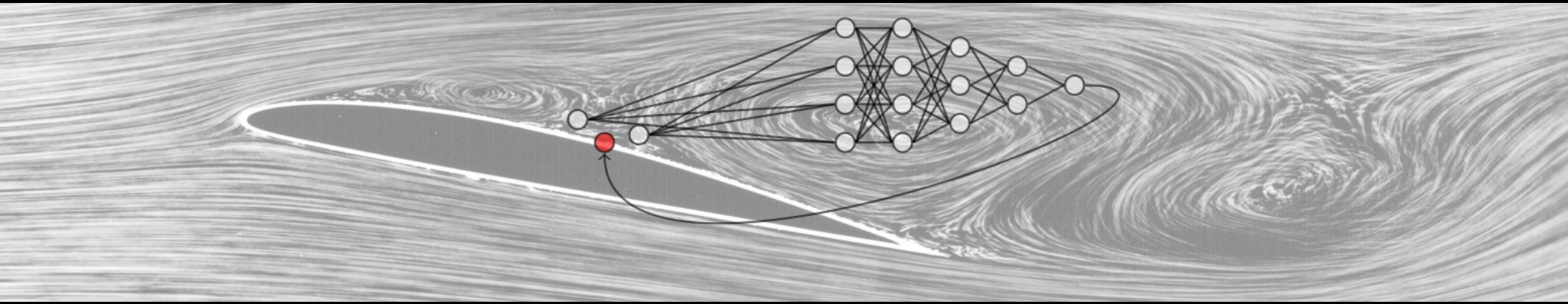
Scale-resolving simulations to support the development of novel turbulence models

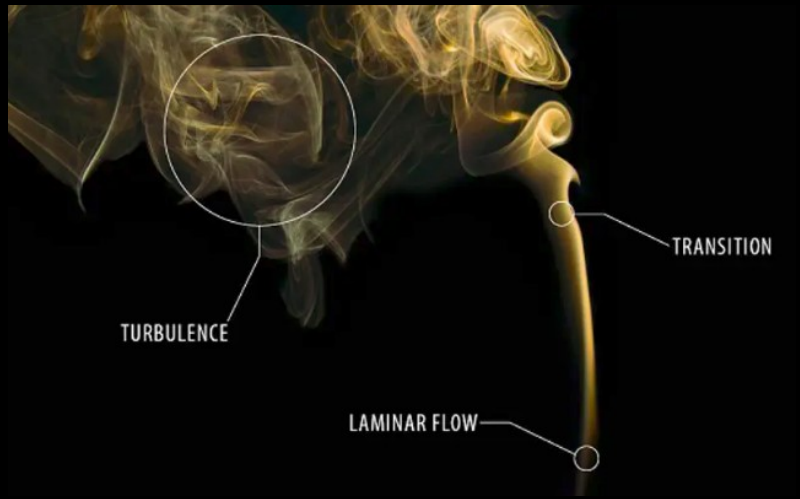
Cenaero's intervention



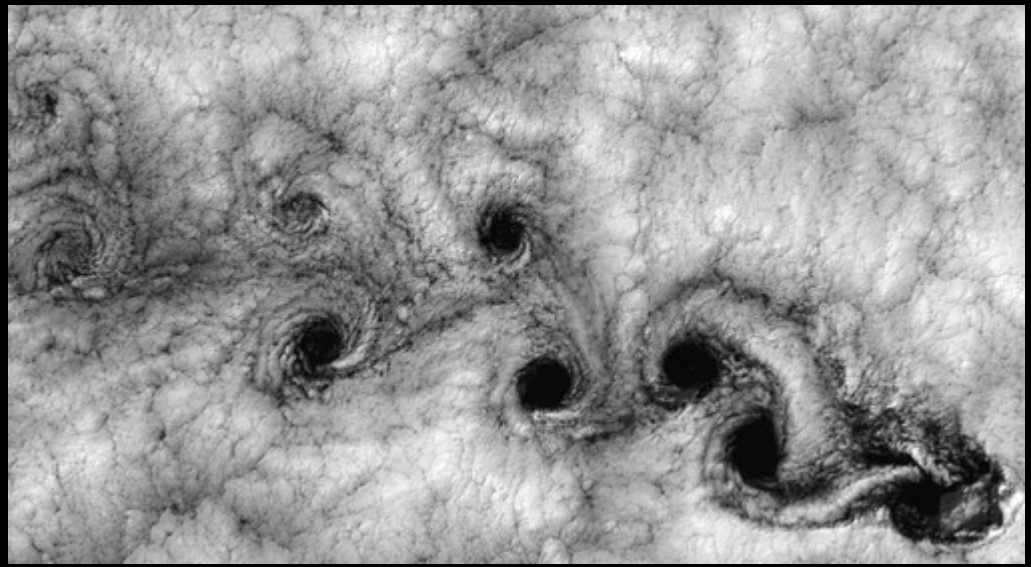
Margaux BOXHO and David HENNEAUX
Research Engineer
Contact: margaux.boxho@cenaero.be

Turbulence

https://www.bronkhorst.com/fr/theories-principes/difference-entre-ecoulement-laminaire-et-turbulent/



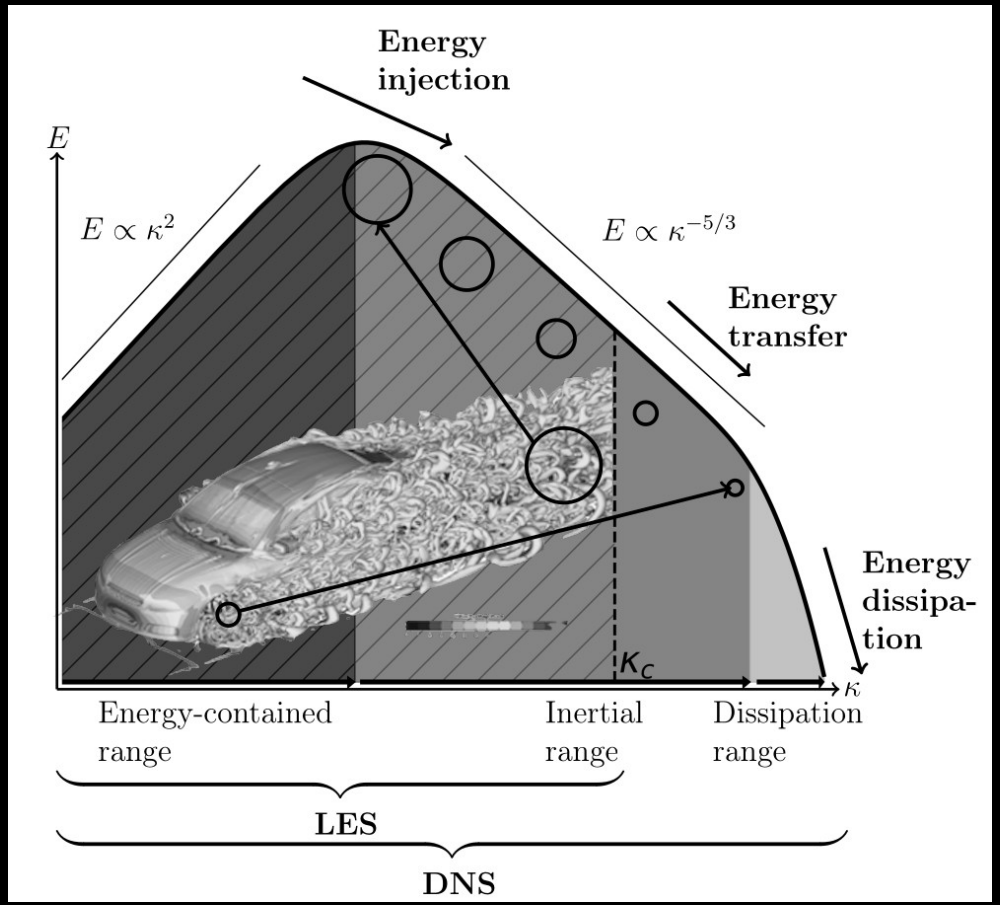
https://www.flowvis.org/2018/01/30/7640/

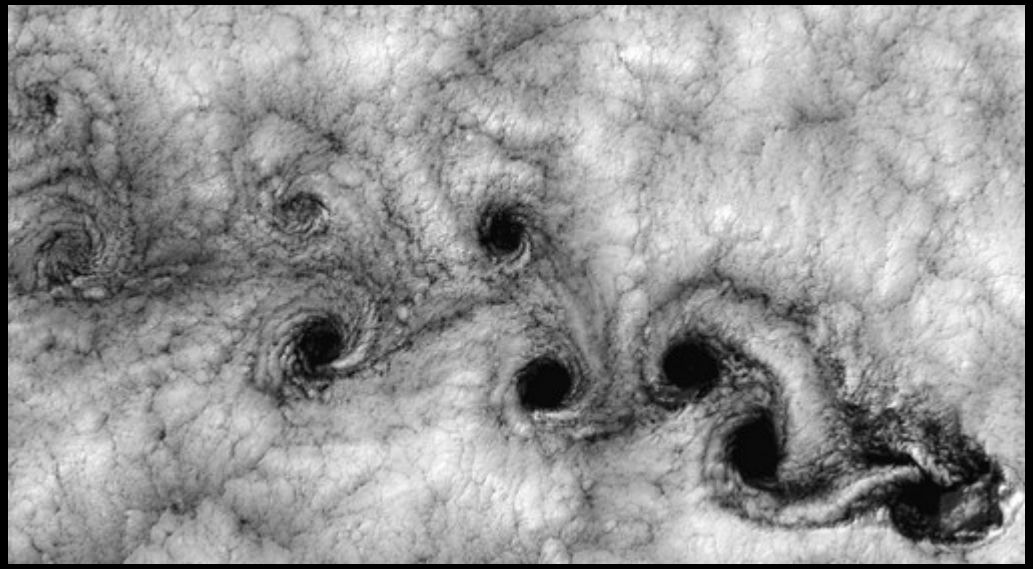


https://www.labroots.com/trending/chemistry-and-physics/18142/turbulence-treat-eyes-minds

- Unpredictable
- Swirls on many scales (eddies or vortices)
- Diffusive (= mixing things together)
- Dissipative

Vortices and Energy





https://www.labroots.com/trending/chemistry-and-physics/18142/turbulence-treat-eyes-minds

- Unpredictable
- Swirls on many scales (eddies or vortices)
- Diffusive (= mixing things together)
- **Dissipative**

Navier Stokes Equations

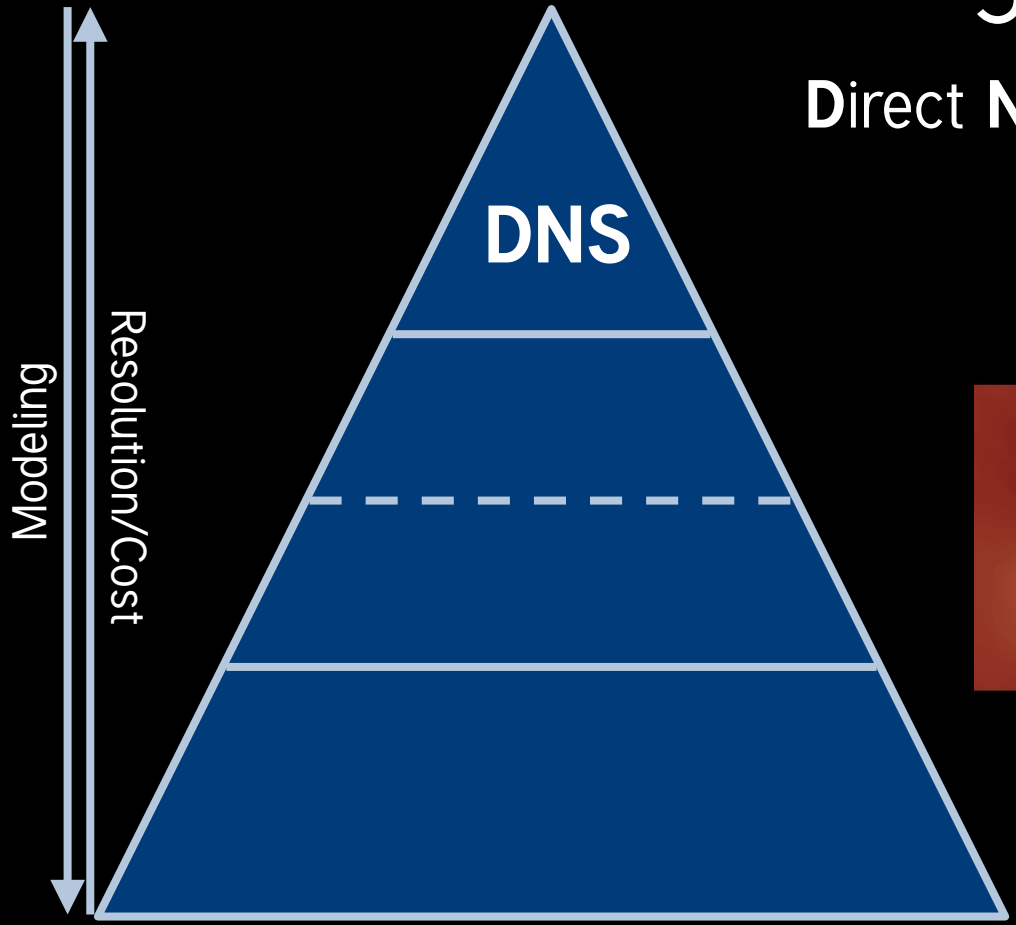
$$\nabla \cdot \boldsymbol{u} = 0$$

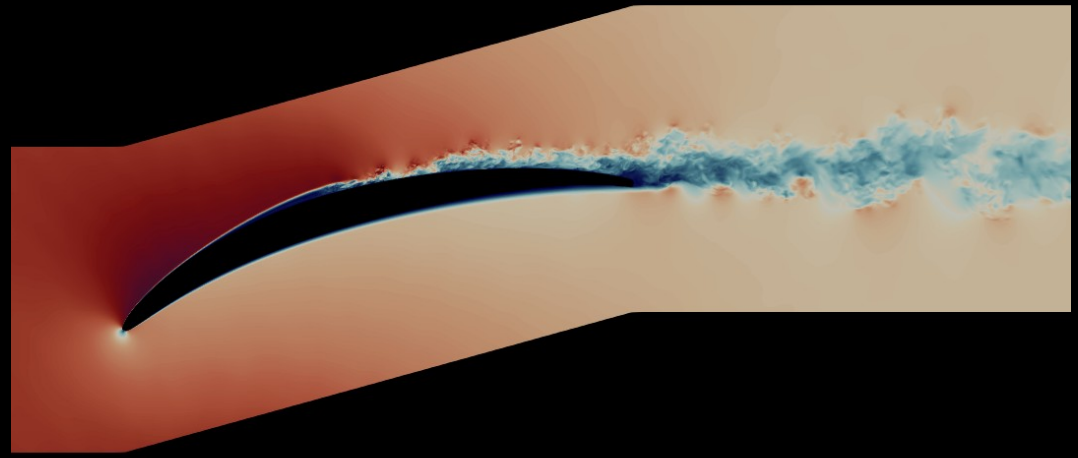
$$\rho \frac{d\boldsymbol{u}}{dt} = -\nabla p + \mu \nabla^2 \boldsymbol{u} + \boldsymbol{F}$$

LMECA2660: https://uclouvain.be/cours-2024-lmeca2660
LMECA2300: https://uclouvain.be/cours-2024-lmeca2300

Pyramid of resolutions

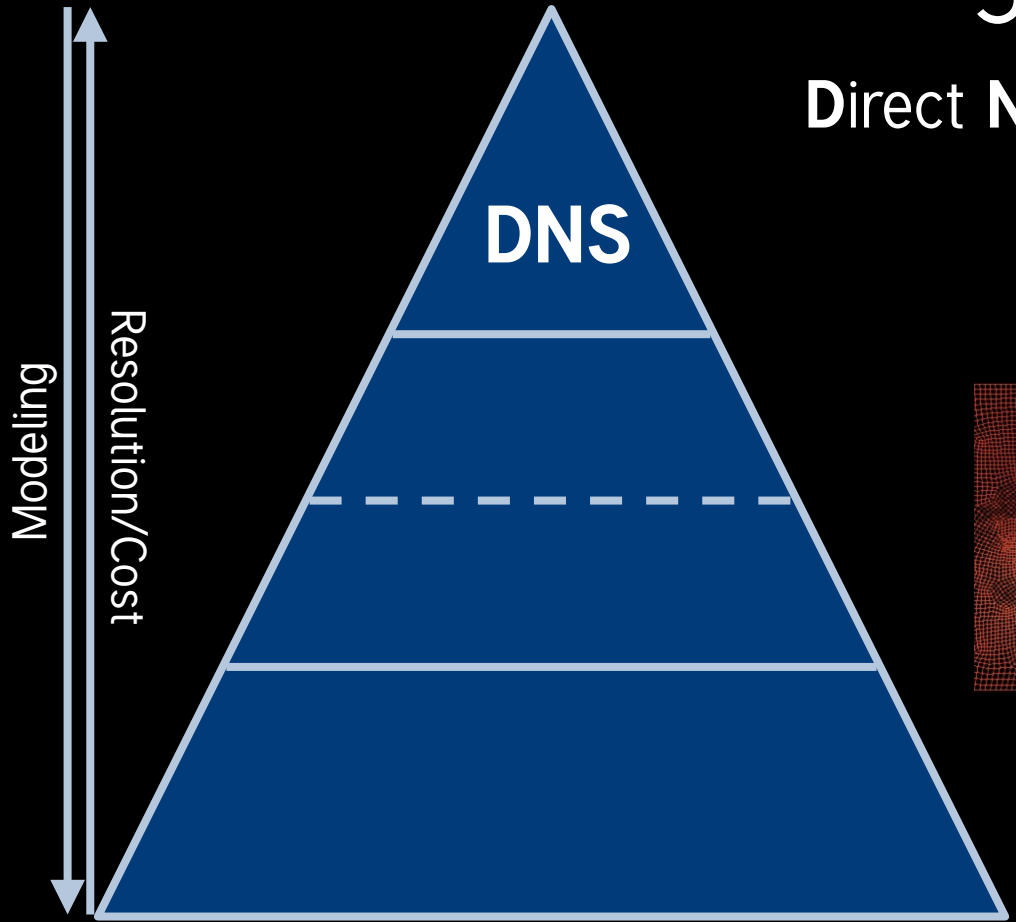
Direct **N**umerical **S**imulation

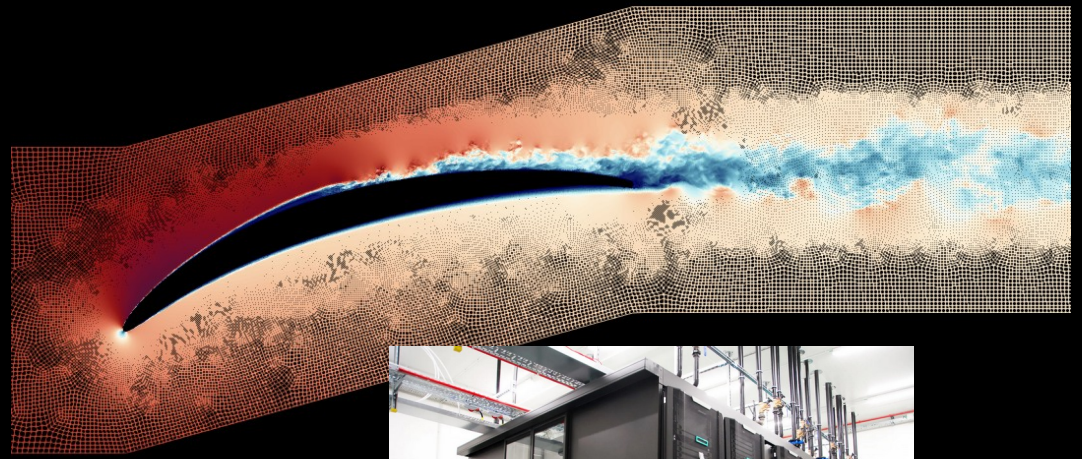




Pyramid of resolutions

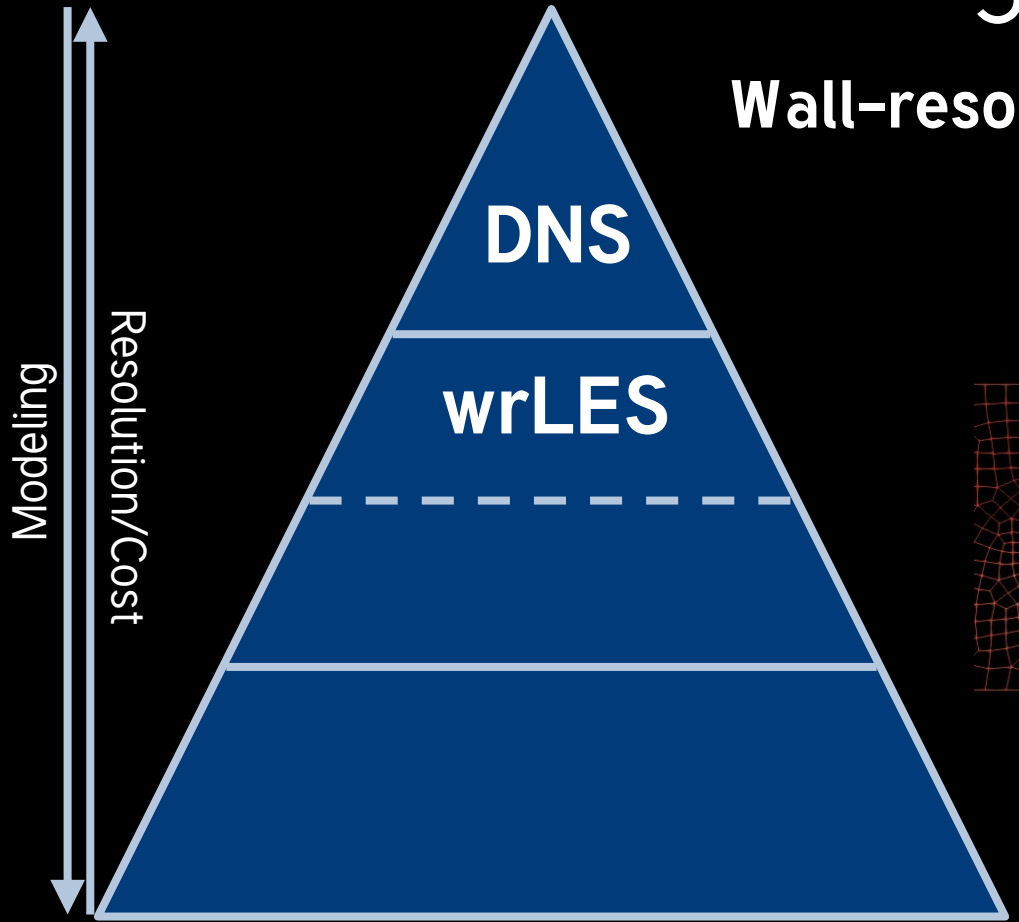
Direct **N**umerical **S**imulation



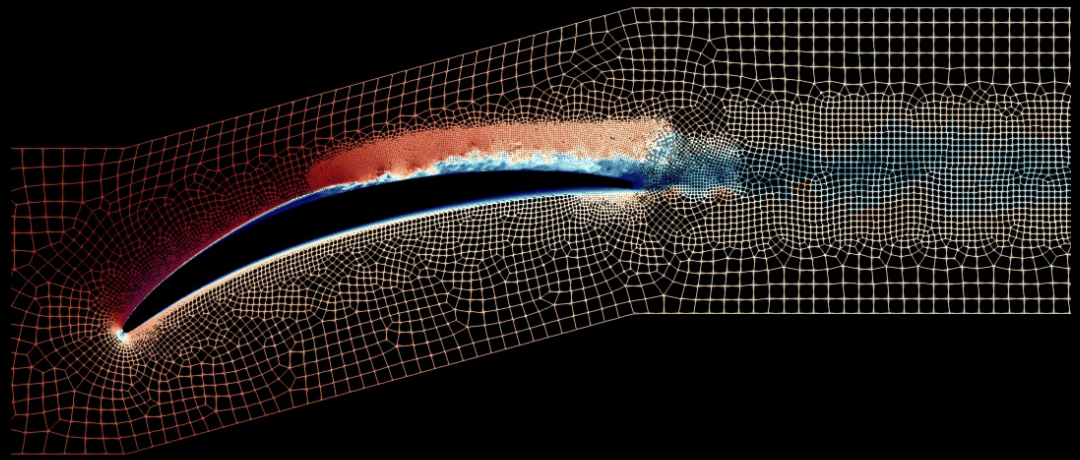


Lucia Tier-1

Pyramid of resolutions

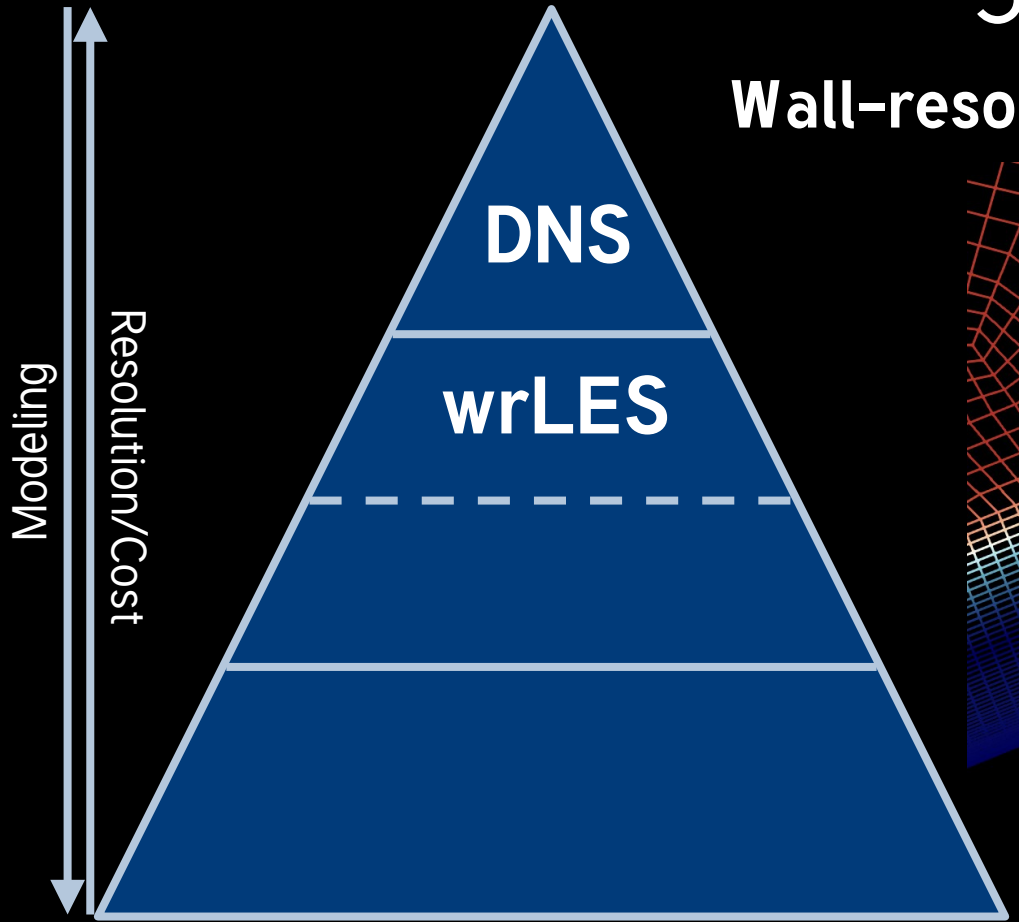


Wall-resolved (wr) Large **E**ddy **S**imulation

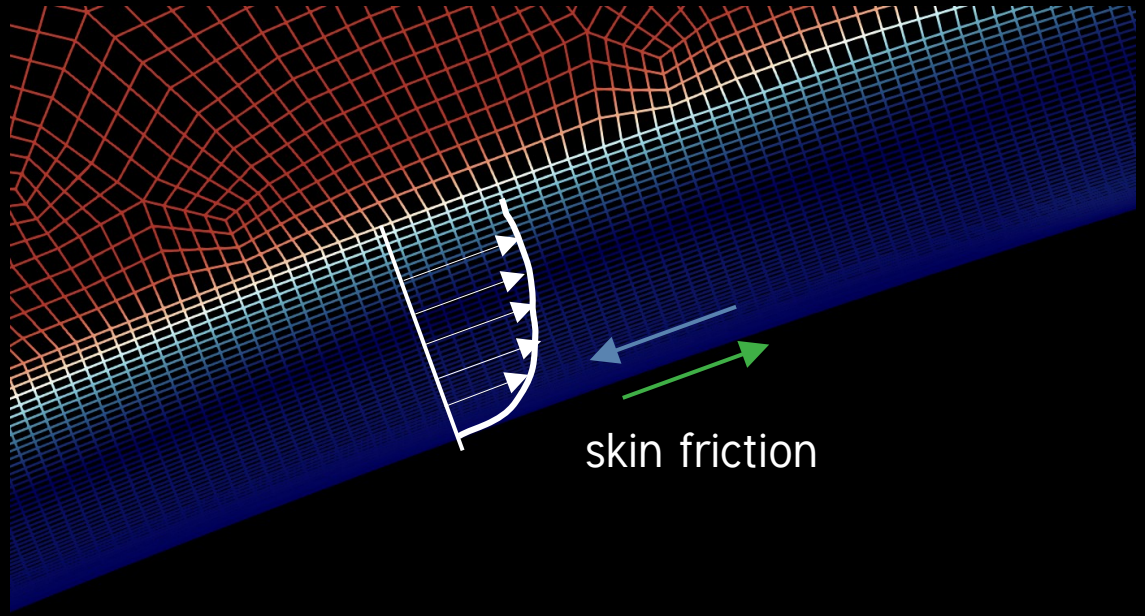


Sub-**G**rid **S**cale (SGS) models to approximate the effect of the smallest scales on the largest scales.

Pyramid of resolutions



Wall-resolved (wr) Large **E**ddy **S**imulation

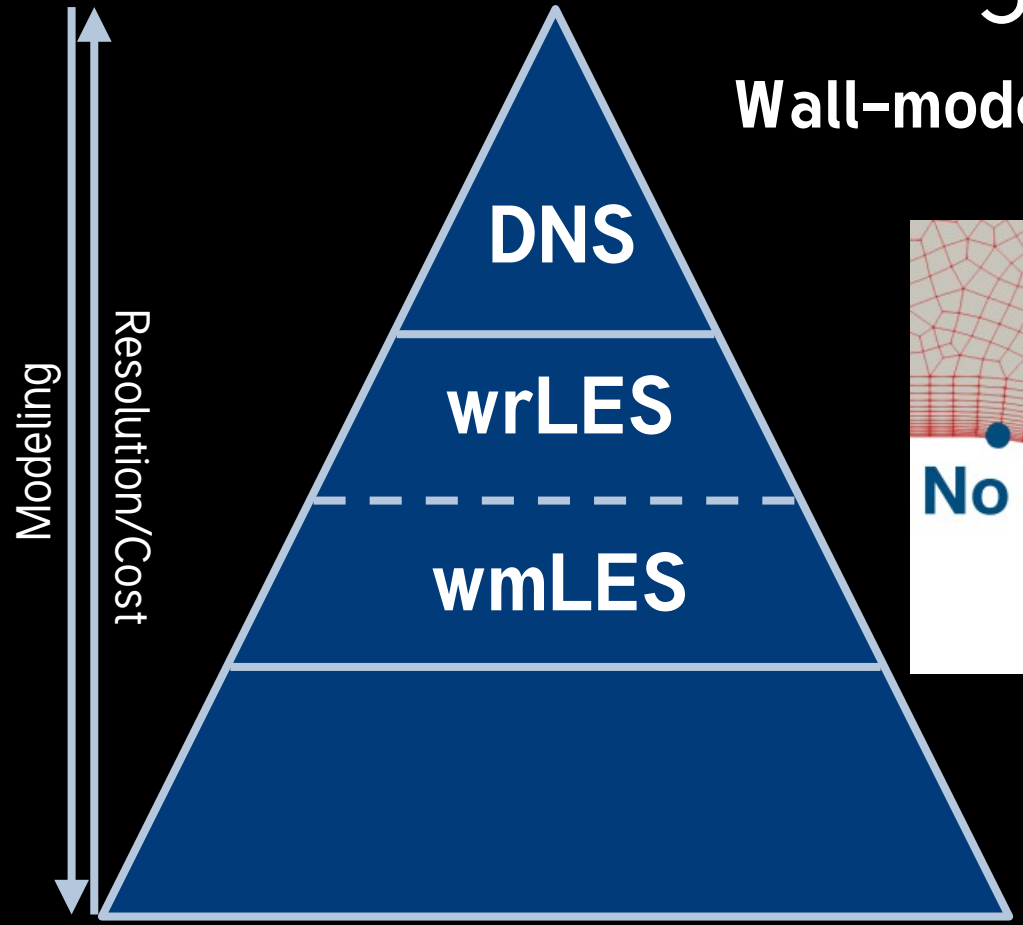


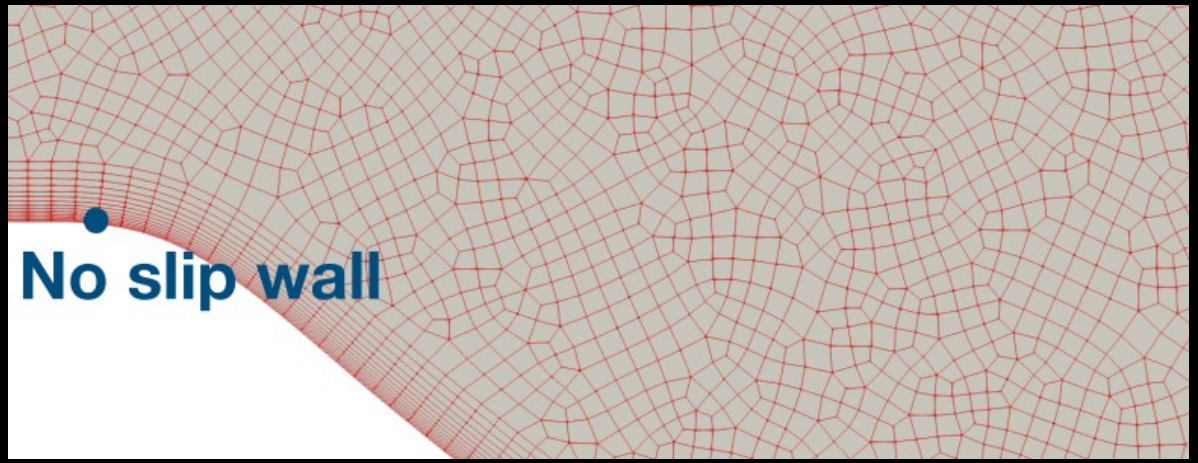
Fine and accurate **resolution** of the boundary layer BUT it is **costly**

LMECA1321: https://uclouvain.be/cours-2025-lmeca1321
LMECA2323: https://uclouvain.be/cours-2024-lmeca2323

Pyramid of resolutions

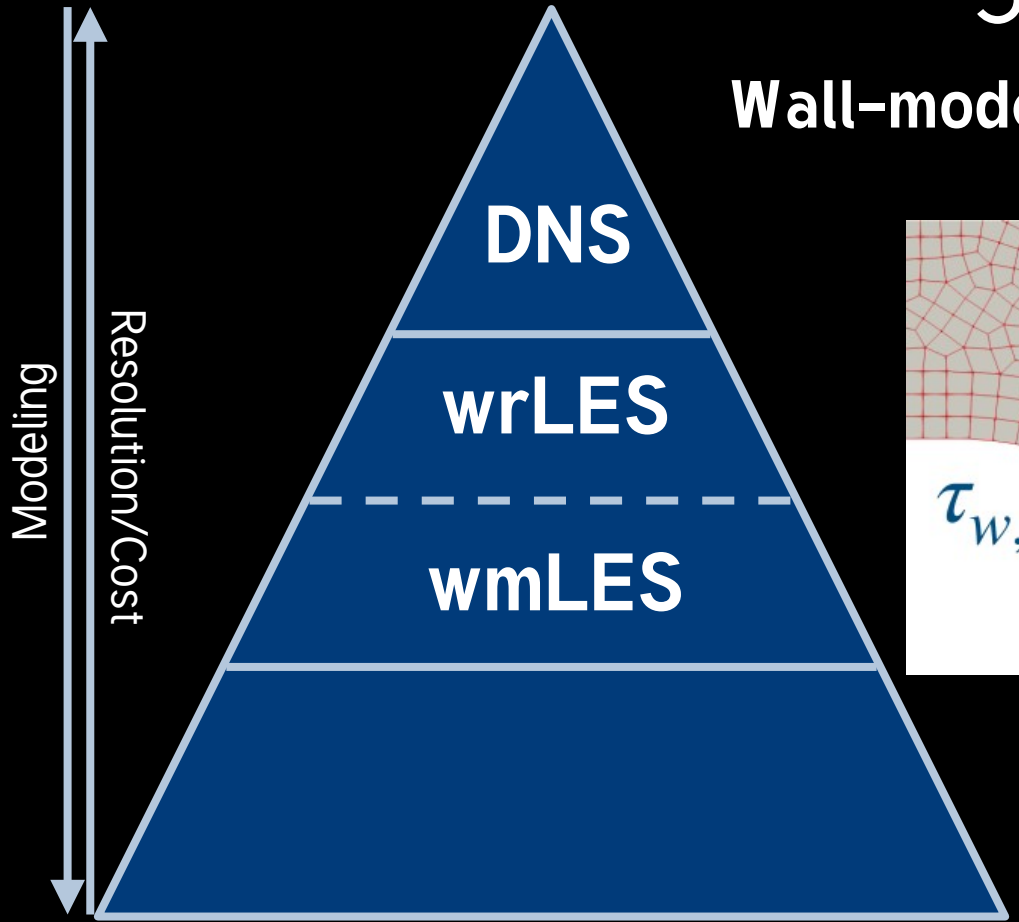
Wall-modeled (wm) **L**arge **E**ddy **S**imulation

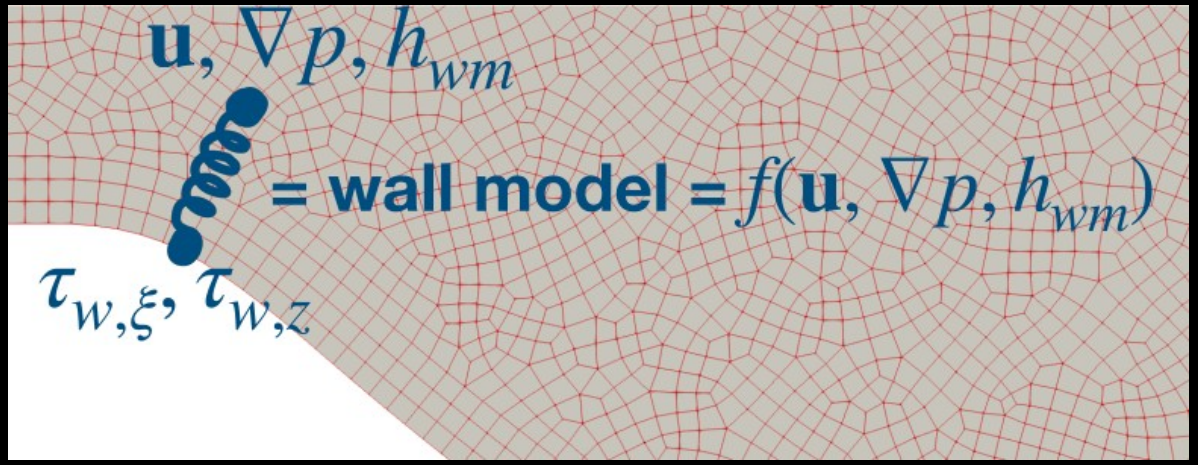




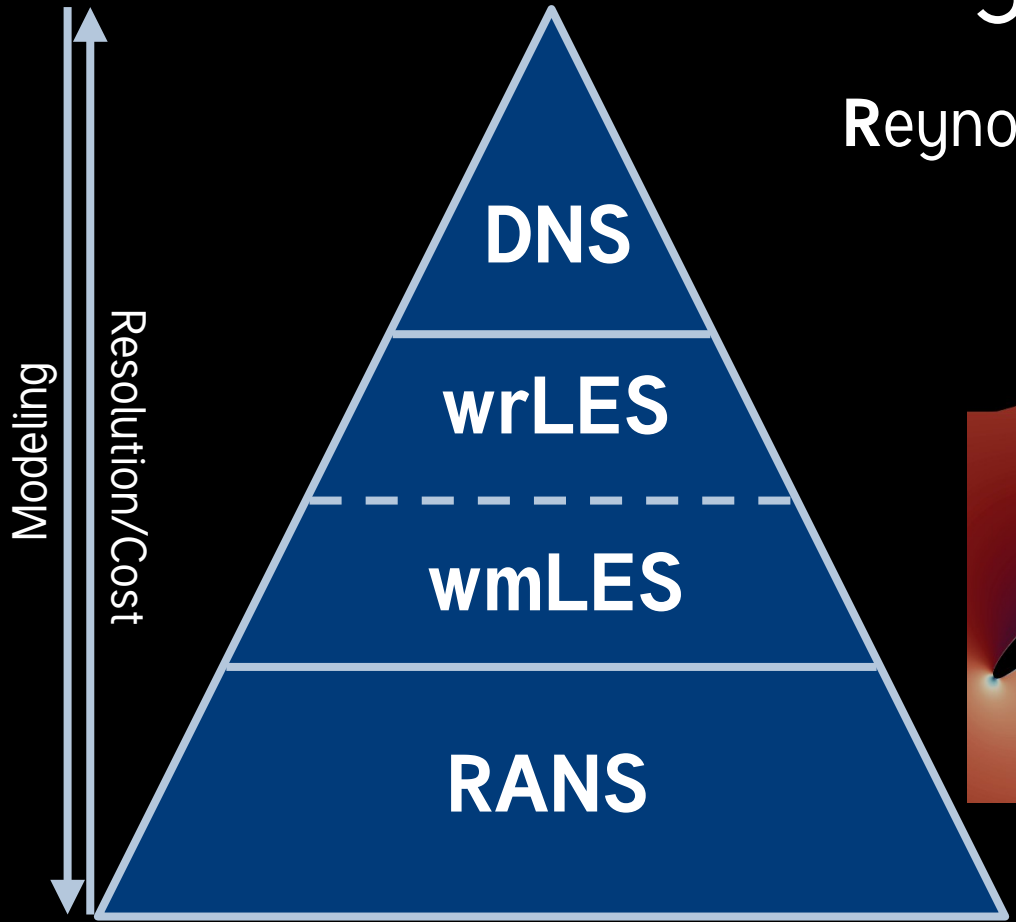
Pyramid of resolutions

Wall-modeled (wm) Large **E**ddy **S**imulation

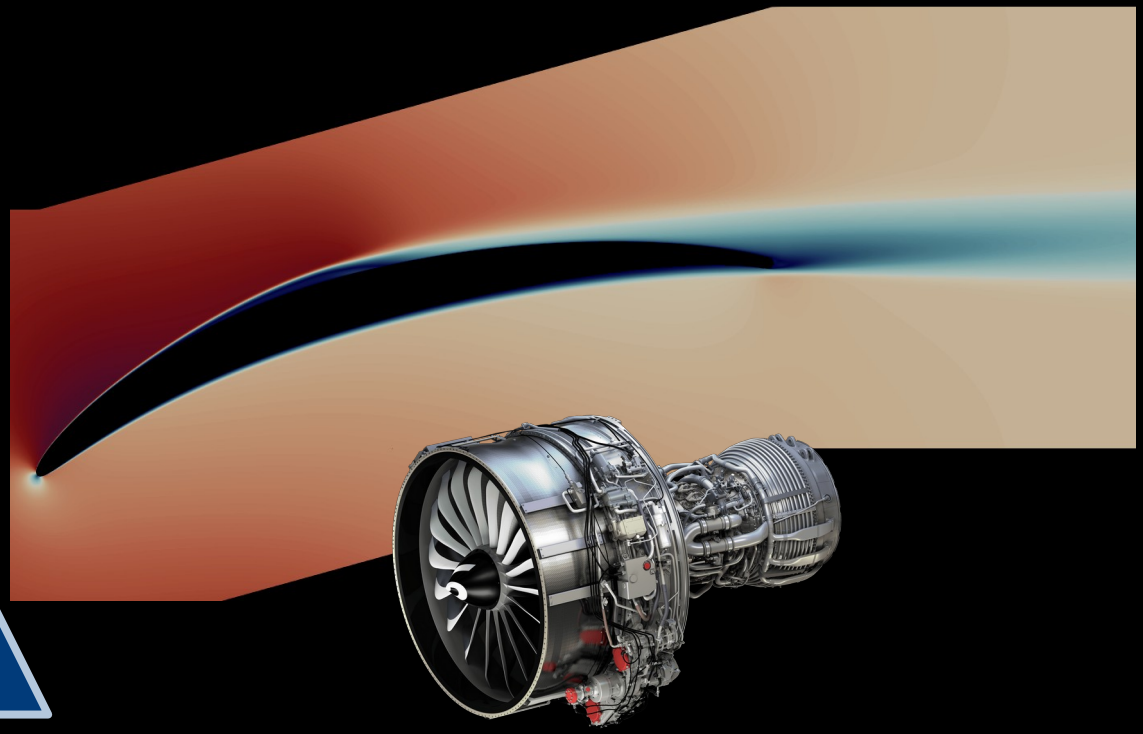




Pyramid of resolutions



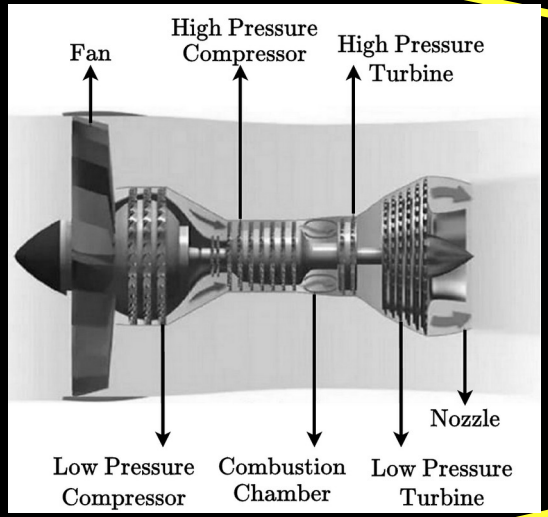
Reynolds-**A**veraged **N**avier-**S**tokes



Leap-1A Safran

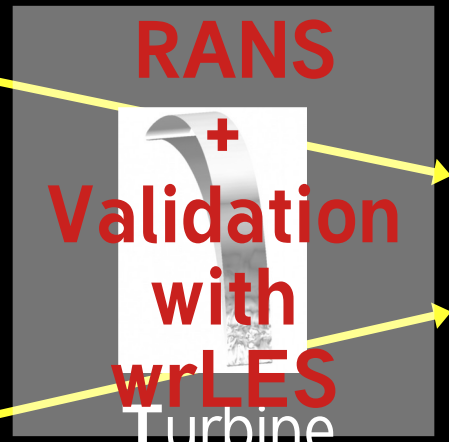
RANS for design and optimization

Full Engine



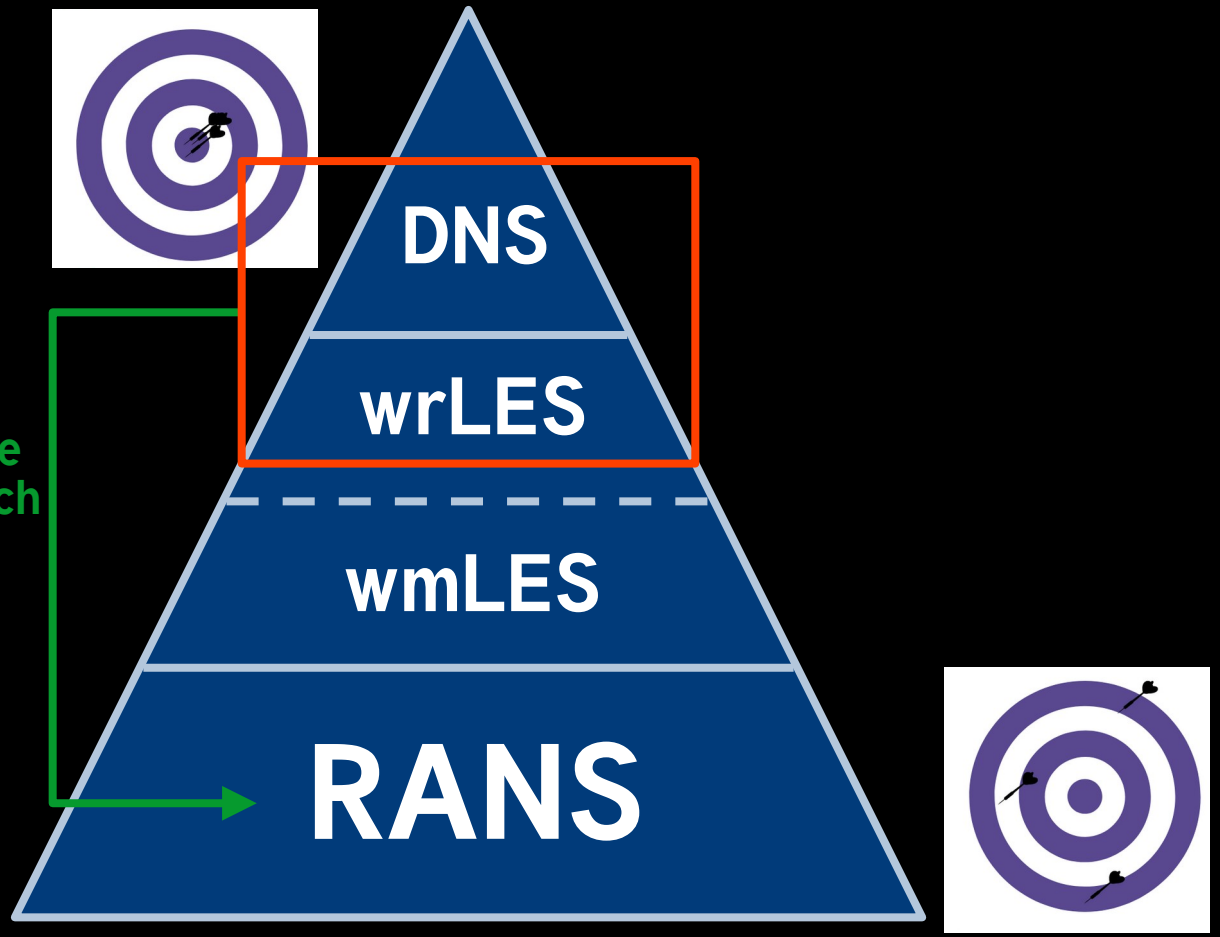
One Stage[7]

Turbine Blade[6]



Turbine Cascade Blade
[Cenaero credits]

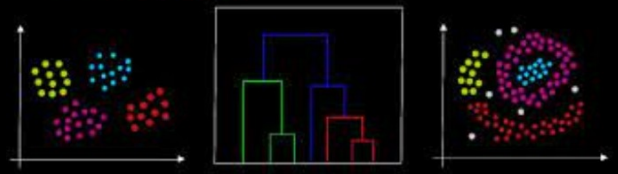
DNS and LES for modeling



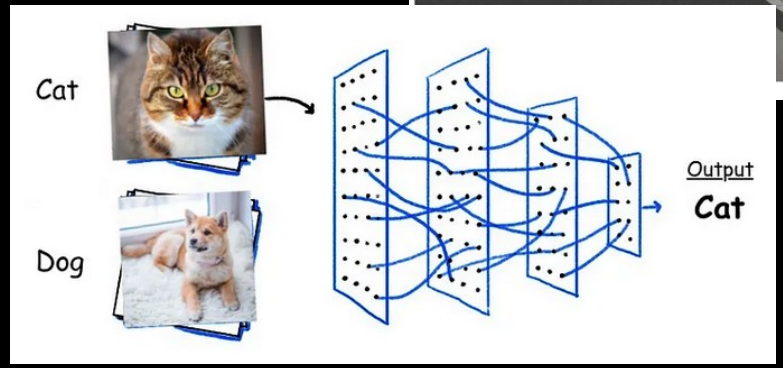
Modeling some terms of the RANS turbulent closure such as the Reynolds stress tensor (RST) or calibrating the RANS coefficients.

Deep Learning techniques

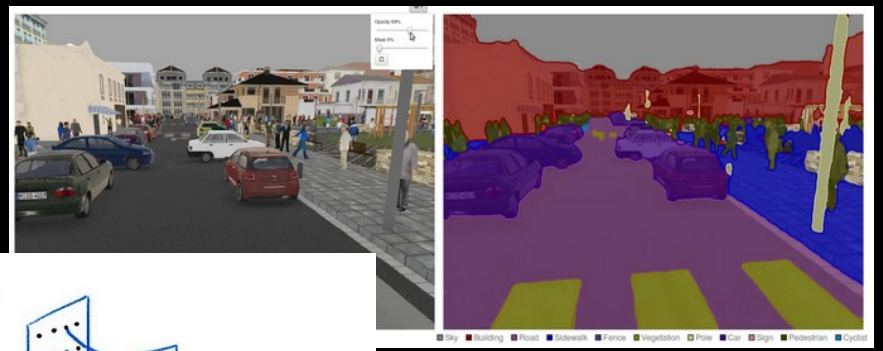
Clustering[2]



Generation[3]

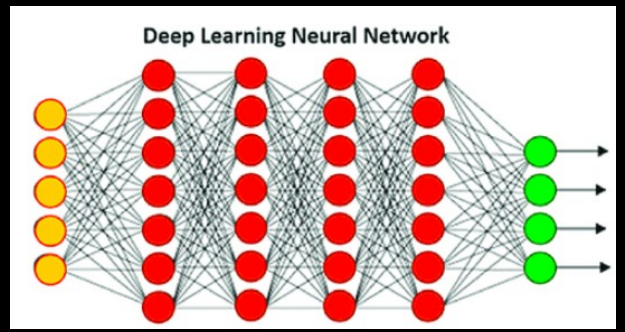


Classification[5]



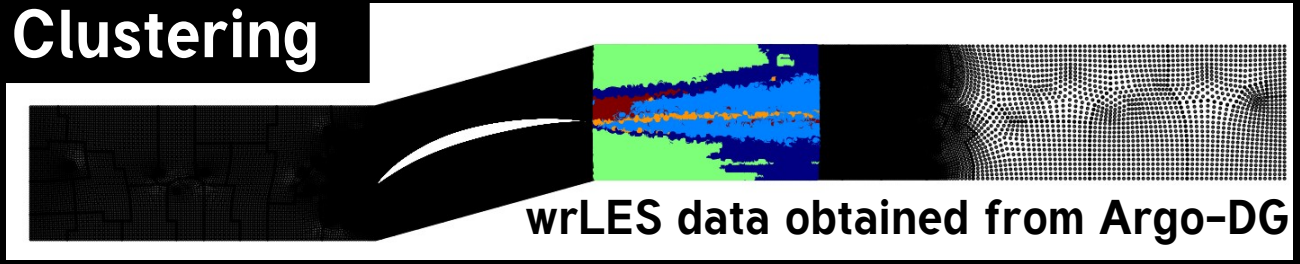
Segmentation[1]

Regression[4]

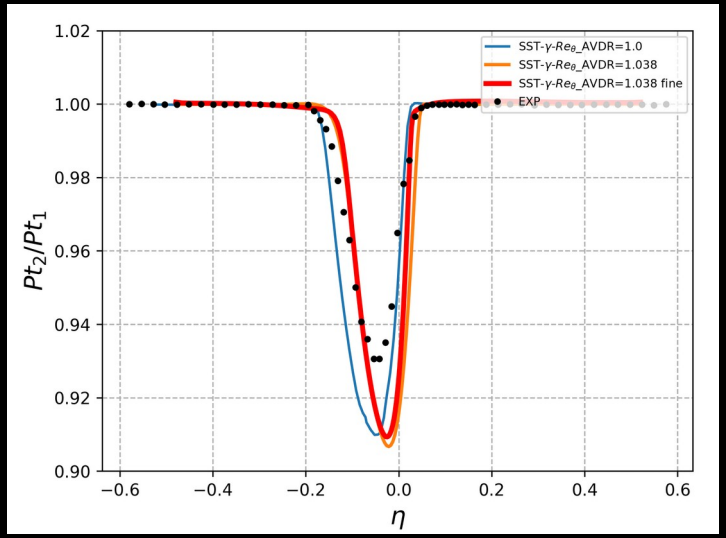


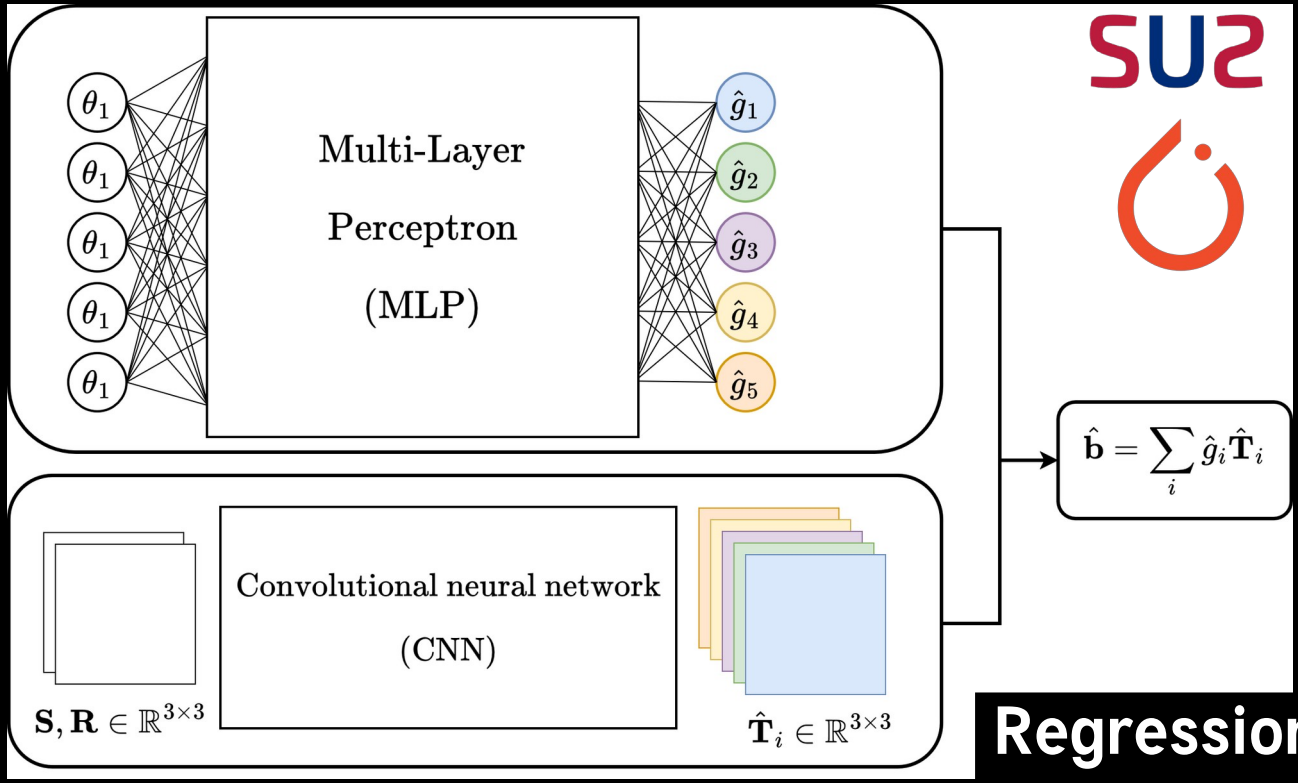
RANS-modeling

Clustering



wrLES data obtained from Argo-DG

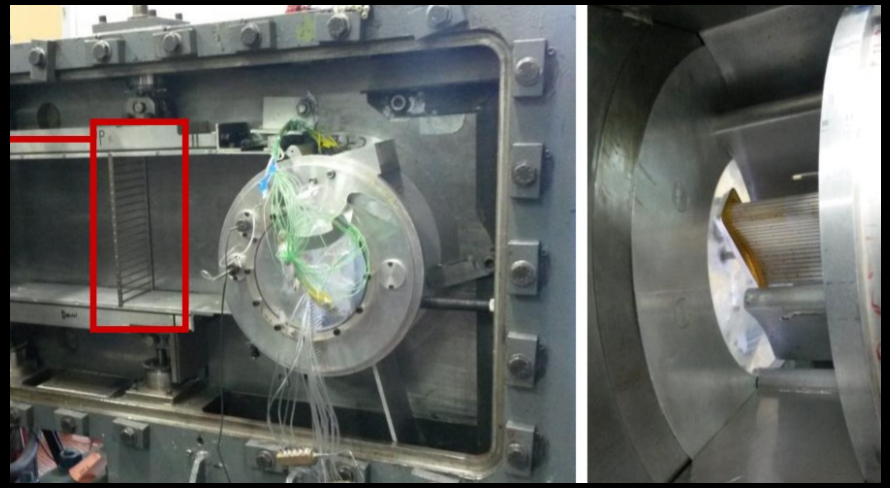




Regression

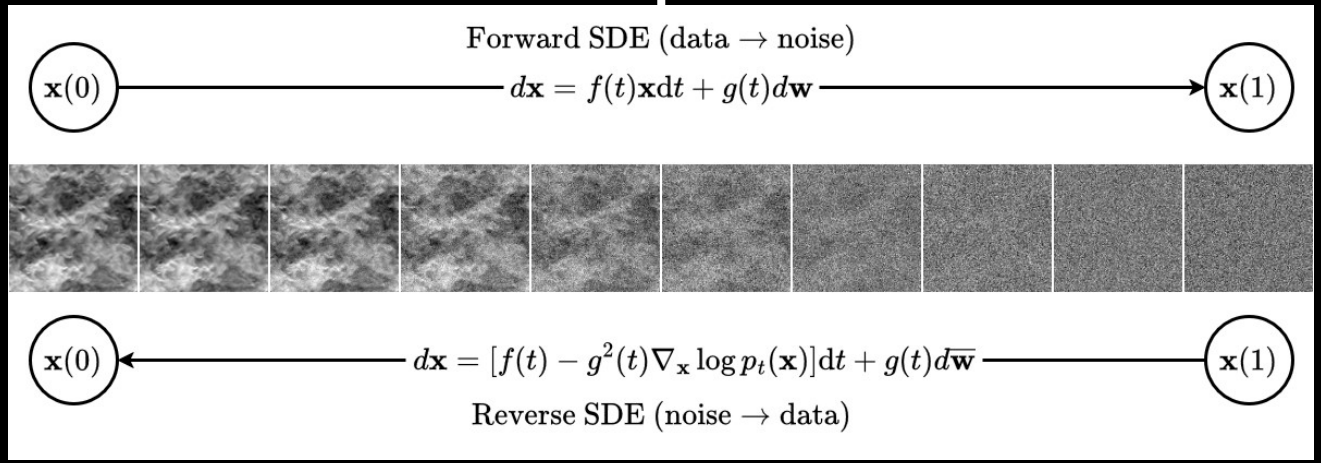
Turbulence Injection

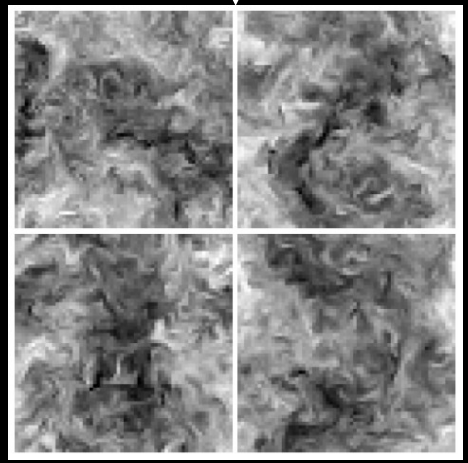
Reproducing **realistic tubulence fluctuations** at the inlet of the numerical domain using generative models (i.e., diffusion models).



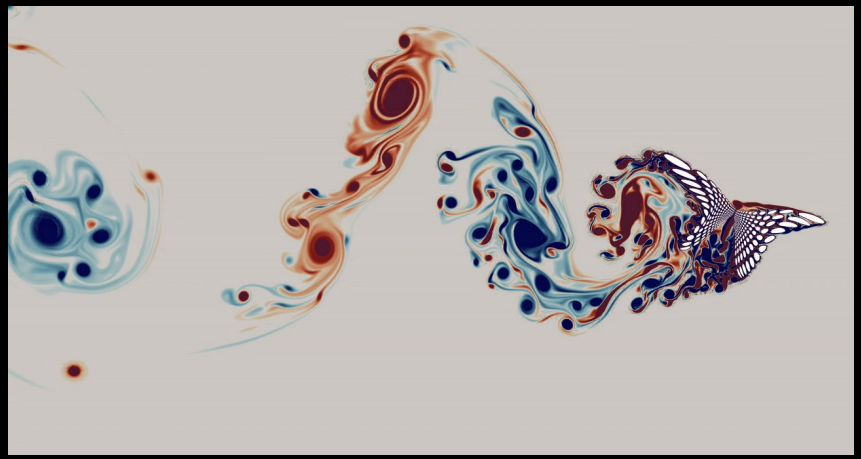
Images of the VKI wind tunnel facility

Sampling capabilities !





Thank you



https://www.cenaero.be/

References

[1] https://becominghuman.ai/how-to-do-semantic-segmentation-using-deep-learning-a09bd6582b66

[2] Jakana Foods, Unsupervised deep learning algorithms

[3] Deep Learning for Computer Vision by Rajalingappaa Shanmugamani

[4] A. Oyawale *et al.*, Integration of data-Intensive, machine Learning and robotic experimental approaches for accelerated discovery of catalysts in renewable energy-related reactions, Materials Reports Energy, 1(3):100049 (2021). DOI: 10.1016/j.matre.2021.100049

[5] https://medium.com/data-science/10-papers-you-should-read-to-understand-image-classification-in-the-deep-learning-era-4b9d792f45a7

[6] F. Casenave and N. Akkari, An Error Indicator-Based Adaptive Reduced Order Model for Nonlinear Structural Mechanics–Application to High-Pressure Turbine Blades. Mathematical and Computational Applications, 24(2):41 (2019). DOI: 10.3390/mca24020041

[7] Schematics of a turbofan engine, image extracted from the website https://mechanicalboost.com/turbofan/