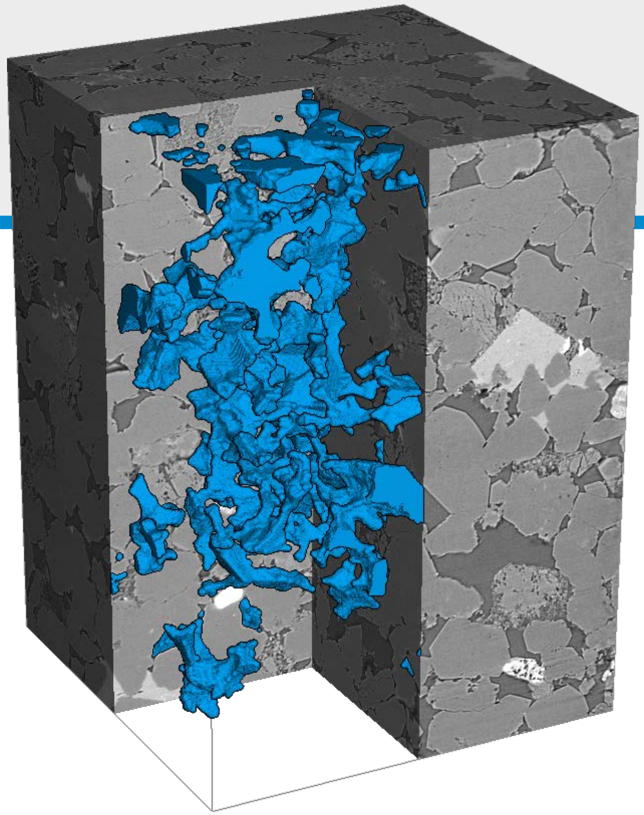
Recent Improvements to the Pore-Morphology Method for Capillary Pressure and Relative Permeability Simulations



GeoCT Workshop

University of Bremen

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Jens-Oliver Schwarz

Erik Glatt

MATH
2 MARKET

Math2Market GmbH
Founding

The Math2Market GmbH is a society of limited liability.

Formerly a group of the department Flow and Material Simulations (SMS) of the Fraunhofer Institute for Industrial Mathematics, ITWM, we spun-off on September 21st, 2011, to become Math2Market GmbH.

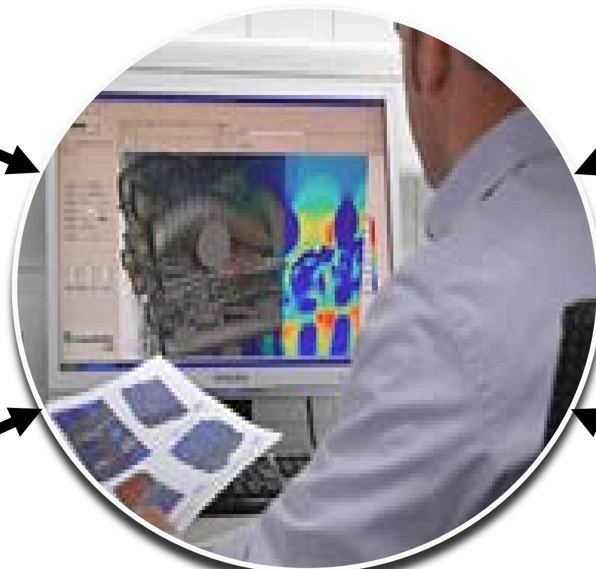
Math2Market GmbH is privately owned by

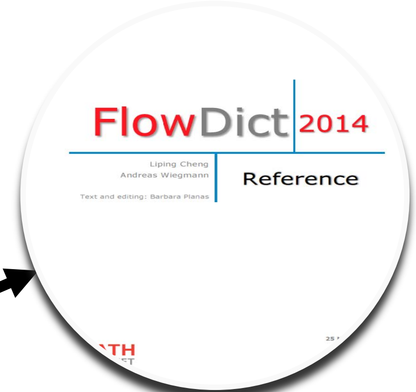
- 3 operative founders, formerly at Fraunhofer ITWM
- 2 separate owners

Services provided to our clients

Software

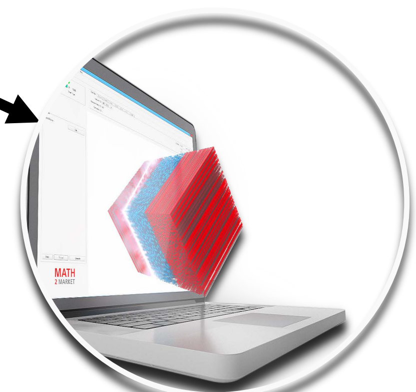
User





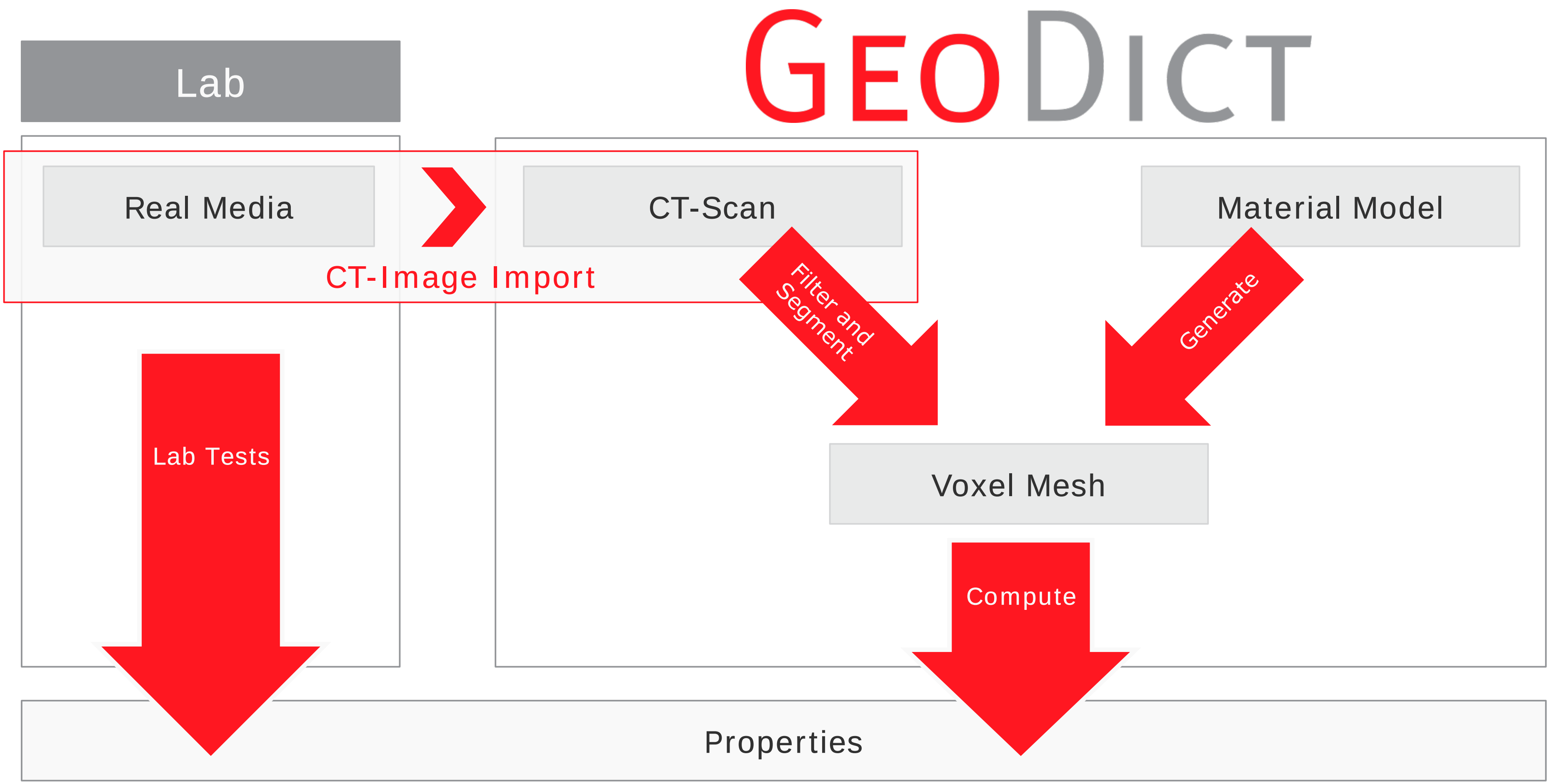
User manual

Support & Training



Consulting & Projects

Material Characterization & Engineering



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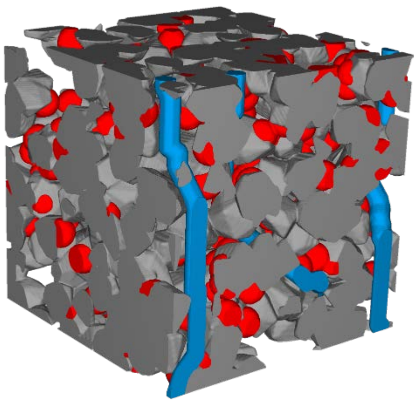
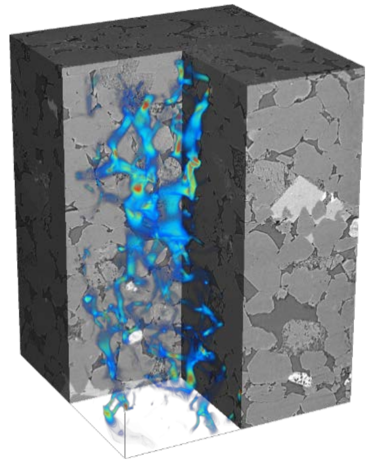
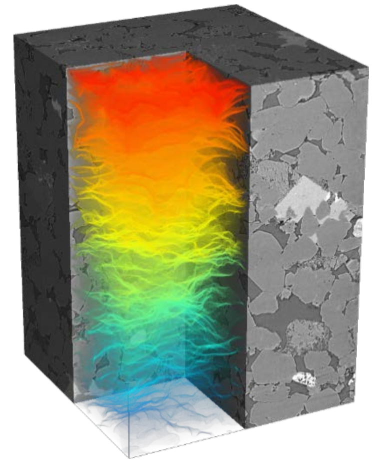
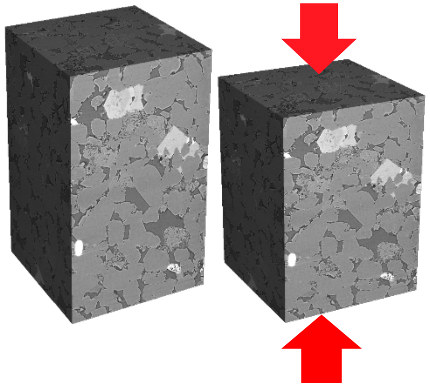
Digital Rock Physics Portfolio









Geometrical parameters	Flow parameters	Electrical Parameters	Mechanical parameters
▪ Porosity	▪ Absolute permeability	▪ Formation factor	▪ Elastic moduli
▪ Pore size distribution	▪ Multi-scale flow	▪ Resistivity index	▪ Stiffness
▪ Percolation	▪ Two-phase flow	▪ Saturation exponent	▪ In-Situ conditions
▪ Surface area	▪ Relative permeability	▪ Cementation exponent	
▪ Tortuosity	▪ Cap. pressure curve		

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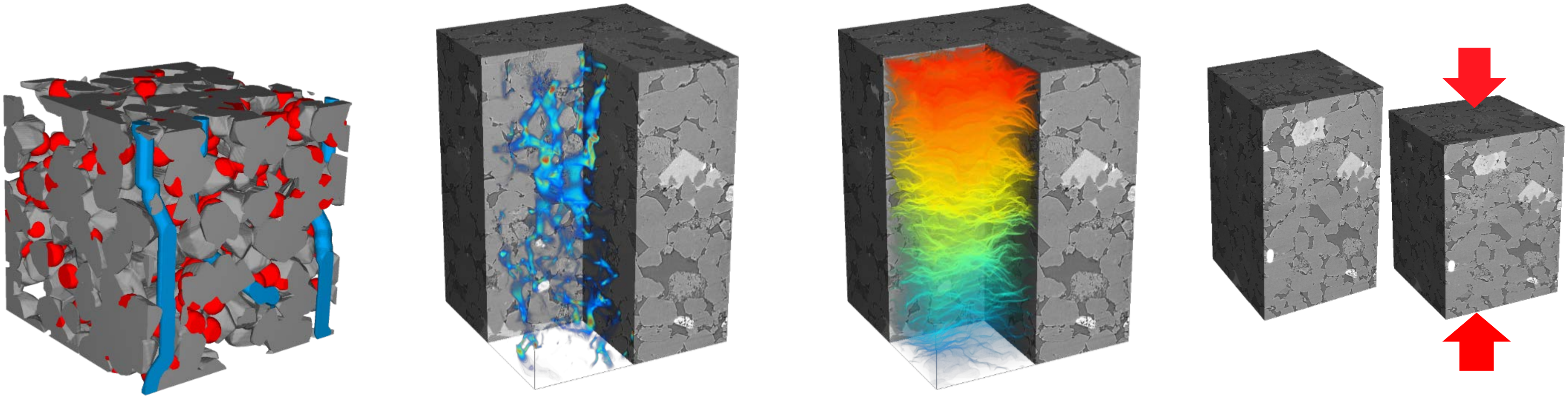
Digital Rock Physics Portfolio



Geometrical parameters	Flow parameters	Electrical Parameters	Mechanical parameters
▪ Porosity ▪ Pore size distribution ▪ Percolation ▪ Surface area ▪ Tortuosity	▪ Absolute permeability ▪ Multi-scale flow ▪ Two-phase flow ▪ Relative permeability ▪ Cap. pressure curve	▪ Formation factor ▪ Resistivity index ▪ Saturation exponent ▪ Cementation exponent	▪ Elastic moduli ▪ Stiffness ▪ In-Situ conditions

Two Phase Flows

- **Two-phase flow**
  - “In fluid mechanis, two-phase flow occurs in a system containing gas and liquid with a meniscus separating the two phases.” [Wiki]
  - One fluid wets the surface, the less affinity is non-wetting
  - SatuDict uses the **Pore Morphology method** to determine the distribution of the two phases inside the porous media.
- **Here**
  - Imbibition:
    - **wetting fluid** displaces **non-wetting fluid**
  - Drainage:
    - **non-wetting fluid** displaces **wetting fluid**

Capillary Pressure

Young – Laplace equation

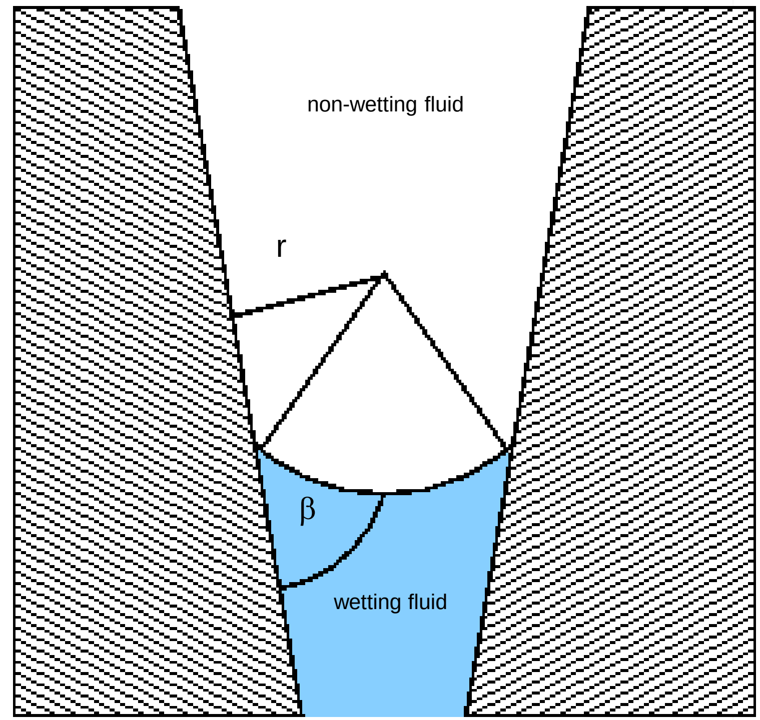
- Describes the capillary pressure difference across interfaces between two fluids
- Relates pressure difference to the shape of the surface

$$p_c = \gamma \, div \, \vec{n}$$
$$= 2\,\gamma H$$
$$= \gamma(\kappa_1 + \kappa_2)$$
$$= \gamma\left(\frac{1}{r_1} + \frac{1}{r_2}\right)$$

Assumption: cylindrical pores with radius r

$$p_c = \frac{2\gamma \cos\beta}{r}$$

capillary pressure ⇔ pore radius



β: contact angle

Pore Morphology Method
Basic Idea

Use this relation between pore size and capillary pressure to predict the distribution of the phases

Advantage:

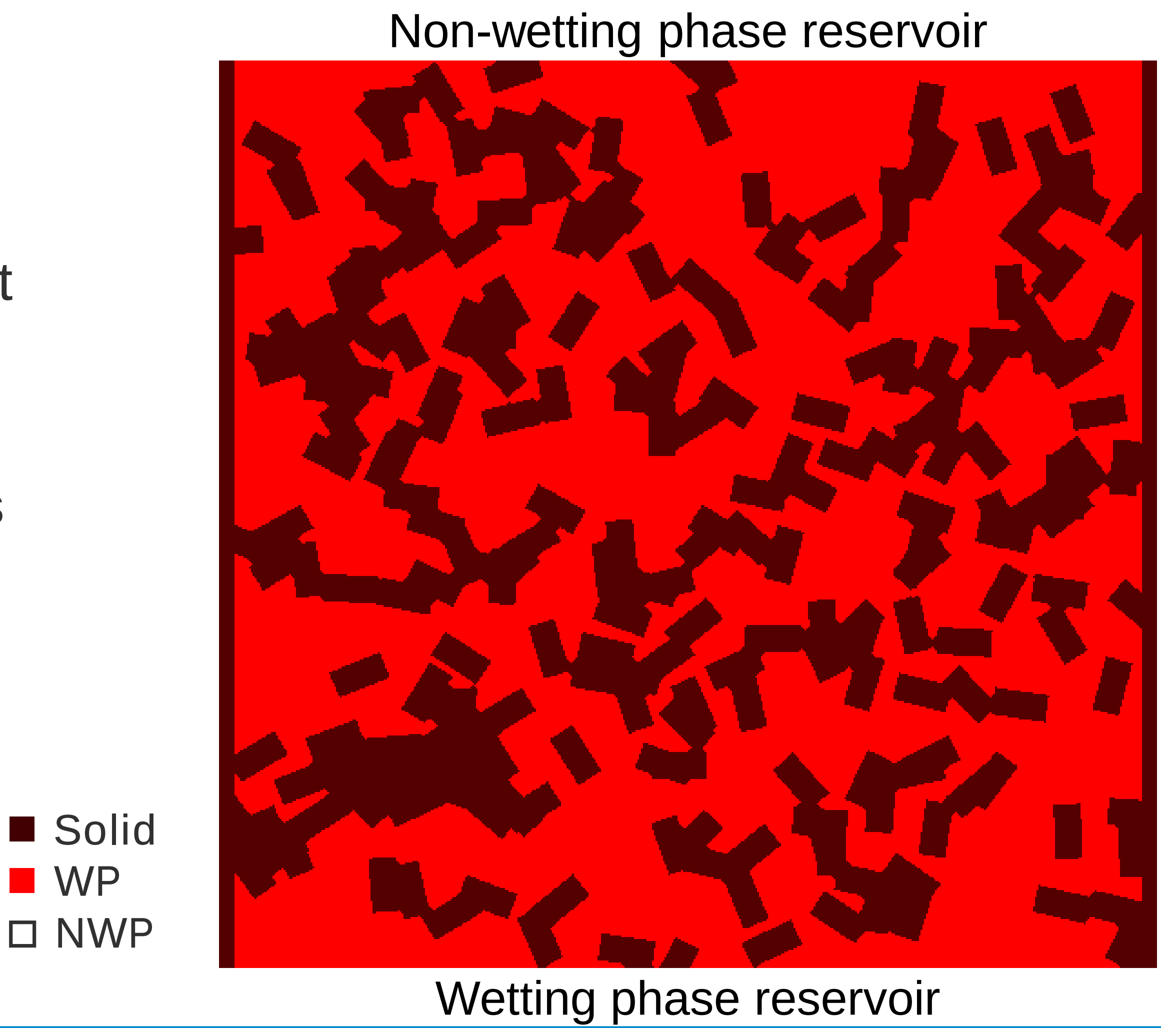
- No partial differential equation (PDE) is solved
- Purely geometrical operations
- Very low runtime and memory requirements

Assumption:

- Quasi-stationary phase distribution
- Cylindrical pores

Drainage I
non-wetting displaces wetting phase

- Connectivity of NWP to reservoir
- Move in spheres
  - Start: completely wet
  - Start: large radius (i.e. small p_c)
  - Steps: smaller radius (higher p_c)
- No residual WP



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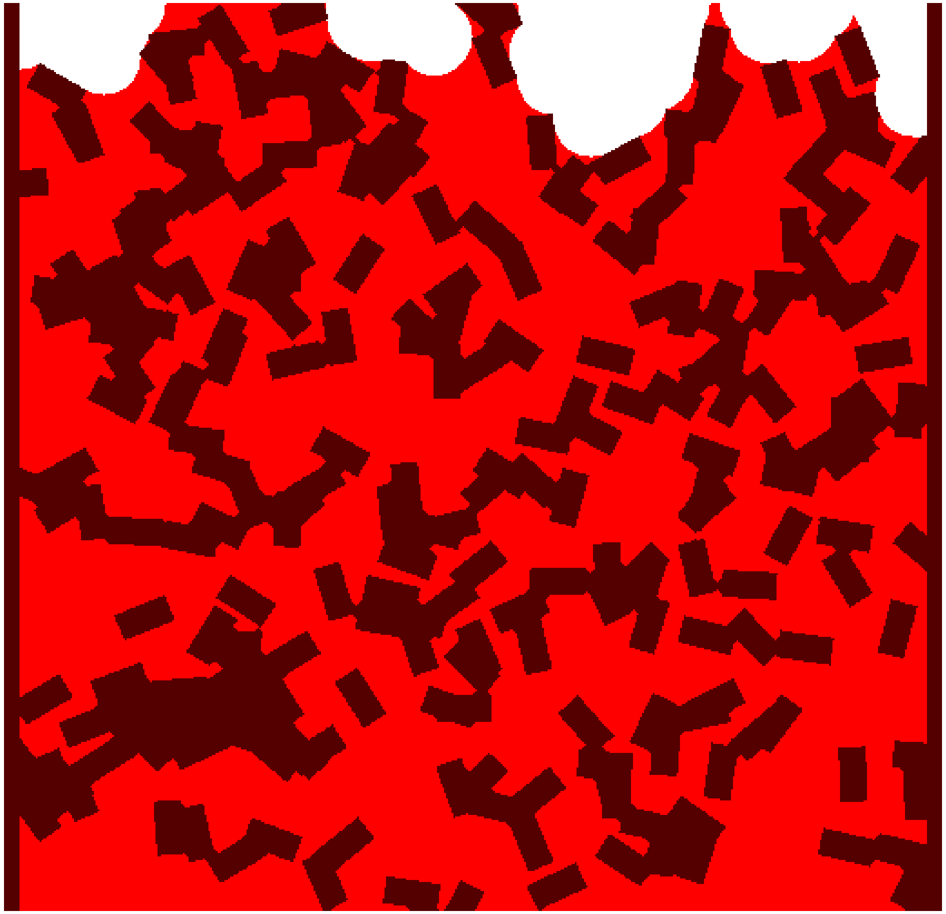
Solid
WP
NWP

Non-wetting phase reservoir



Wetting phase reservoir

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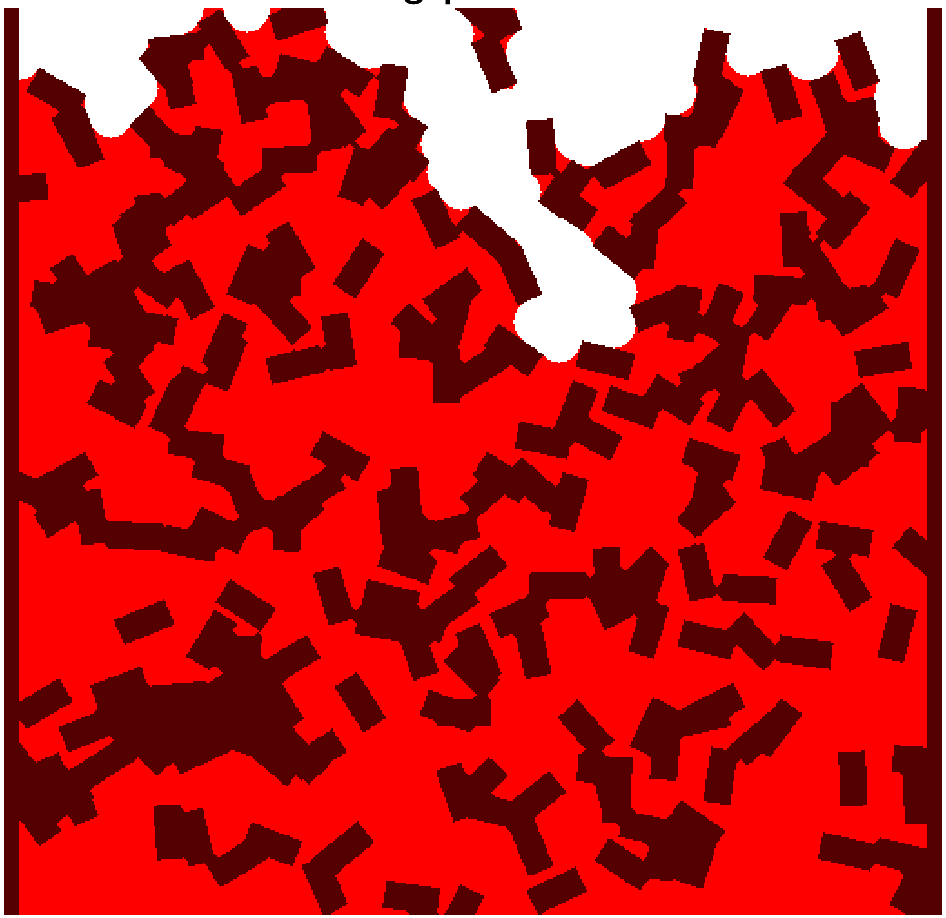

Wetting phase reservoir

■ Solid
■ WP
□ NWP

Drainage I
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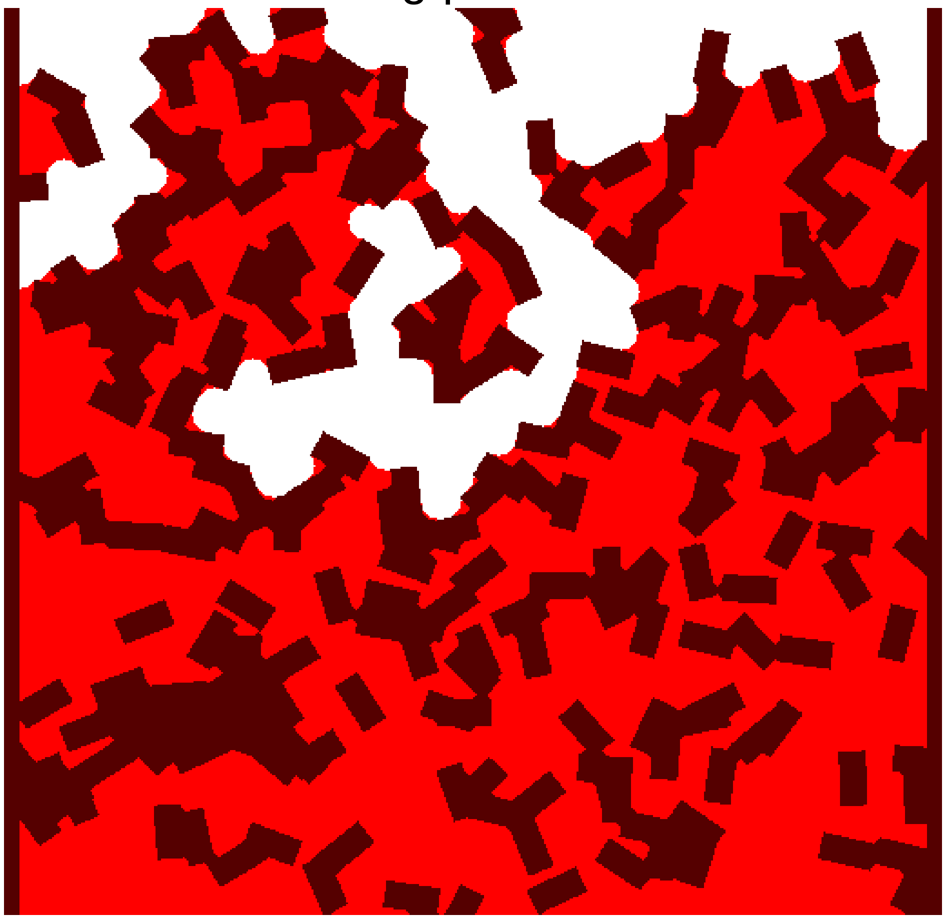

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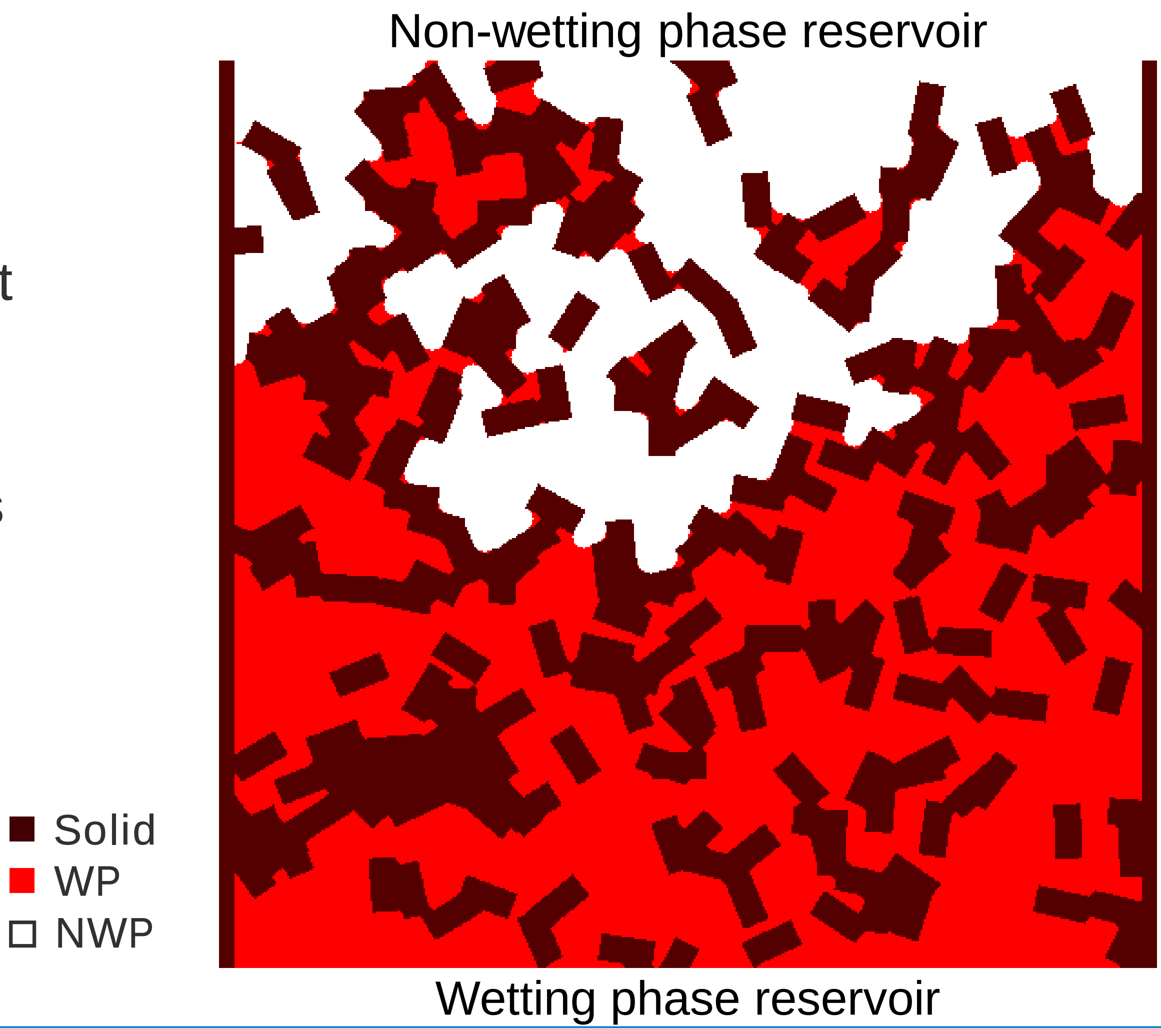

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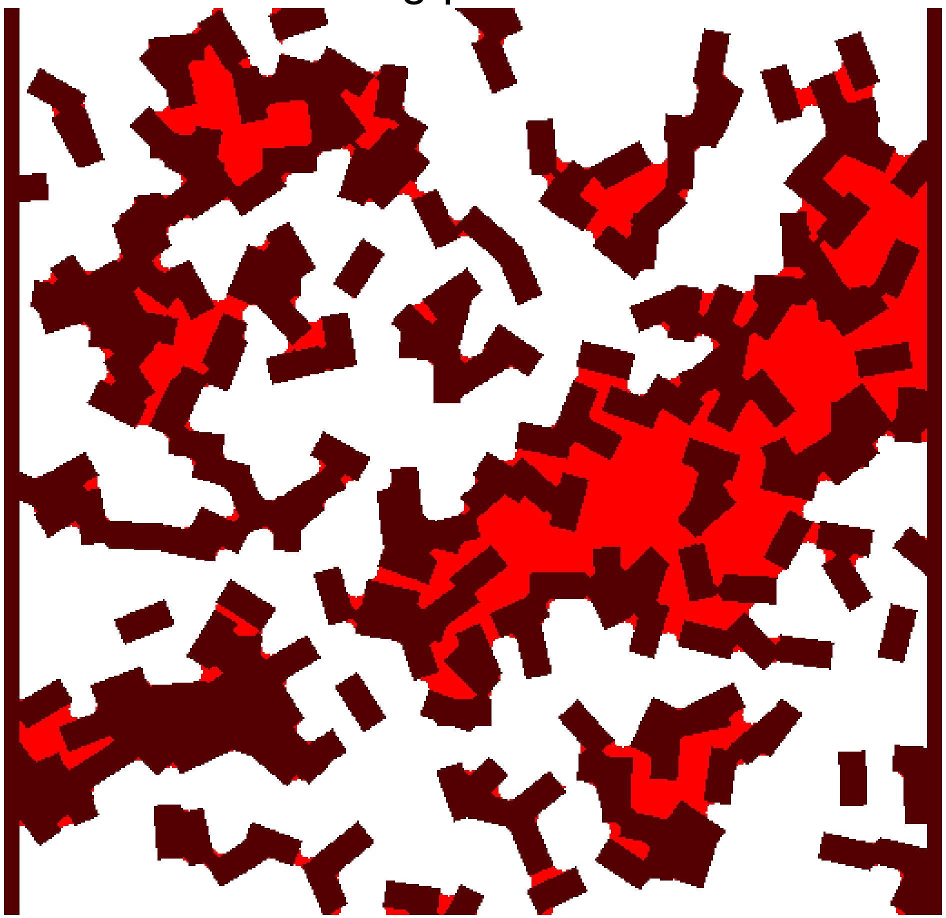

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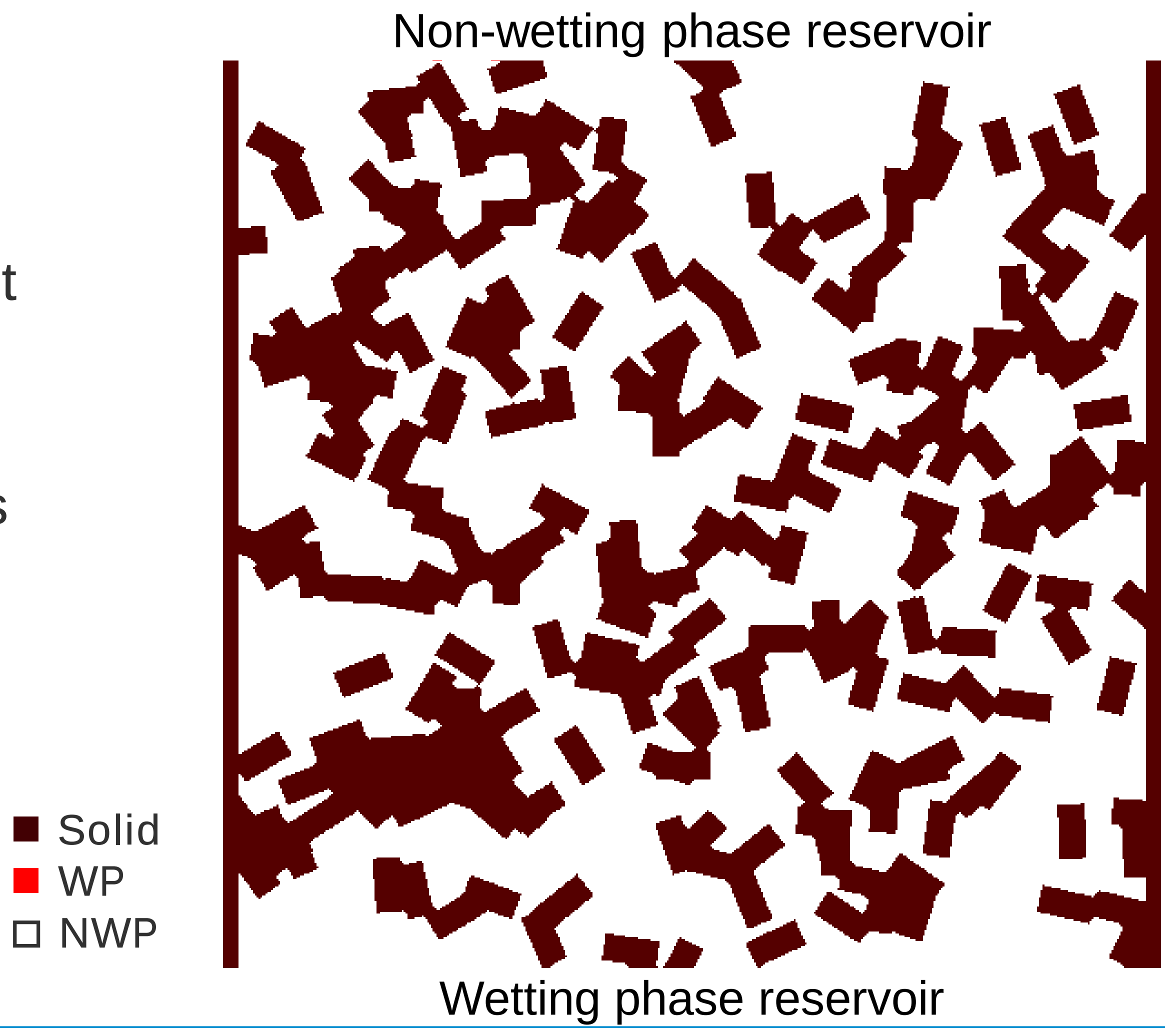
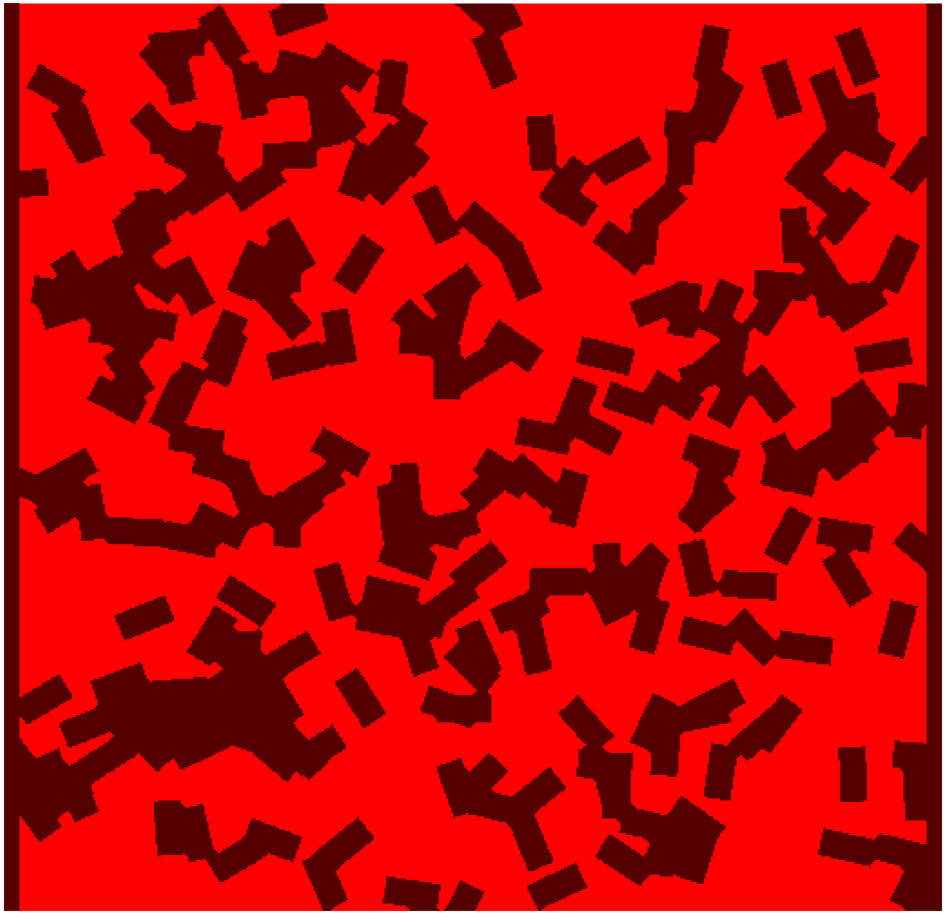


Drainage II
non-wetting displaces wetting phase

- Ahrenholz et al. 2008
- WP must be connected to reservoir
- Residual WP (orange)

Non-wetting phase reservoir



Wetting phase reservoir

■ Solid
■ WP
■ Res. WP
□ NWP

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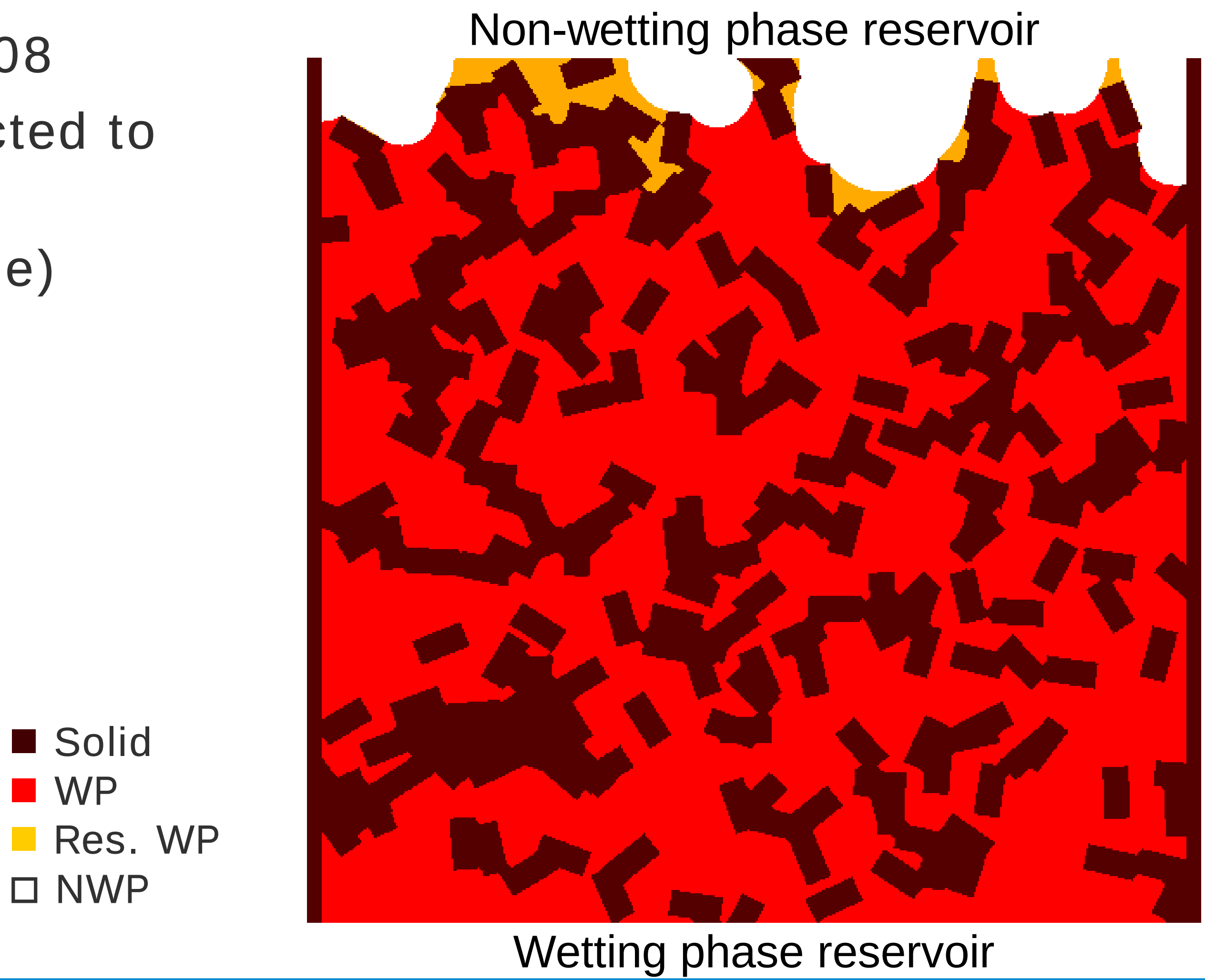

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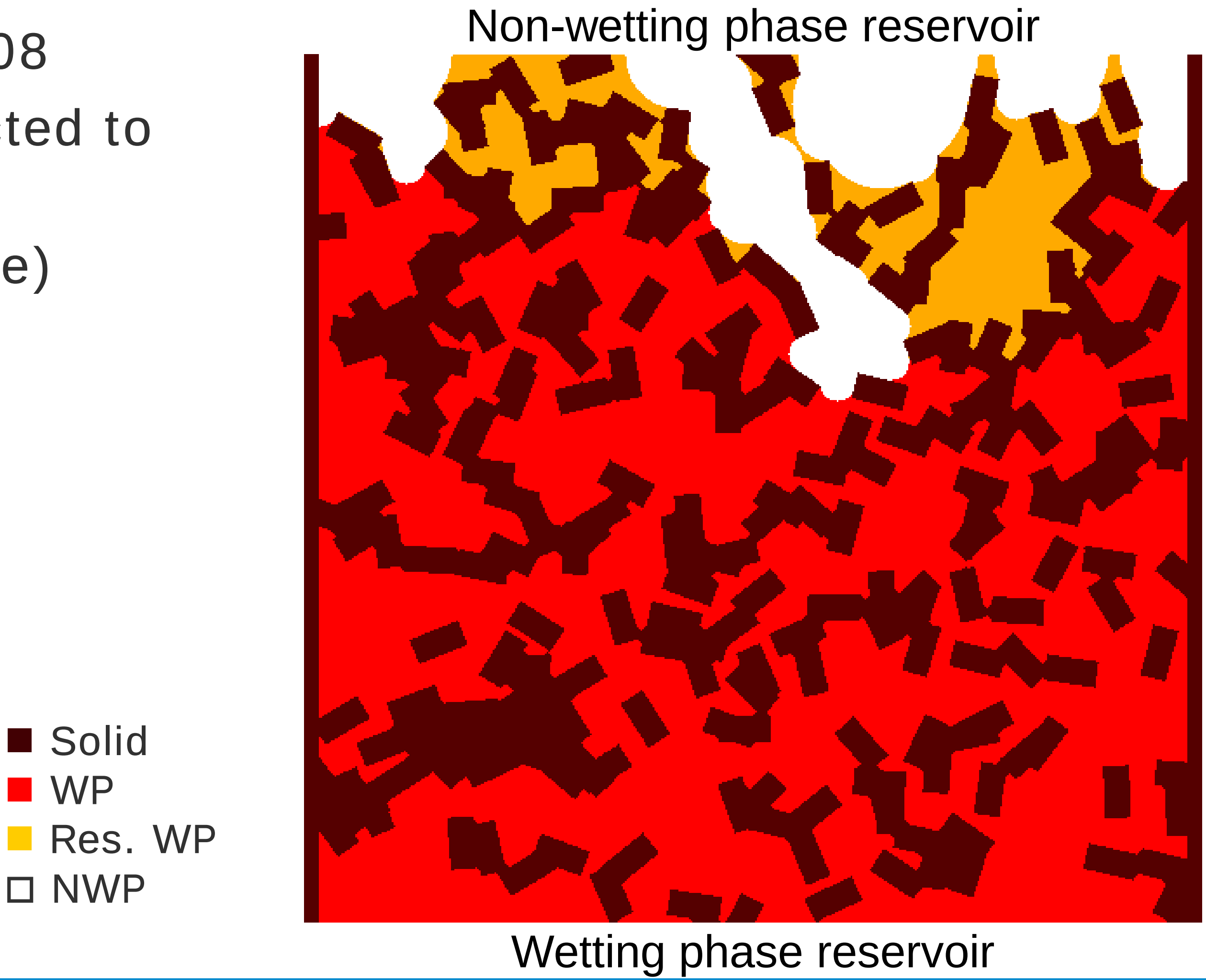

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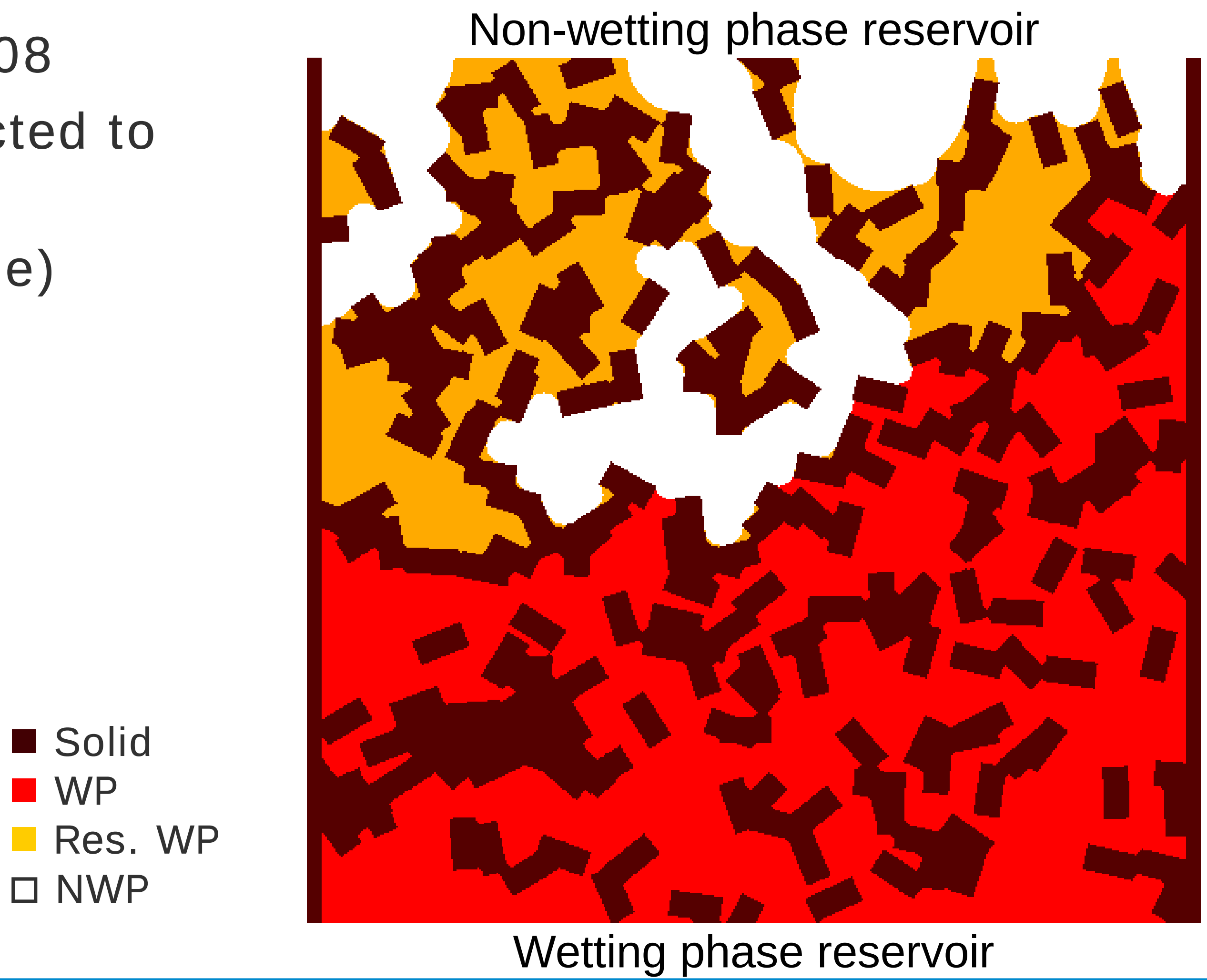

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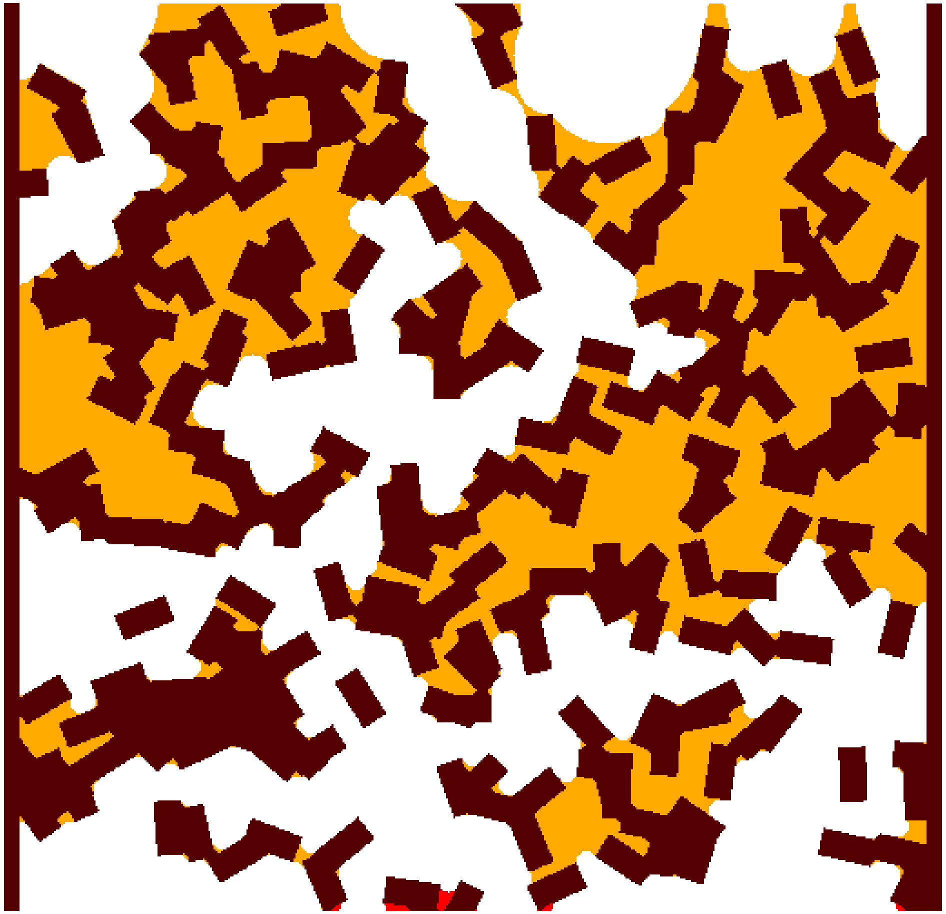
Non-wetting phase reservoir



Wetting phase reservoir

■ Solid
■ WP
■ Res. WP
□ NWP

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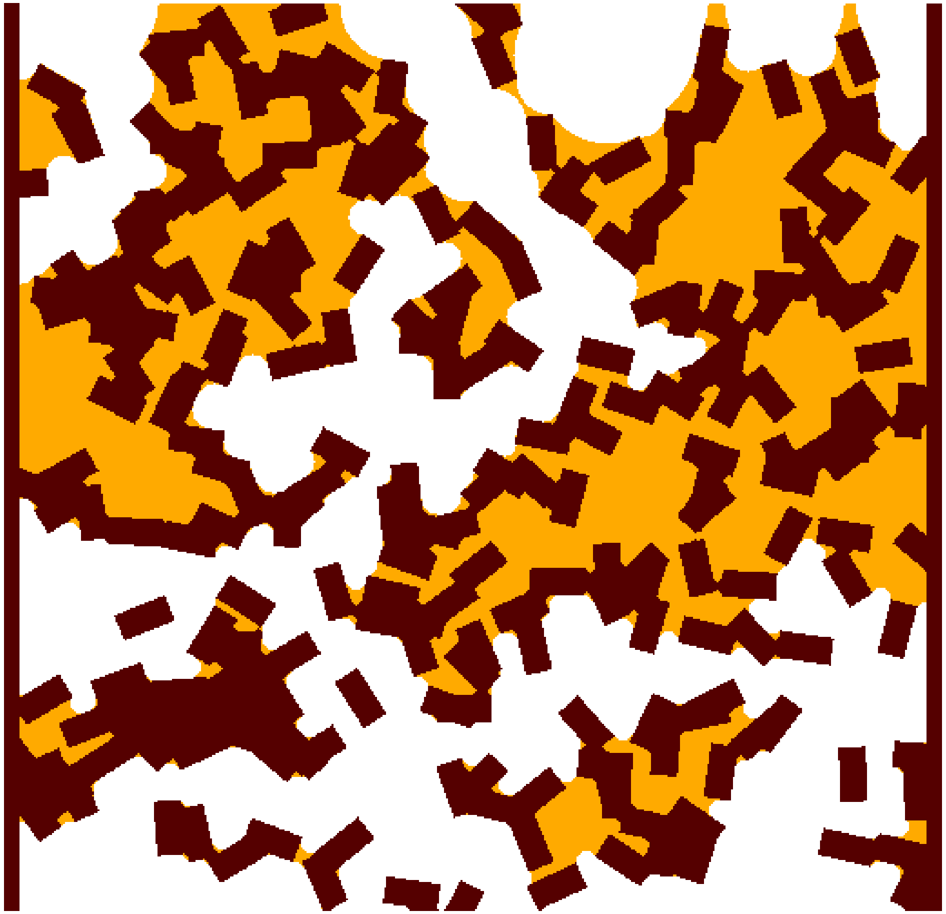
Non-wetting phase reservoir



Wetting phase reservoir

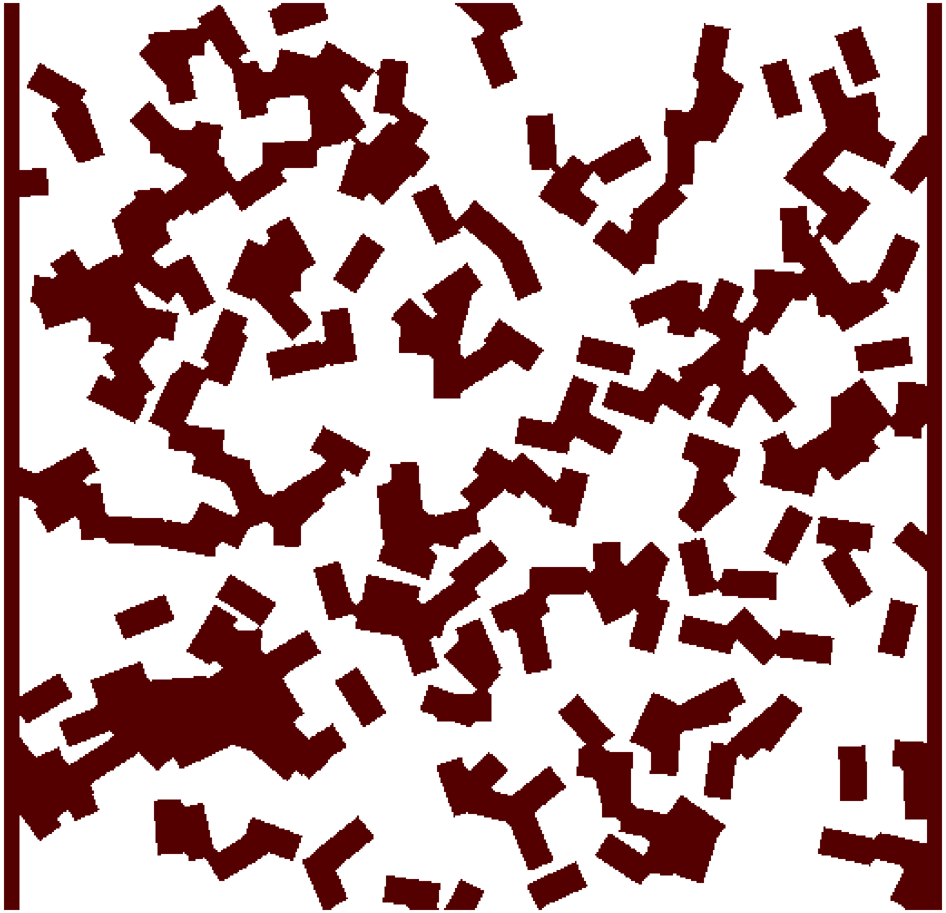
- Solid
- WP
- Res. WP
- NWP

Imbibition III
wetting displaces non-wetting phase

- WP must be connected to reservoir
- NWP must be connected to NWP reservoir
- Move out spheres
  - Start: completely dry
  - Start: small radius (i.e. large p_c)
  - Steps: larger radius (smaller p_c)

Solid
WP
NWP
Res. NWP

Non-wetting phase reservoir



Wetting phase reservoir

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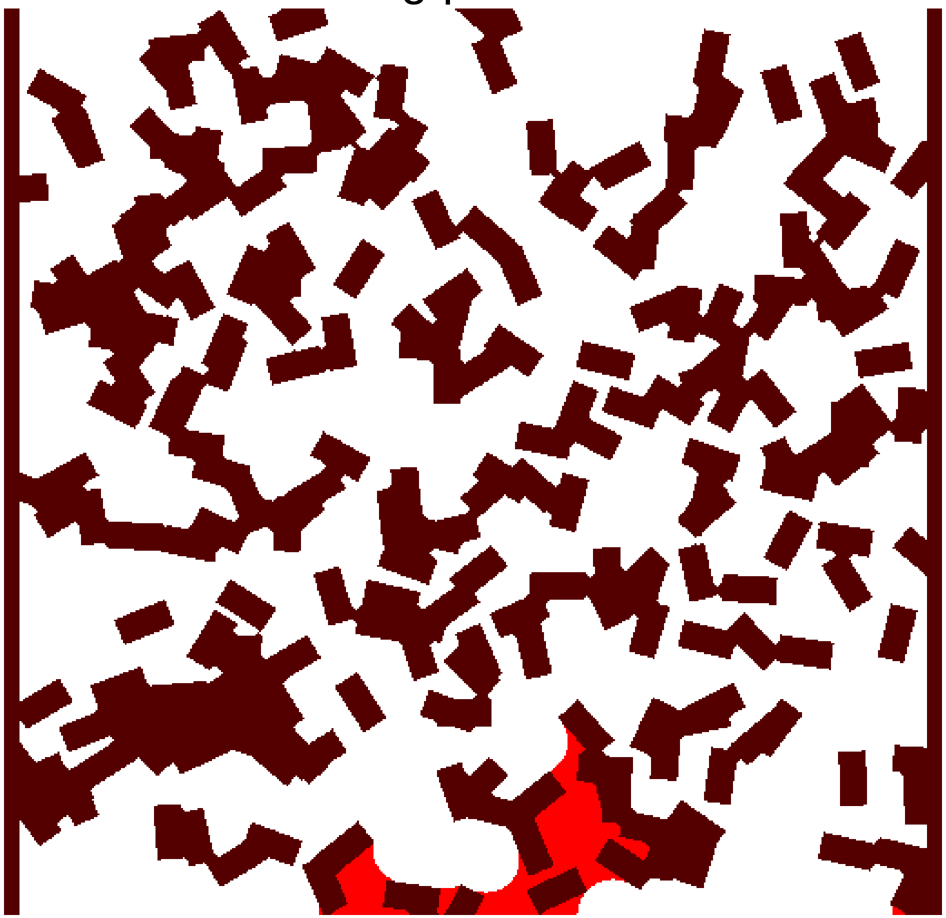
Non-wetting phase reservoir



Wetting phase reservoir

■ Solid
■ WP
□ NWP
■ Res. NWP

Imbibition III
wetting displaces non-wetting phase

SatuDict

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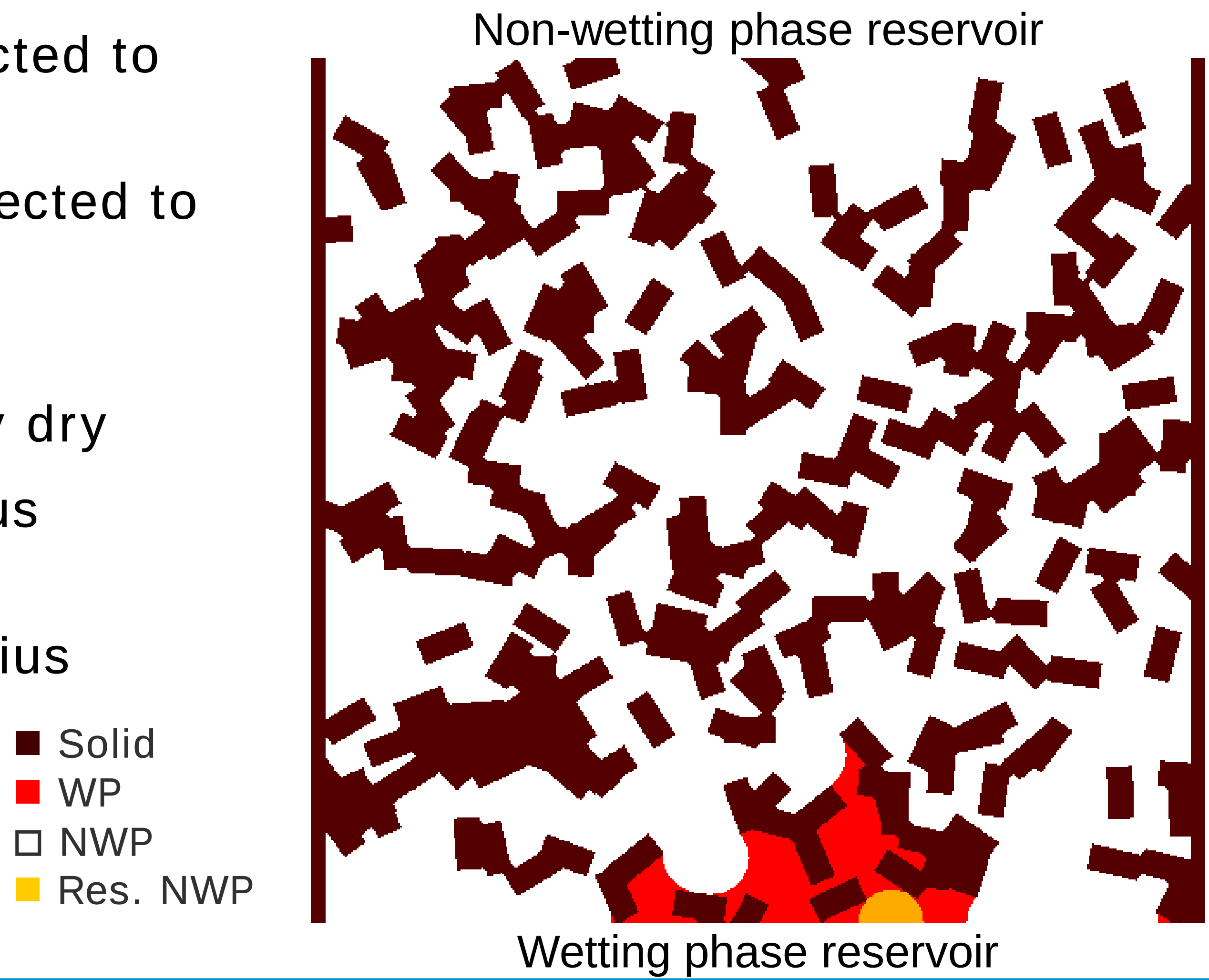

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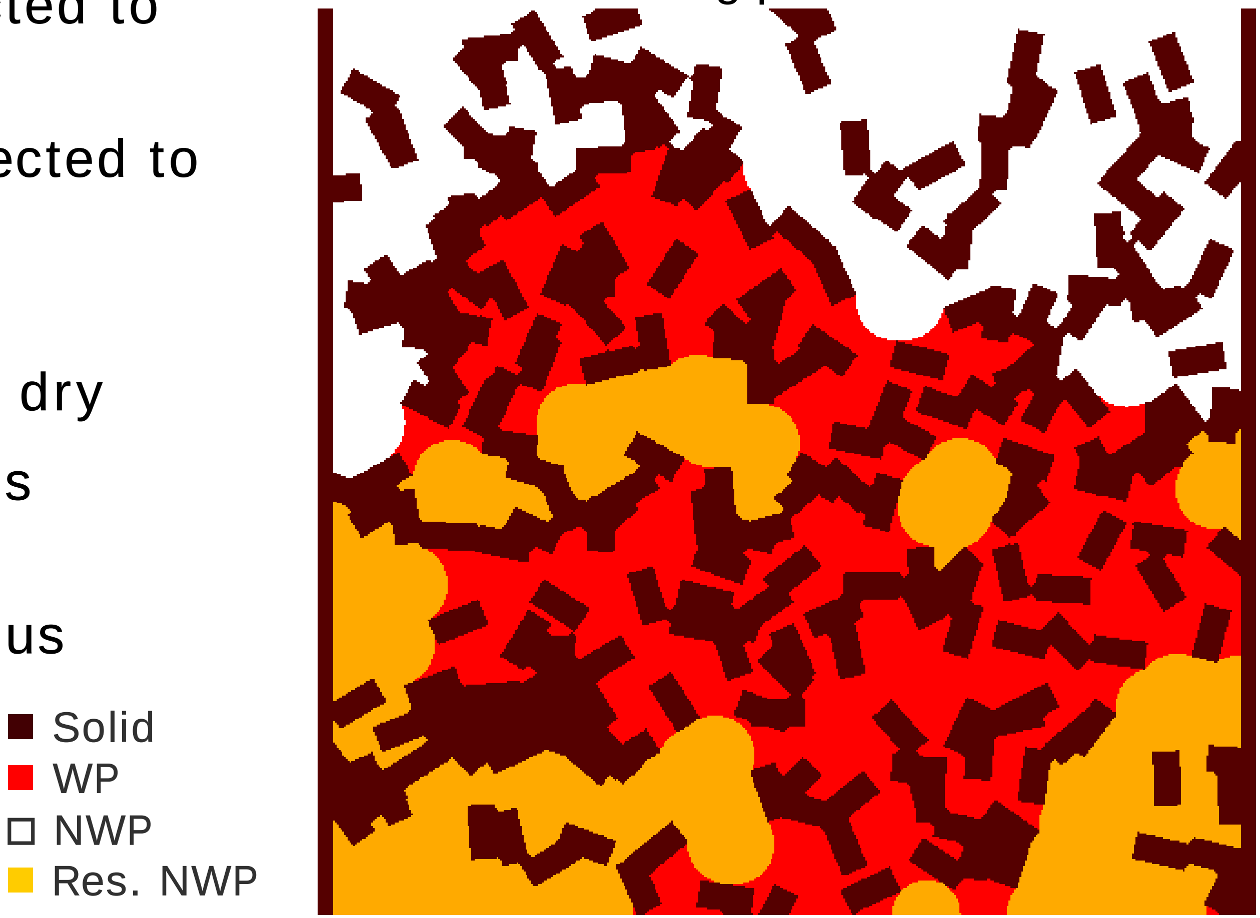
Non-wetting phase reservoir



Wetting phase reservoir

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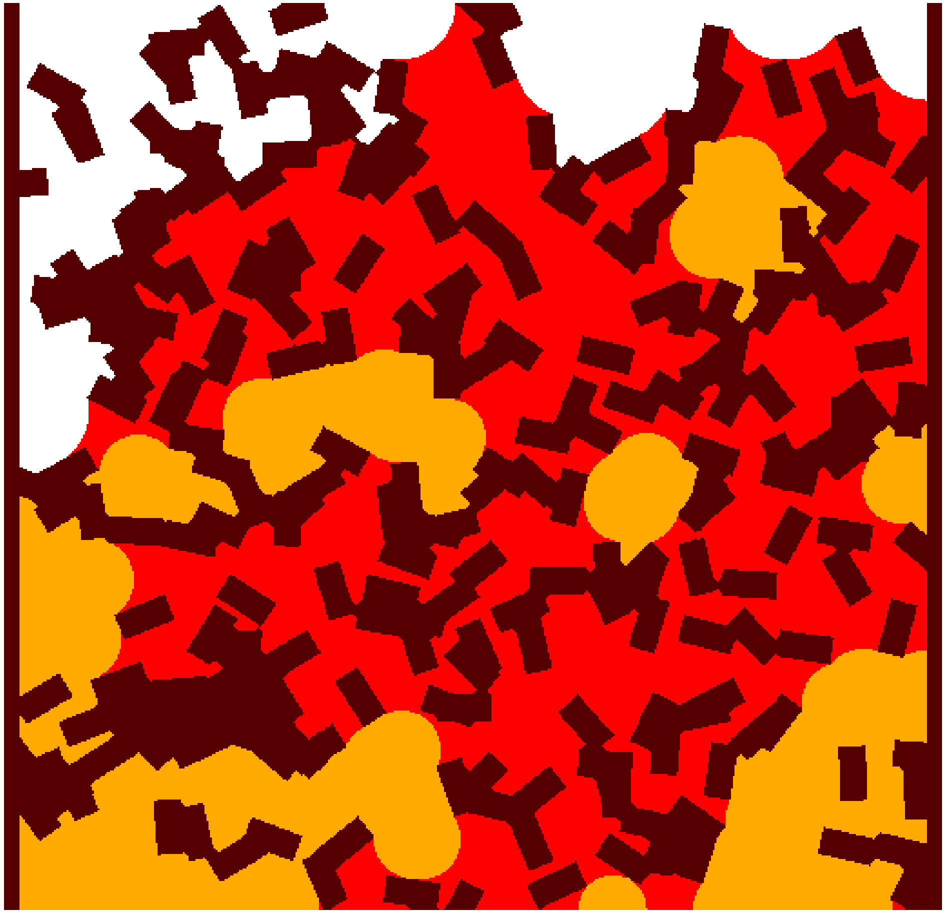
Non-wetting phase reservoir



Wetting phase reservoir

- Solid
- WP
- NWP
- Res. NWP

Imbibition III
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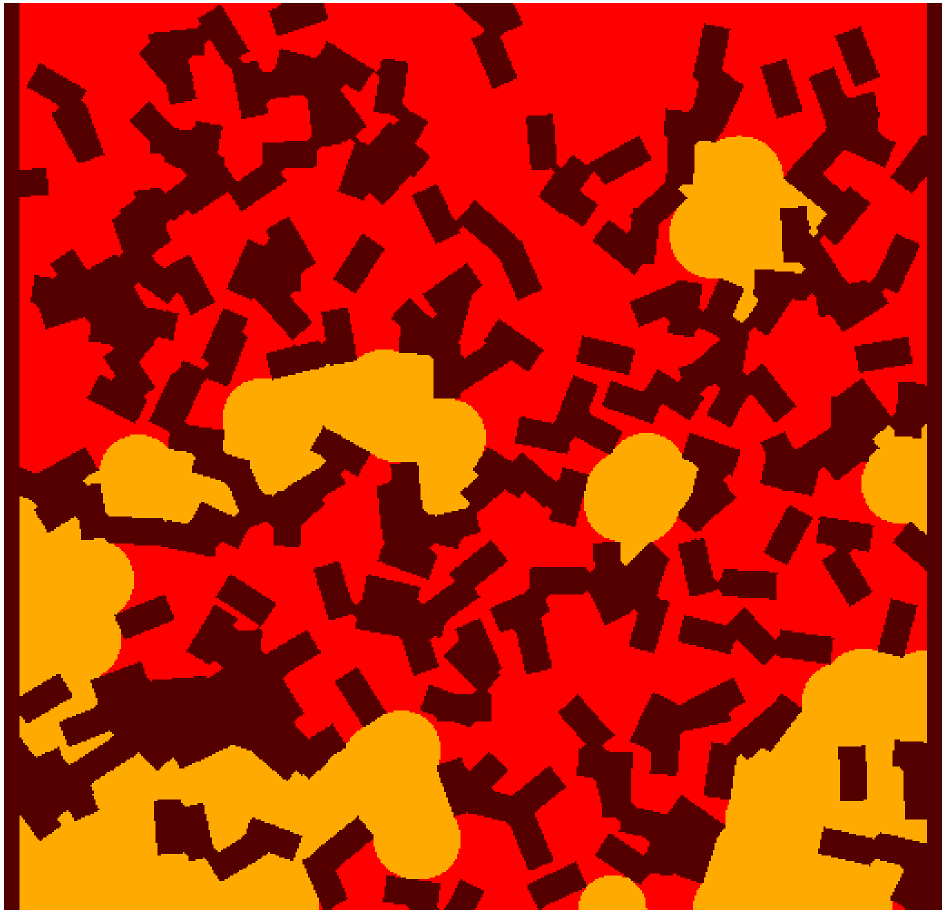
Solid
WP
NWP
Res. NWP

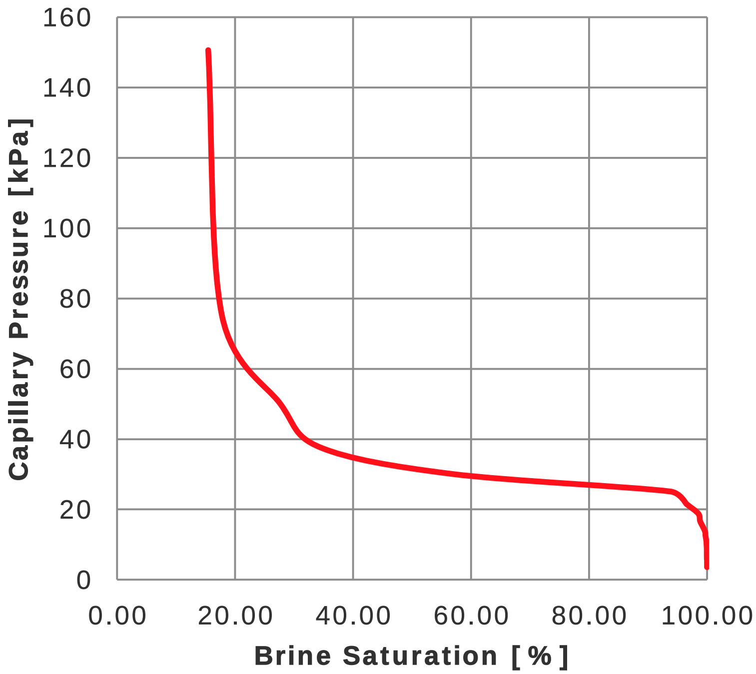
Non-wetting phase reservoir

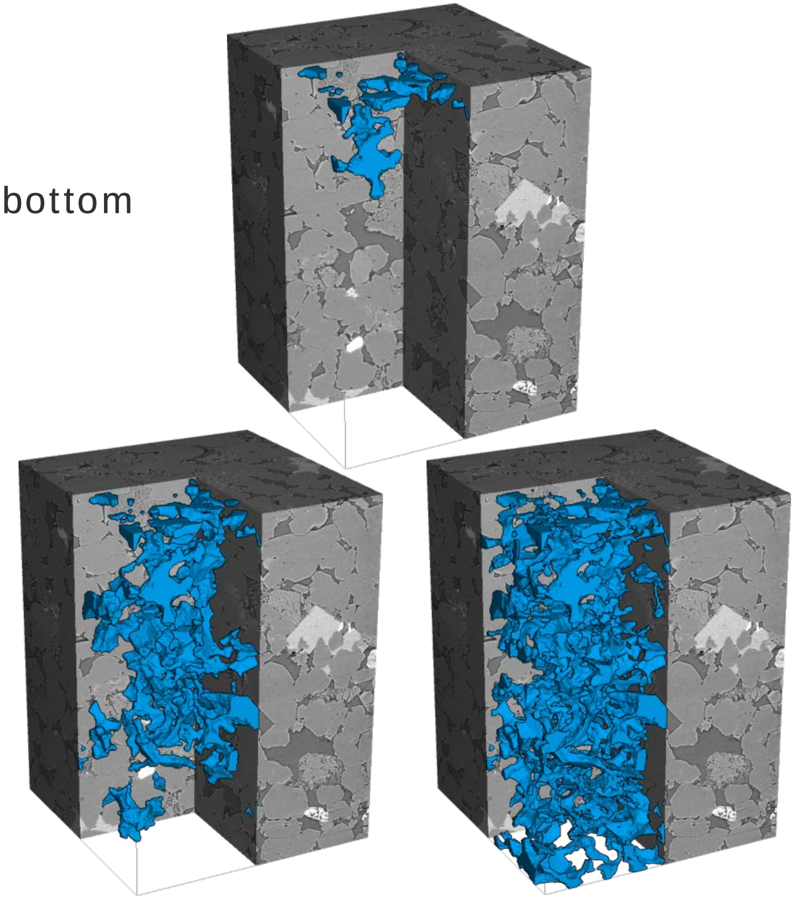


Wetting phase reservoir

Example: Capillary Pressure for Berea Sandstone

- Drainage experiment
  - Air (NWP) drains brine (WP)
  - 40° contact angle
  - NWP reservoir at the top and WP reservoir at the bottom





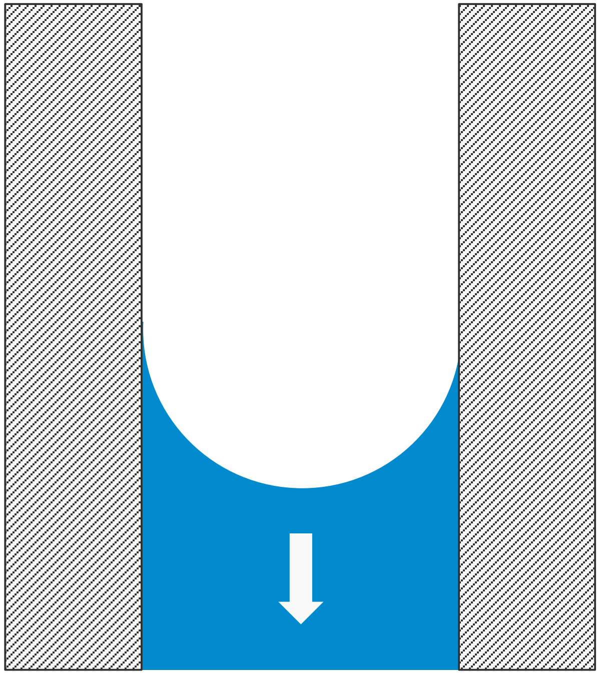
Air drains brine and we visualize air saturations of 25%, 50% and 75%.

Pore Morpholoy Method

Limitations

- Contact angle is always zero for computed phase distributions
- Constant contact angle for the whole domain

Saturation with Variable Wettability



When does the NWP (air) enter a cylindrical capillary?

$$p = \frac{2\gamma}{r}$$

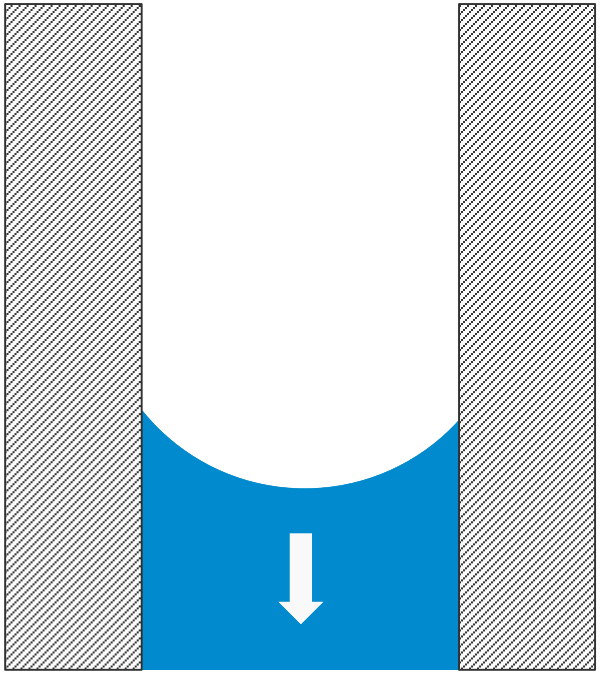
p differential pressure

r pore radius

γ surface tension

complete wetting $\beta = 0$

Saturation with Variable Wettability



When does the NWP (air) enter a cylindrical capillary?

$$p = \frac{2\gamma}{r} \cos \beta$$

p differential pressure

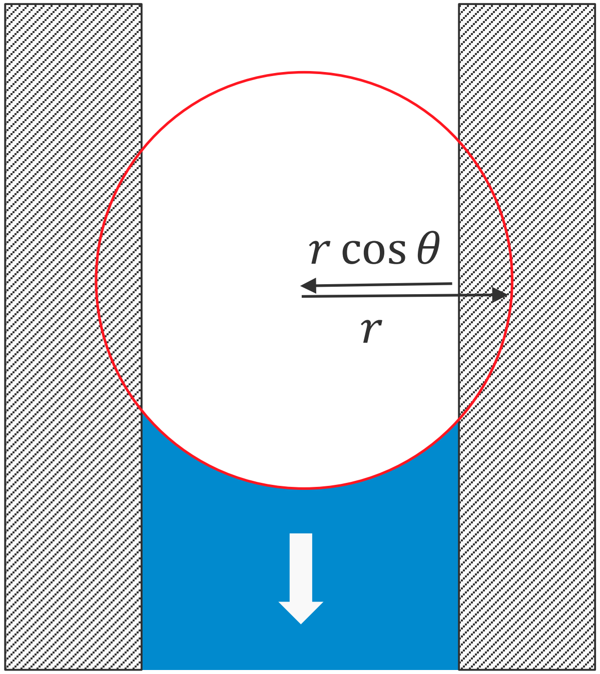
r pore radius

γ surface tension

β contact angle

partial wetting $0° < \beta < 90°$

New Idea: Can we have variable contact angles?



Idea (Schulz et al, 2014)

- dilate by $r\cos\theta$ (pore radius)
- erode by r (sphere radius)

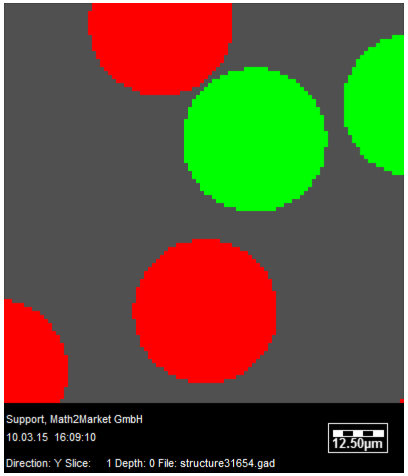
Result: contact angle θ on pore wall

Young-Laplace: $p = \frac{2\gamma}{r}$

V.P. Schulz, E. A. Wargo, E. Kumbur, Pore-Morphology-Based Simulation of Drainage in Porous Media Featuring a Locally Variable Contact Angle, Transport in Porous Media, 2014.

Multiple Contact Angles

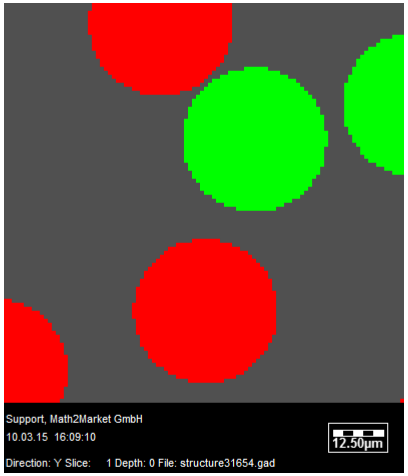
SatuDict

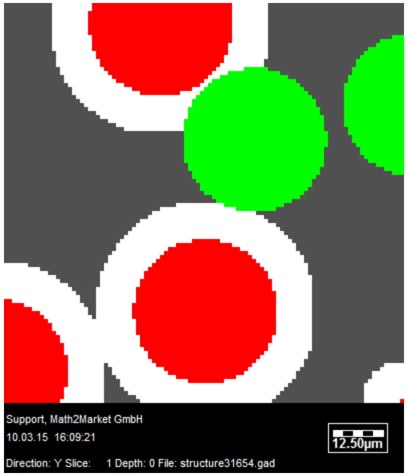


- Material 1
- Material 2
- NWP
- WP

Multiple Contact Angles

SatuDict





1. Dilate material 1

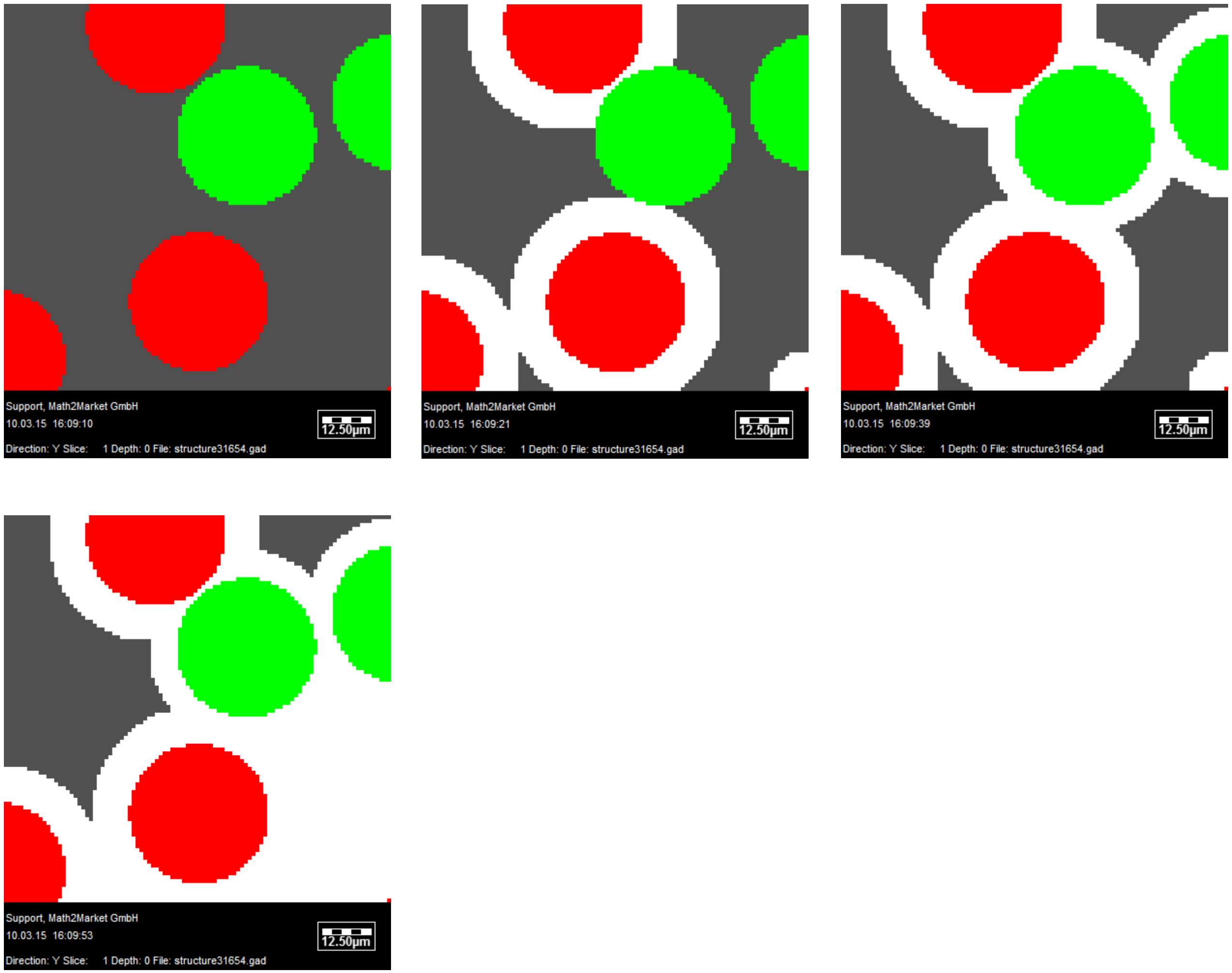
- Material 1
- Material 2
- NWP
- WP

Multiple Contact Angles

1. Dilate material 1
2. Dilate material 2

- Material 1
- Material 2
- NWP
- WP

Multiple Contact Angles



1. Dilate material 1
2. Dilate material 2
3. Check connectivity

- Material 1
- Material 2
- NWP
- WP

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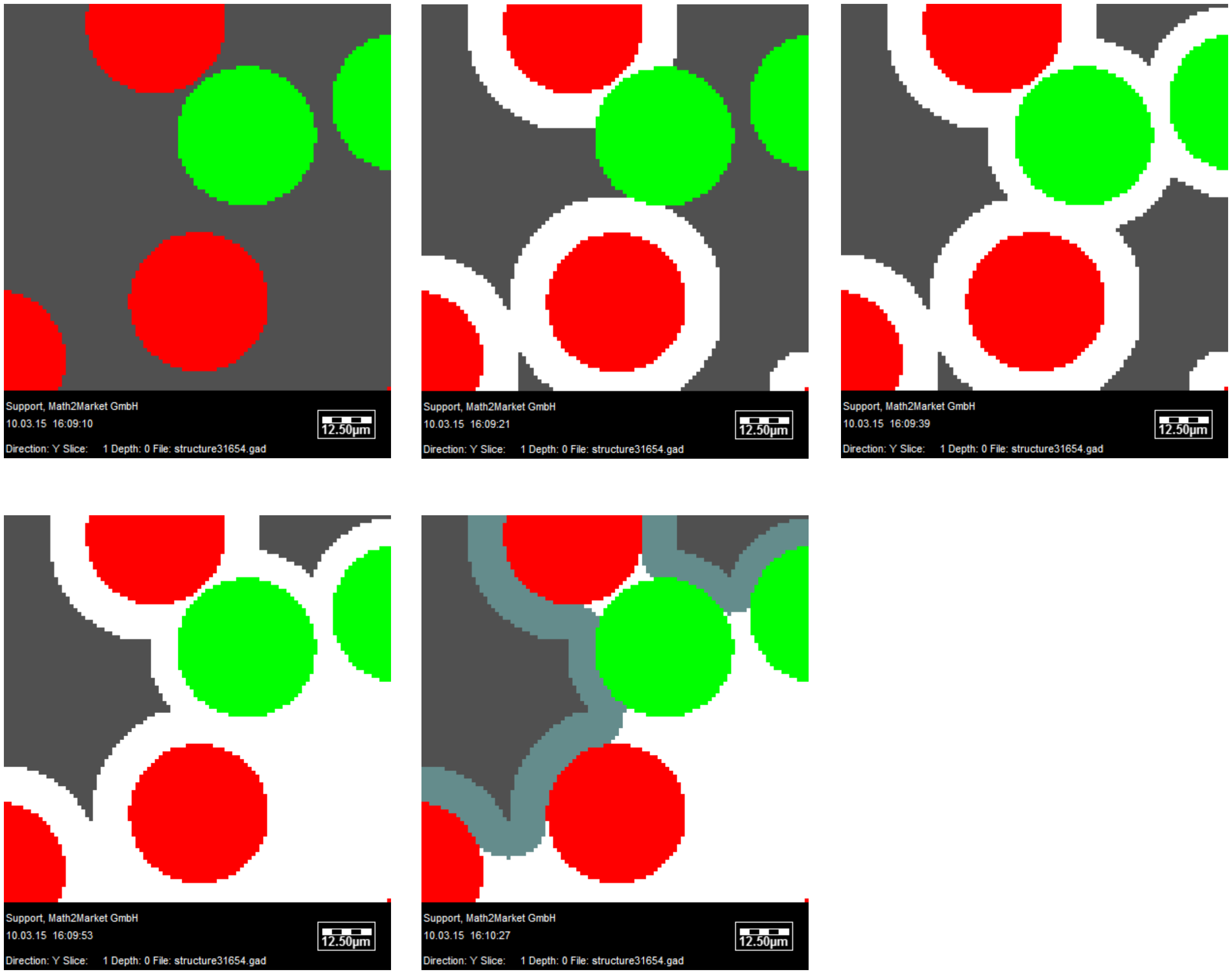
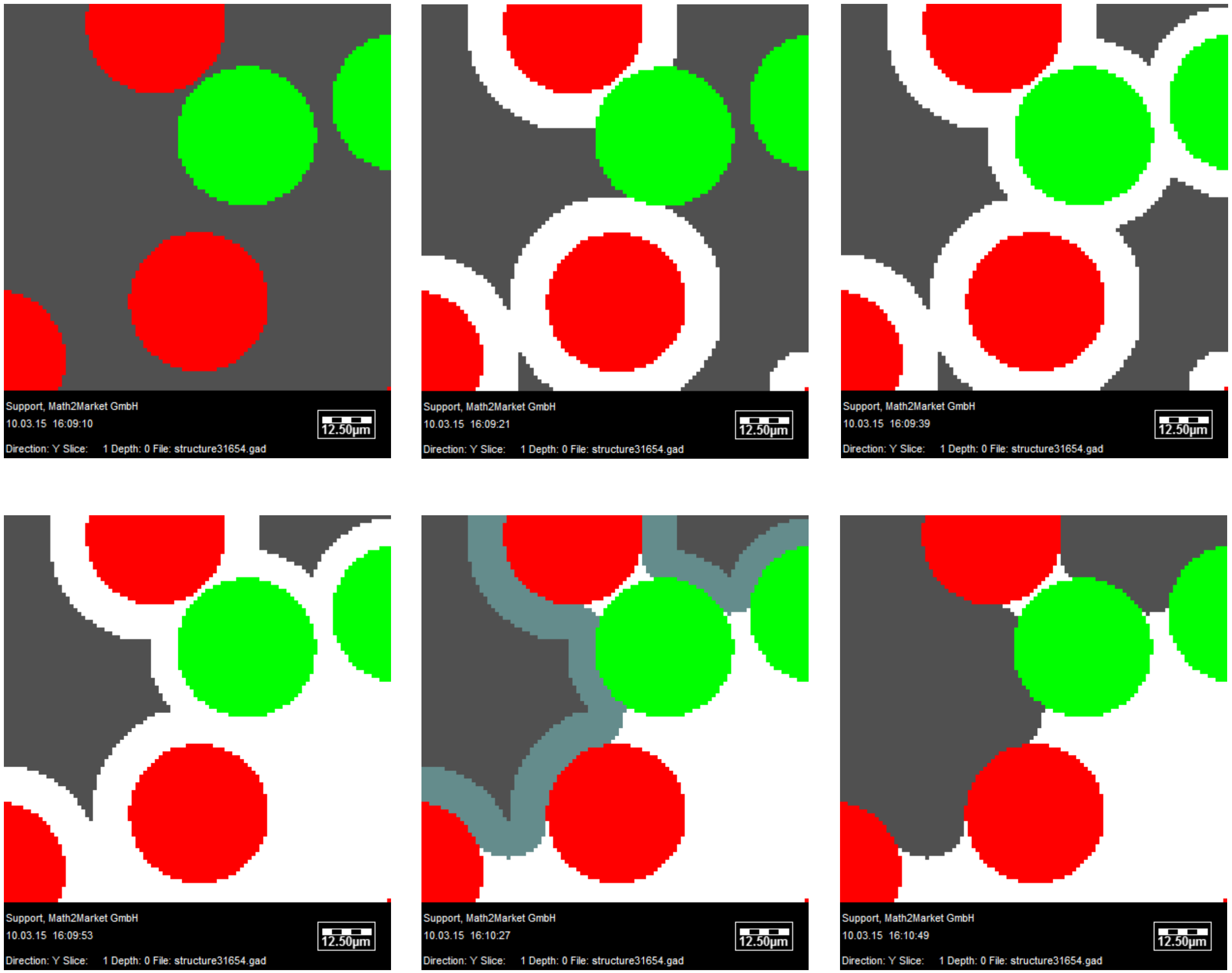
Multiple Contact Angles



1. Dilate material 1
2. Dilate material 2
3. Check connectivity
4. Erode

- Material 1
- Material 2
- NWP
- WP

Multiple Contact Angles

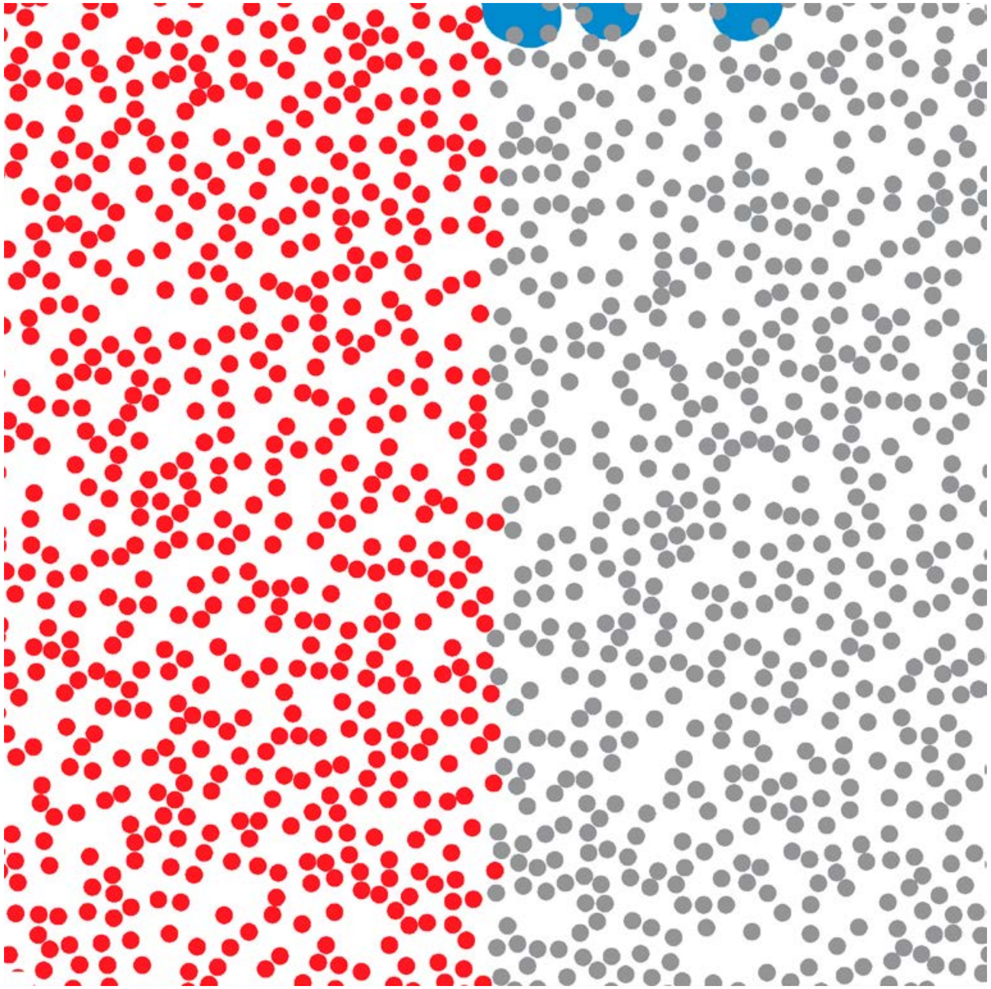


1. Dilate material 1
2. Dilate material 2
3. Check connectivity
4. Erode
5. Final result

- Material 1
- Material 2
- NWP
- WP

2D Example

- Contact angle 0°
- Contact angle 40°
- Water (non-wetting)
- Air (wetting)



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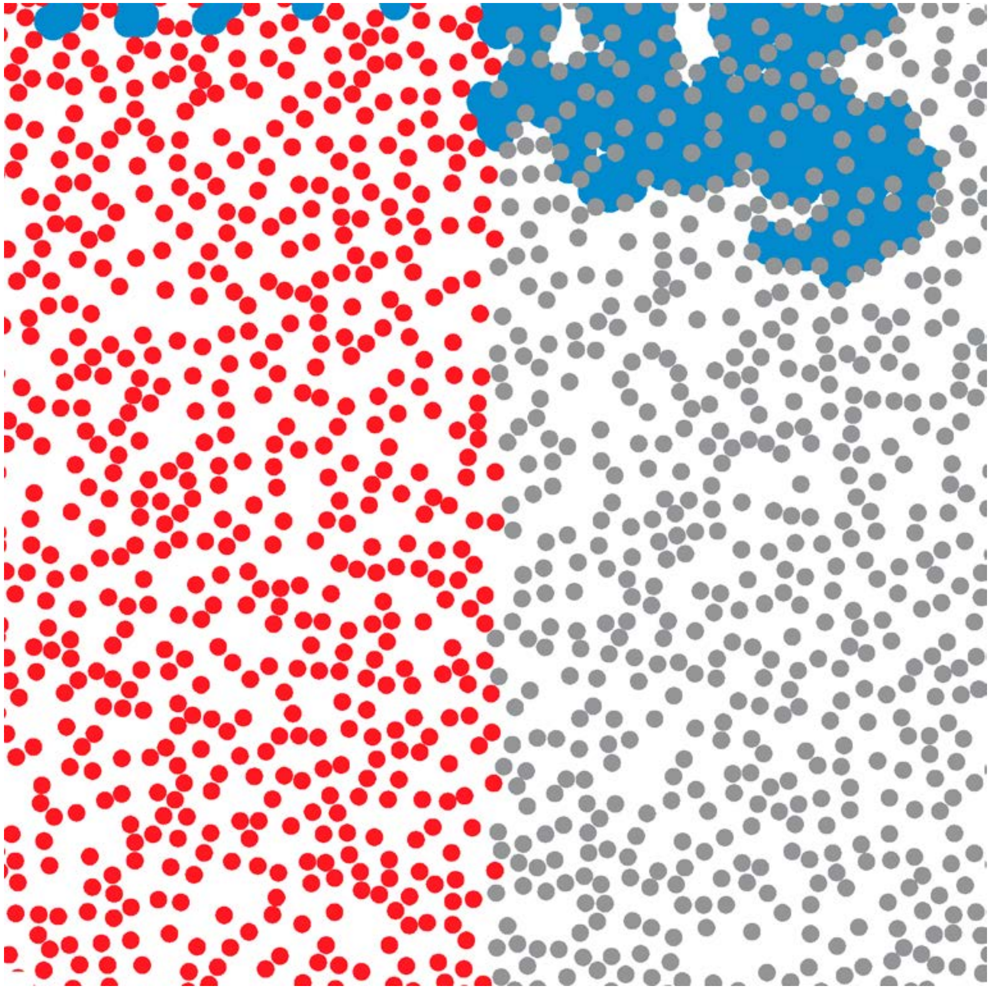

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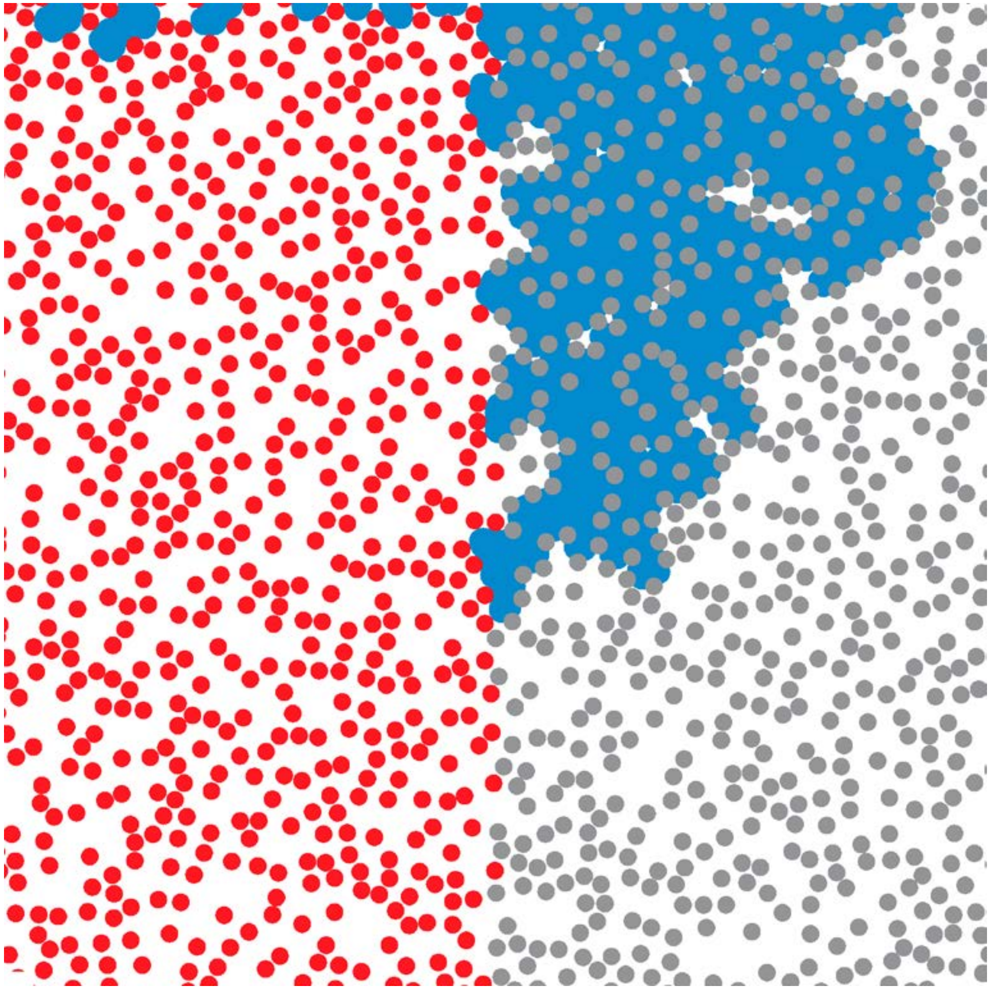

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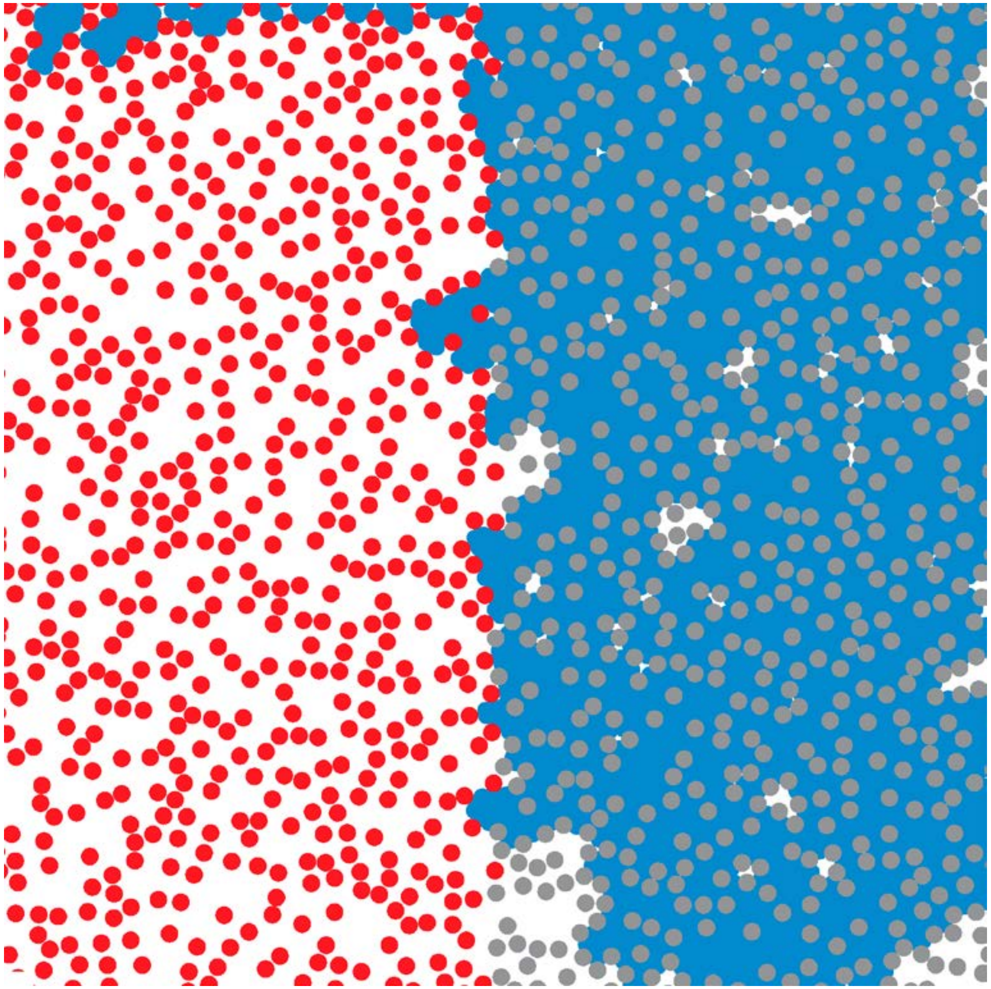

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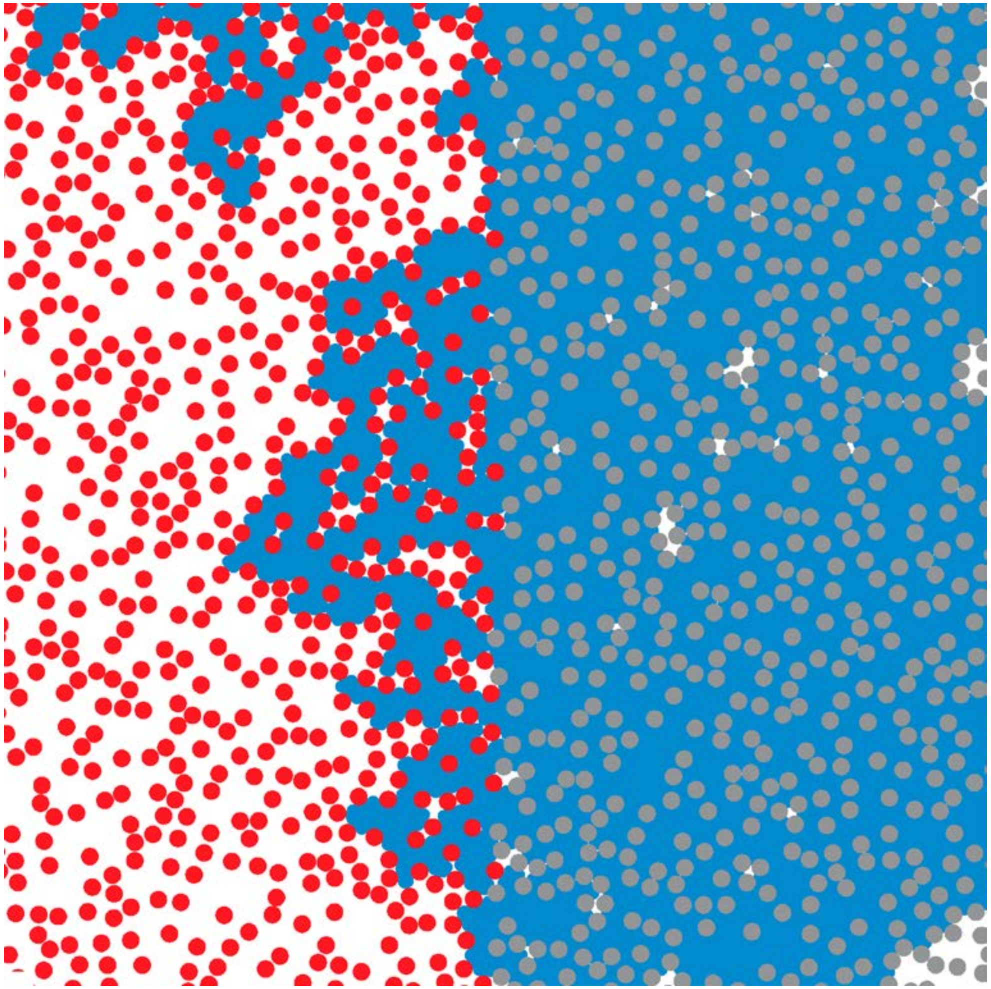

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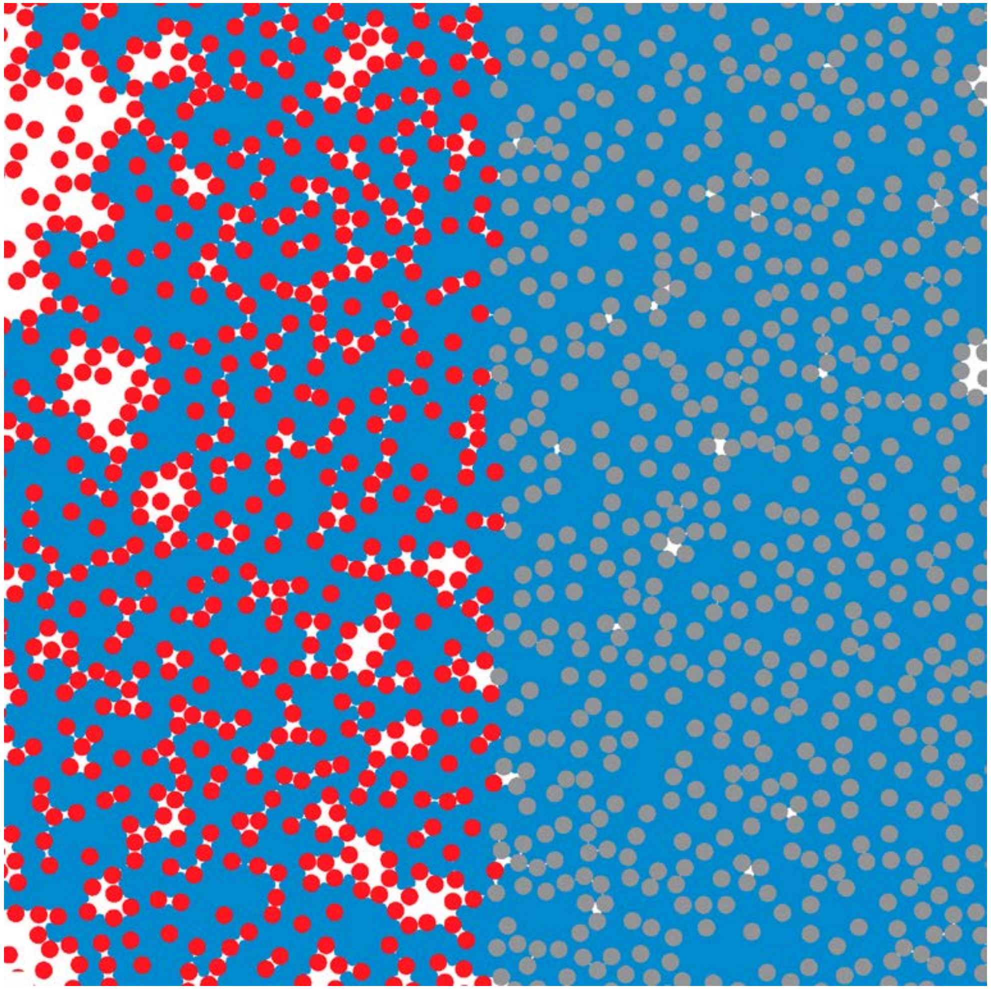
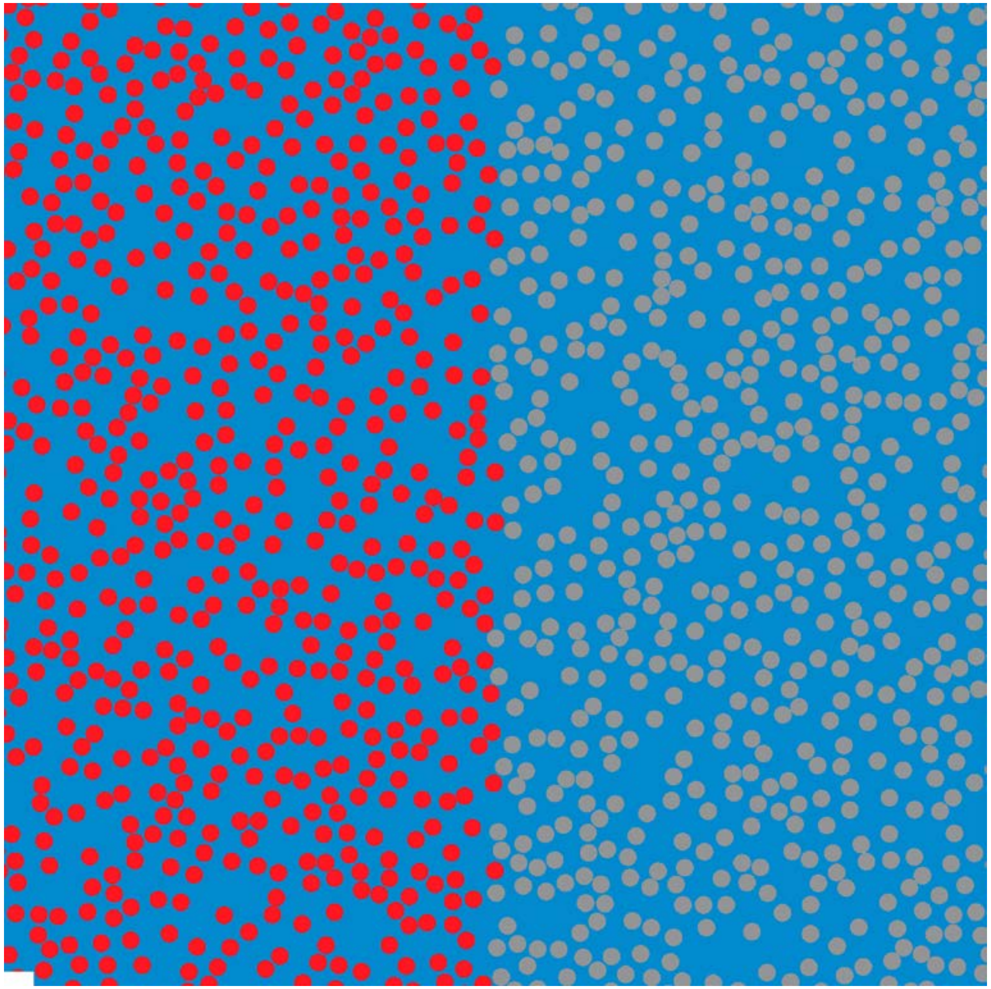
- Contact angle 0°
- Contact angle 40°
- Water (non-wetting)
- Air (wetting)



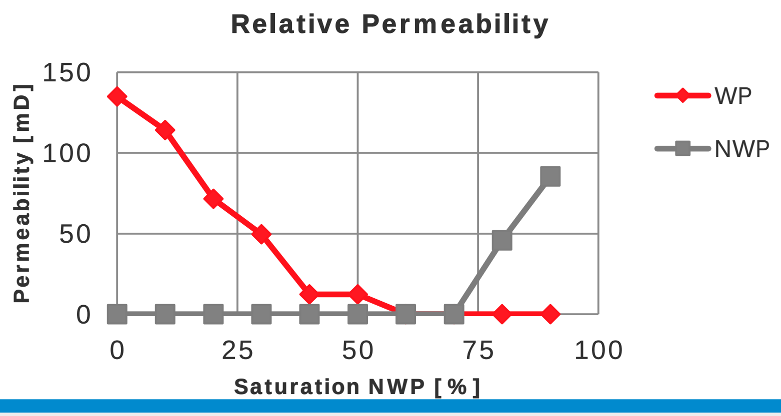
2D Example

- Contact angle 0°
- Contact angle 40°
- Water (non-wetting)
- Air (wetting)

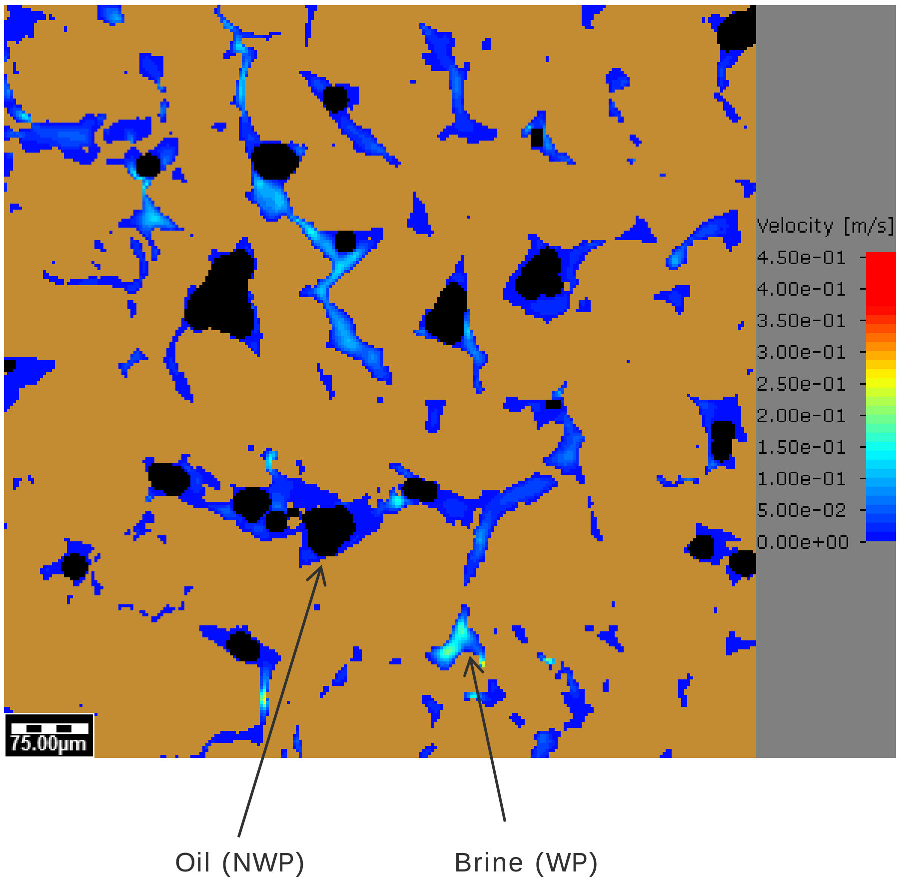


Relative Permeability
Basic Idea

- Choose
  - Saturation level and
  - Wetting model
- Find
  - Oil distribution (black) and
  - Brine distribution
- Solve Stokes equations in
  - Brine phase and treat oil phase as solid
  - Oil phase and treat brine phase as solid



Stokes Flow in Wetting Phase



Relative Permeability

Challenges

- DRP Parameter that is most expensive to compute
- Low saturation states are most expensive but results are the smallest

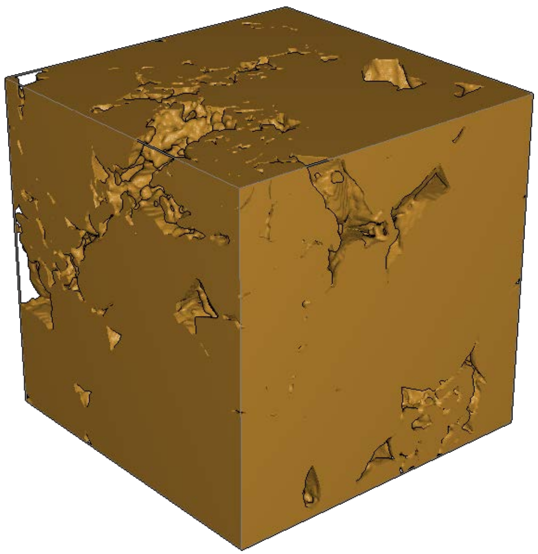
Improvements

- Speedup of solvers
- Restart of computations
  - Compute permeability from highest to lowest saturation state
  - Use result from previous computation to speed up the next one
- New stopping criterion
  - Relative difference to the permeability of the full saturated state

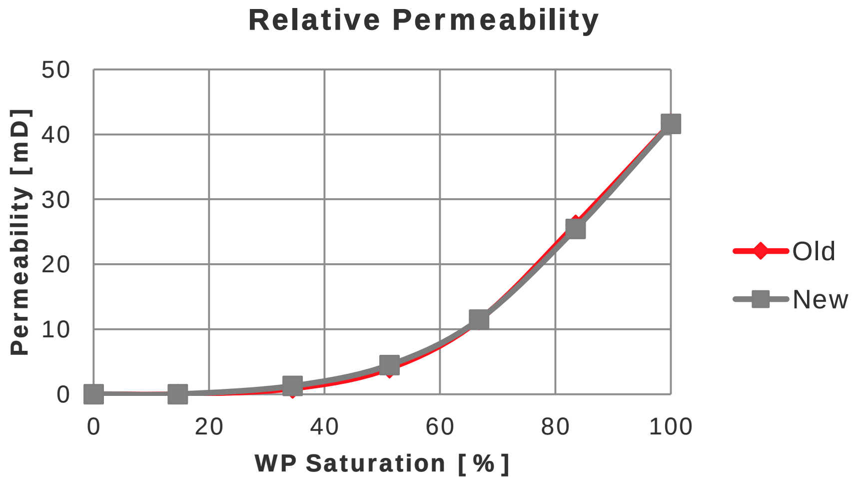
Relative Permeability Example: Berea Sandstone

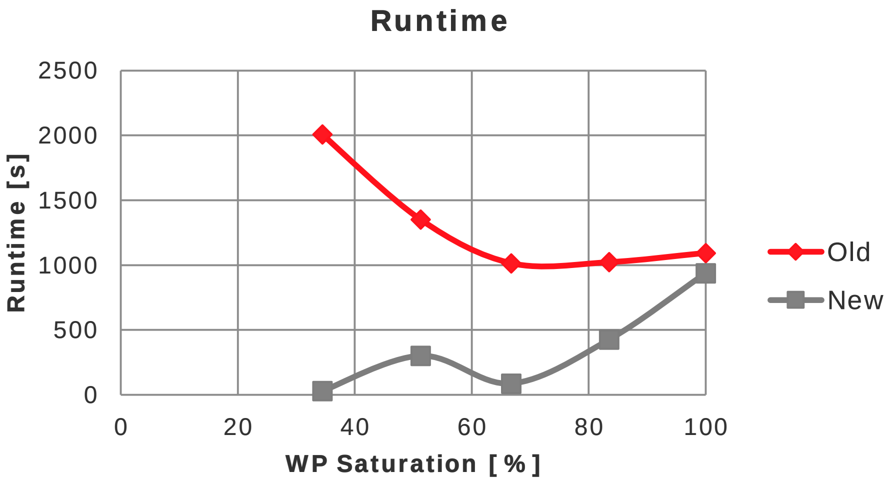
Benchmark

- Structure: Berea Sandstone
- Compute Relative Permeability for WP
- Compare old and improved computations



Segmented Berea Sandstone with 256³ voxels and 0.74 µm voxel length





Thank you for your attention!