Statistical Modeling of CO_2 Migration in Layered Systems

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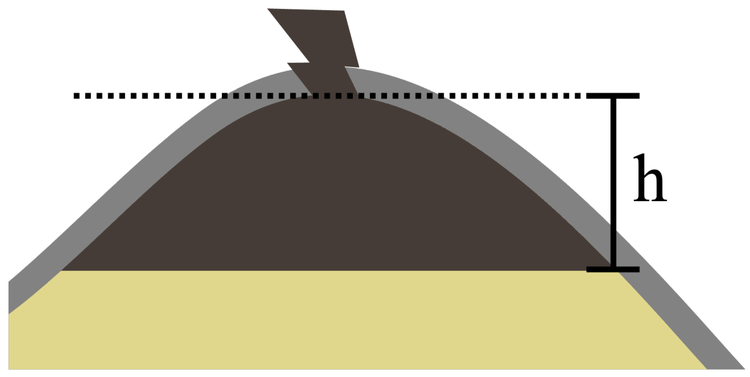
Vertical movement through low-permability layers

- When buoyancy pressure exceeds the capillary threshold of the overlying layer.
- Pressure increases with column height and density contrast between CO_2 and brine.
- Residual trapping in each layer reduces further upward transportation.



Assessing uncertainty through Monte Carlo simulations

- Randomly sample layer geometries and capillary thresholds, then simulate the CO_2 flow.
- Perform multiple repetitions to capture variability, requiring efficient models.
- Callioli Santi et al. (2025) describe migration as a Markov process between layers.

Simulation with nearest-neighbor approach

- Simple representation where where cells are filled or unfilled.
- Implemented in Rust, simulating the filling of **25 million cells** takes **6.2 seconds** on a single CPU core.

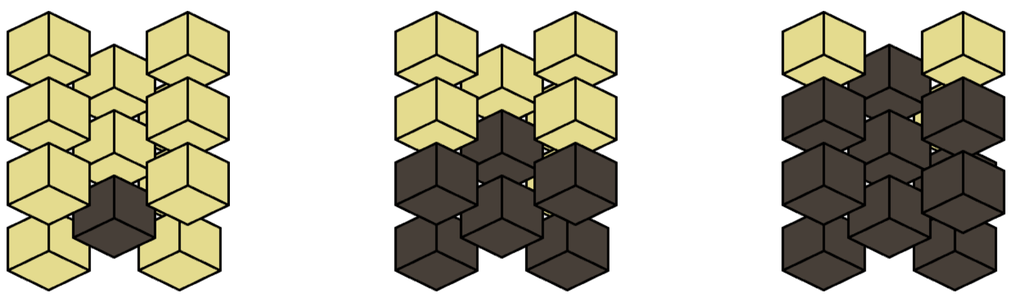
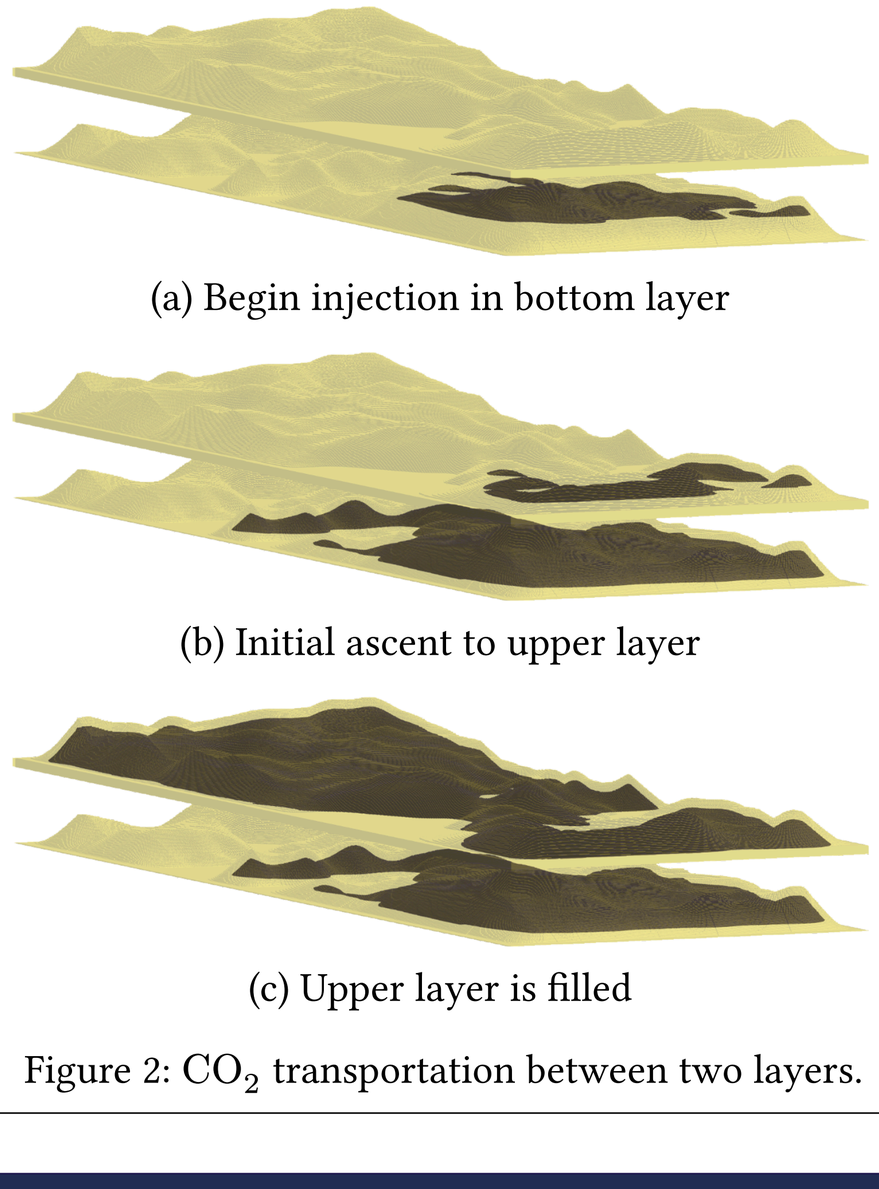
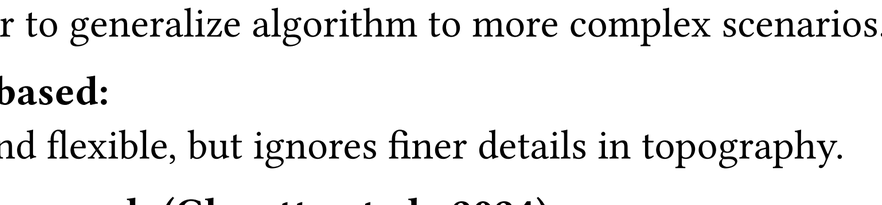


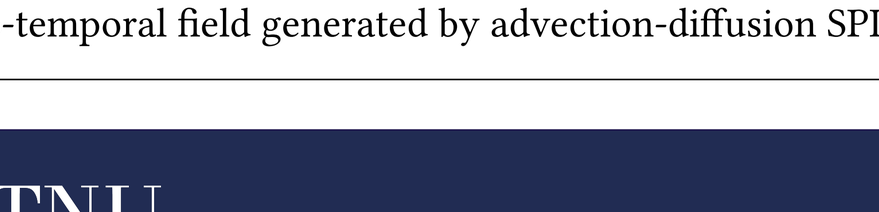
Figure 1: Filling nearest empty neighbors.



(a) Begin injection in bottom layer



(b) Initial ascent to upper layer



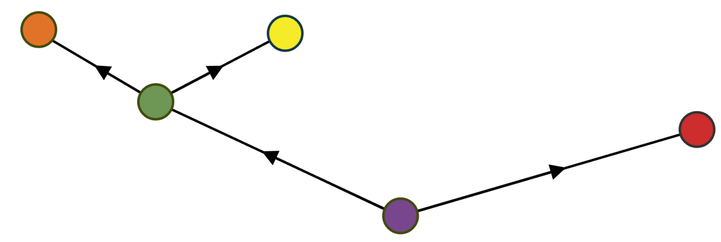
(c) Upper layer is filled

Figure 2: CO_2 transportation between two layers.

Simulation with graph-based approach

- Representing the caprock topography as a directed graph.
- Inspired by concepts in water management like drainage areas and waterway networks.

(a) Cross-section marking local and global traps



(b) Graph representation

Figure 3: Representing traps as nodes in a graph.

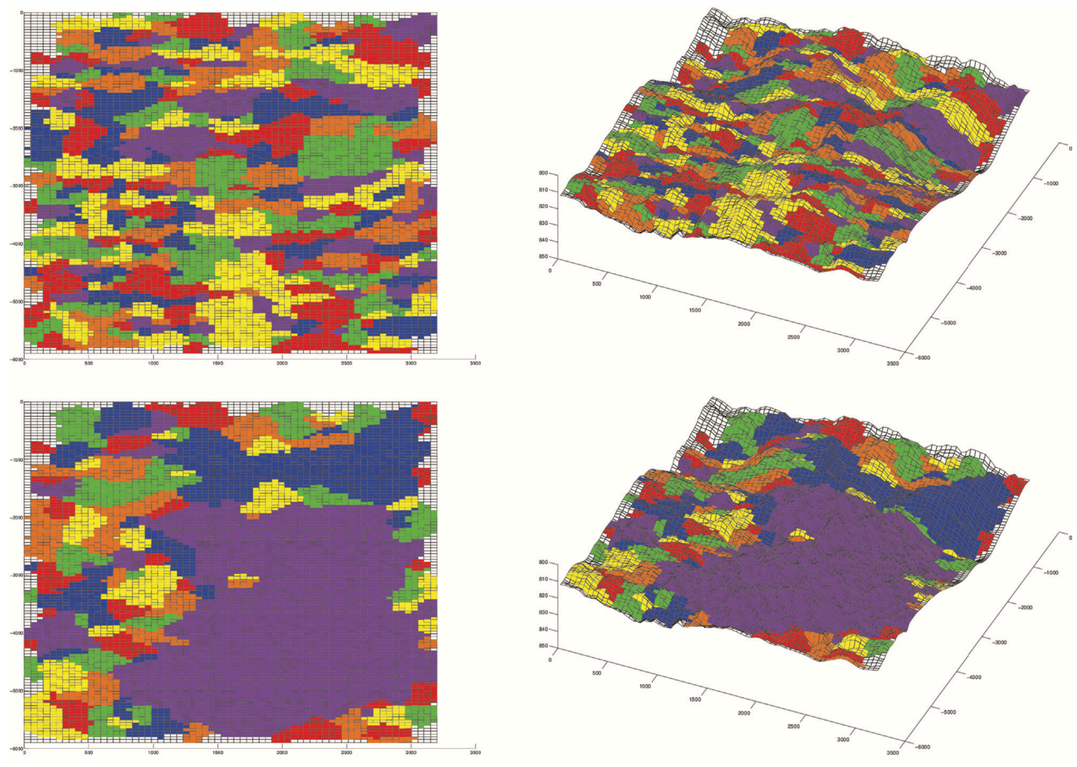


Figure 4: Figure from `MRST-co2lab` (Møll Nilsen et al., 2015).

Outlook and future work

Nearest-neighbor:

- Harder to generalize algorithm to more complex scenarios.

Graph-based:

- Fast and flexible, but ignores finer details in topography.

SPDE-approach (Clarotto et al., 2024):

- Spatio-temporal field generated by advection-diffusion SPDE.

Bibliography

Callioli Santi, A., Ringrose, P., Eidsvik, J., Haugdahl, T.A., 2025. Invasion percolation Markov Chains – A probabilistic framework for assessing vertical CO2 migration. International Journal of Greenhouse Gas Control 142, 104338.. https://doi.org/10.1016/j.ijggc.2025.104338

Clarotto, L., Allard, D., Romary, T., Desassis, N., 2024. The SPDE approach for spatio-temporal datasets with advection and diffusion [WWW Document].. https://doi.org/10.48550/arXiv.2208.14015

Møll Nilsen, H., Lie, K.-A., Møyner, O., Andersen, O., 2015. Spill-point analysis and structural trapping capacity in saline aquifers using MRST-co2lab. Computers & Geosciences 75, 33–43.. https://doi.org/10.1016/j.cageo.2014.11.002