Coupling of a vertical-equilibrium model to a full-dimensional model

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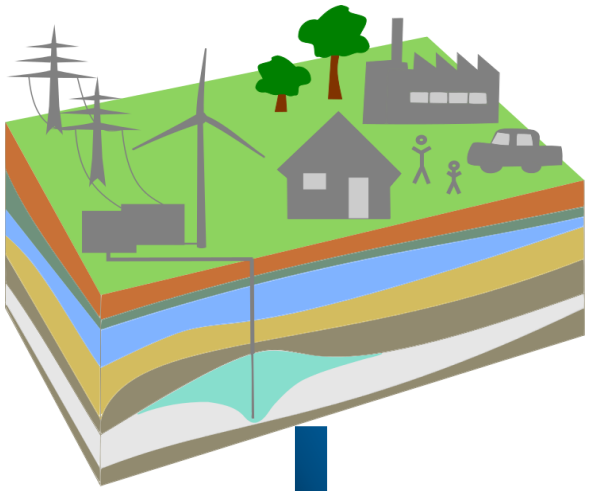
Subsurface energy storage

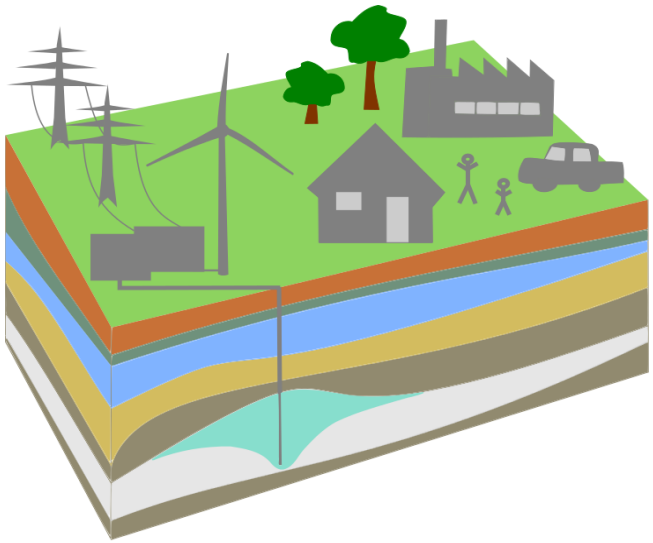


- Mechanical
  - Compressed air energy storage
- Chemical
  - Hydrogen/SNG storage
- Thermal
  - Hot/cold water storage

Why modeling energy storage?

Leakage to surface

Influence groundwater flow pattern and quality



Leakage into groundwater

Mechanical stress

Structural failure

Brine displacement

Groundwater contamination

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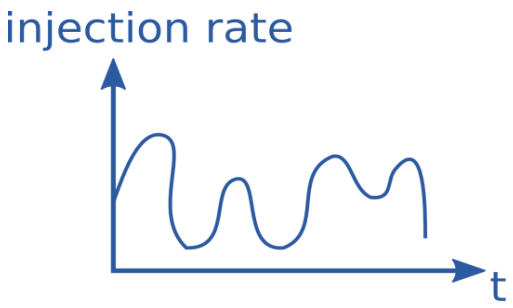
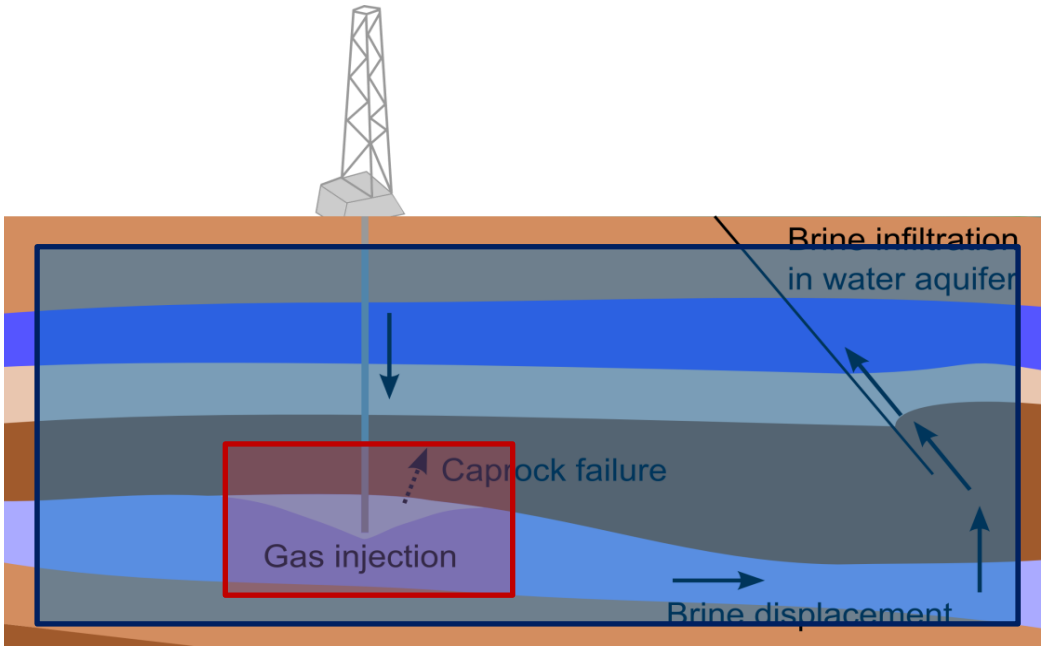
Modeling challenges



Injection

Withdrawal

Fluctuations:
- daily
- weekly
- seasonally



Highly complex

Less complex

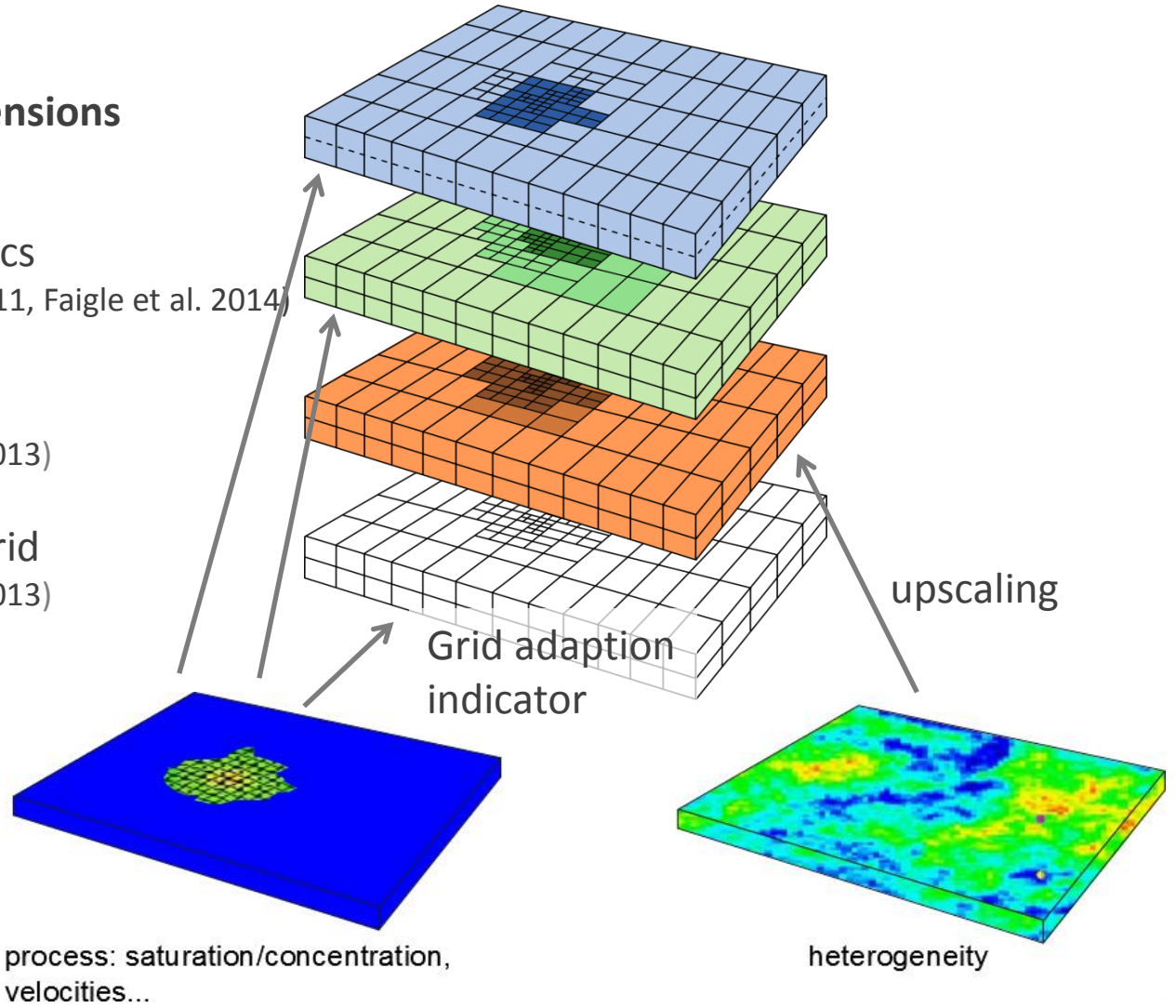
Adaptive modeling: a vision

Multi dimensions

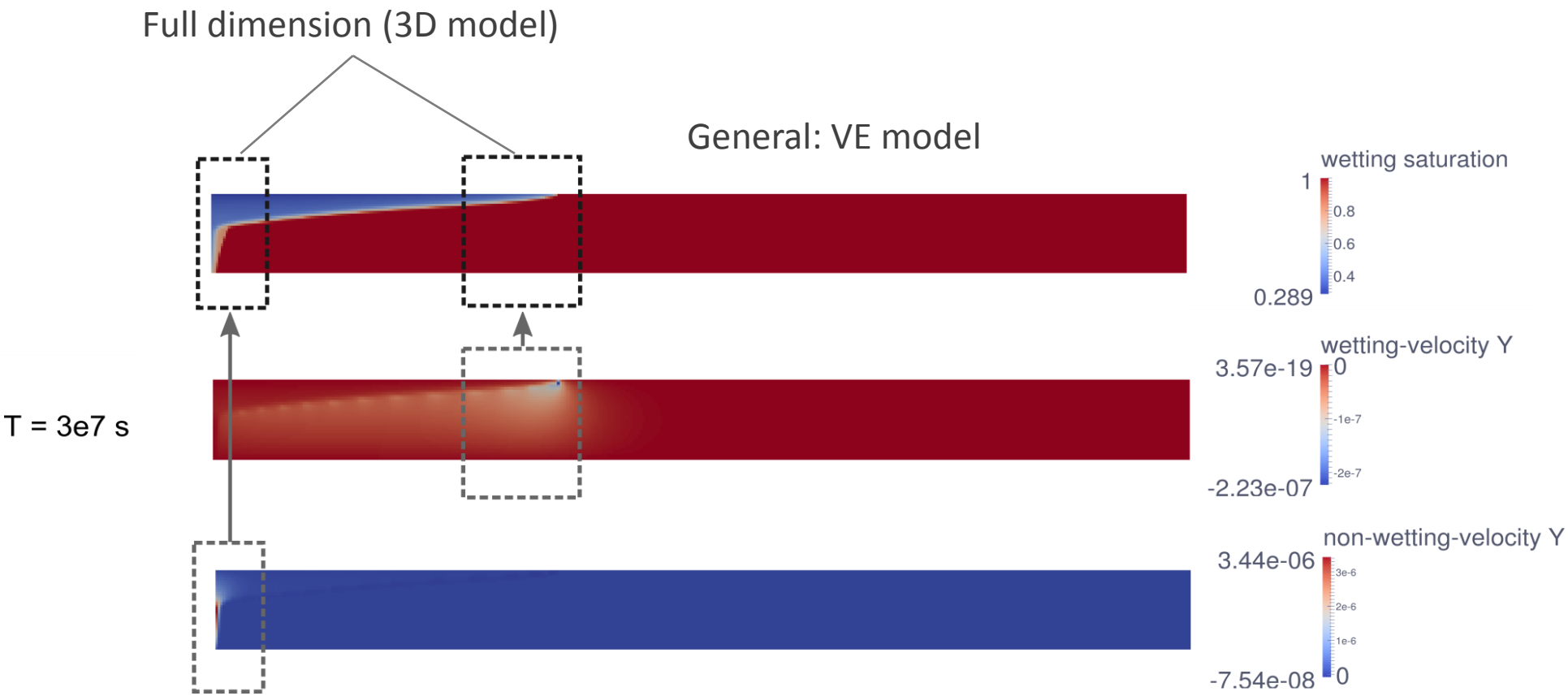
Multi physics
(Fritz et al. 2011, Faigle et al. 2014)

Multi scale
(Wolff et al. 2013)

Adaptive grid
(Wolff et al. 2013)



Coupling of a VE to a 3D model



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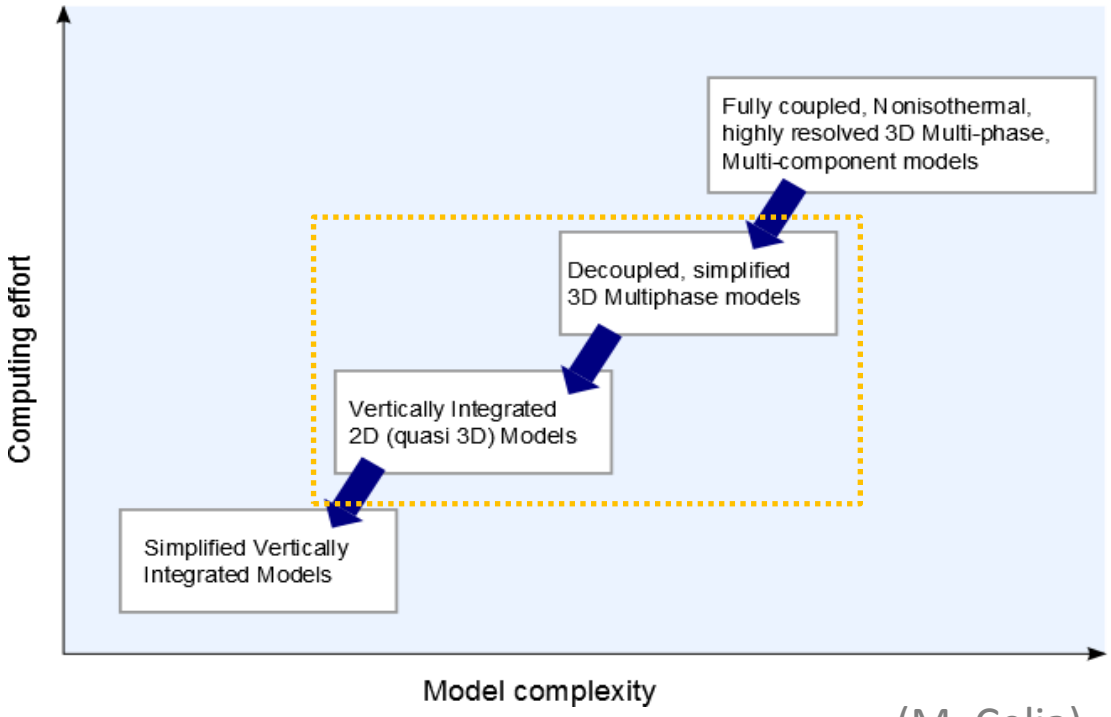
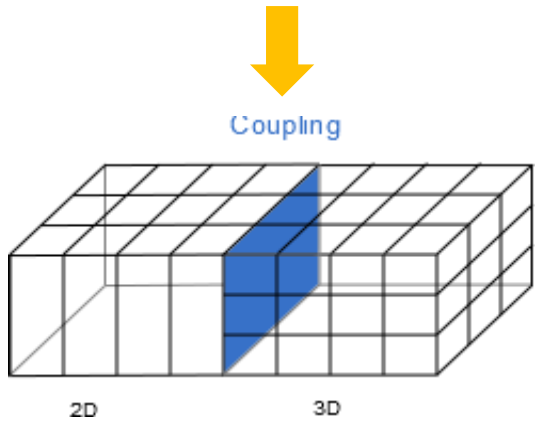
Model complexity and coupling

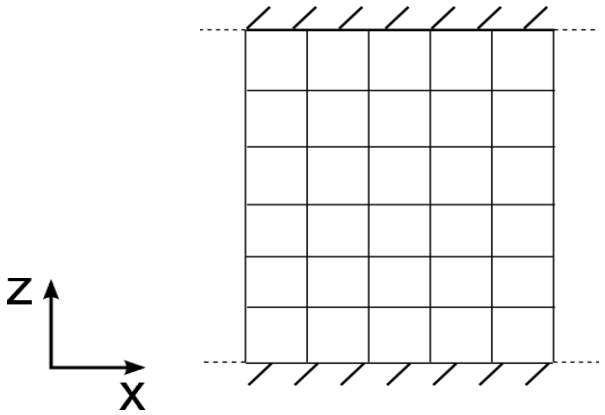


(M. Celia)

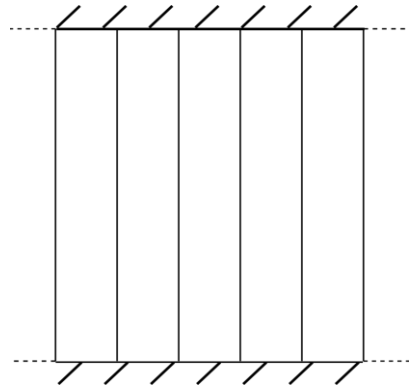


Governing equations

2D



VE



$$\frac{\partial}{\partial t}(\varrho_\alpha \phi s_\alpha) + \nabla \cdot (\varrho_\alpha \boldsymbol{u}_\alpha) = \varrho_\alpha \psi^\alpha$$

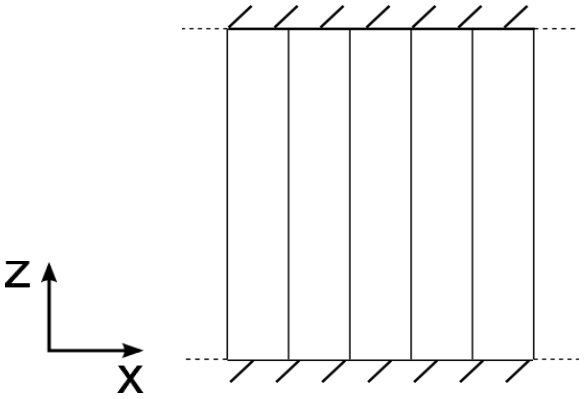
$$\frac{\partial}{\partial t}(\varrho_\alpha \Phi S_\alpha) + \nabla \cdot (\varrho_\alpha \boldsymbol{U}_\alpha) = \varrho_\alpha \Psi^\alpha$$

$$\boldsymbol{u}_\alpha = -\frac{k_{r,\alpha}\boldsymbol{k}}{\mu_\alpha}(\nabla p_\alpha - \varrho_\alpha \mathbf{g})$$

$$\boldsymbol{U}_\alpha = -\mathbf{K}\Lambda_\alpha(\nabla P_\alpha - \varrho_\alpha \mathbf{G})$$

(Nordbotten & Celia, 2012)

Reconstruction



$$\frac{\partial}{\partial t}(\varrho_\alpha \Phi S_\alpha) + \nabla \cdot (\varrho_\alpha \boldsymbol{U}_\alpha) = \varrho_\alpha \Psi^\alpha$$

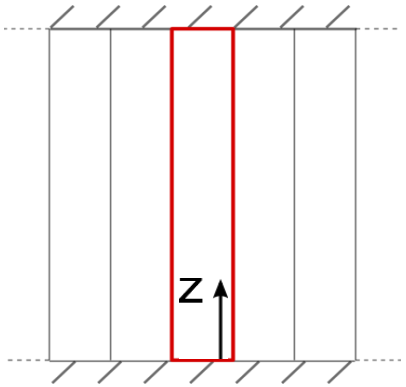
$$\boldsymbol{U}_\alpha = -\mathbf{K}\Lambda_\alpha(\nabla_{||} P_\alpha - \varrho_\alpha \mathbf{G})$$

$$P^{\mathrm{cap}}(S_\alpha)$$

$$\sum S_\alpha = 1$$

$$S_\alpha,\ P_\alpha$$

Static (Dupuit) reconstruction



$$p_\alpha(z) = P_\alpha + \varrho_\alpha(\boldsymbol{g} \cdot \boldsymbol{e}_z)z$$

$$p_c(s_w)^{-1}$$

(Nordbotten & Celia, 2012)

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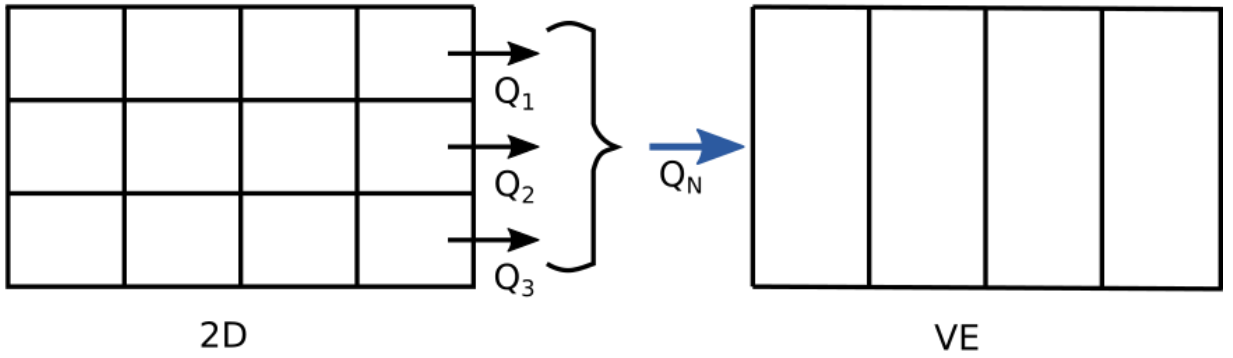
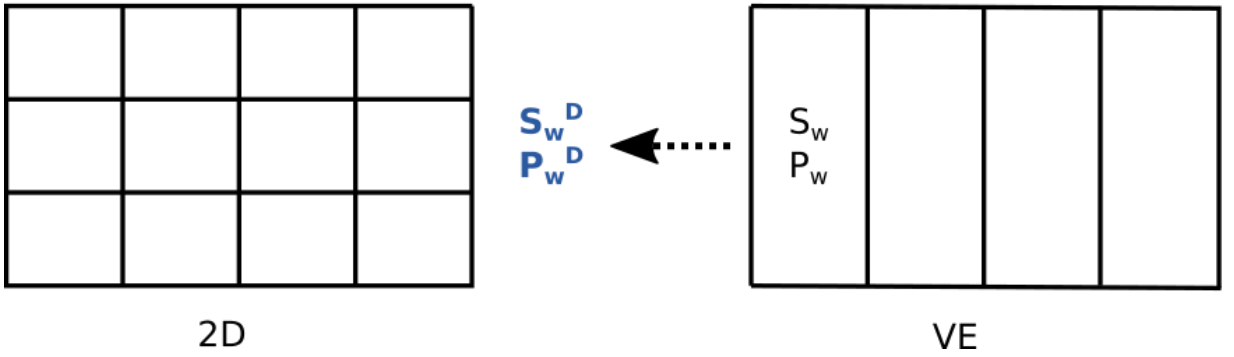
Coupling boundary

Neumann condition for VE-model



Dirichlet condition for FullD-model



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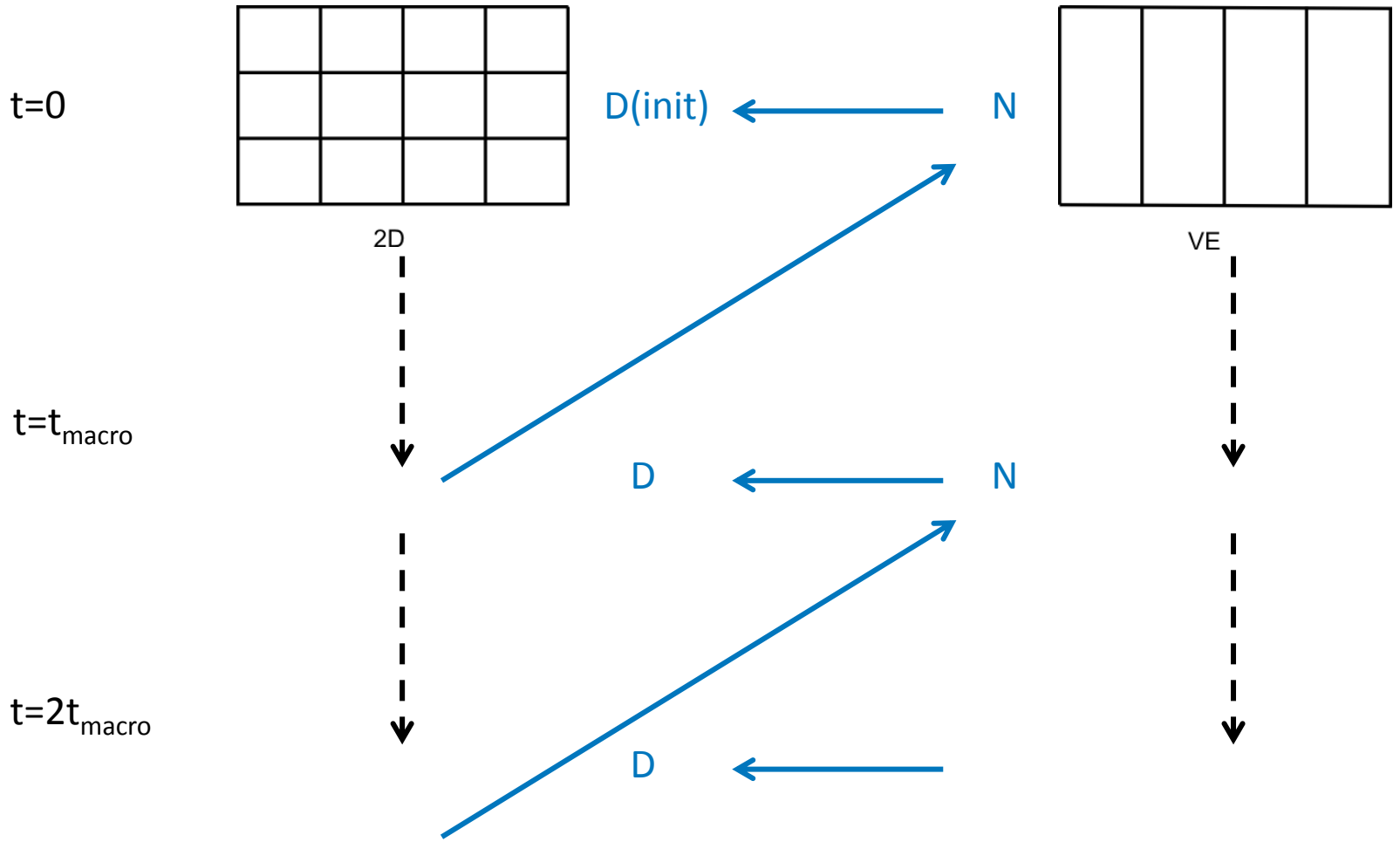
Sequential coupling



How to implement: modelcoupling

One coupling problem:

- init()
- timeIntegration()

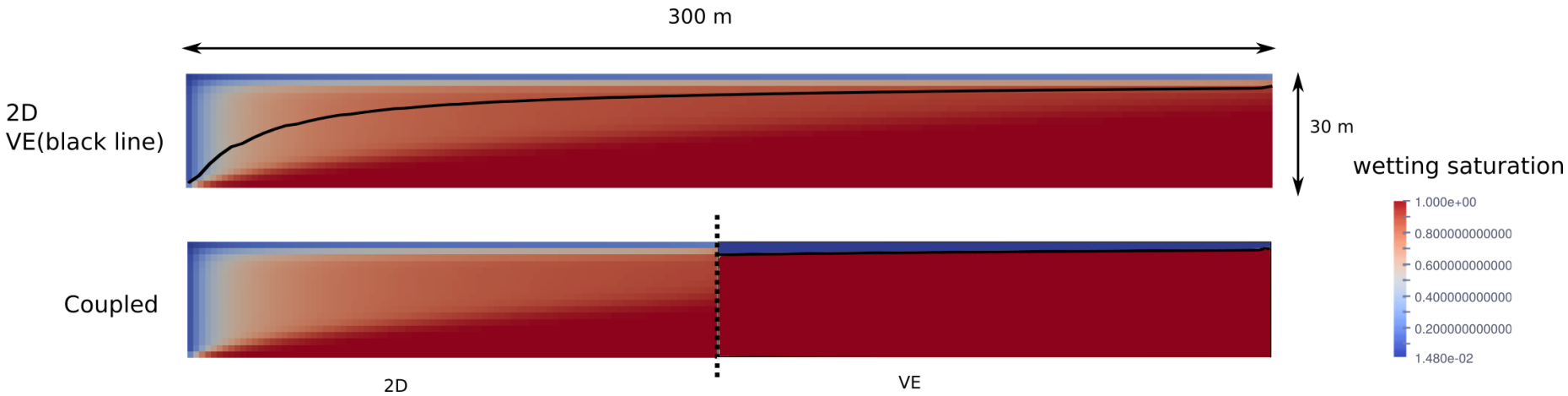
Two sub-problems:

- Need to be able to run in episodes
- Need to be able to give boundary information to the other model
- Need to be able to receive boundary information from the other model

The coupling model

The sub-model

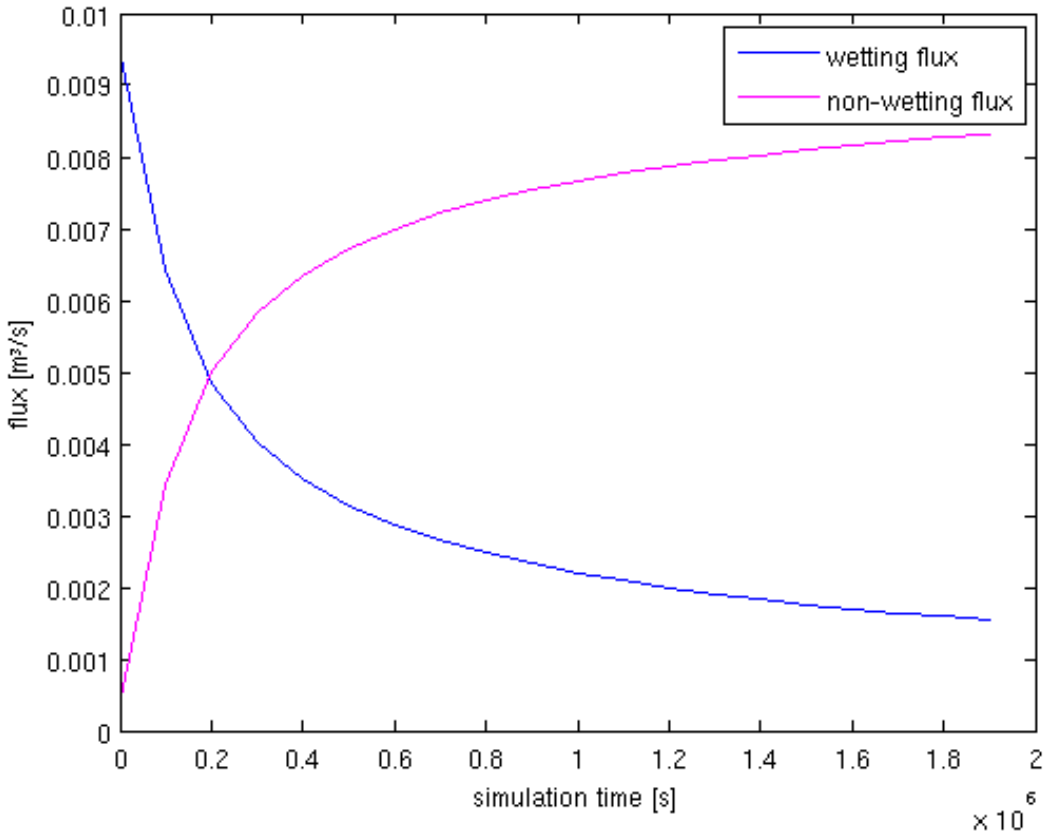
Results: 2D and VE model vs. coupling model



CPU time:

- 2D model: 100%
- VE model: 3%
- Coupled model: 30%

Results: Flux at coupling boundary



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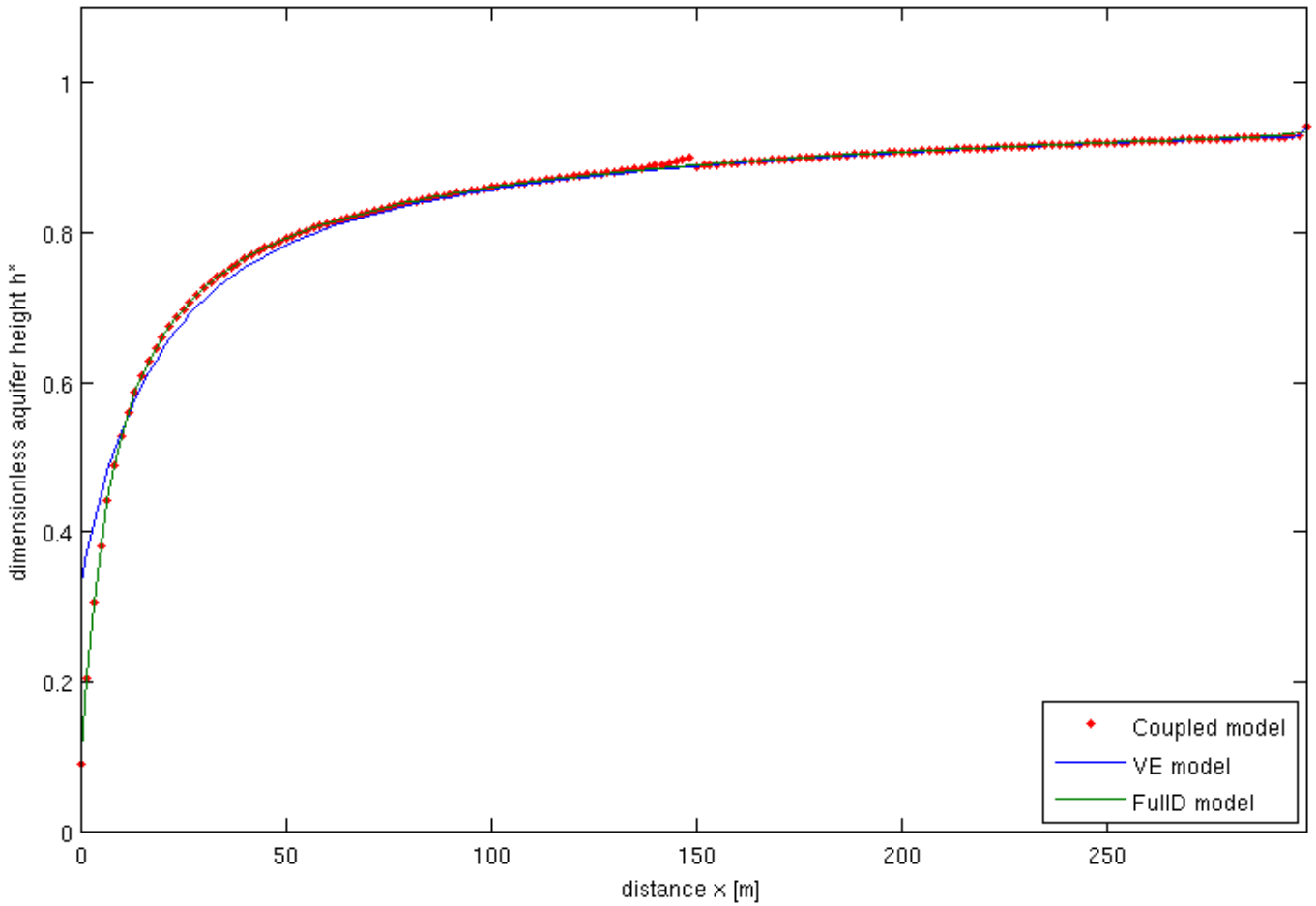
Results: Vertically integrated saturation



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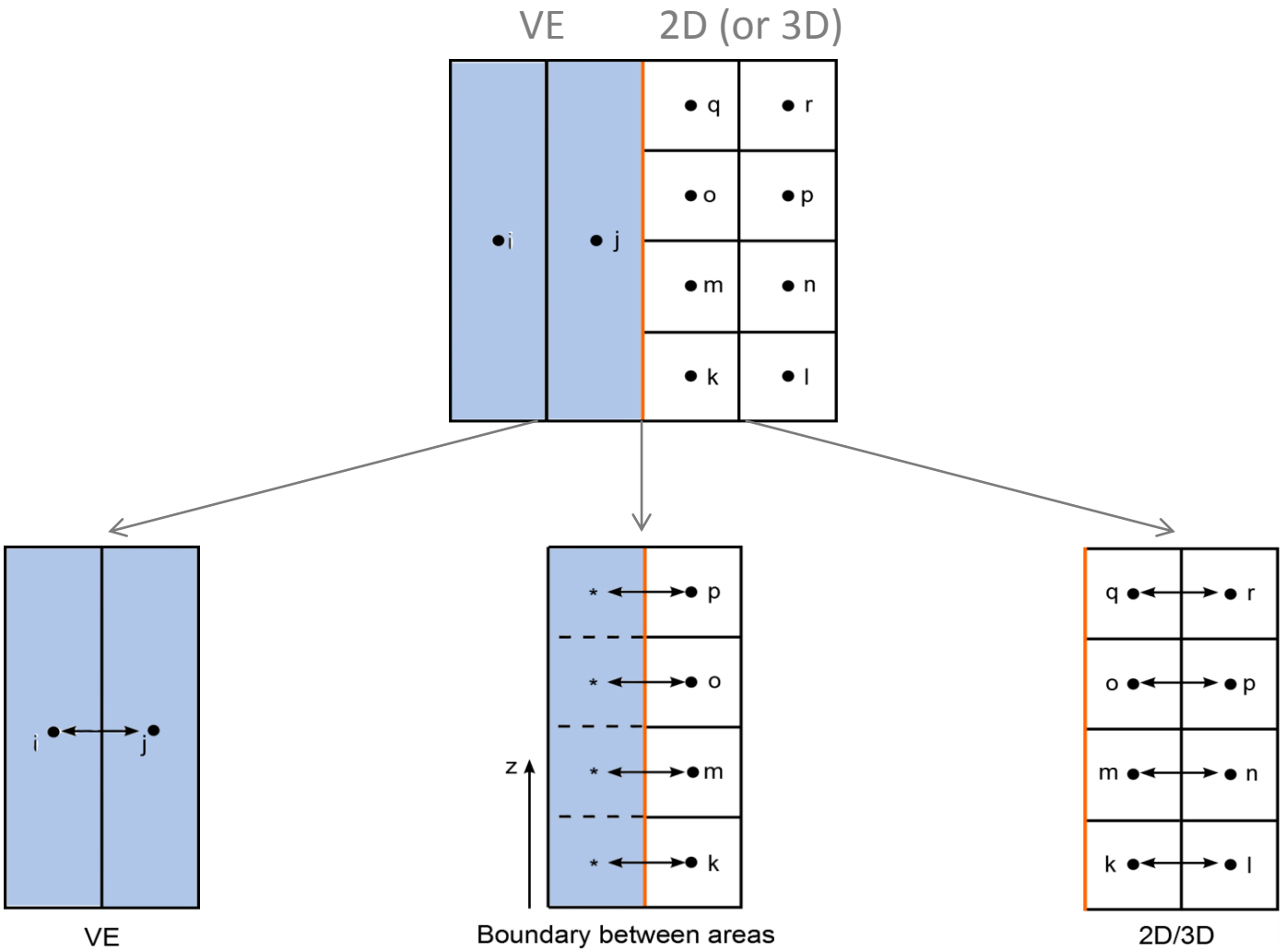
Outlook: Monolithic coupling concept



* Dupuit reconstruction of pressure:

$$p_\alpha(z) = P_{\alpha,j} + \varrho_\alpha(\mathbf{g}\cdot\mathbf{e}_z)z$$

Summary and outlook

First steps:

- Coupling of VE model to Full-D model
- Model switching criteria ➡ adaptive coupling
- In cooperation with Bo Guo and Mike Celia, Princeton University

Including heterogeneity

Including hysteresis (Papafotiou, et al. 2010)

Including multi-physics

References

Faigle, B., Helmig, R., Aavatsmark, I. & Flemisch, B. (2013). Efficient multi-physics modeling with adaptive grid-refinement using a MPFA method. Computational Geoscience, 1-12.

Faigle, B., Elfeel, M. A., Helmig, R., Becker, B., Flemisch, B., & Geiger-Boschung, S. (2014). Multi-physics modeling of non-isothermal compositional flow on adaptive grids. Computer Methods in Applied Mechanics and Engineering.

Guo, B., Bandilla, K. W., Doster, F., Keilegavlen, E. and Celia, M. A. (2014). A vertically integrated model with vertical dynamics for CO2 storage, Water Ressources Research, 50.

Nordbotten, J. M. & Celia, M. A. (2012). Geological Storage of CO2 - Modeling Approaches for Large-Scale Simulation. John Wiley & Sons.

Papafotiou, A., Sheta, H., & Helmig, R. (2010). Numerical modeling of two-phase hysteresis combined with an interface condition for heterogeneous porous media. Computational Geosciences, 14(2), 273-287.

Wolff, M., Flemisch, B. & Helmig, R. (2013). An adaptive multi-scale approach for modeling two-phase flow in porous media including capillary pressure. Water Resources Research, 49(12), 8139–8159.