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Centrum Wiskunde & Informatica
Eindhoven University of Technology

DLES, Thursday May 21, 2026

Are we modeling the wrong stress tensor in LES?

In collaboration with Benjamin Sanderse and Roel Verstappen

Lifecycle of turbulence

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The Burgers' equation (1D)

$$\partial_t u = \underbrace{\nu \partial_{xx} u}_{\text{Diffusion}} - \underbrace{\partial_x \left(u^2/2\right)}_{\text{Convection}}$$

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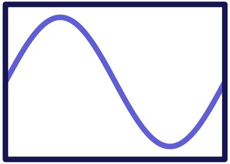
Effect on a Fourier mode

$$u = \mathrm{e}^{\mathrm{i}kx}$$



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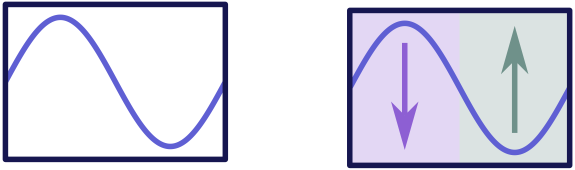

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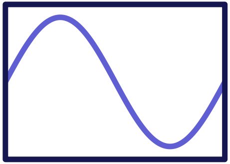

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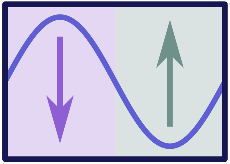
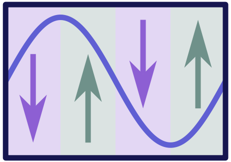


$$\partial_x \left(u^2/2\right) = \mathrm{i}k\mathrm{e}^{\mathrm{i}(2k)x}$$



Spectral distribution of energy

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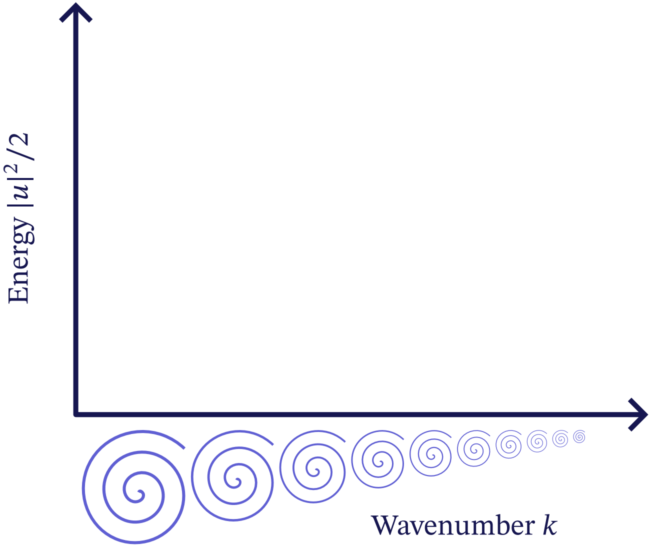

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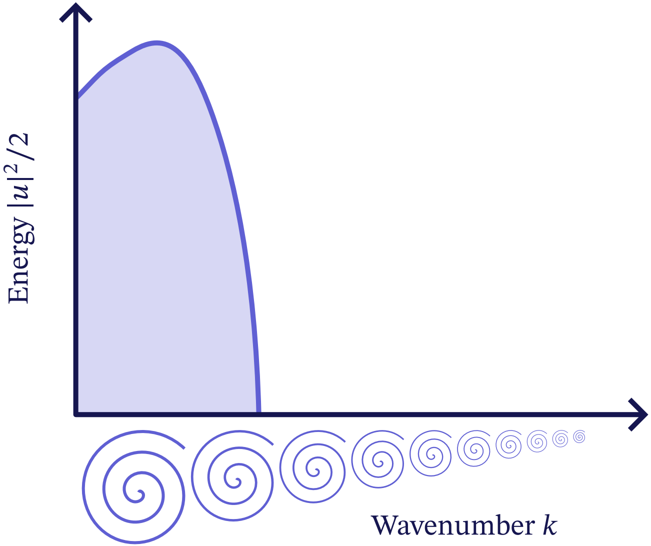

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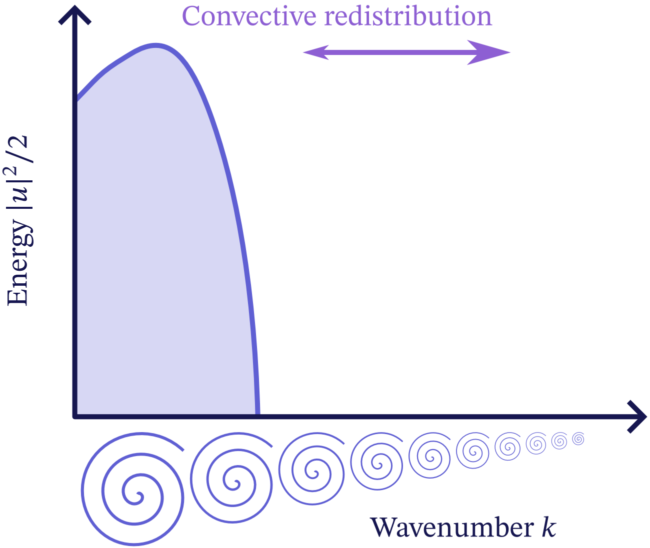

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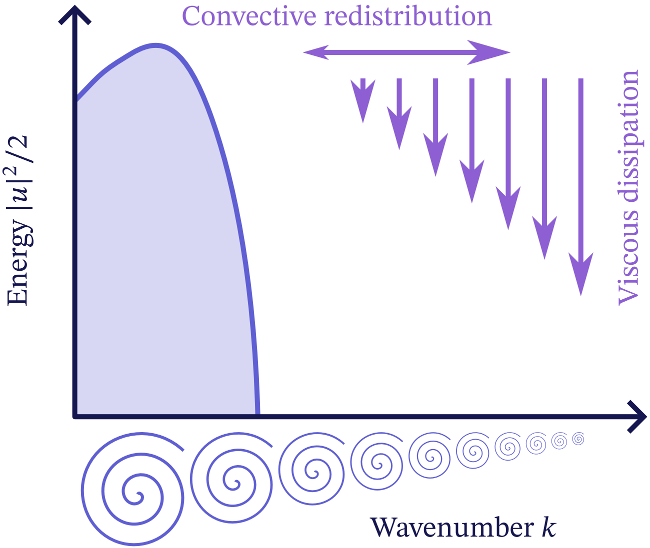

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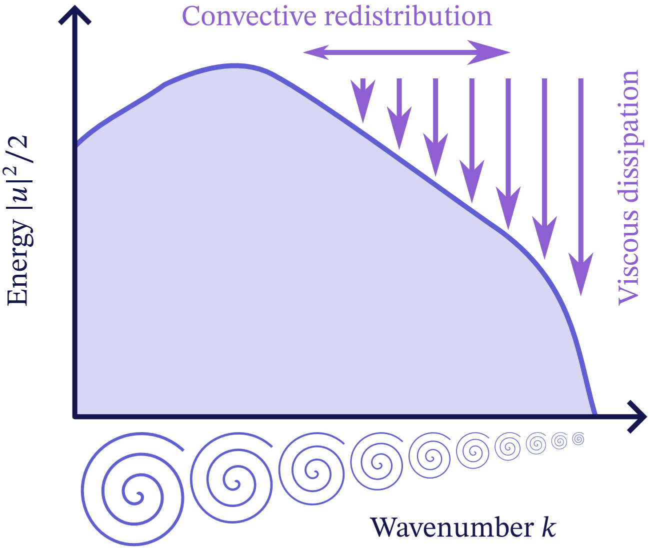

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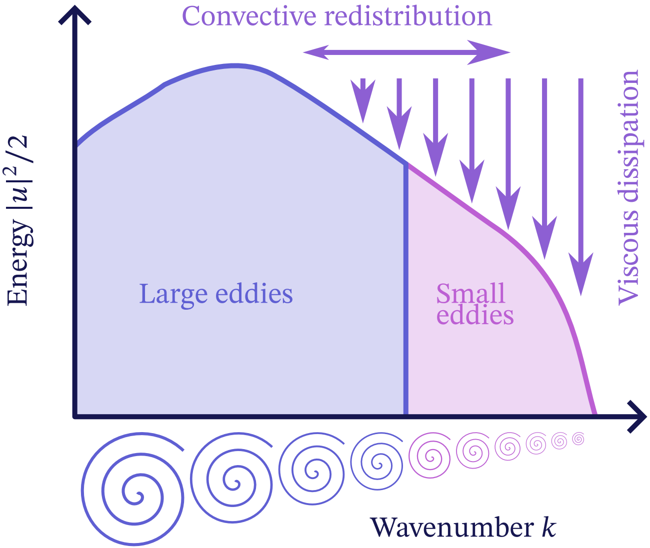

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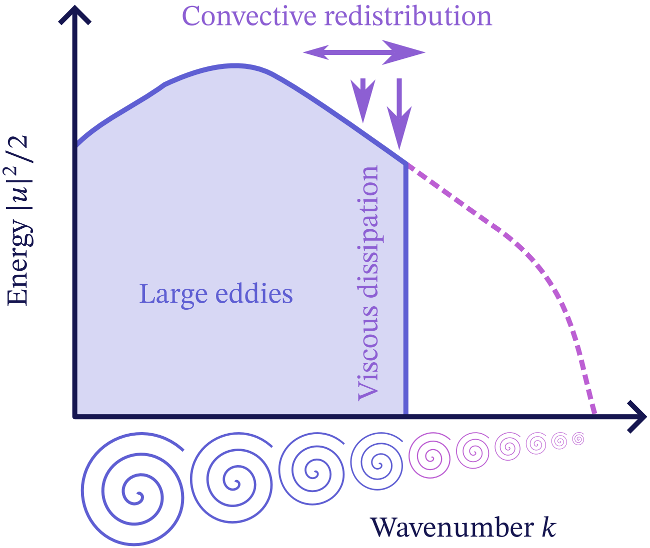

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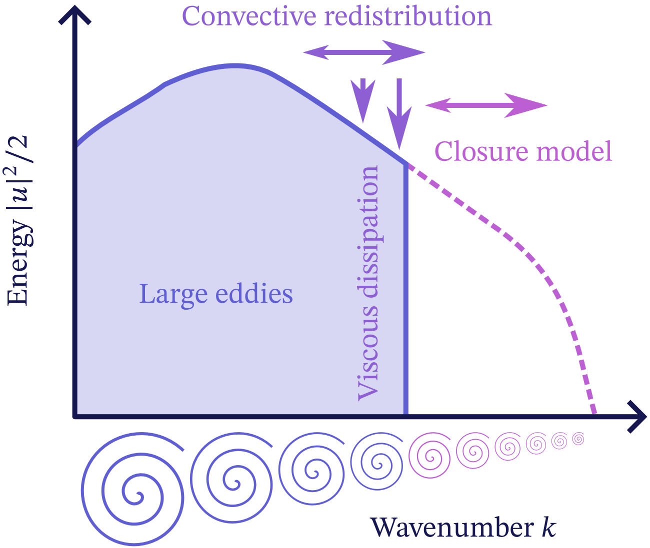

LES and FVM: the toolbox

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Filtering

$$\overline{(\cdot)}^{\Delta}, \quad \overline{(\cdot)}^{h}$$

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Divergence theorem

$$\partial_x^h = \overline{(\cdot)}^{h} \circ \partial_x$$

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Closure modeling

$$\tau^{\Delta}(u) \approx m^{\Delta}(\bar{u}^{\Delta})$$

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$$\sigma(u) \approx \sigma^h(\bar{u}^h)$$

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$$\operatorname{div} \circ \pi = 0, \qquad \pi \pi = \pi$$

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Flux reconstruction

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Time integration

$$u^* = u^n + \Delta t \dots$$
$$u^{n+1} = \pi u^*$$

Filtering

LES filter

$$\bar{u}^{\Delta}(x) = \int_{\Omega} G^{\Delta}(x - y) u(y) \, \mathrm{d}y$$

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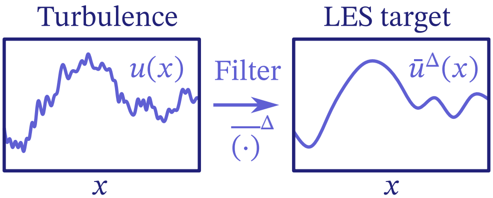

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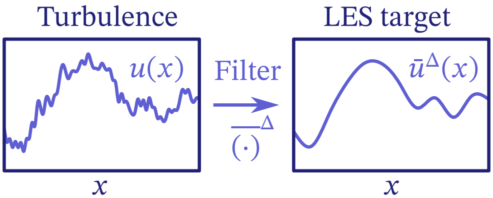

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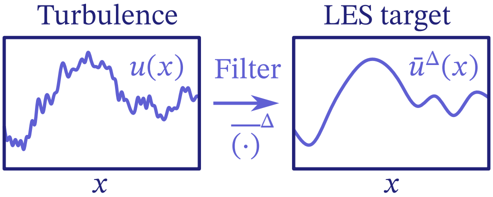

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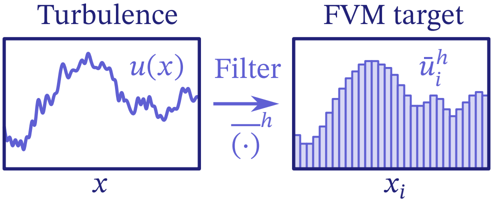

Divergence theorem

The mechanism powering the FVM

Divergence theorem

The mechanism powering the FVM

$$\partial_x^h u(x) = \frac{u\left(x + \frac{h}{2}\right) - u\left(x - \frac{h}{2}\right)}{h} = \frac{1}{h} \int_{x-h/2}^{x+h/2} \partial_y u(y) \, \mathrm{d}y = \overline{\partial_x u}^h (x)$$

Stress in LES

S. D. Agdestein

Divergence theorem

The mechanism powering the FVM

$$\partial_x^h u(x) = \frac{u\left(x + \frac{h}{2}\right) - u\left(x - \frac{h}{2}\right)}{h} = \frac{1}{h} \int_{x-h/2}^{x+h/2} \partial_y u(y) \, \mathrm{d}y = \overline{\partial_x u}^h (x)$$

The discrete divergence ∂_x^h is induced by the FVM filter $\overline{(\cdot)}^h$

$\implies$ exact discrete conservation laws for $\bar{u}^h$

Closure modeling

Models rely on τ^Δ being the unresolved stress

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$$\tau^\Delta(u) = \overline{uu}^\Delta - \bar{u}^\Delta \bar{u}^\Delta, \quad S(u) = (\nabla u + \nabla u^T)/2$$

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Structural models

$$m^\Delta(\bar{u}^\Delta) = \frac{\Delta^2}{12} (\nabla \bar{u}^\Delta)(\nabla \bar{u}^\Delta)^T, \quad \text{(Taylor series truncation)}$$

$$m^\Delta(\bar{u}^\Delta) = \tau^{(2\Delta)}(\bar{u}^\Delta), \quad \text{(scale-similarity)}$$

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Functional models

$$m^\Delta(\bar{u}^\Delta) = -2\nu^\Delta S(\bar{u}^\Delta), \quad 2\nu^\Delta_{\text{ideal}} = -\frac{S(\bar{u}^\Delta) : \tau^\Delta(u)}{S(\bar{u}^\Delta) : S(\bar{u}^\Delta)}, \quad \text{(eddy-viscosity)}$$

Flux recontruction

Infinitesimal flux

$$\sigma(u) = uu$$

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Discrete flux

$$\sigma^h(u)(x) = \left[\frac{u\left(x + \frac{h}{2}\right) + u\left(x - \frac{h}{2}\right)}{2} \right]^2 \quad \text{(energy-conserving central)}$$

$$\sigma^h(u)(x) = \begin{cases} u\left(x - \frac{h}{2}\right)^2, & \text{if } u\left(x - \frac{h}{2}\right) > 0, \\ u\left(x + \frac{h}{2}\right)^2, & \text{if } u\left(x + \frac{h}{2}\right) < 0, \\ 0, & \text{otherwise,} \end{cases} \quad \text{(dissipative upwind)}$$

Projection and time integration

Incompressible Navier-Stokes as a conservation law

Projection and time integration

Incompressible Navier-Stokes as a conservation law

With pressure and constraint

$$\nabla \cdot u = 0, \quad \partial_t u + \nabla \cdot (\sigma(u) + p\delta) = f, \quad \sigma(u) = uu - \nu \left(\nabla u + \nabla u^T \right)$$

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Pressure-free formulation

$$\partial_t u + \nabla \cdot \pi \sigma(u) = \pi f$$

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Time integration

$$\begin{aligned} u^* &= u^n + \Delta t (f - \nabla \cdot \sigma(u^n)) \\ u^{n+1} &= \pi u^* \end{aligned}$$

Discretization-aware LES

Correcting for an inconsistency

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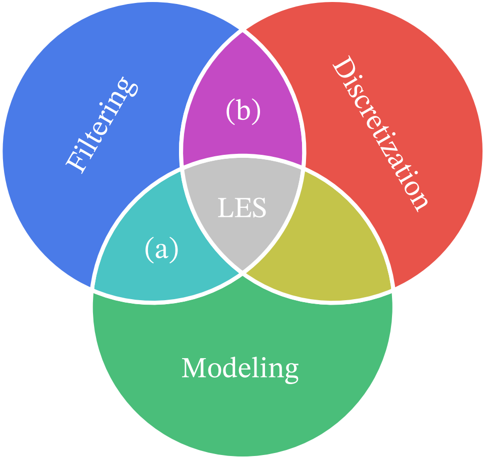
Correcting for an inconsistency



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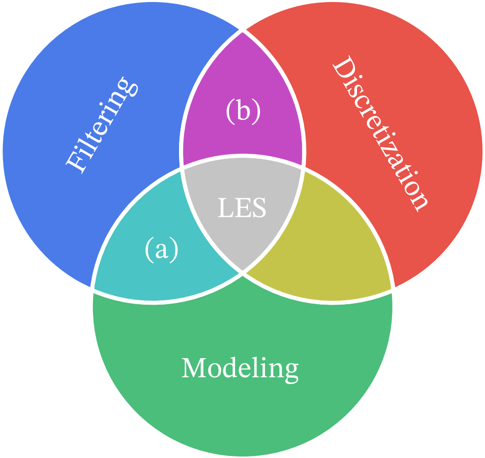
Discretization-aware LES

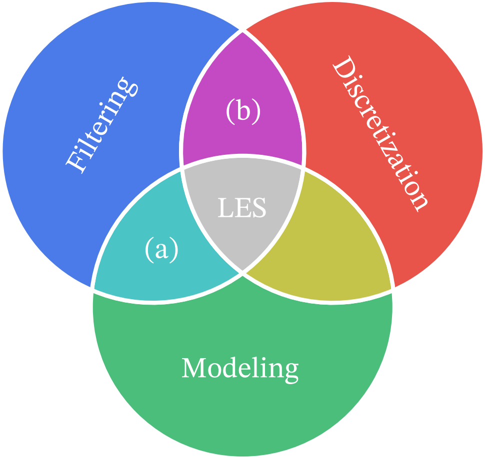
Correcting for an inconsistency



a Classical approach: Filter and model, then discretize.

Discretization-aware LES

Correcting for an inconsistency



- a Classical approach: Filter and model, then discretize.
- b New approach: Filter and discretize, then model.

Burgers' equation

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Unresolved discrete flux

$$\tau^{\Delta,h}(u) = \overline{\sigma(u)}^{\Delta} - \sigma^h(\bar{u}^{\Delta,h})$$

Incompressible Navier-Stokes

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Projection form

$$\partial_t u = -\nabla \cdot \pi \sigma(u), \quad \sigma(u) = uu - \nu \left(\nabla u + \nabla u^T \right)$$

Stress in LES

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Exact LES equations

$$\text{Infinitesimal LES:} \quad \partial_t \bar{u} = -\overline{\nabla \cdot \pi\sigma(u)} = -\nabla \cdot \pi\overline{\sigma(u)}$$

$$\text{Discrete LES:} \quad \partial_t \bar{u}^h = -\overline{\nabla \cdot \pi\sigma(u)}^h = -\nabla_h \cdot \overline{\pi\sigma(u)}^{h,*}$$

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Exact LES equations

τ_{11}	τ_{12}	τ_{13}
τ_{12}	τ_{22}	τ_{23}
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τ_{31}	τ_{32}	τ_{33}

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How much of the sub-filter flux comes from the discretization?

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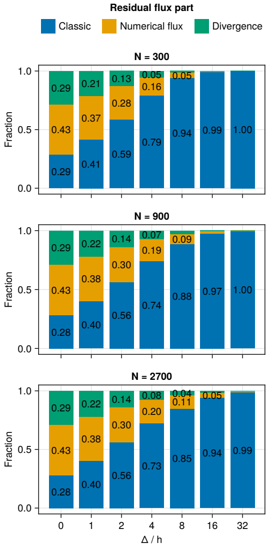

Discretization-aware closure

Fitting the Smagorinsky constant for Burgers' equation

Discretization-aware closure

Fitting the Smagorinsky constant for Burgers' equation

$$m(u, \theta) = -\theta s(u), \quad m^h(u, \theta) = -\theta s^h(u),$$

$$s(u) = \left|\partial_x u\right| \partial_x u, \quad s^h(u) = \left|\partial_x^h u\right| \partial_x^h u,$$

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$$s(u) = \left|\partial_x u\right| \partial_x u, \quad s^h(u) = \left|\partial_x^h u\right| \partial_x^h u,$$

$$\theta_{\text{classic}} = -\frac{s(\bar{u}) \tau(u)}{s(\bar{u}) s(\bar{u})},$$

$$\theta_{\text{informed}} = -\frac{s^h(\bar{u}) \tau^h(u)}{s^h(\bar{u}) s^h(\bar{u})}.$$

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Comparison:
$m^h(\cdot, \theta_{classic})$ *vs* $m^h(\cdot, \theta_{informed})$

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> *Comparison:*
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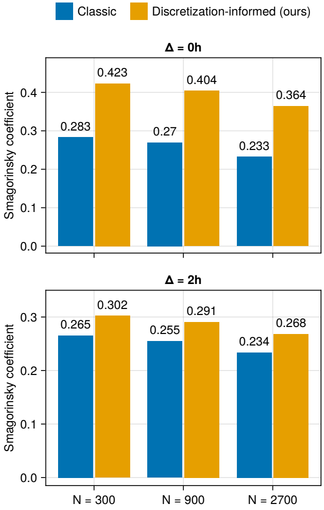

Discretization-aware closure

Errors and spectra

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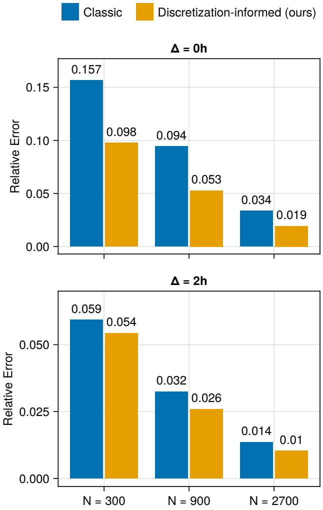

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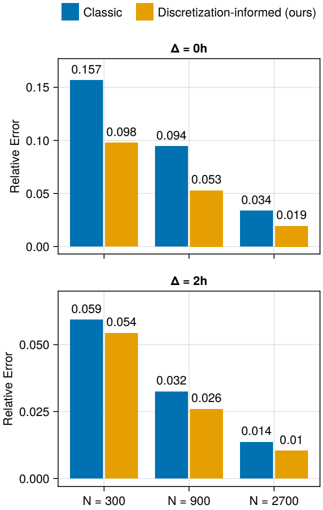

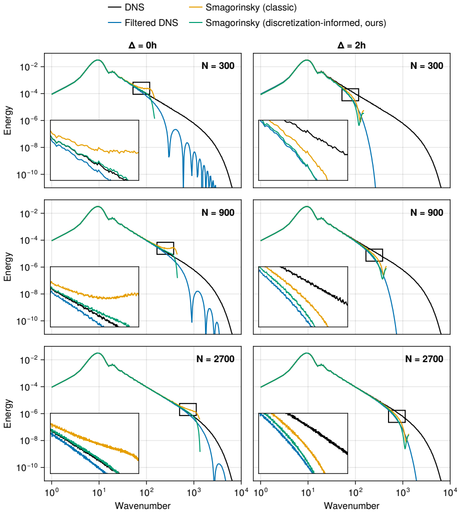

DNS-aided LES

Stress expressions for incompressible Navier-Stokes

LES equation

$$\partial_t \bar{u}^h = -\nabla_h \cdot \pi^h \left[\sigma^h(\bar{u}^h) + \tau^h(u)\right]$$

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Five stress candidates

DNS-aided LES

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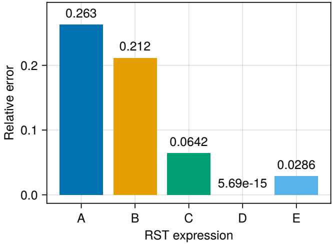

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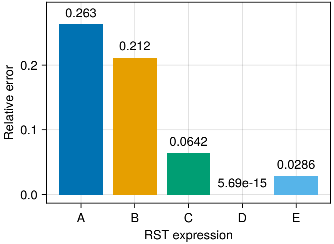

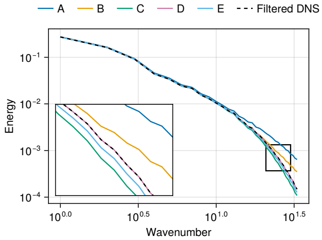

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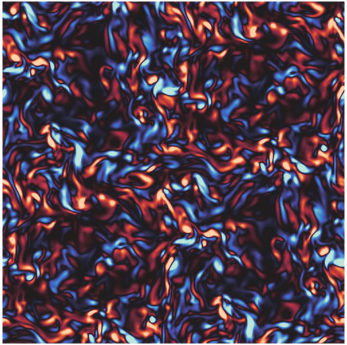
For incompressible Navier-Stokes, the LES-FVM stress tensor is non-local and non-symmetric.

Infinitesimal structural closure models have the wrong structure.

Infinitesimal functional closure models have the wrong dissipation profile.

Implicit and explicit LES unified into one coherent framework.

Thank you!



https://agdestein.github.io/