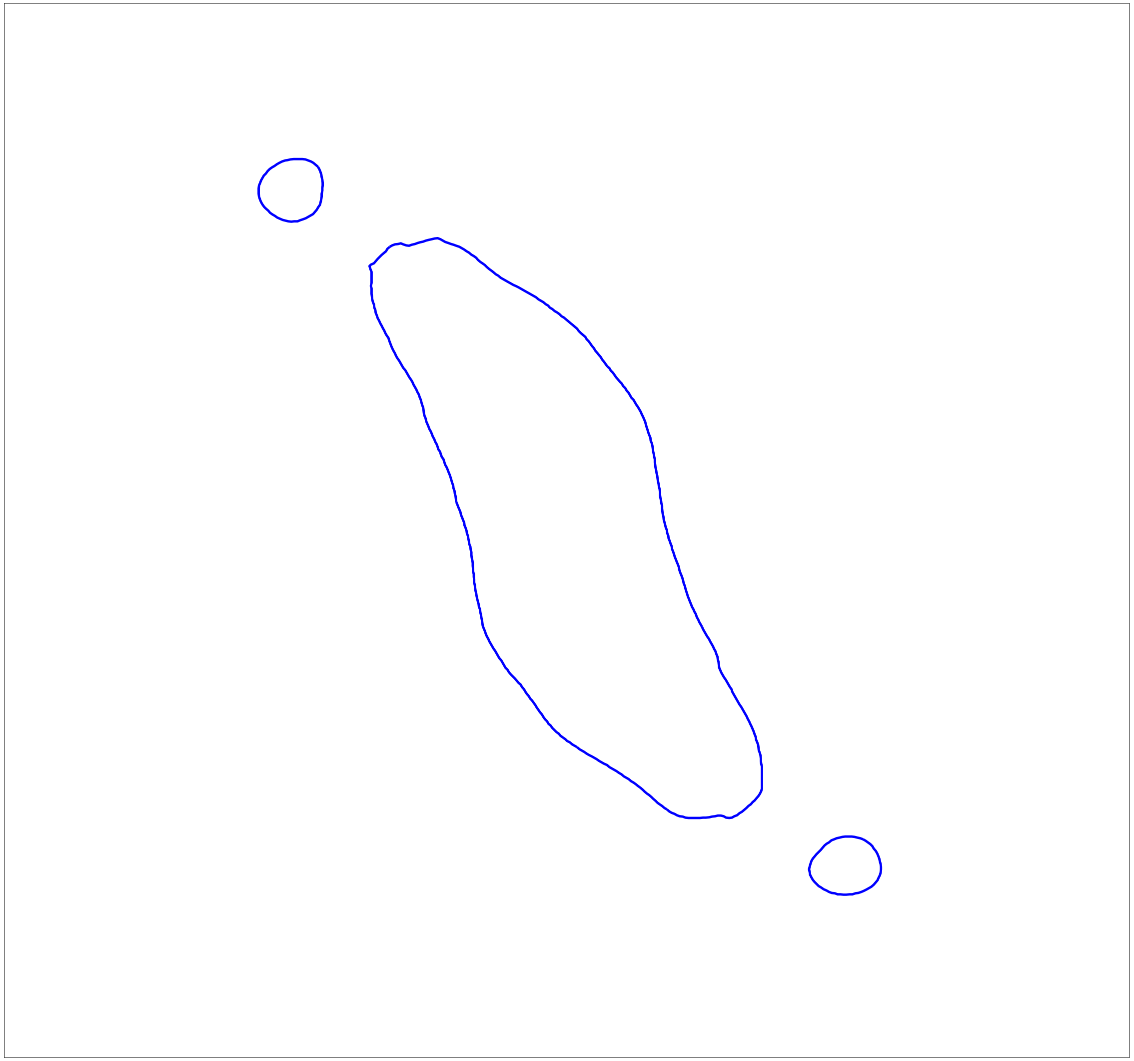

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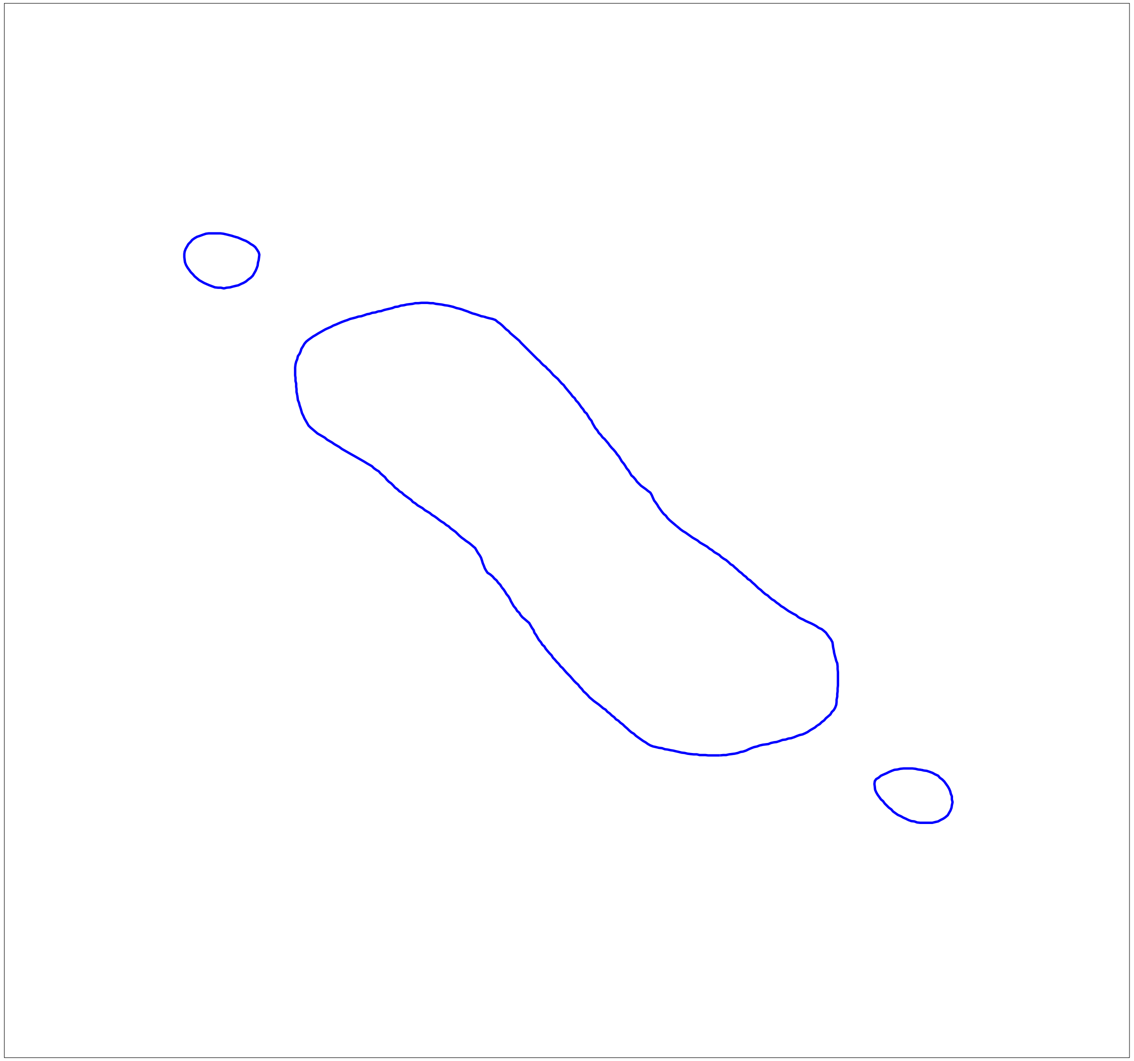

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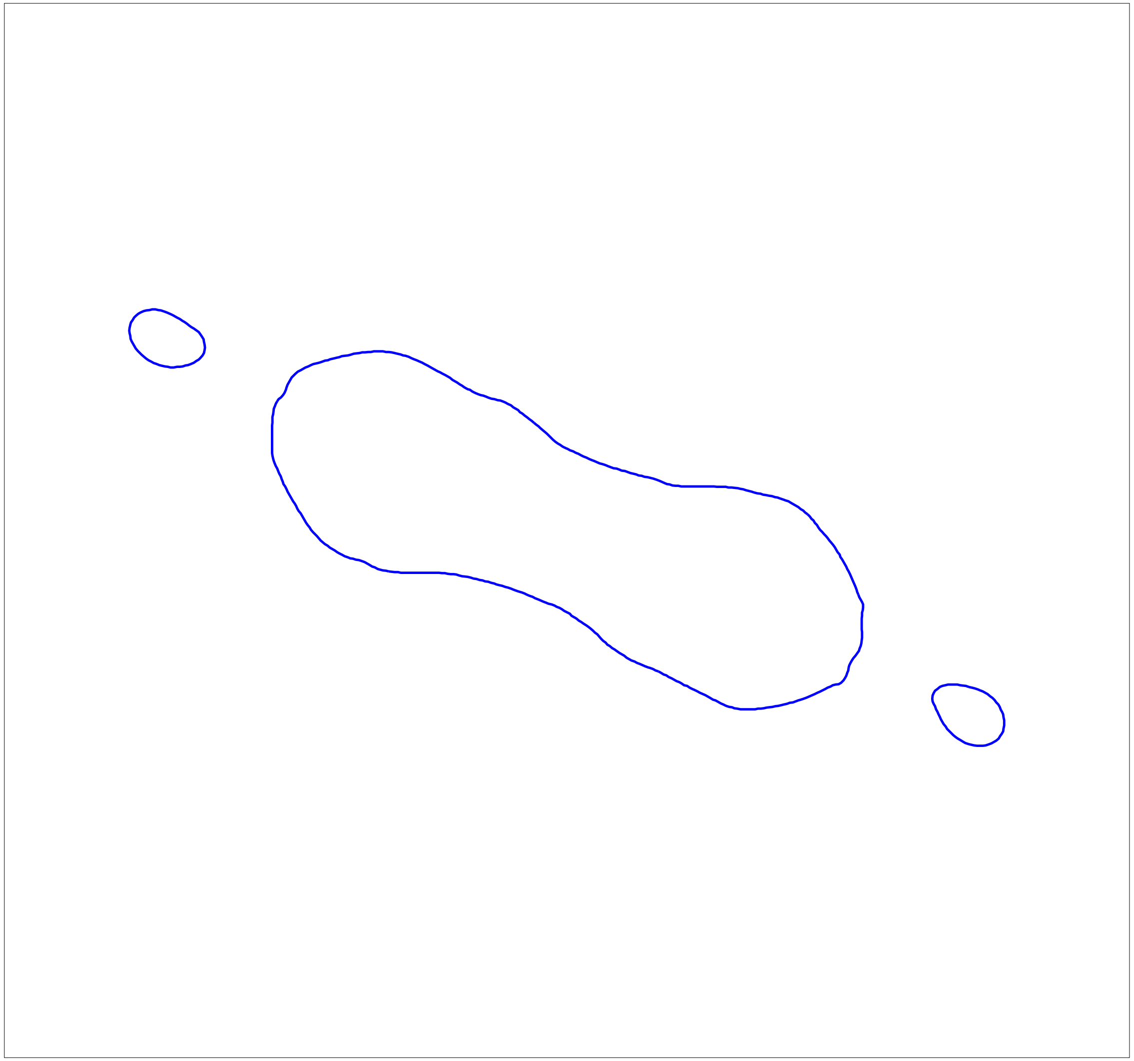

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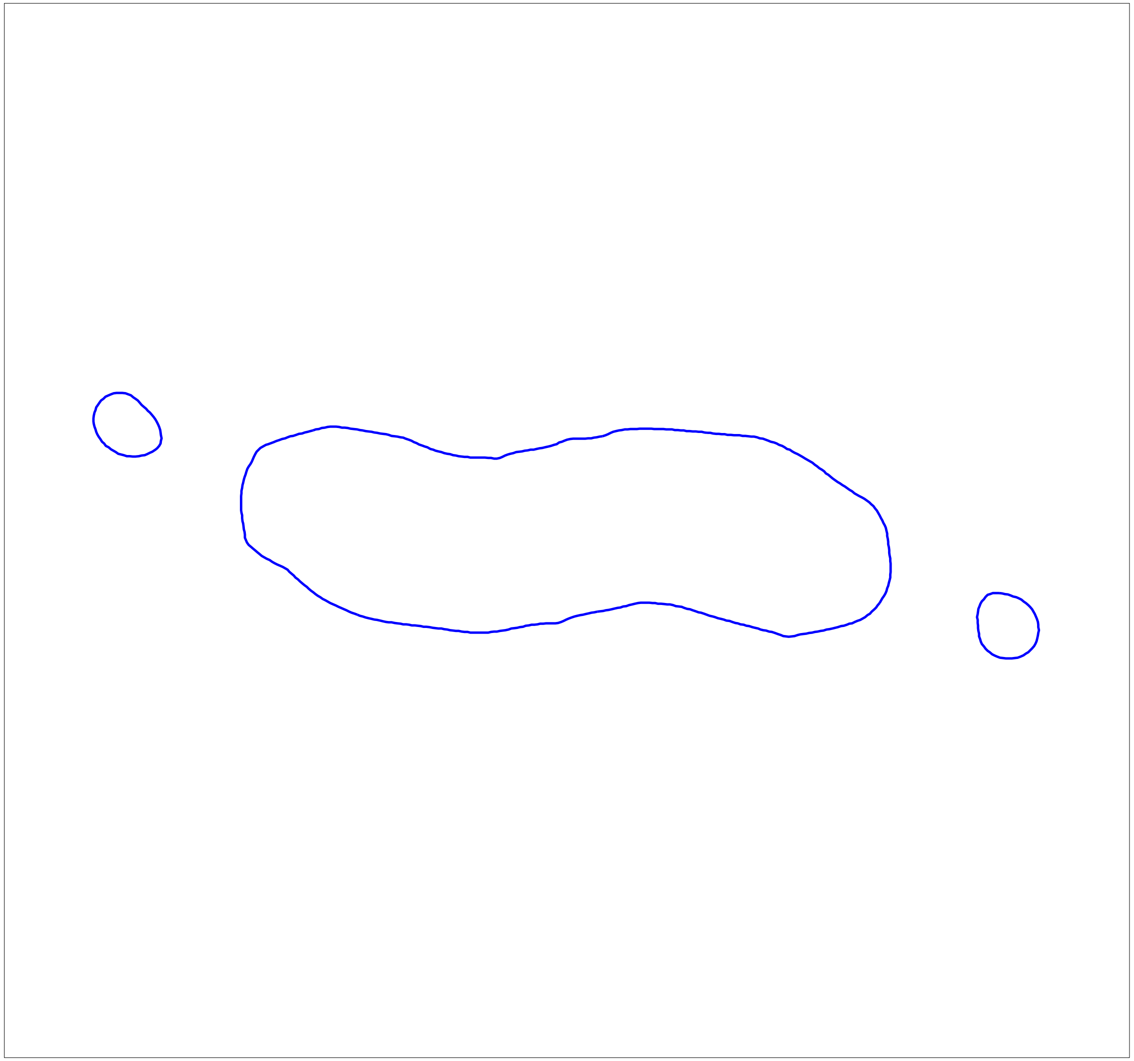

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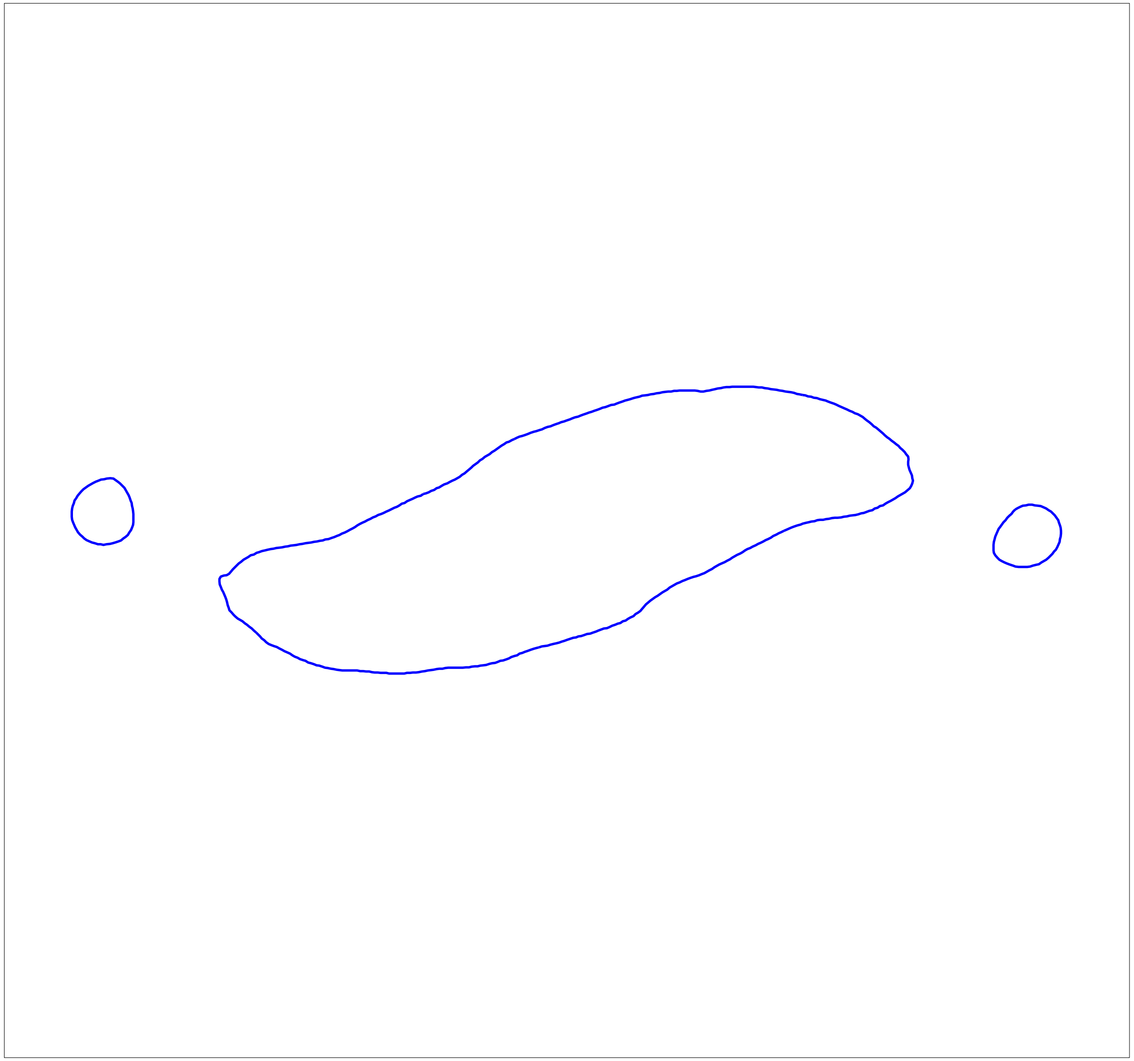

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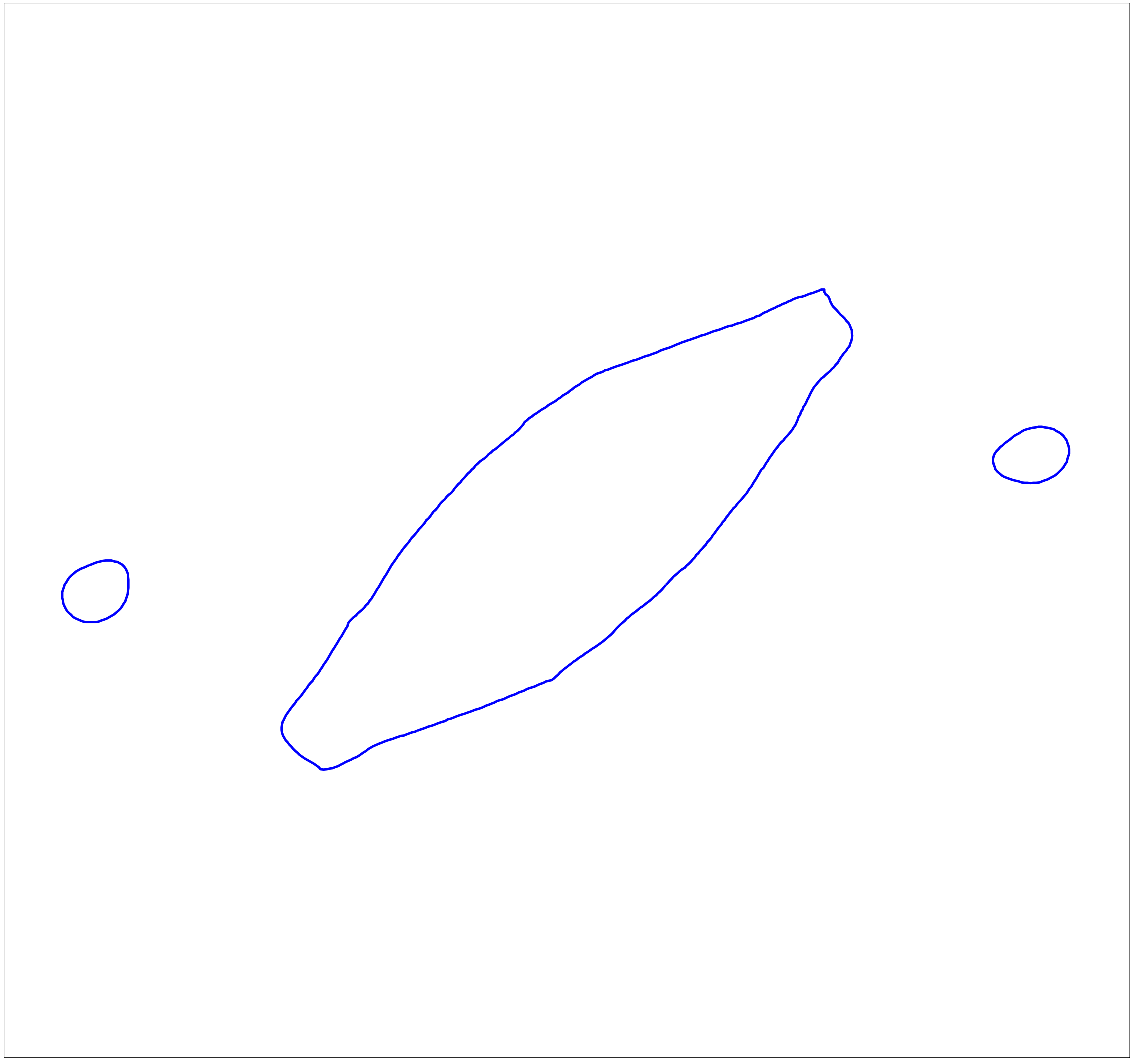

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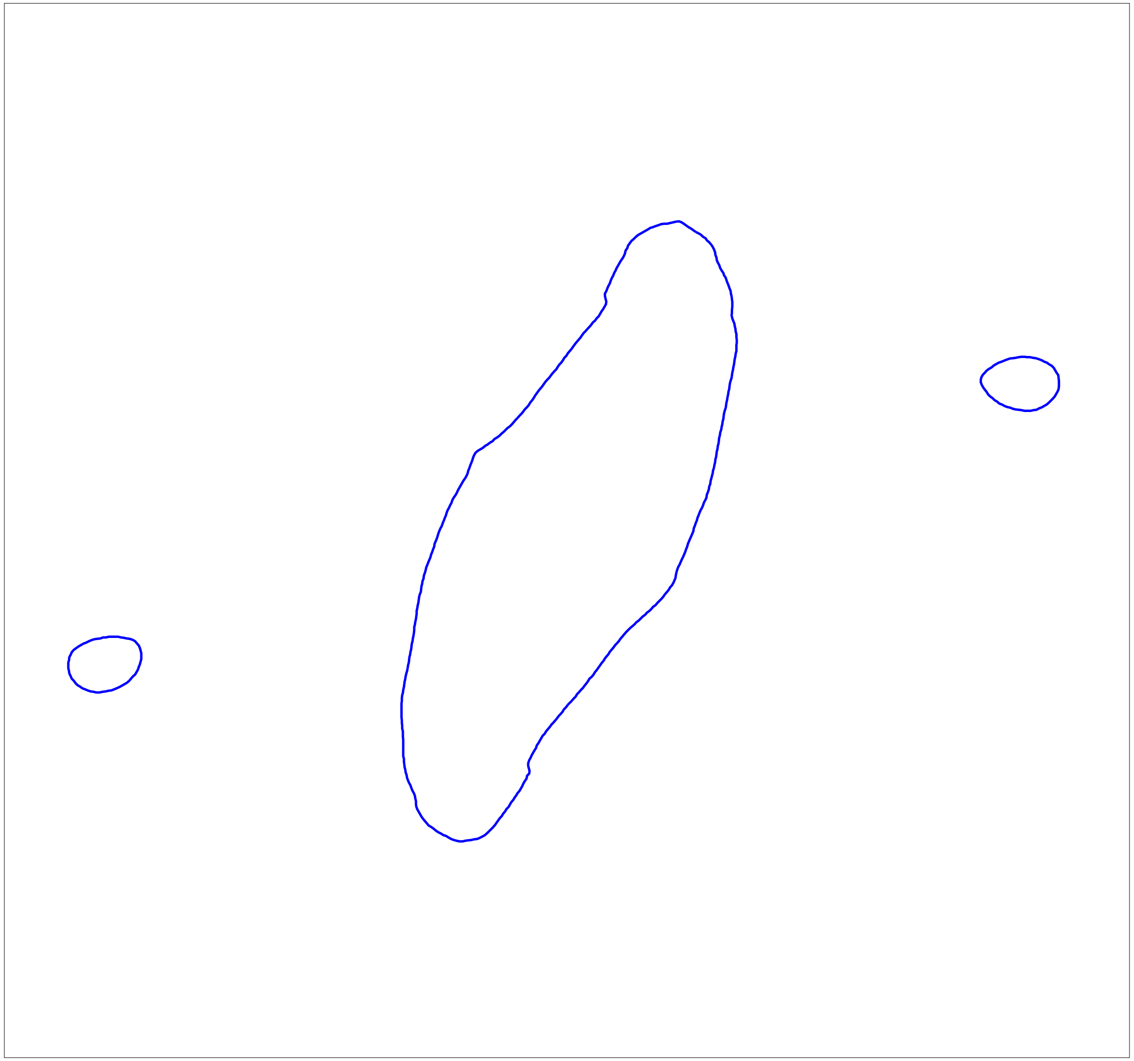

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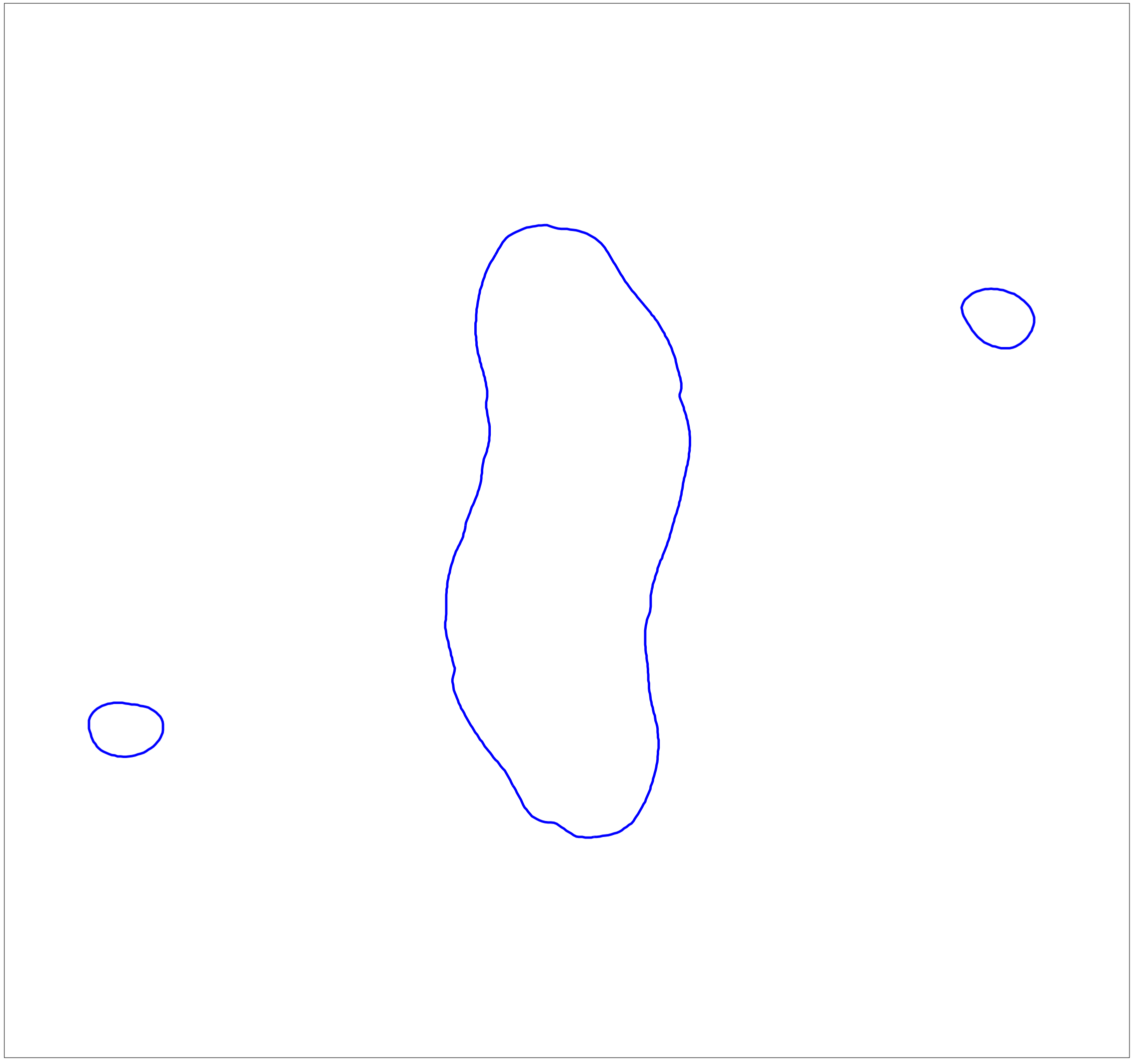

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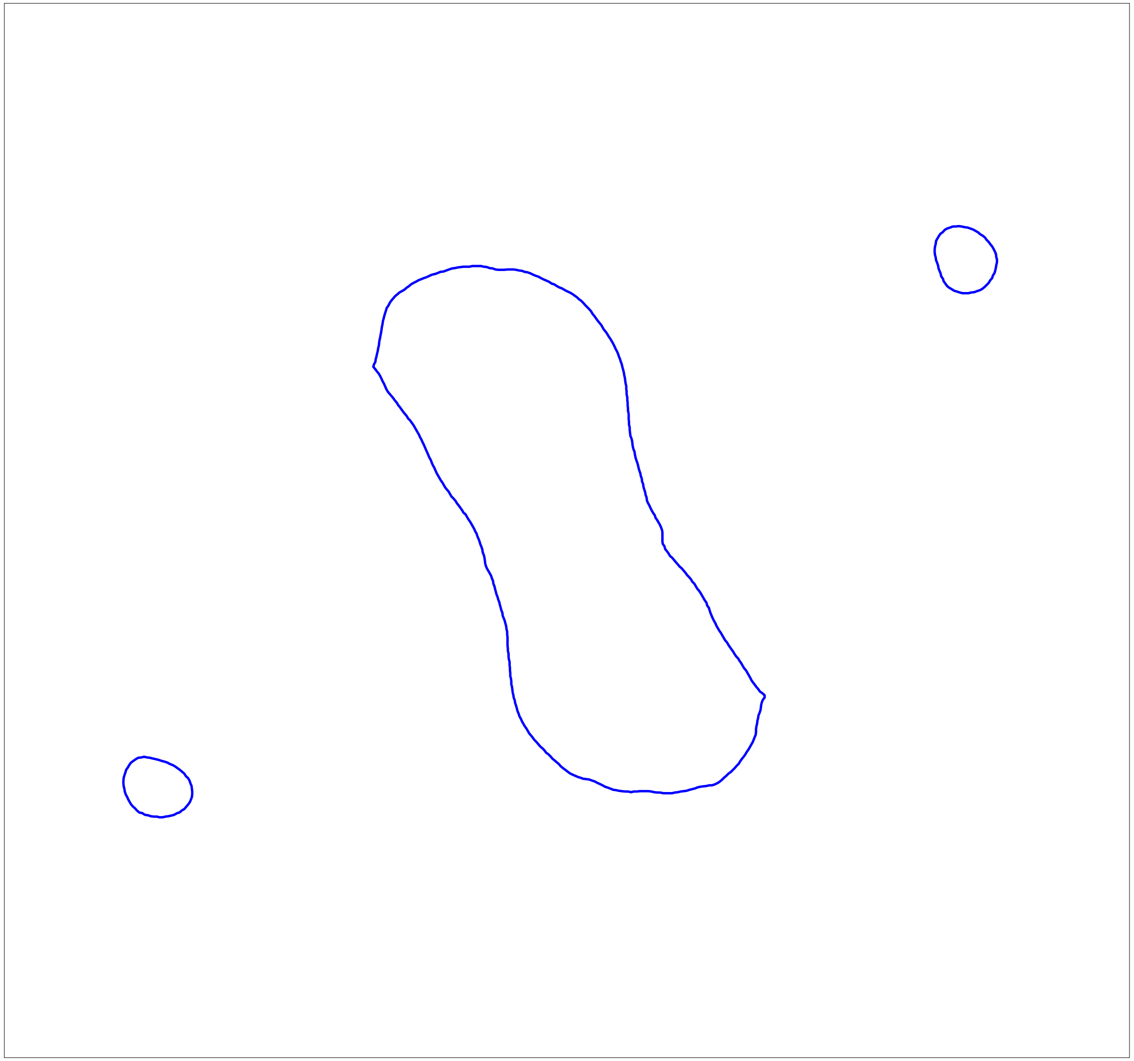

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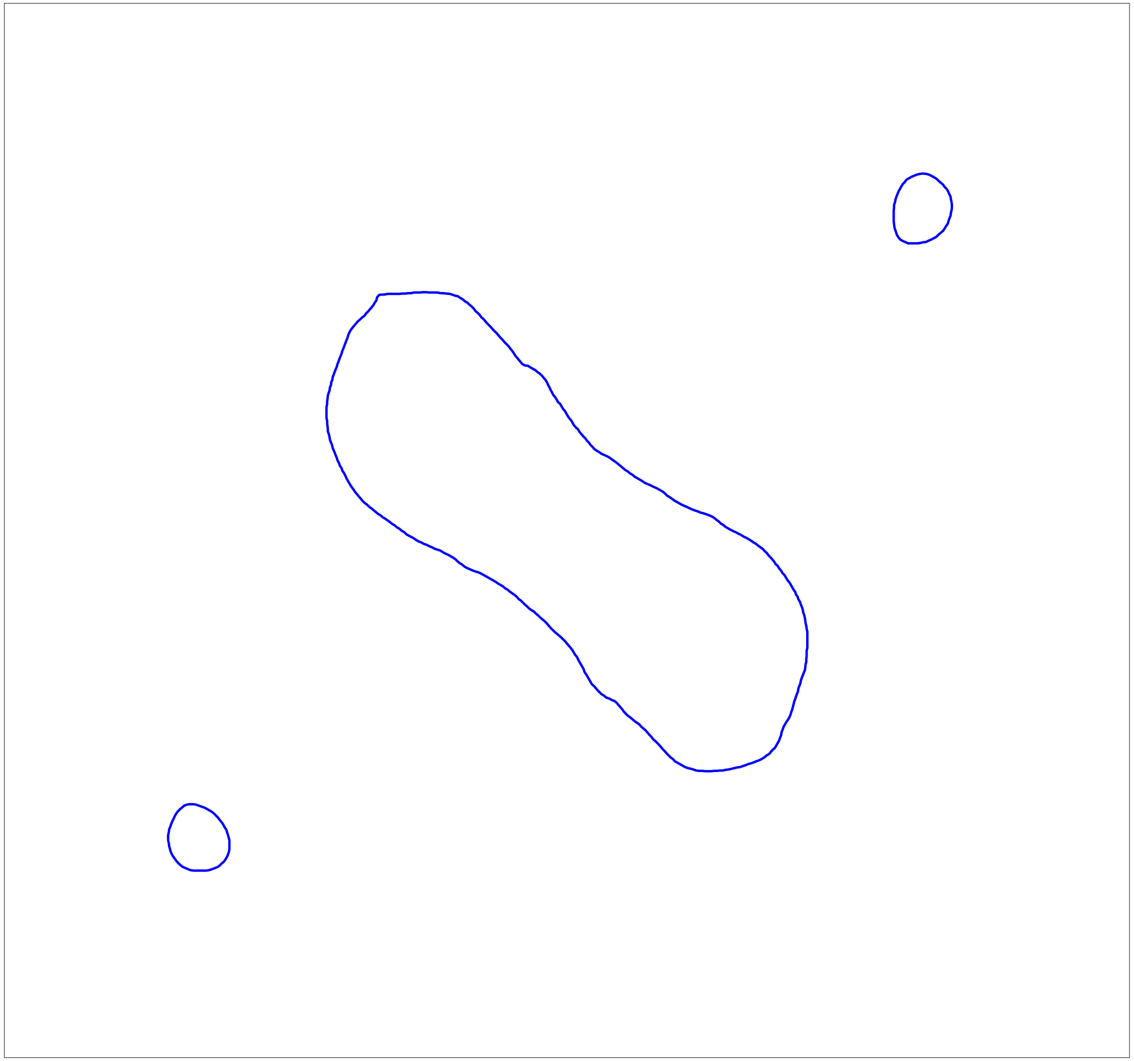

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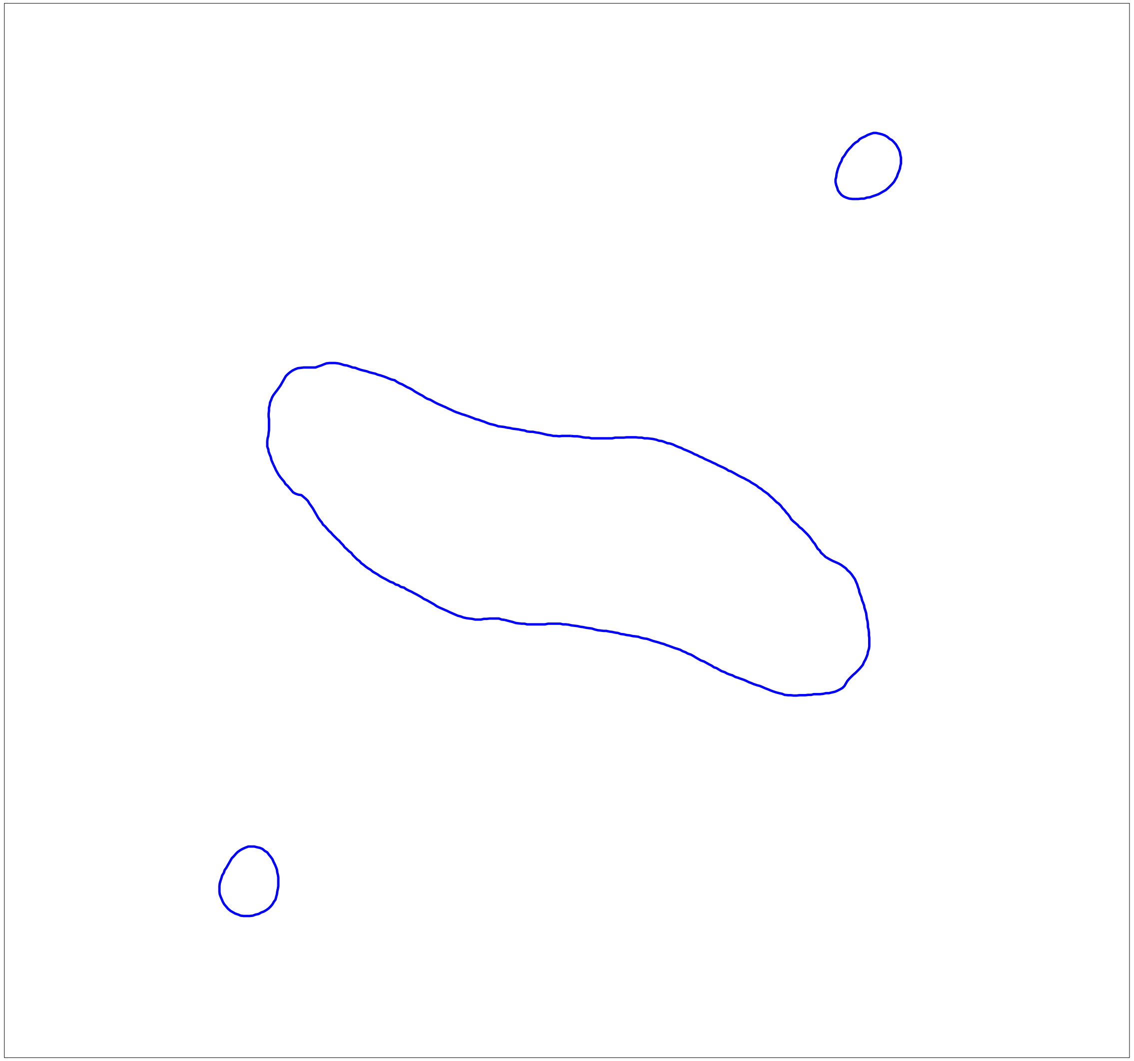

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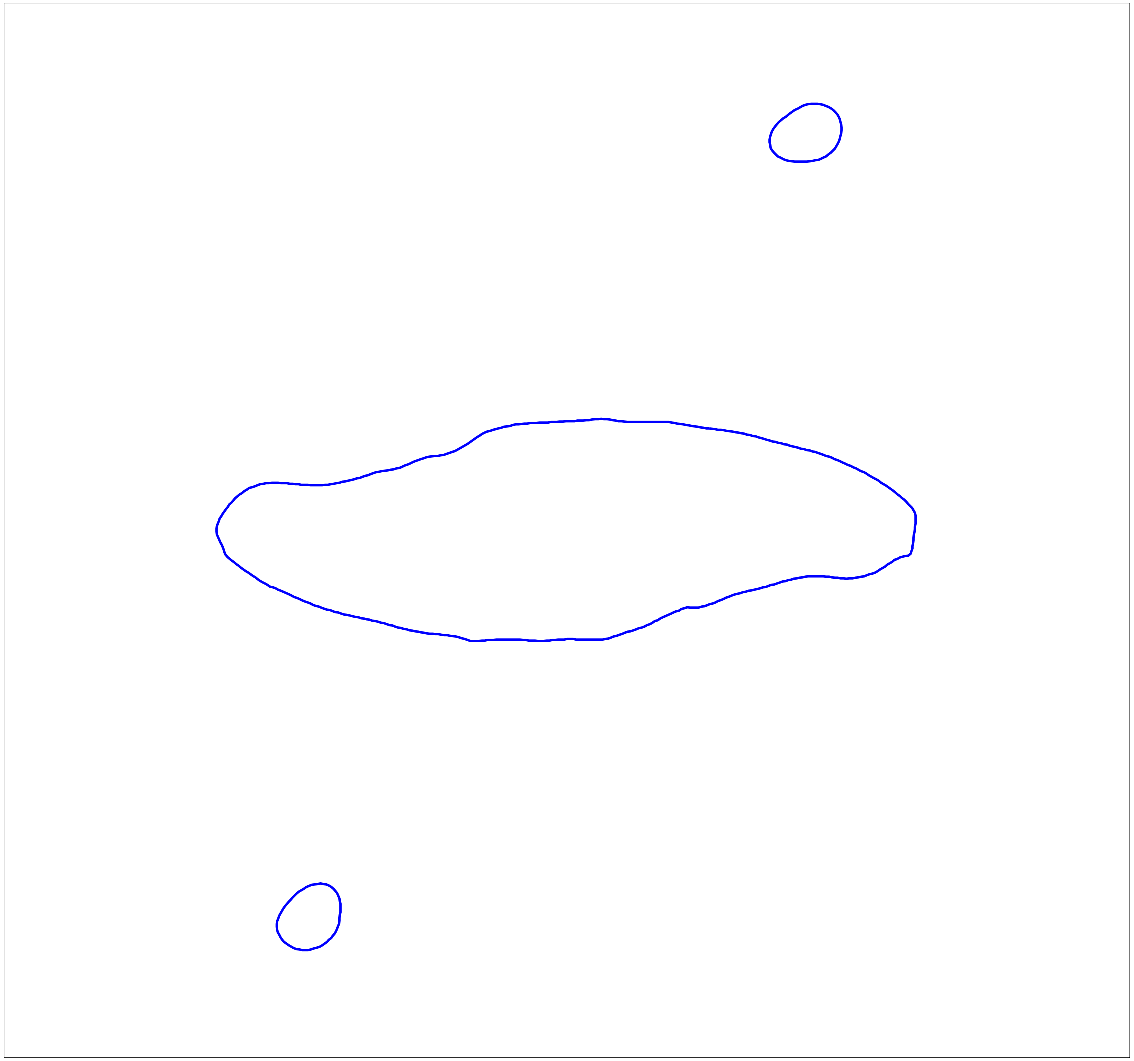

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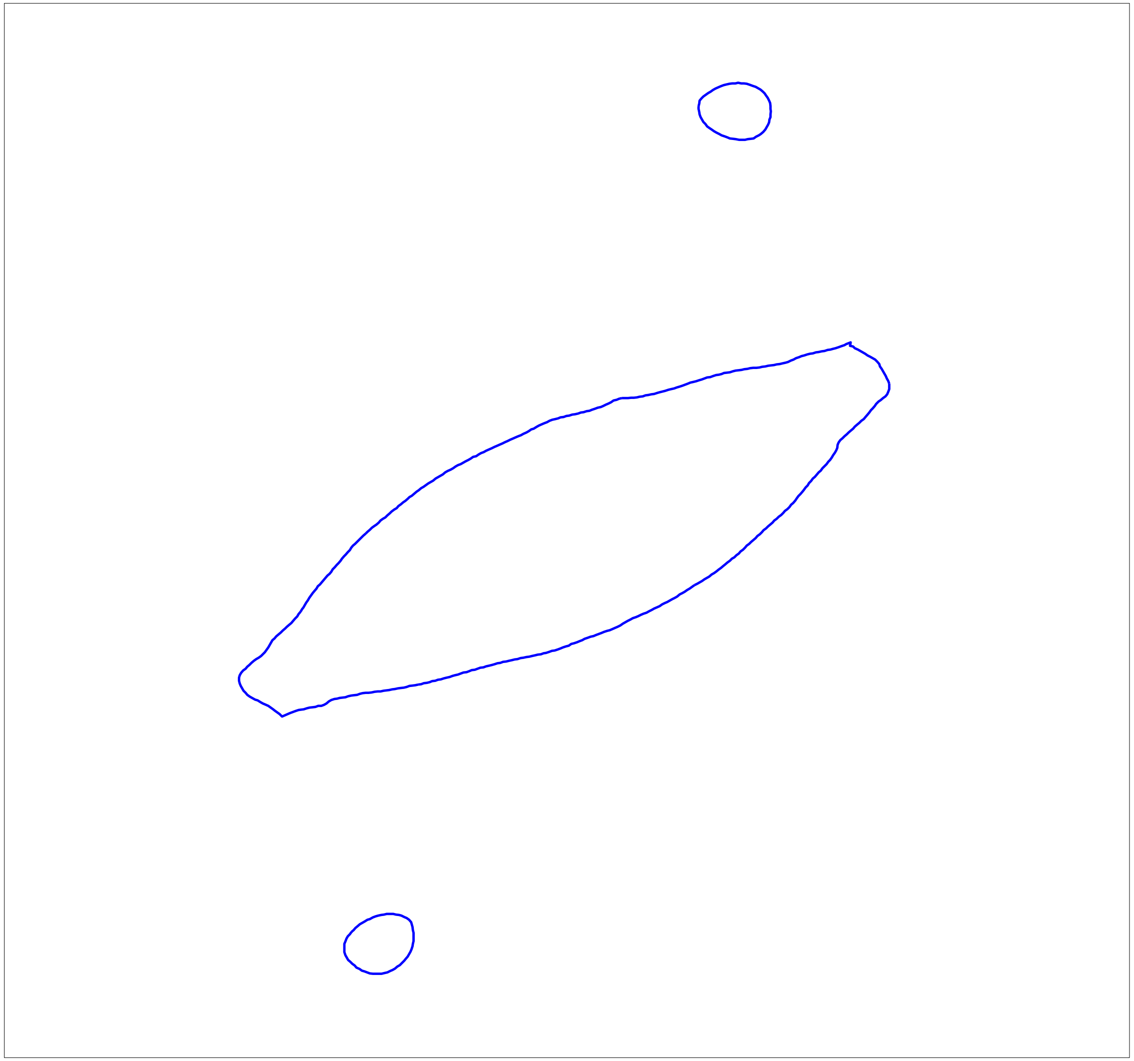

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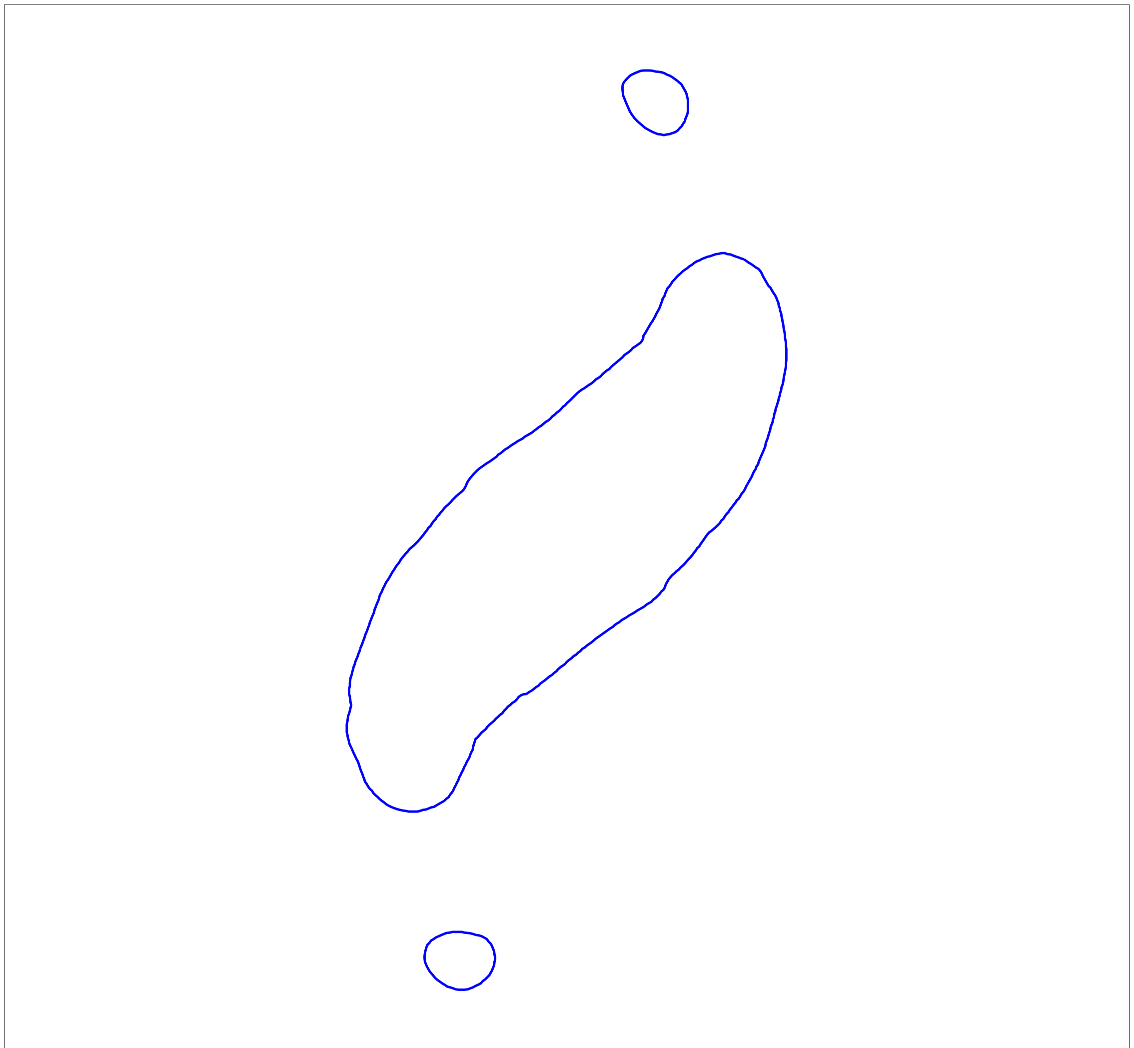

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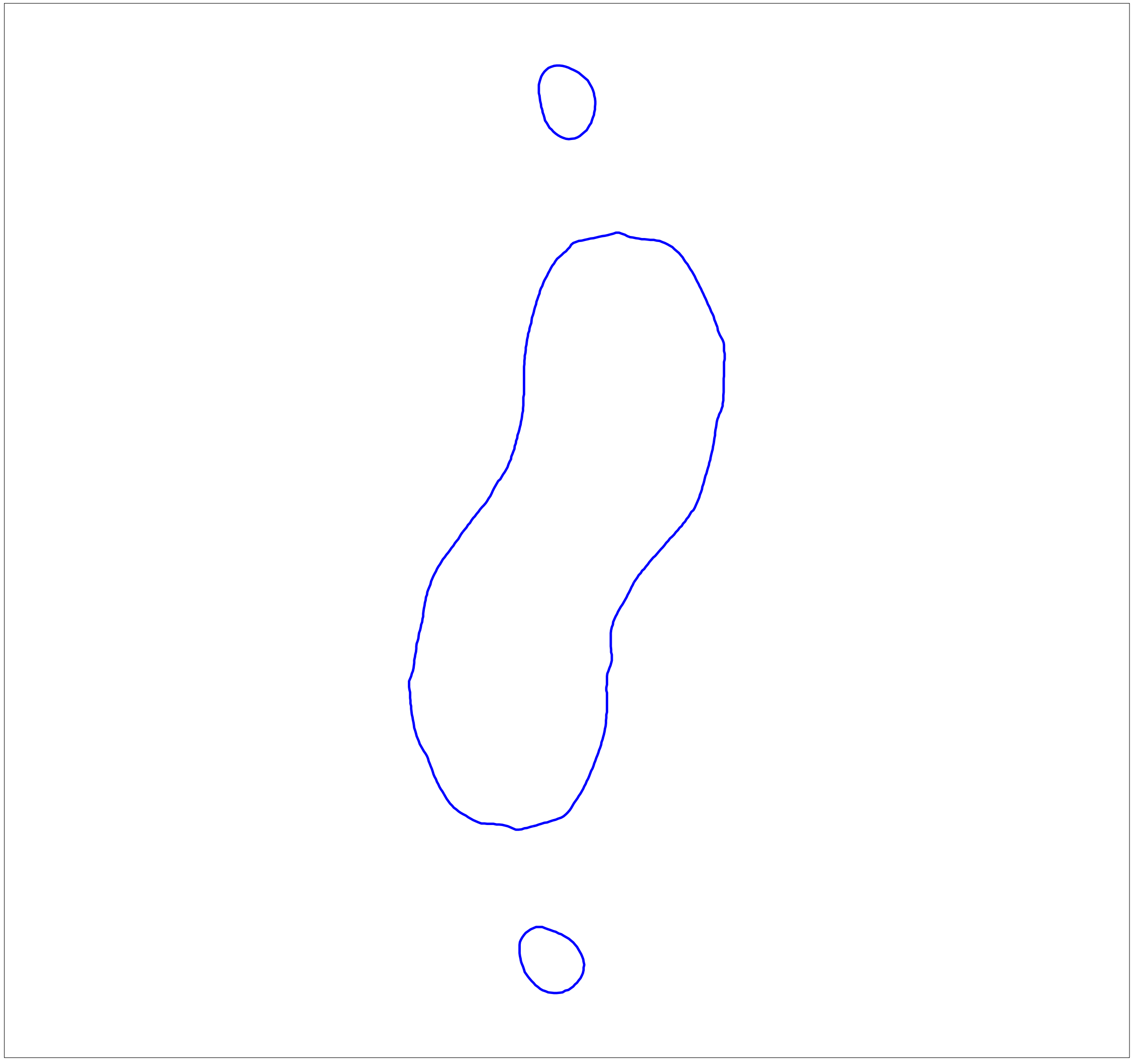

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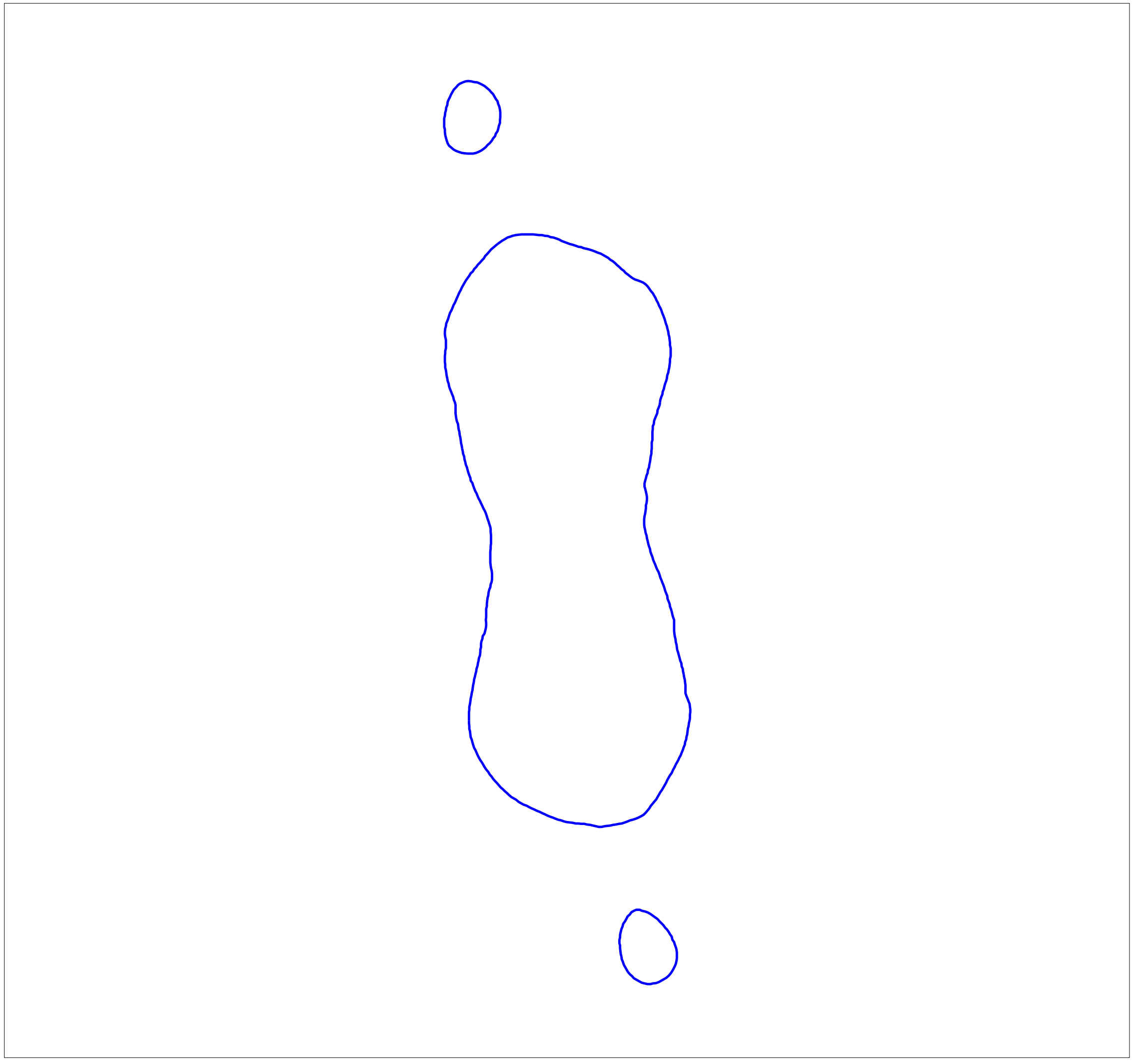

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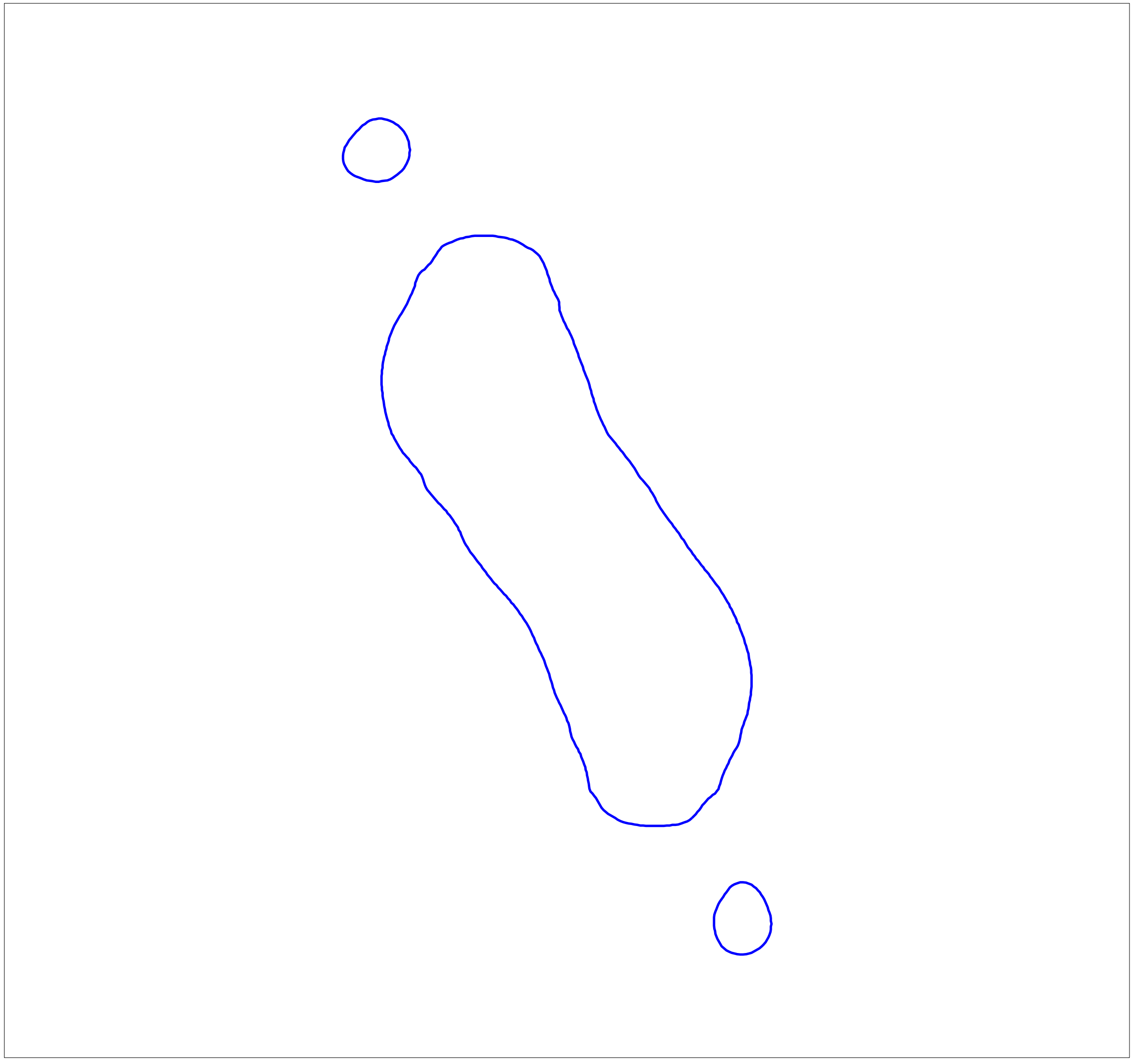

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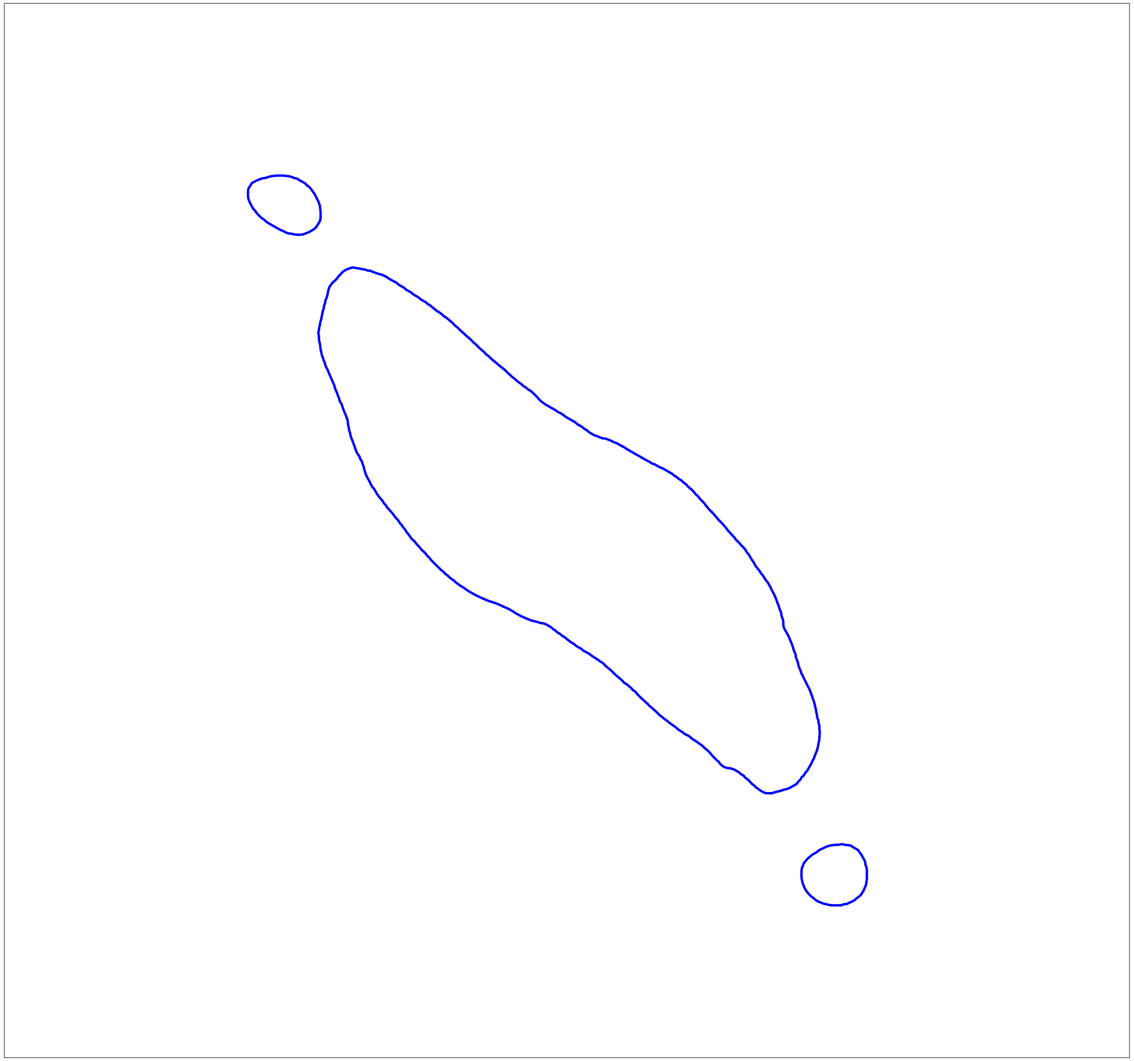

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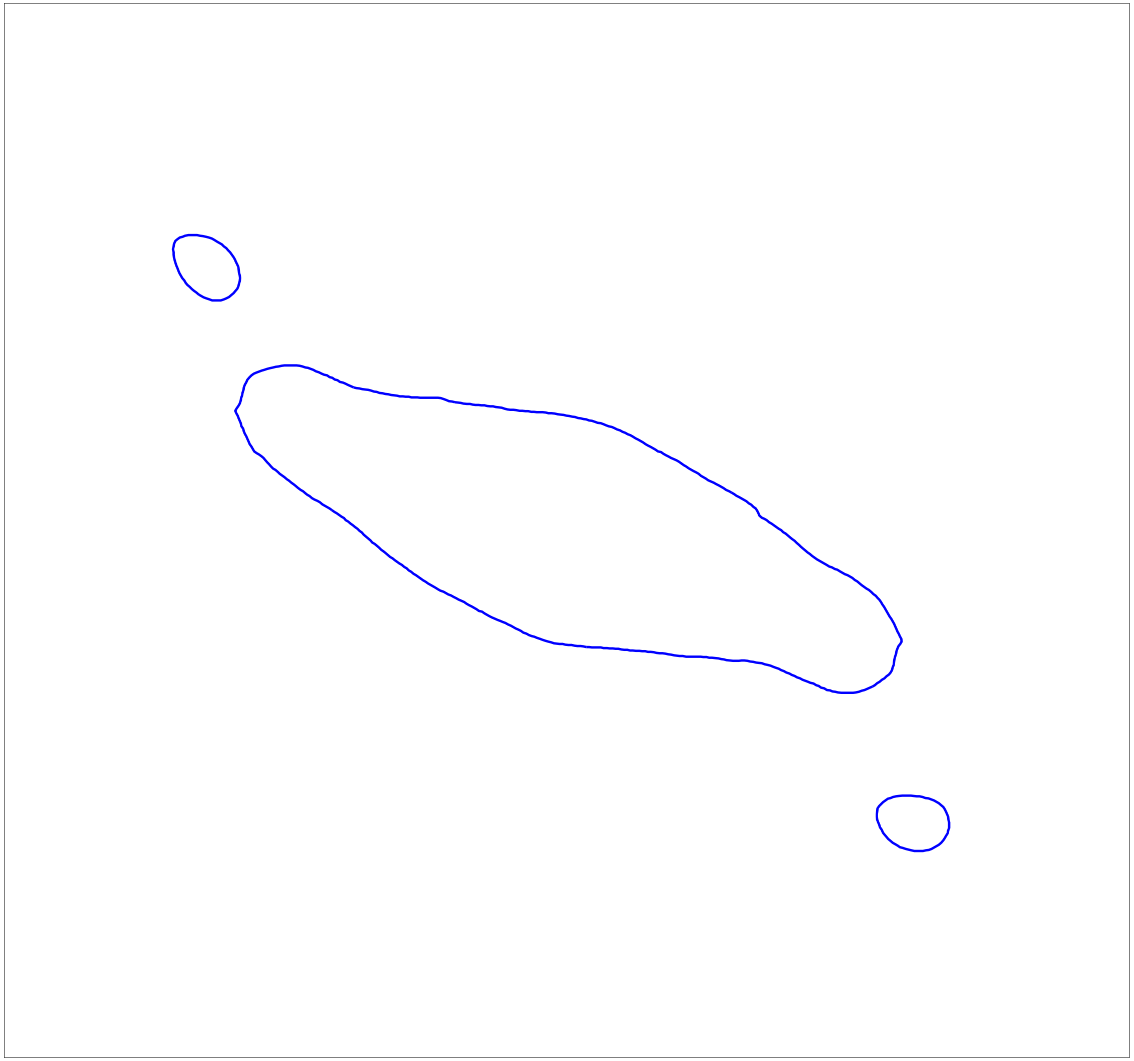

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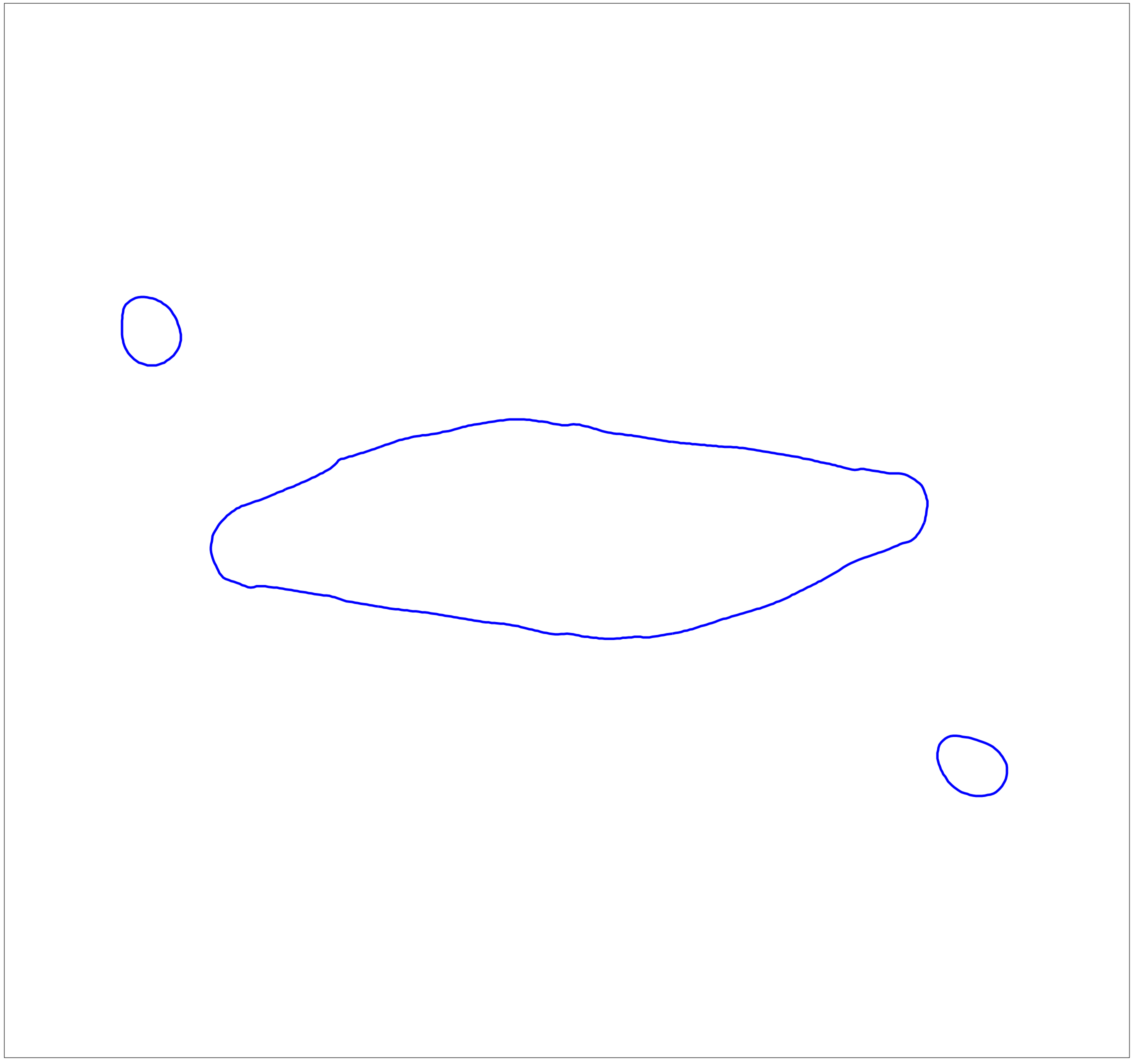

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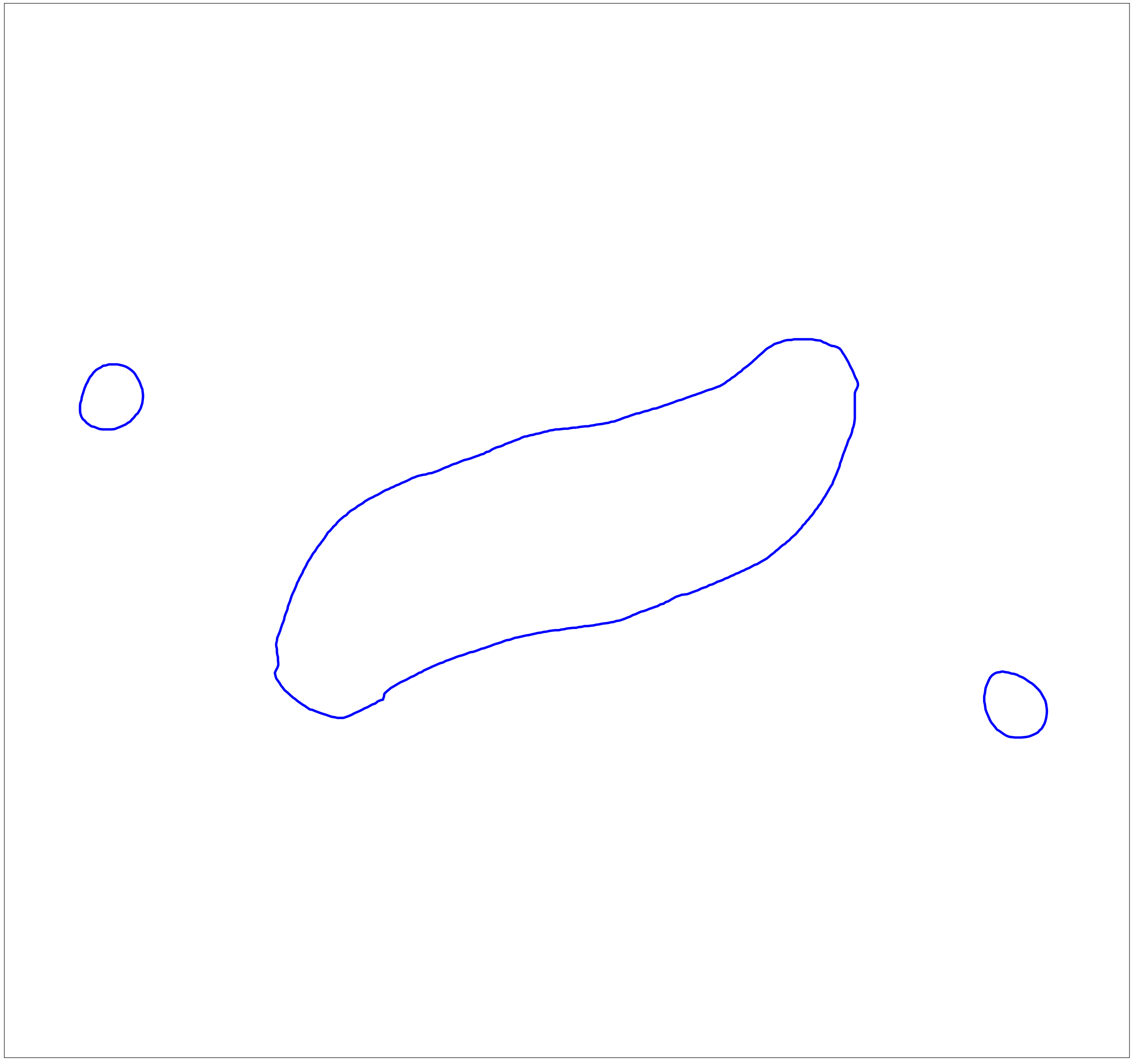
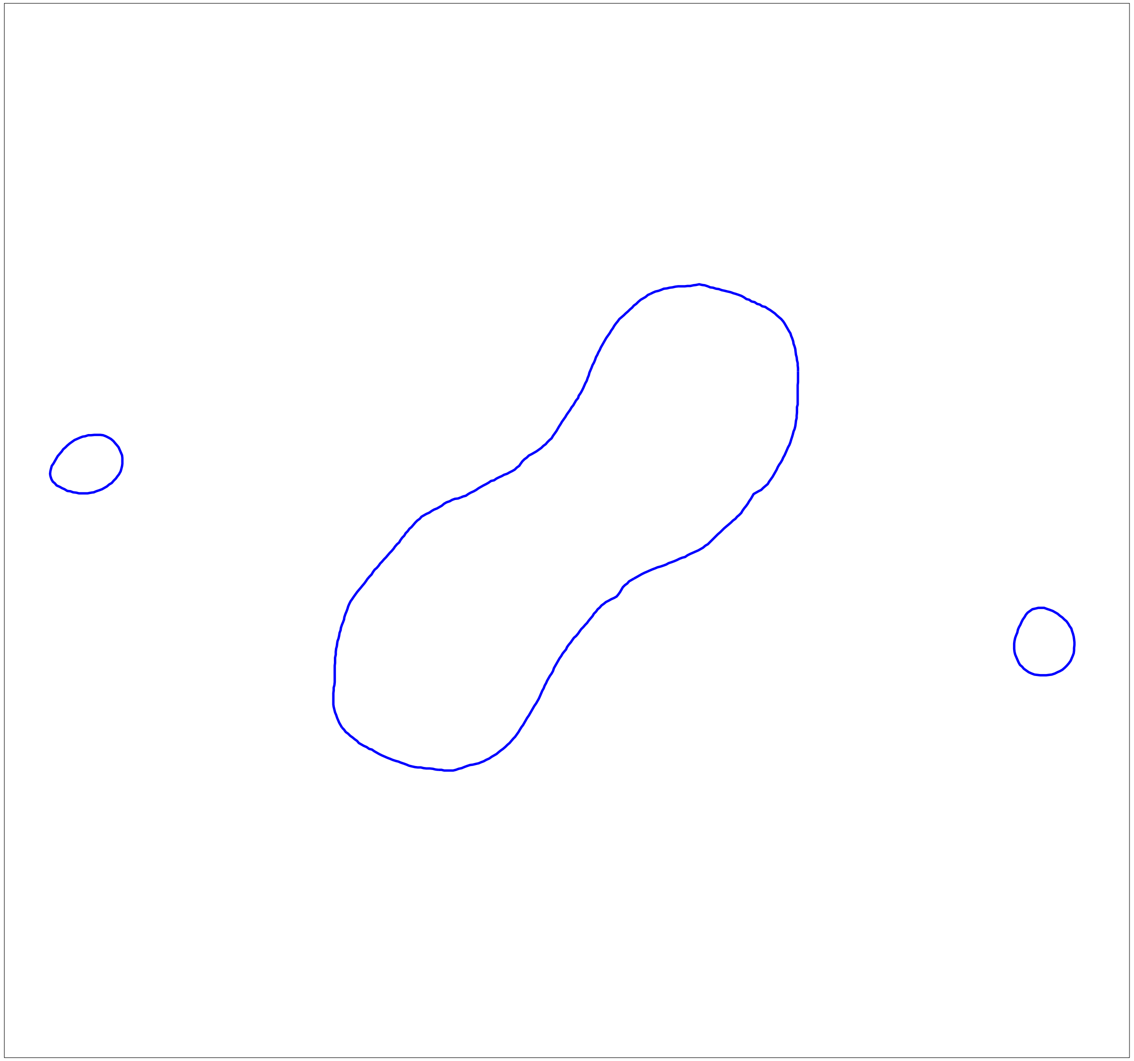
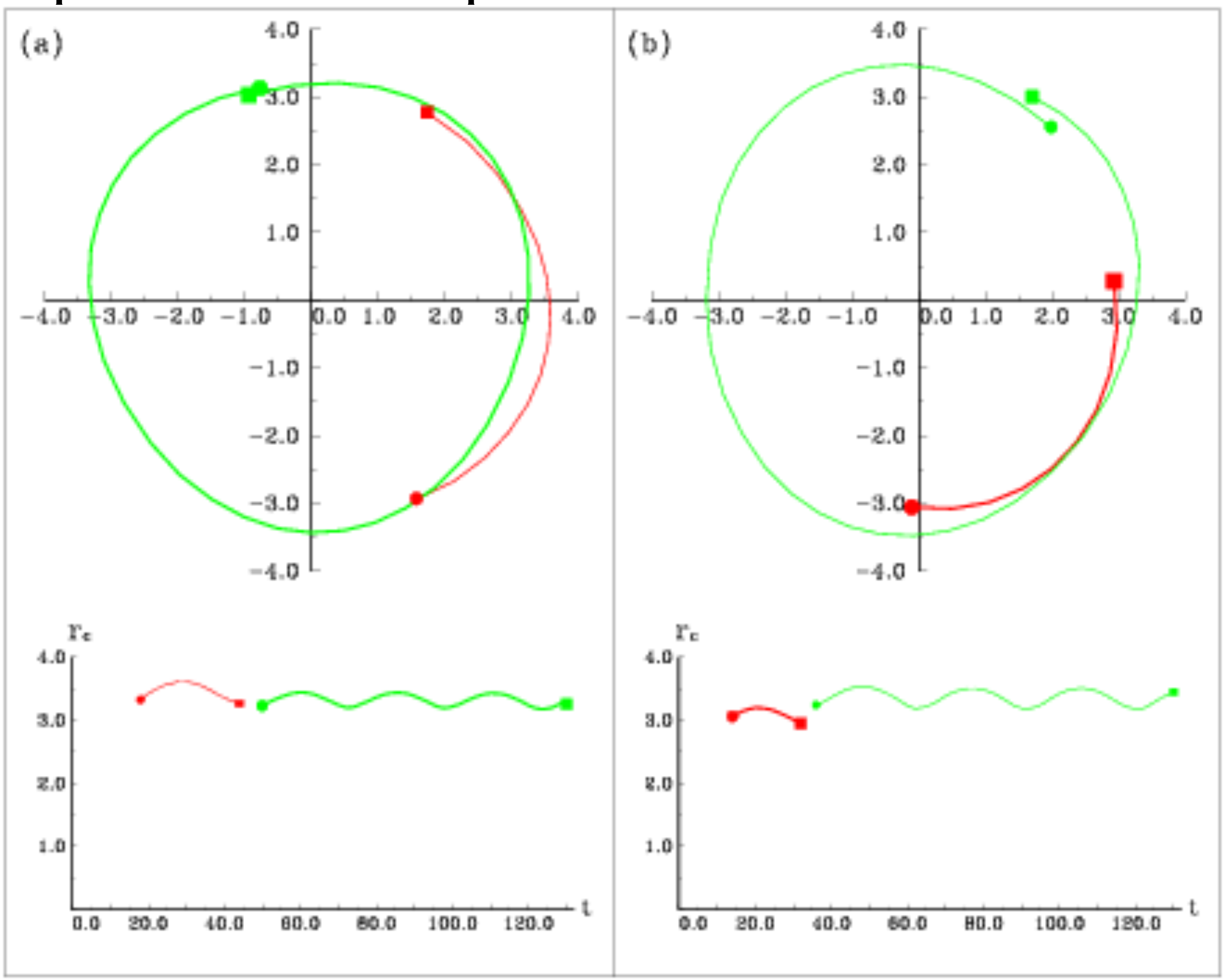


t=130



From above: the trajectories of centers of one of the peripheral vortices belonging to the triplet of the upper layer. Bellow: distances r_c as functions of time. Panels (a) and (b) correspond to cases 1 and 2, respectively. The red lines represent the trajectories of these centers in the time interval before re-merging, and the green lines are their trajectories after the second separation. Everywhere, a circle marker corresponds to beginning point of the motion, and square marker to its end point.



Summary

1. The boundary between the domains of stability and coalescing of two identical top-layer circular vortices is a non-monotonous function of the stratification parameter.
2. Reduction the upper layer thickness contributes to the expansion of the stability domain (there is allowed an abnormally close relative position of the vortex-patch centers when they behave as point vortices).
3. The coalescing area has a complex structure. The general trend is as follows: when the distance between the vortex centers being decreasing, there takes place the transition between states merger/symmetric separation -- merger/non-symmetric separation -- merger/triplet – merger takes place.
4. The process of the vortex-patch merging creates an intensive mixing of water masses located inside the vortices.
5. A sub-domain of parameters is found within the area merger/triplet which stimulate a new movement subtype: a double merger/triplet, when the triplet of the first evolution phase is unstable, and an intermediate phase of vortex-patch triplet merging takes place; then there follows the secondary separation into three parts (double merger/triplet). The latter structure represents a quasi-periodic steady state.

PS

The question to pioneers* of this problem:

Is possible to obtain experimentally the stable triplet vortex structures as a result of interaction of two identical circular vortex columns of upper layer in two-layer rotating fluid?

*** Ross Griffiths, Emil Hopfinger**

Thank you very much!