Reservoir Simulation
Gridding and Well Modelling

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(after Ken Sorbie)

Outline

- Gridding in Reservoir Simulation
- Calculation of Block to Block Flows in Reservoir Simulators
- Wells in Reservoir Simulation

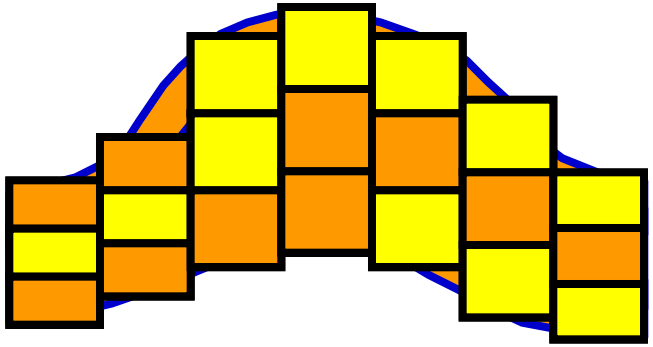
Gridding in Reservoir Simulation

- Reservoir Simulation Model
  - **grid block** model of a petroleum reservoir…
- Gridding
  - process of dividing up a reservoir into grid blocks (spatial discretization)
- Discretization
  - process of dividing up a continuous quantity into discrete intervals

Gridding in Reservoir Simulation

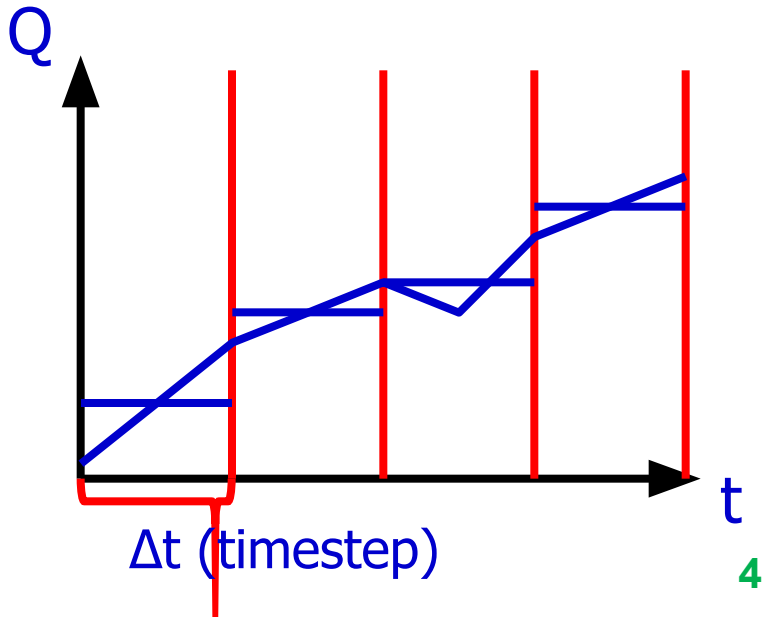
Discretization

Spatial

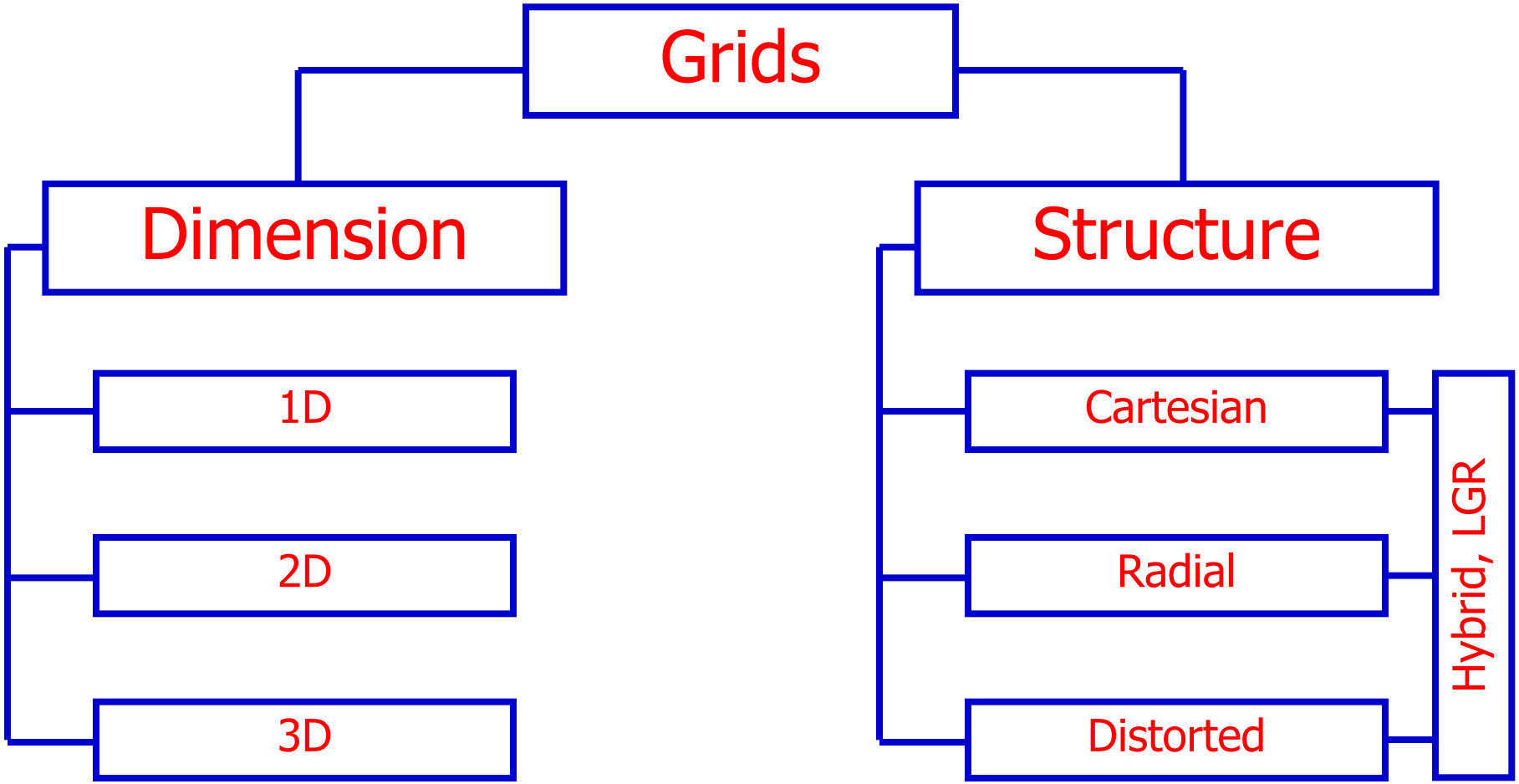


Δx, Δy, Δz
φ, k, c, S, p
PVT

Temporal



Gridding in Reservoir Simulation



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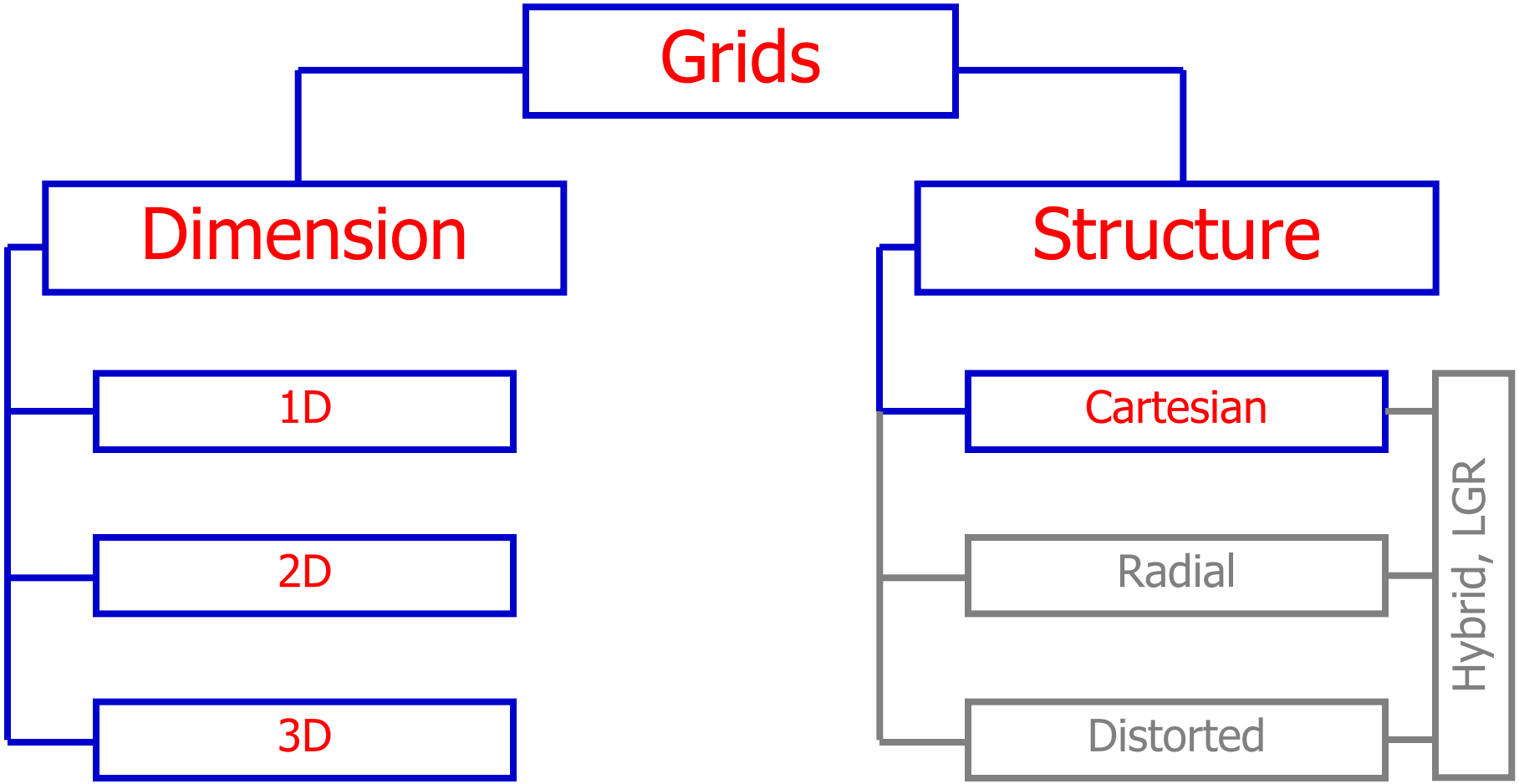
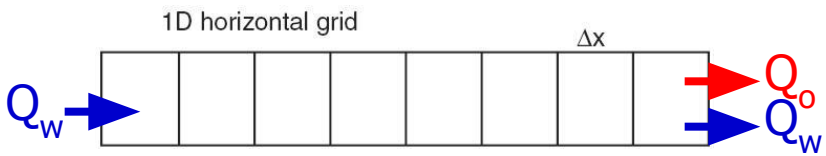
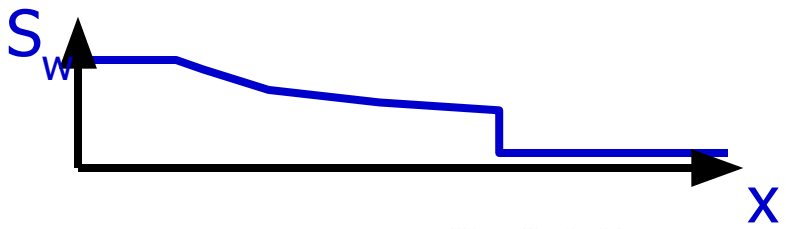


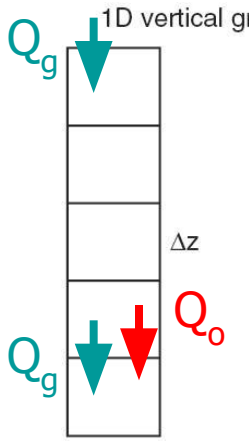
Gridding in Reservoir Simulation

- 1D Cartesian (Linear) Grids
  - Horizontal
    - Buckley-Leverett type water displacement





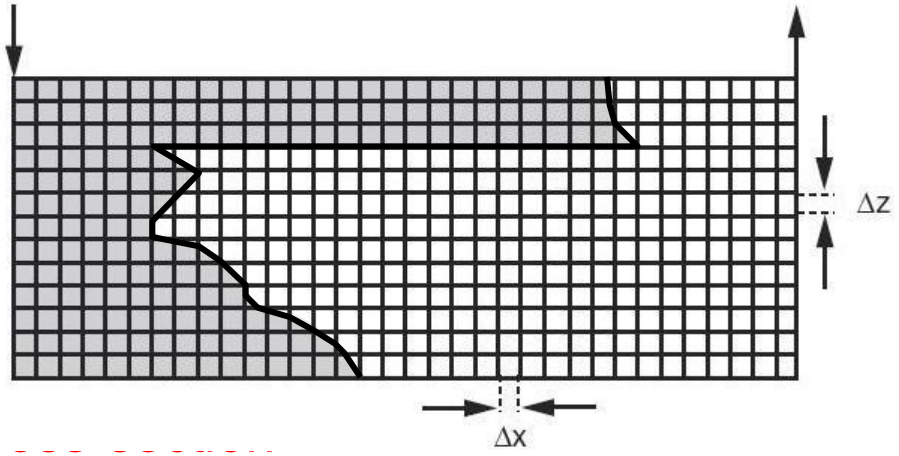
  - Vertical
    - gravity drainage
    - gravity stable gas displacement of oil



Gridding in Reservoir Simulation

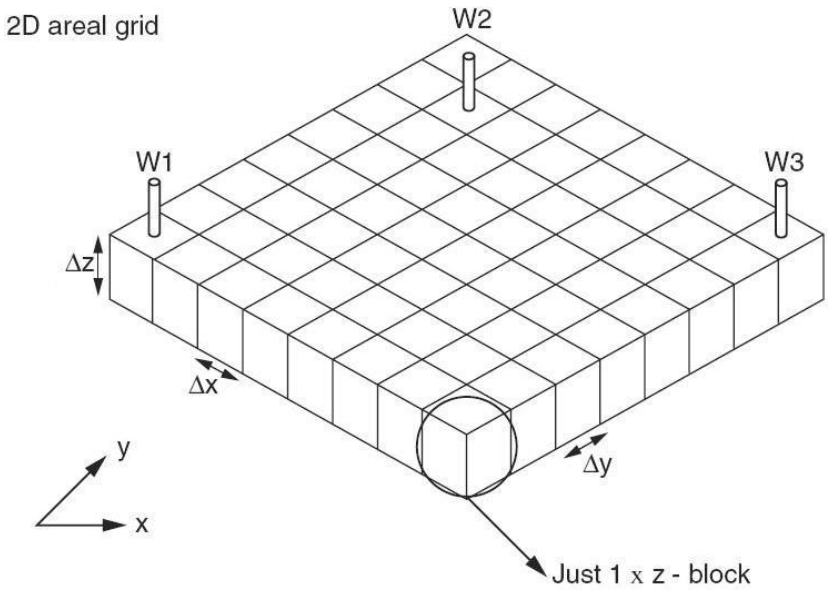
- 2D Cartesian Grids
  - Cross-sectional (x/z)
    - vertical sweep efficiency
    - water/oil displacements i
      geostatistically generatec
    - generation of pseudo-relative permeabilities (2 phase upscaling)
    - mechanism of gas displacement (importance of gravity)

2D (x/z) cross-sectional model showing a waterflood



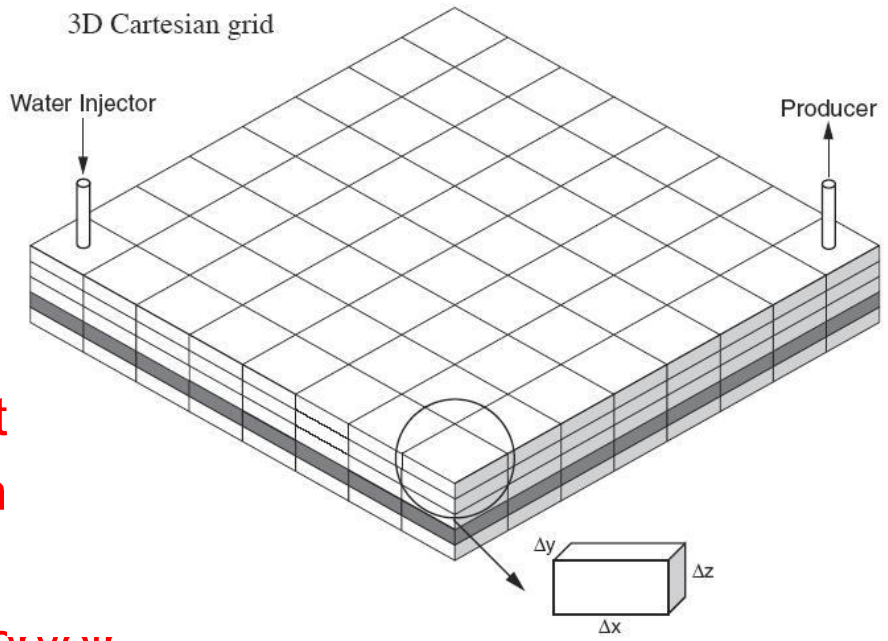
Gridding in Reservoir Simulation

- 2D Cartesian Grids
  - Areal (x/y)
    - areal sweep efficiency (water/gas flooding)
    - benefits of infill drilling in an areal pattern flood
    - near-miscible gas injection in a homogeneous layer

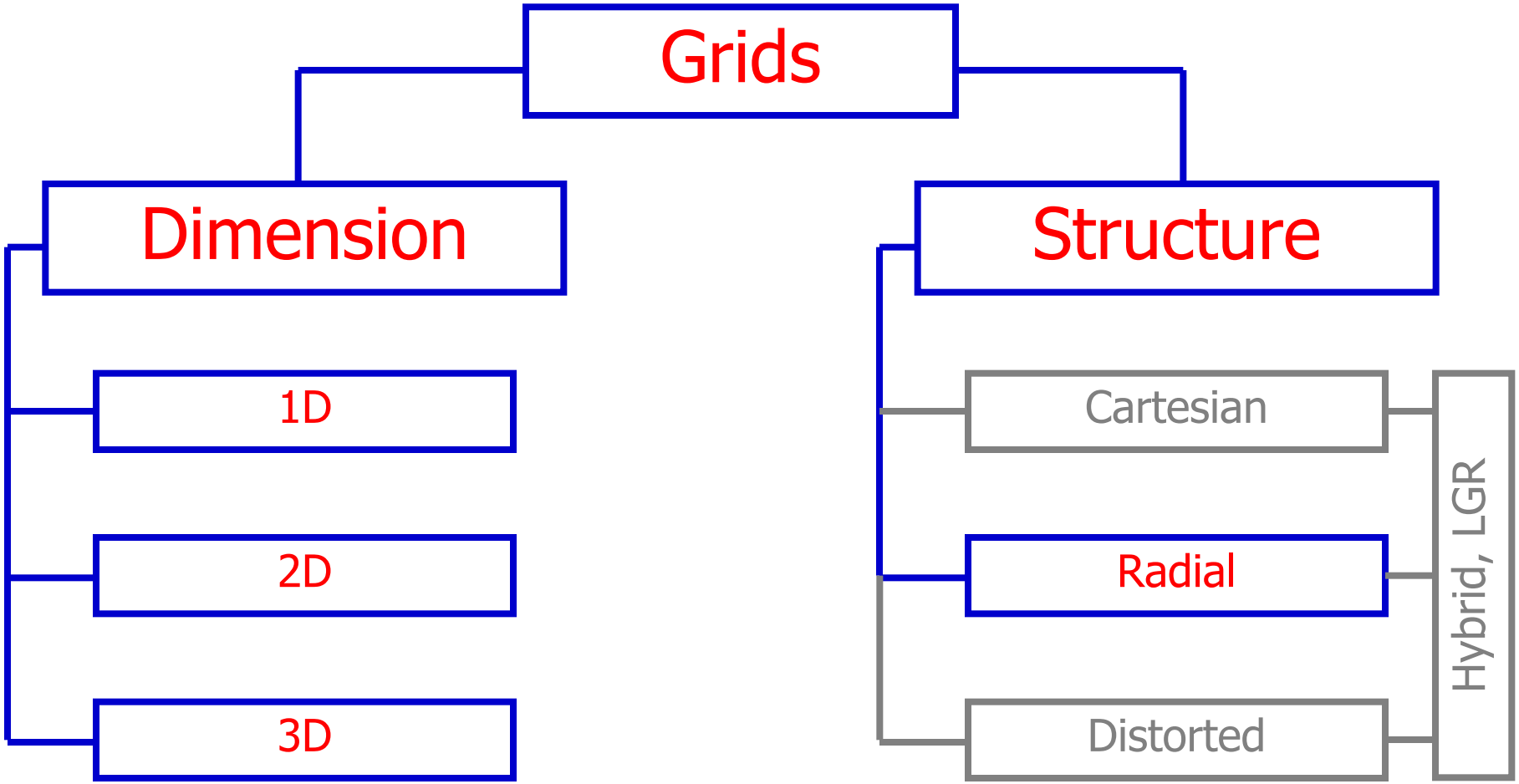


Gridding in Reservoir Simulation

- 3D Cartesian Grids
  - Default grid type
    - easy to set up
    - less time consuming simulat (equations are derived for th
    - wide range of field wide reservoir production processes (full field simulation of water/gas flooding and etc.)

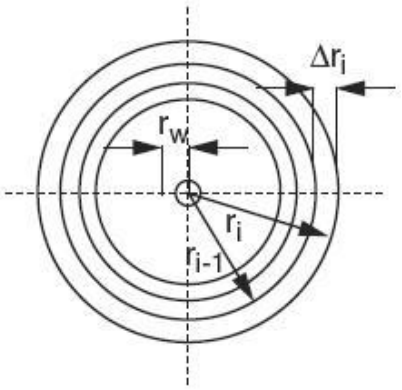


Gridding in Reservoir Simulation

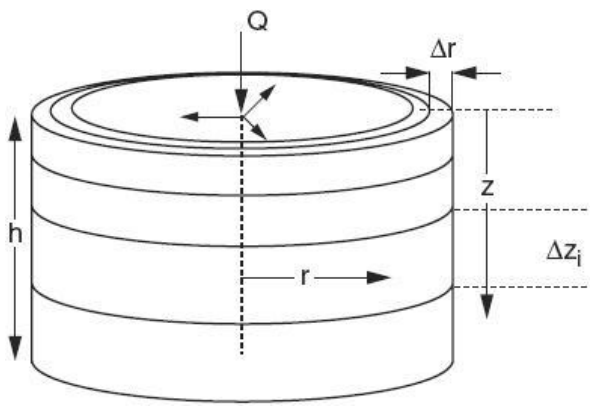


Gridding in Reservoir Simulation

- Radial Grids
  - 1D
    - pressure front propagation



  - 2D (r/z), 3D
    - near wellbore processes (water/gas coning)



Gridding in Reservoir Simulation

- Radial Grids
  - pressure change near well is stee

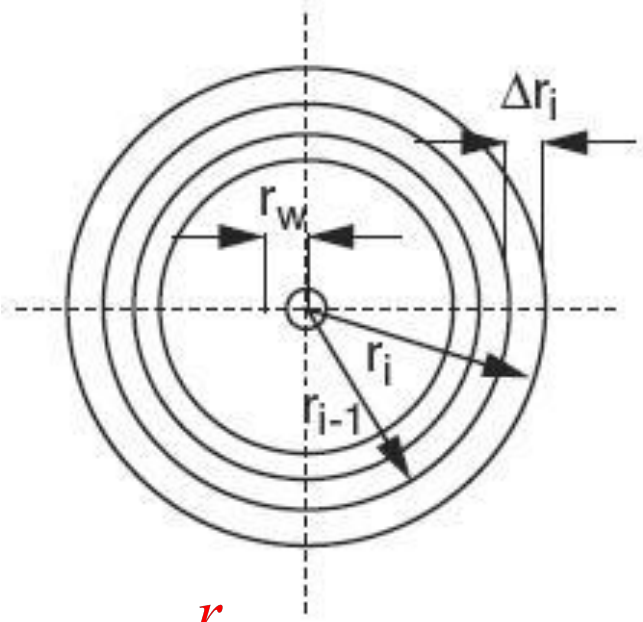
$$\Delta P(r) \sim \ln\left(\frac{r}{r_w}\right)$$

  - logarithmically-spaced grid
    - grid is divided such that

$$\Delta r_i = r_i - r_{i-1}$$

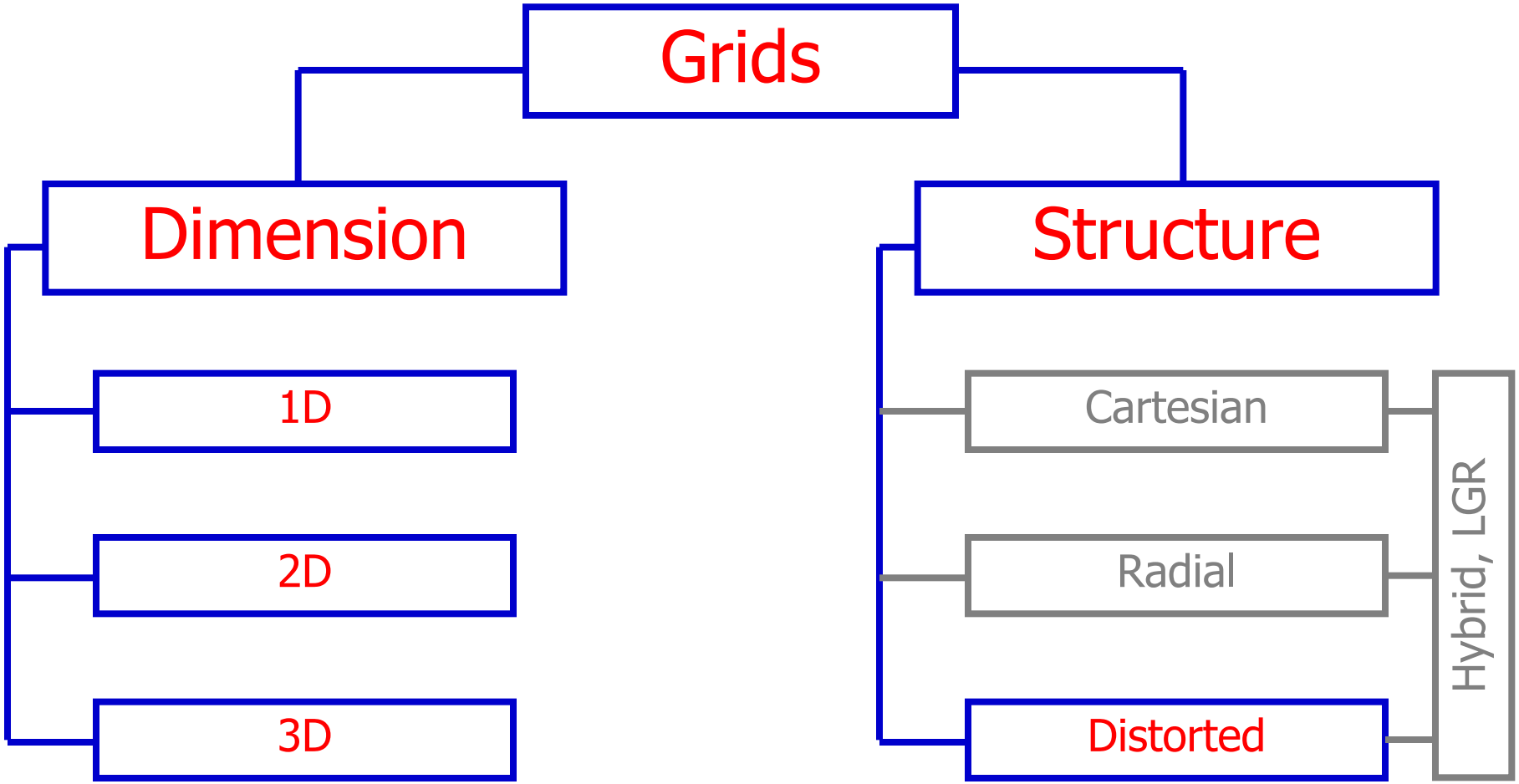
$$P(r_i) - P(r_{i-1}) - \text{const}$$

$$P(r_i) - P(r_{i-1}) \sim \ln\left(\frac{r_i}{r_{i-1}}\right)$$



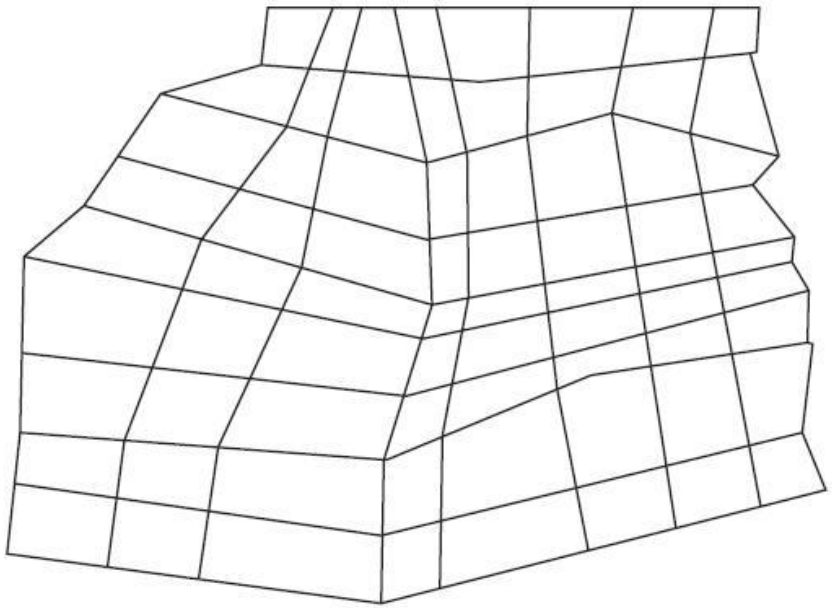
$$\frac{r_i}{r_{i-1}} - \text{const}$$

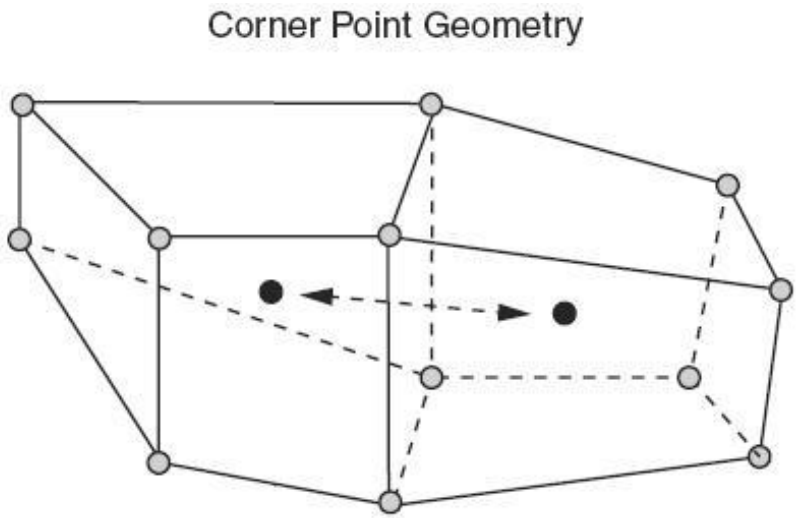
Gridding in Reservoir Simulation



Gridding in Reservoir Simulation

- Distorted grids
  - Corner Point
    - account structure features (faults)

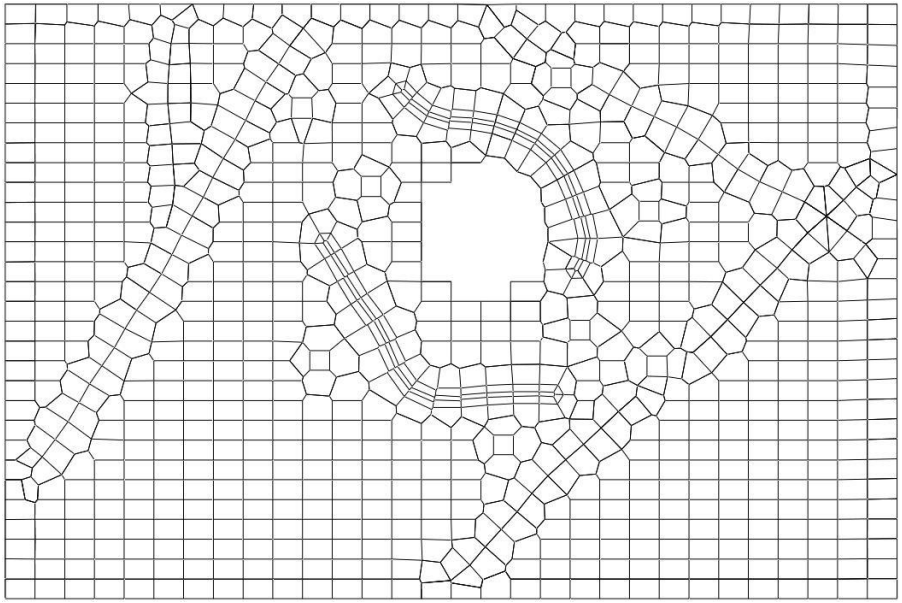




8 corners

Gridding in Reservoir Simulation

- Distorted grids
  - Perpendicular Bisector (PEBI), Voronoi
    - account structure features (faults)
    - horizontal well modelling



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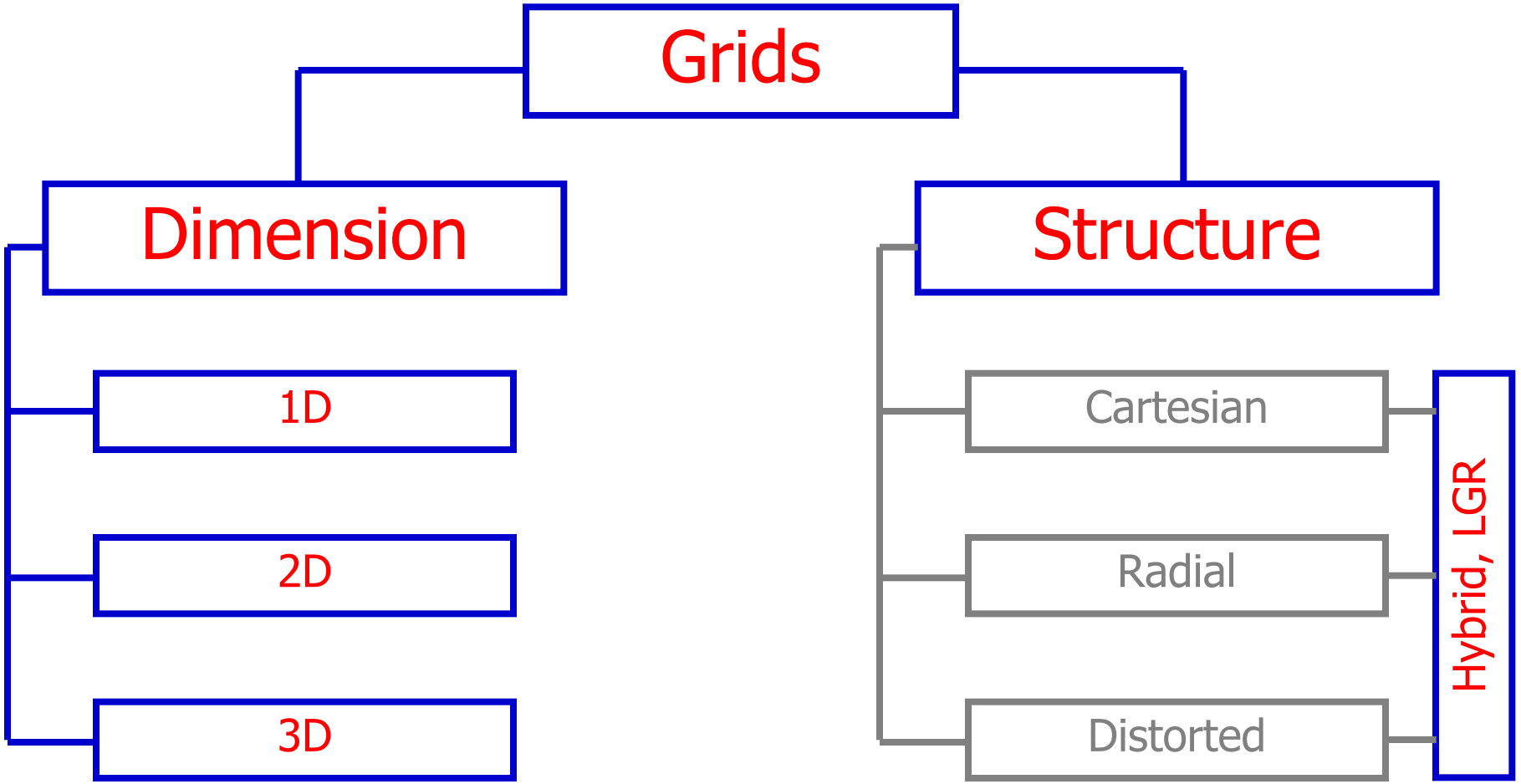
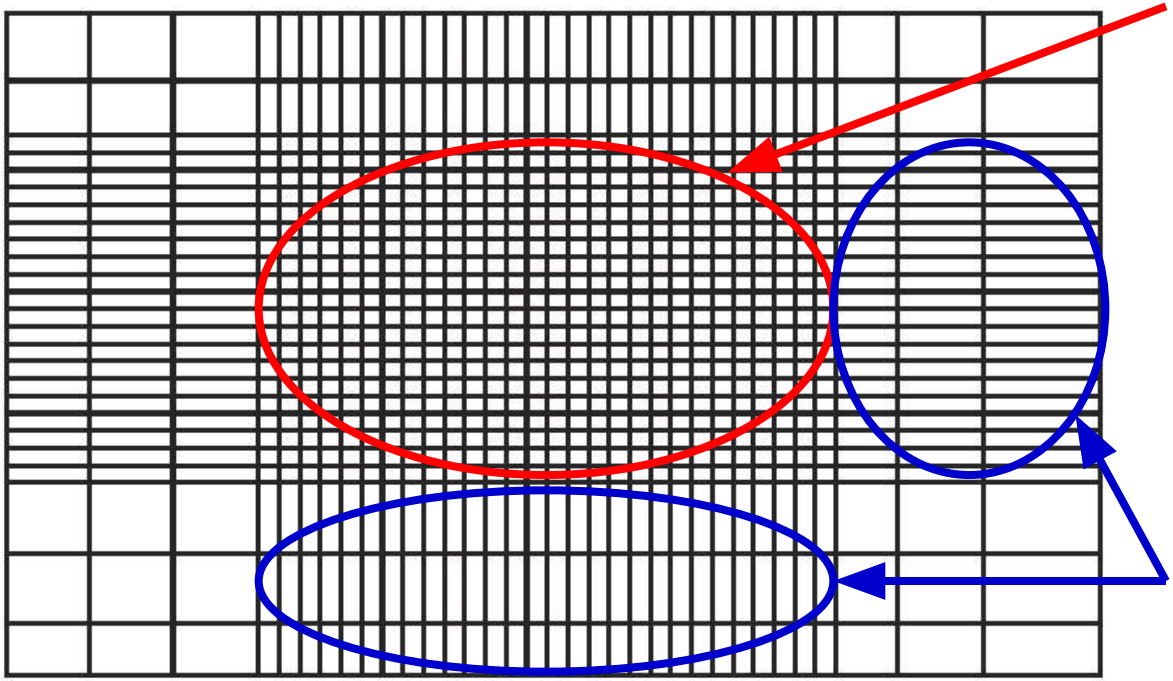


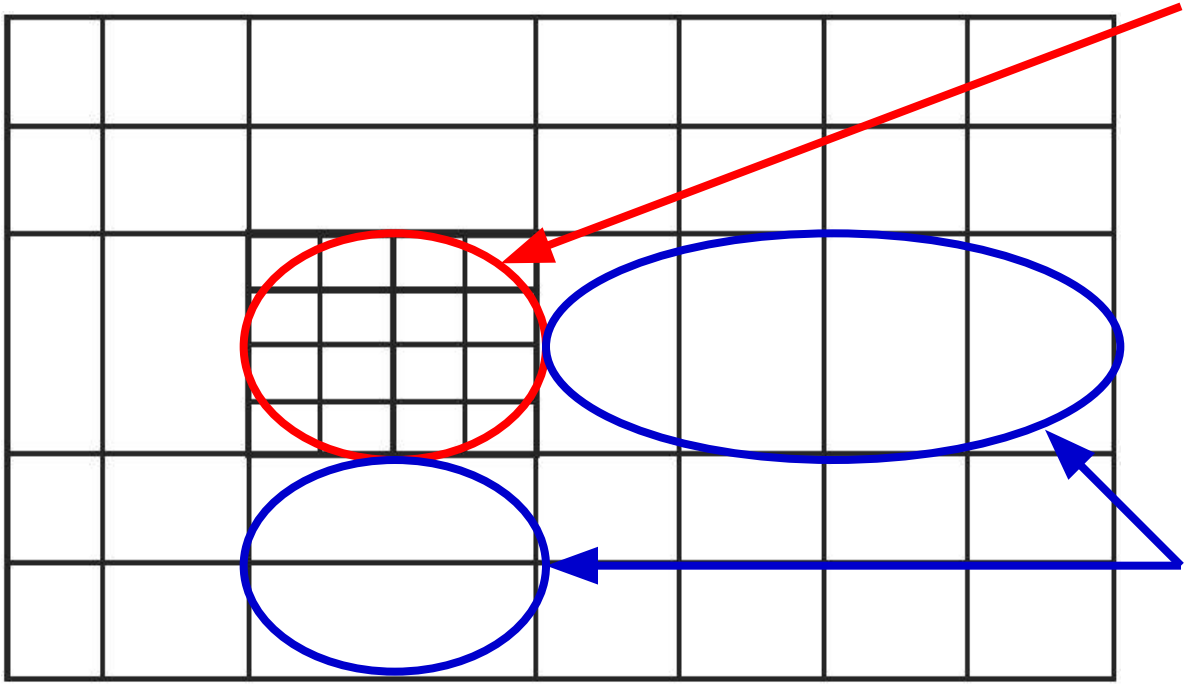
Gridding in Reservoir Simulation

- Local Grid Refinement (LGR)
  - Simple grid refinement



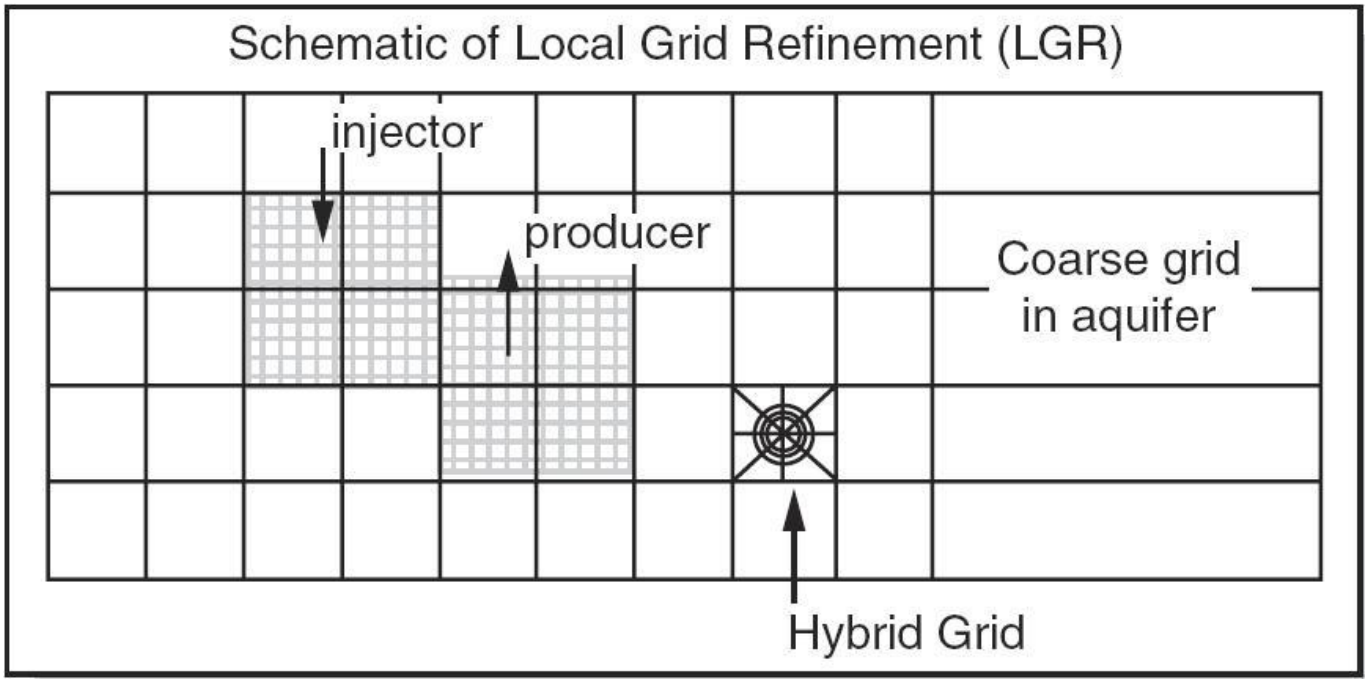
Gridding in Reservoir Simulation

- Local Grid Refinement (LGR)
  - Local Grid Refinement



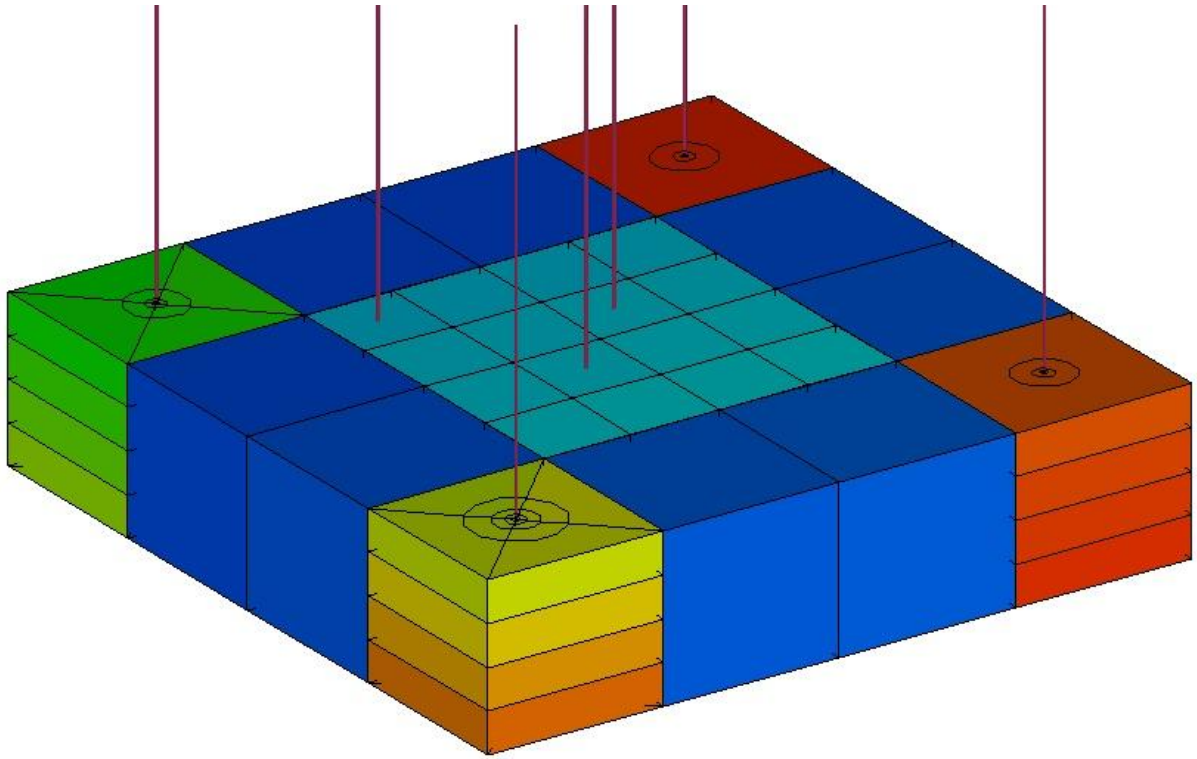
Gridding in Reservoir Simulation

- Local Grid Refinement (LGR)
  - Hybrid Grid Local Grid Refinement



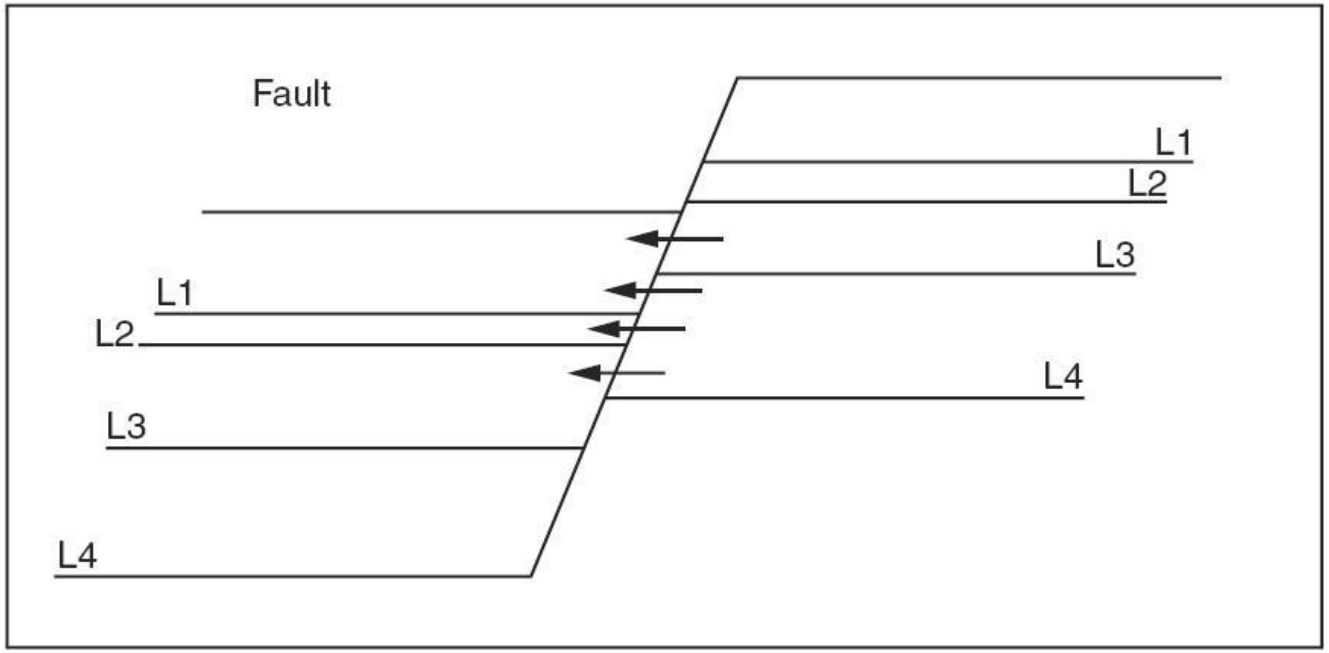
Gridding in Reservoir Simulation

- Local Grid Refinement (LGR)
  - Hybrid Grid Local Grid Refinement



Gridding in Reservoir Simulation

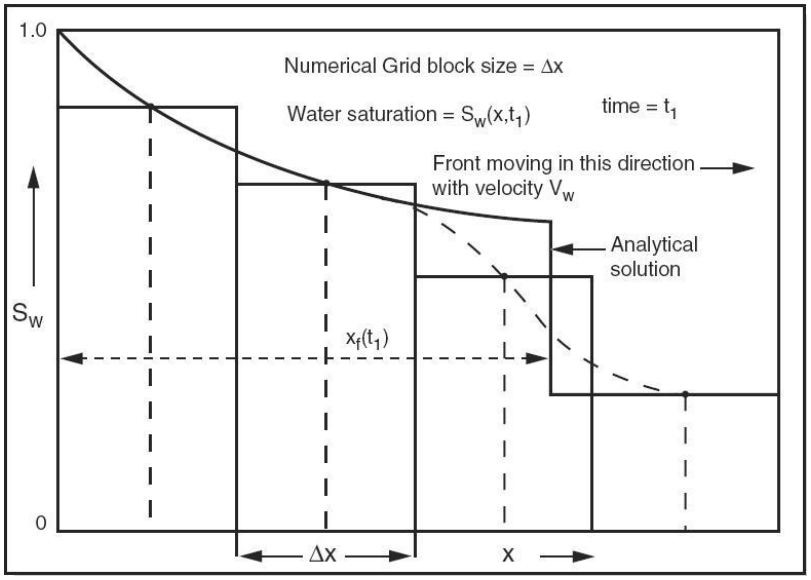
- Distorted grids
  - Faults modelling
    - Non-neighbor connections (NNC)



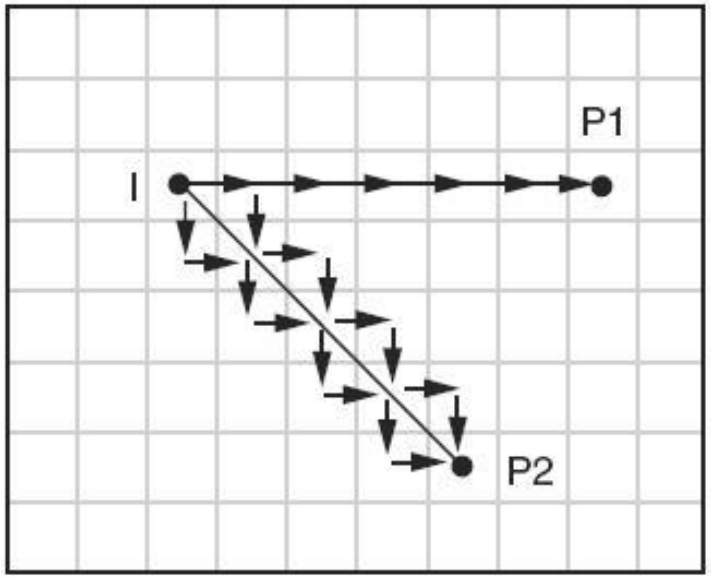
Gridding in Reservoir Simulation

Numerical problems

Numerical dispersion



Grid orientation



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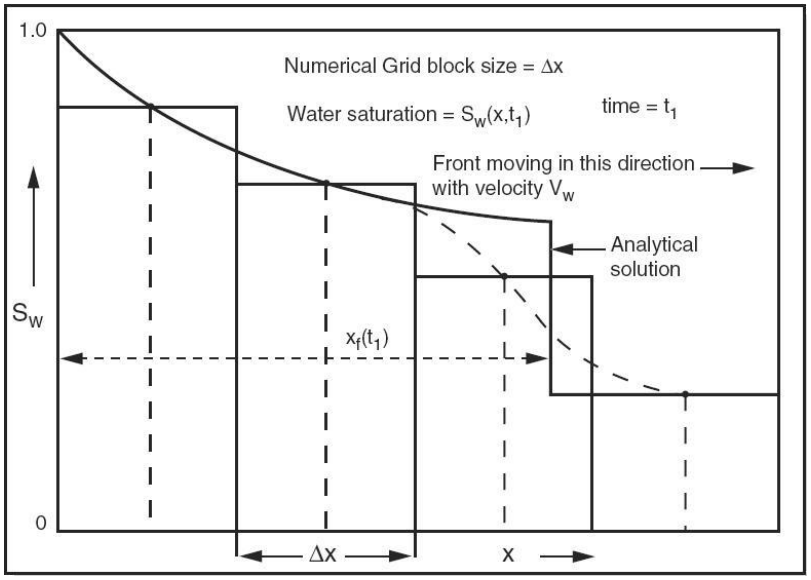

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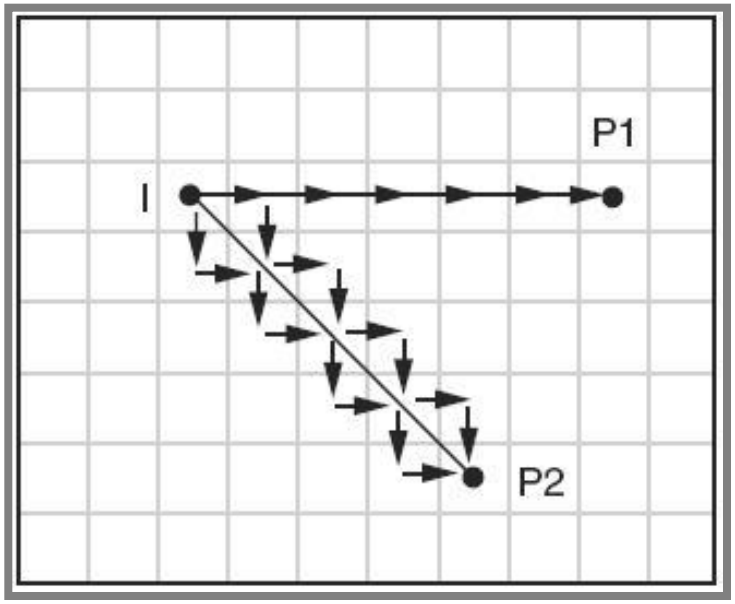
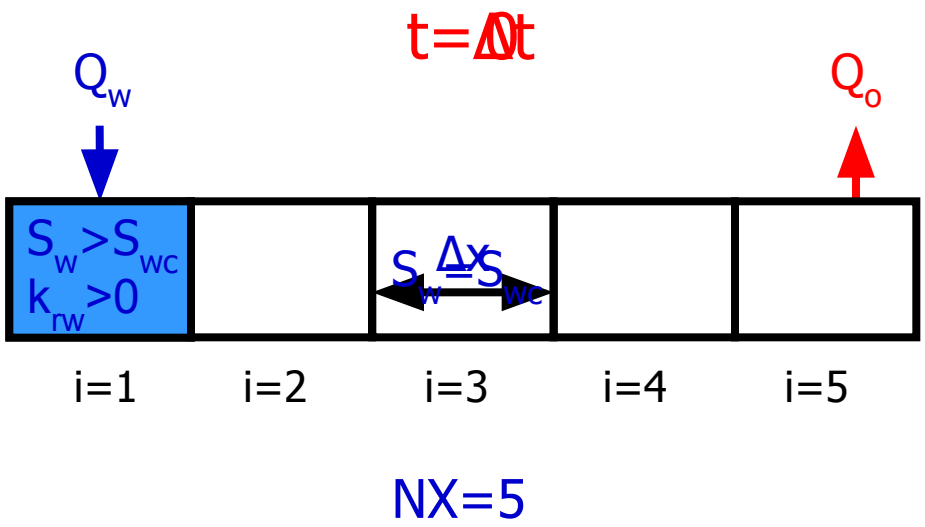
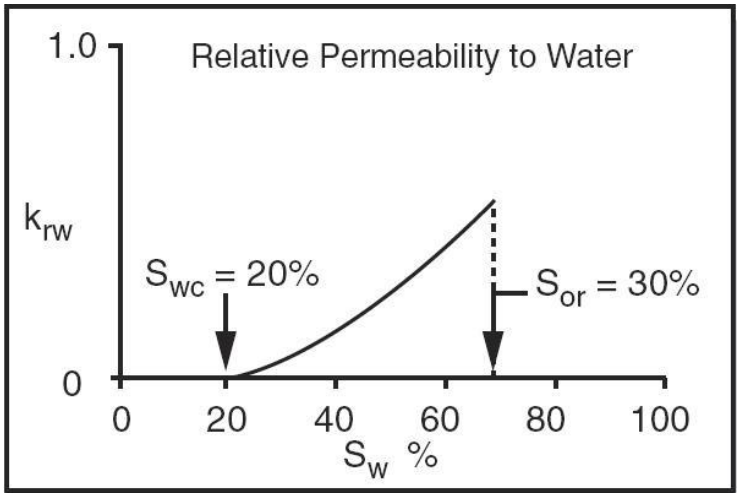


Gridding in Reservoir Simulation

- Numerical Dispersion
  - numerical error due to grid block approximation for solving the flow equations





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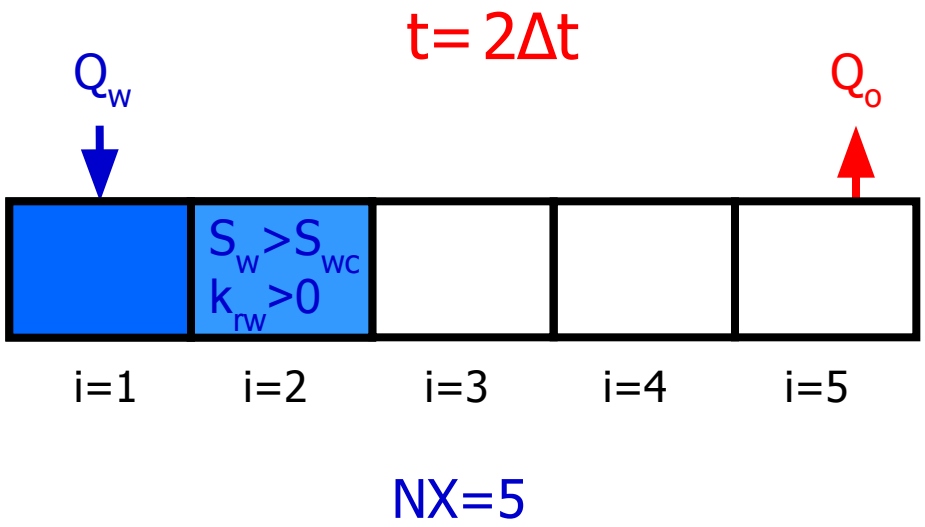

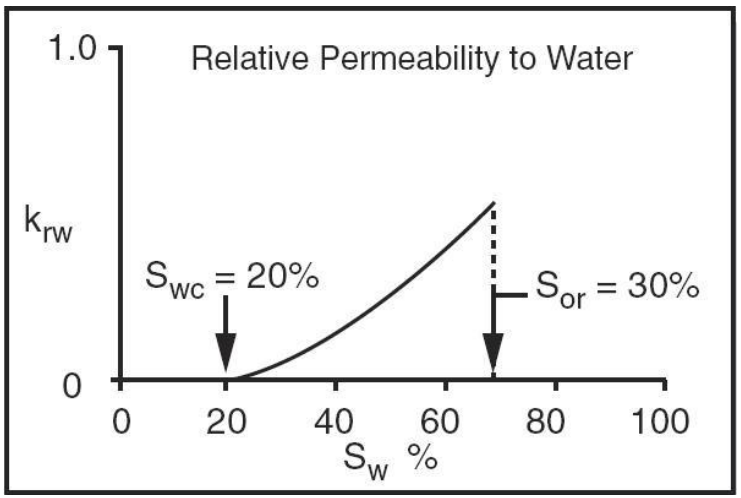

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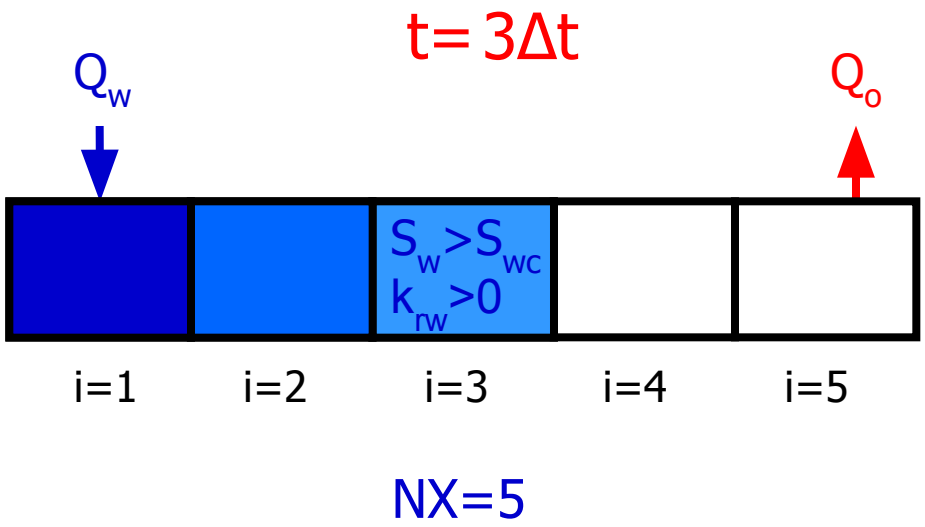

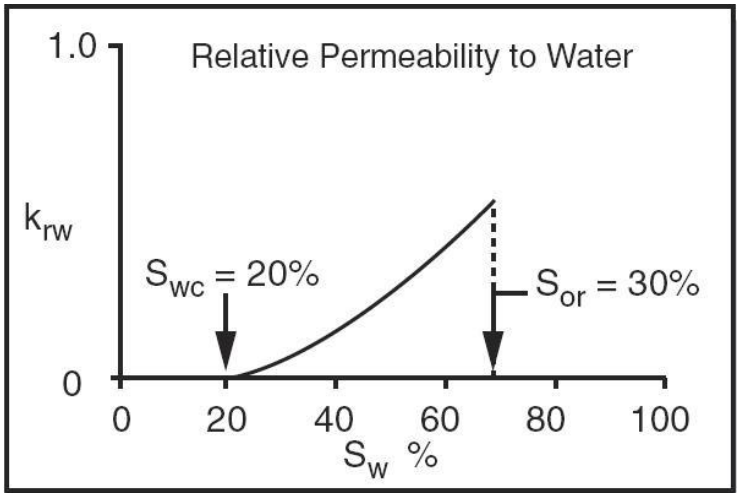

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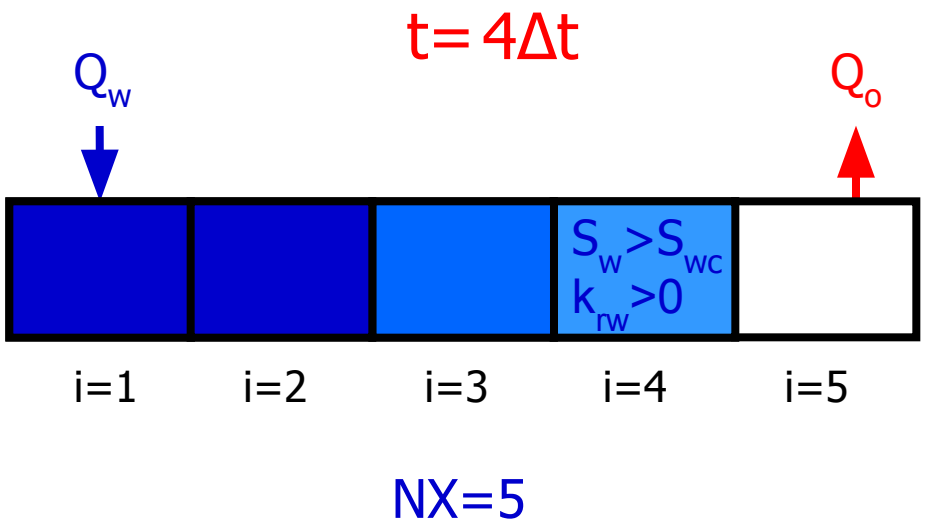

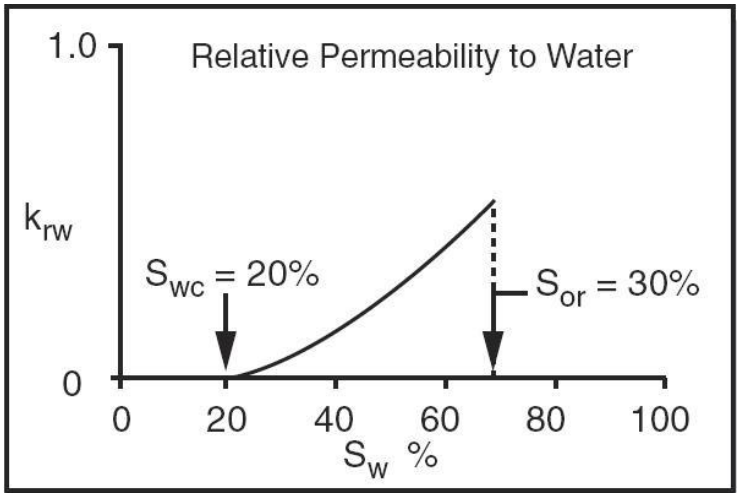

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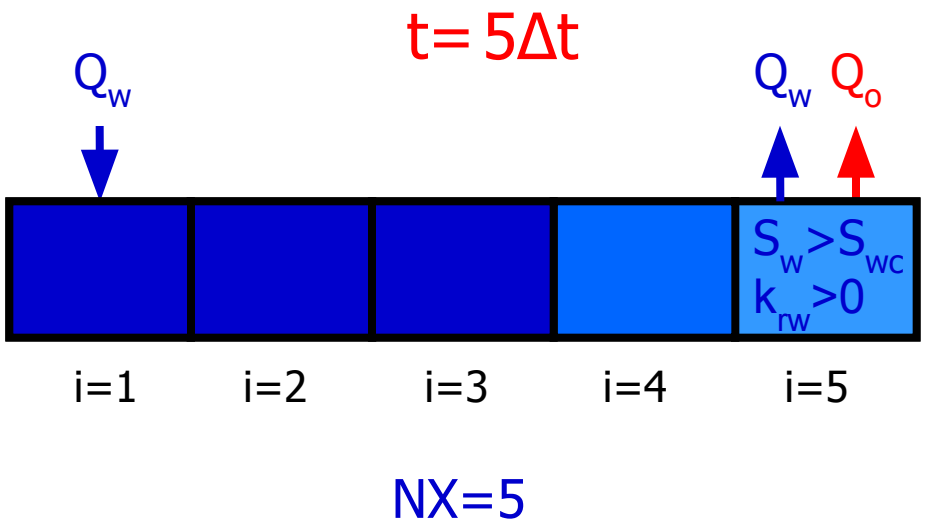
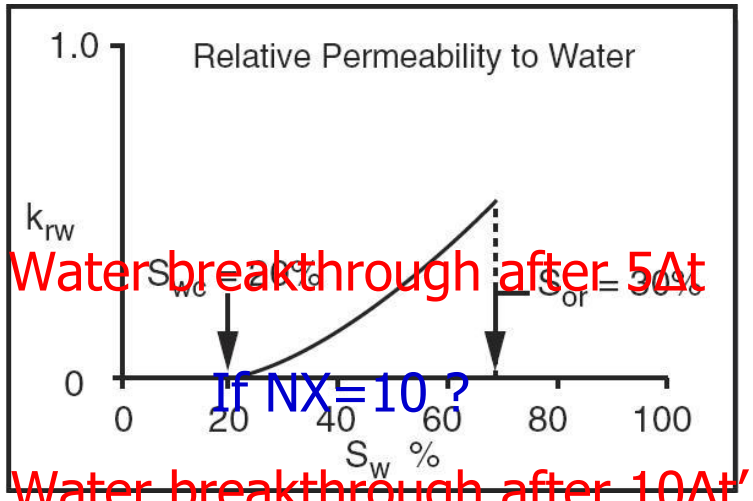
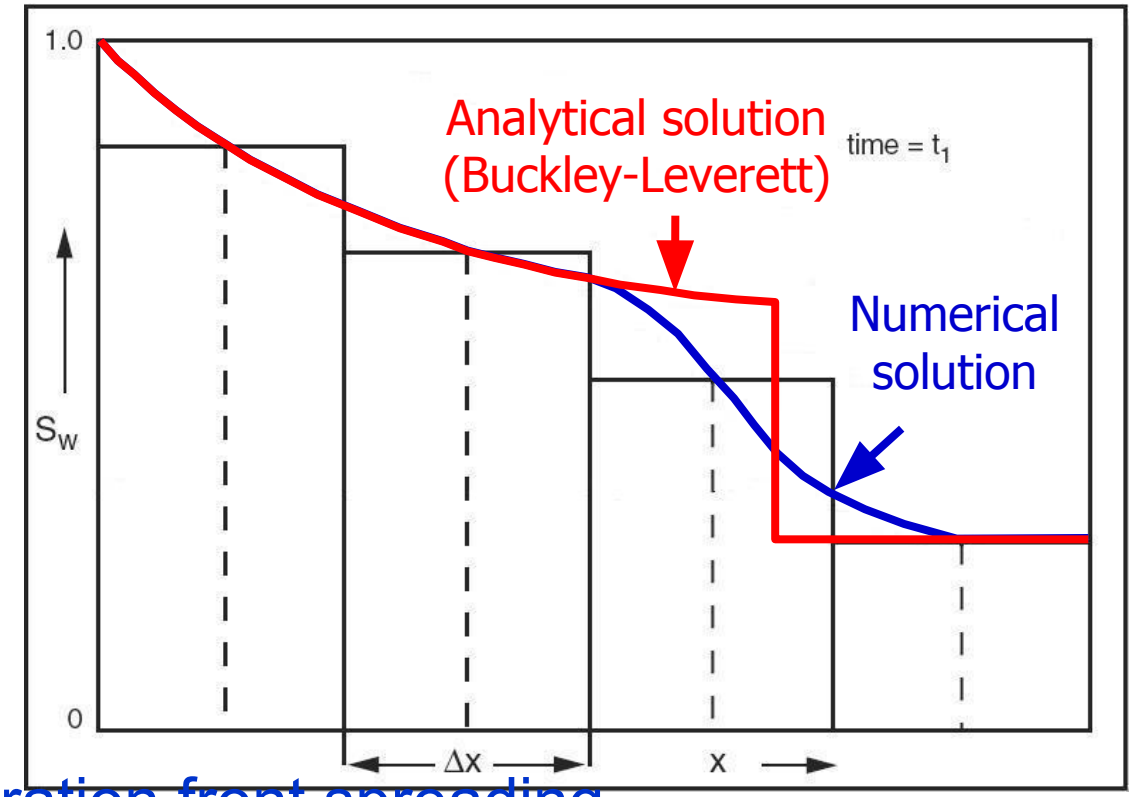




Gridding in Reservoir Simulation

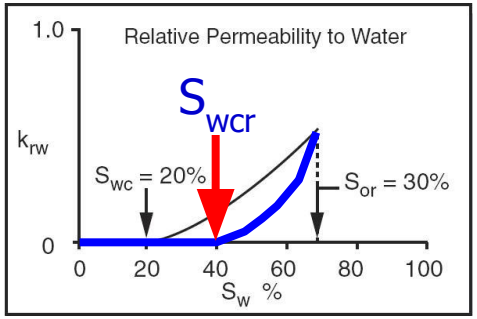
- Numerical Dispersion



  - saturation front spreading

Gridding in Reservoir Simulation

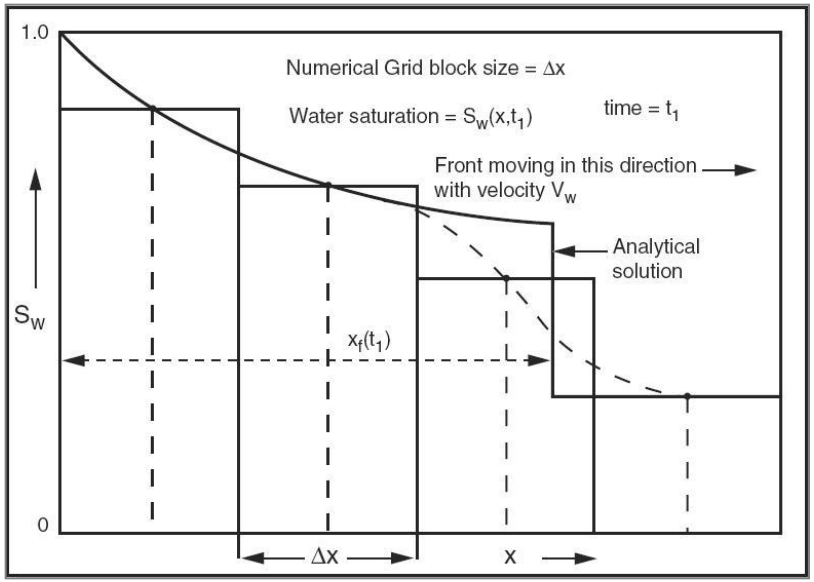
- Numerical Dispersion
  - Methods of reducing
    - Grid refinement (increase in number of grid blocks)
    - Use of Pseudo-relative permeabilities (2 phase upscaling)
    - Use of alternative simulation scheme (Streamline simulation)



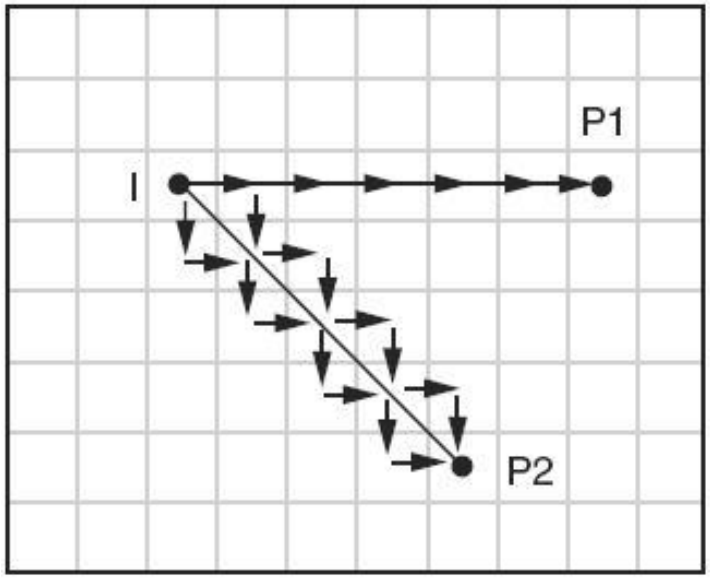
Gridding in Reservoir Simulation

Numerical problems

Numerical dispersion

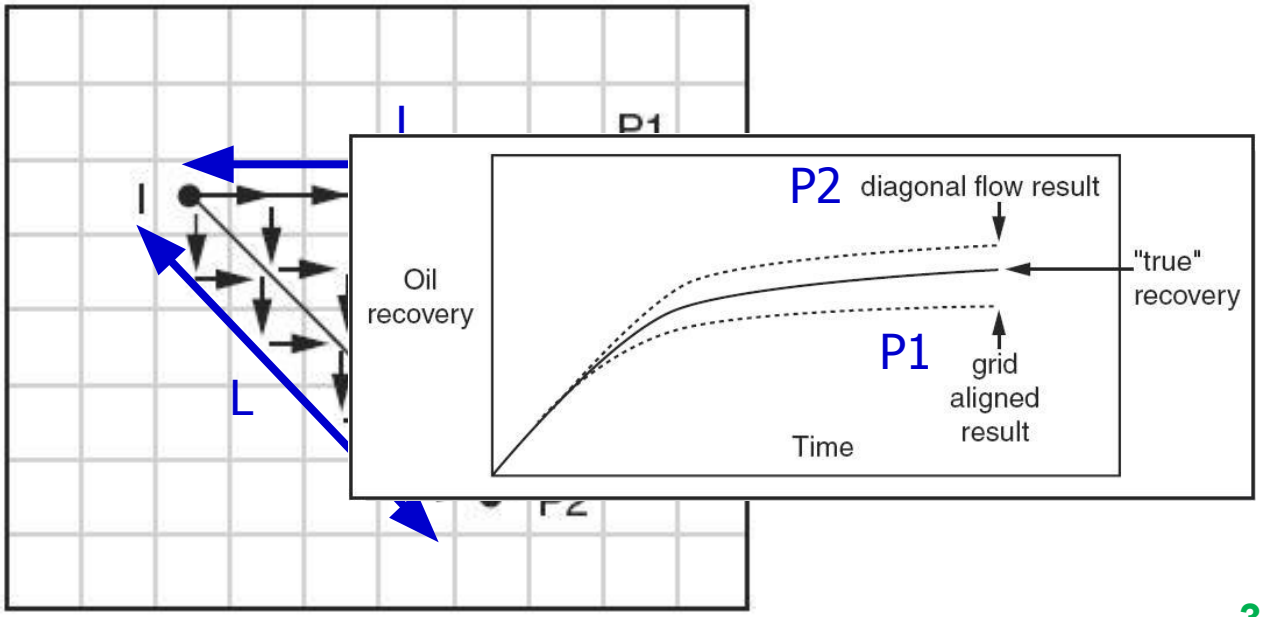


Grid orientation



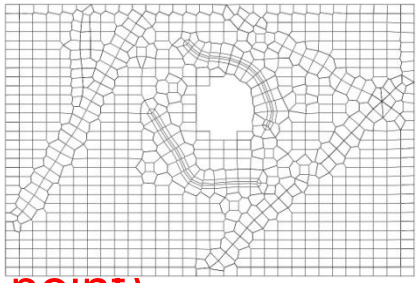
Gridding in Reservoir Simulation

- Grid Orientation effect
  - arises when the fluid flow both oriented with the principal and diagonal grid direction



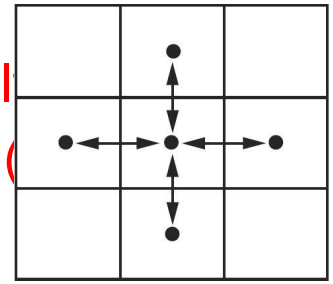
Gridding in Reservoir Simulation

- Grid Orientation effect
  - Methods of reducing
    - Grid refinement (increase in number of grid blocks)
    - Use of distorted grids (PEBI)

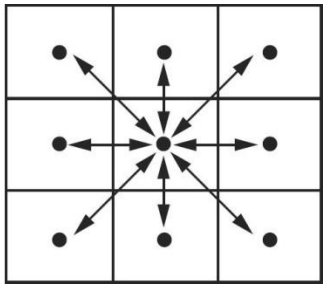


    - Use of improved numerical schemes (9-point)
    - Use of al ulation scheme (mulation)

5-point



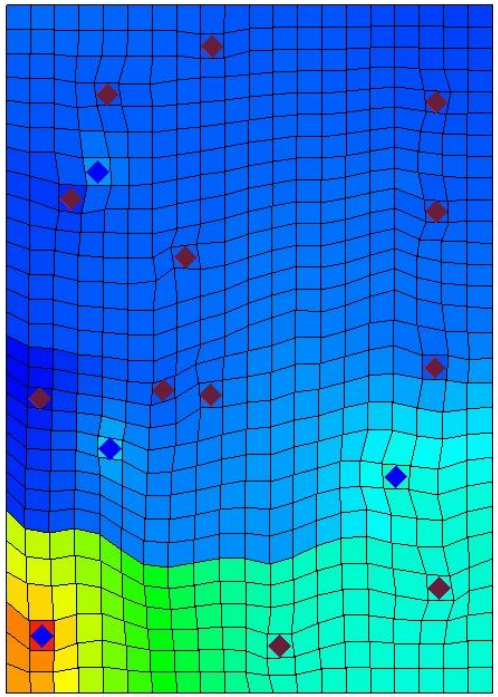
9-point



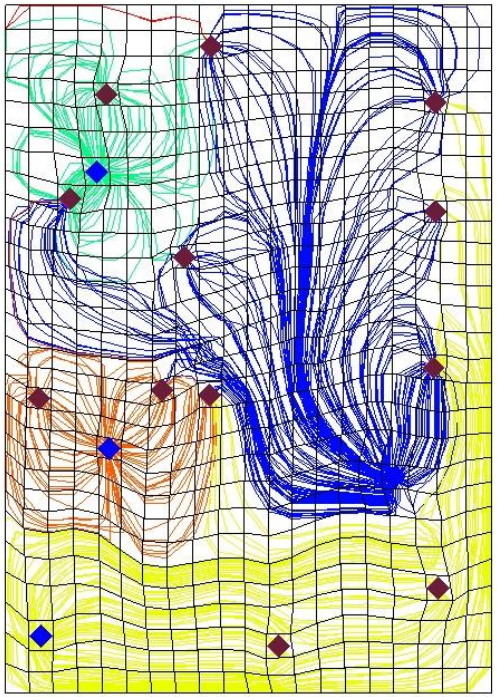
Gridding in Reservoir Simulation

- Streamline Simulation

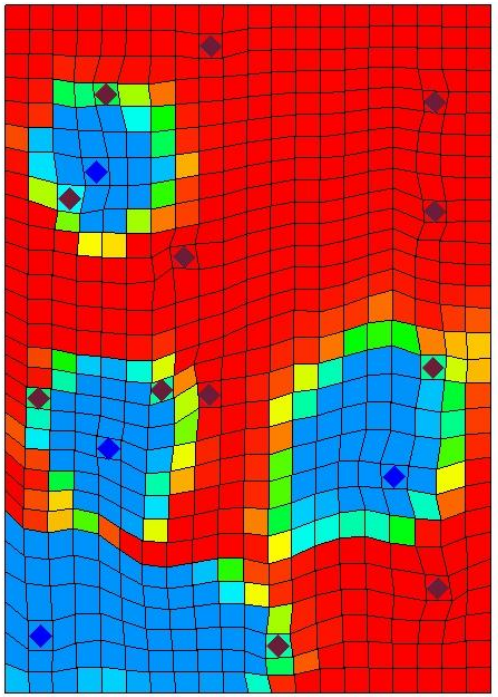
Pressure



Streamlines



Saturation



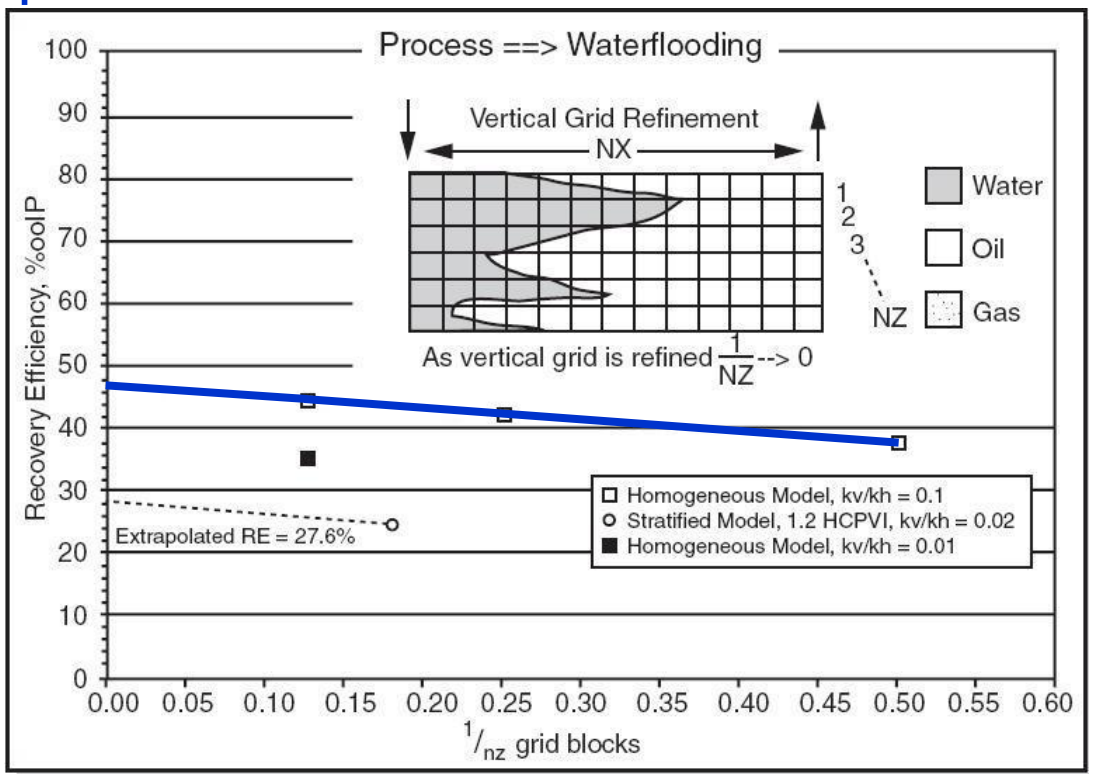
Gridding in Reservoir Simulation

- Issues in Choosing Reservoir Simulation Grid
  - Grid Dimension
    - 1D, 2D, 3D ?
  - Grid Geometry/Structure
    - Cartesian, Distorted, LGR ?
  - Grid Fineness/Coarseness
    - Grid block size (number of grid blocks) ?

should be related to the simplicity/complexity of the problem

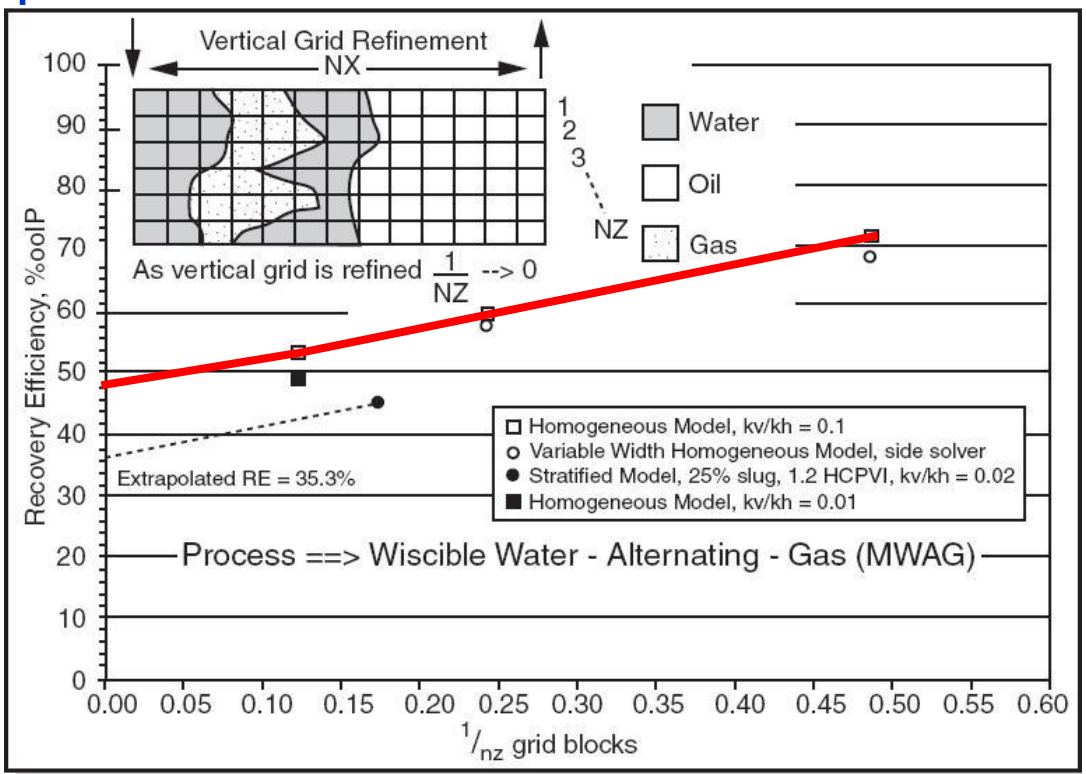
Gridding in Reservoir Simulation

- Issues in Choosing Reservoir Simulation Grid
  - Example 1



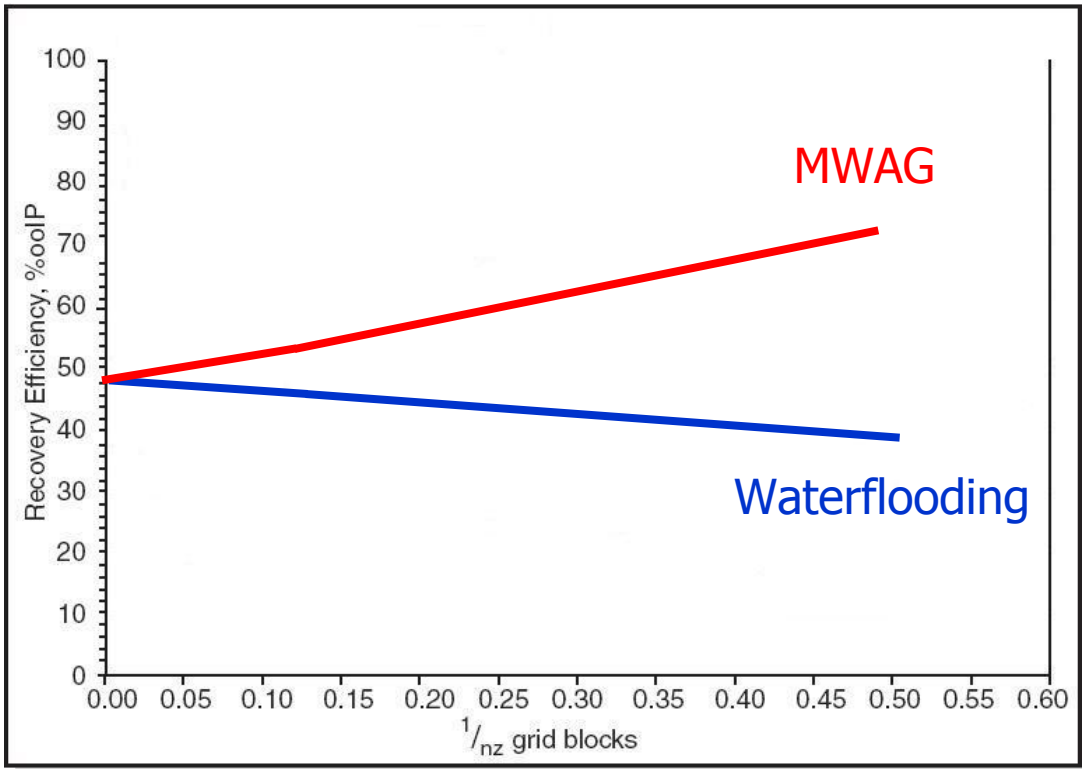
Gridding in Reservoir Simulation

- Issues in Choosing Reservoir Simulation Grid
  - Example 1



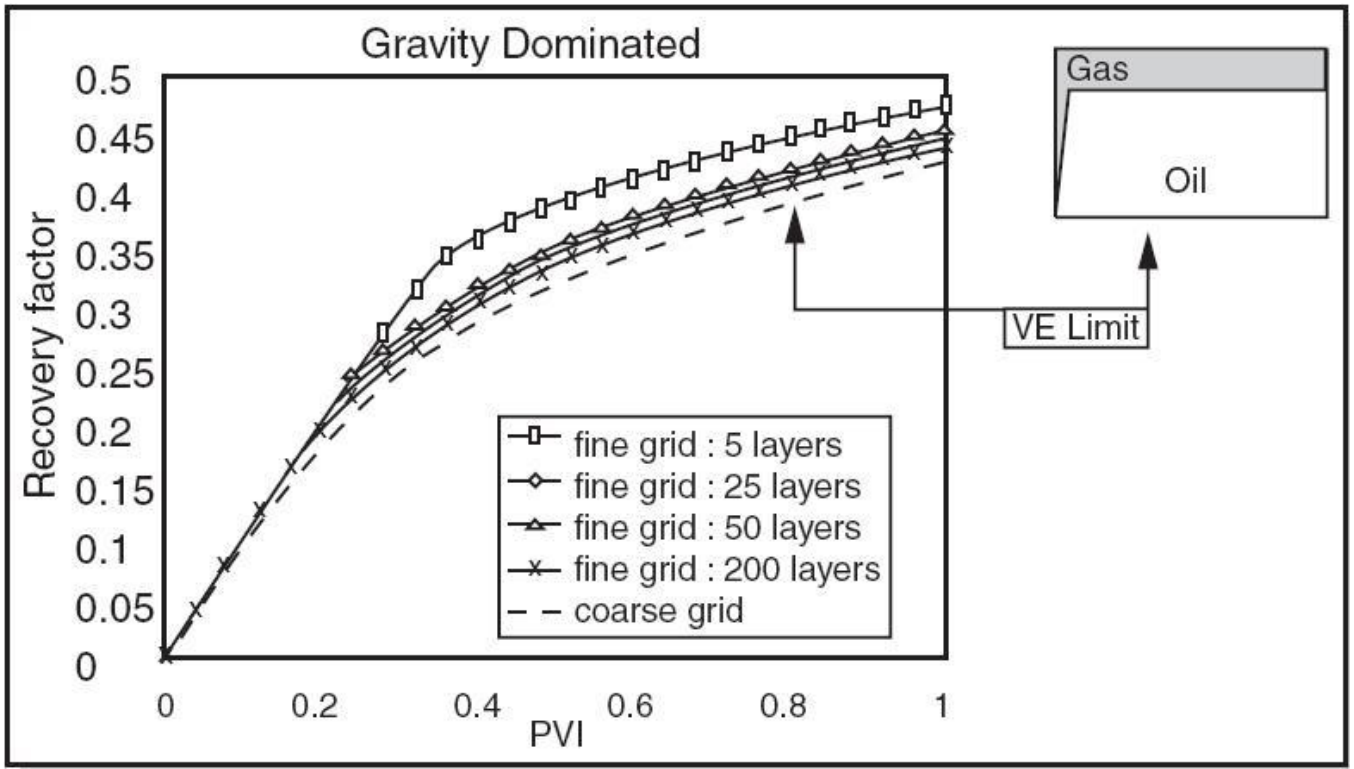
Gridding in Reservoir Simulation

- Issues in Choosing Reservoir Simulation Grid
  - Example 1



Gridding in Reservoir Simulation

- Issues in Choosing Reservoir Simulation Grid
  - Example 2

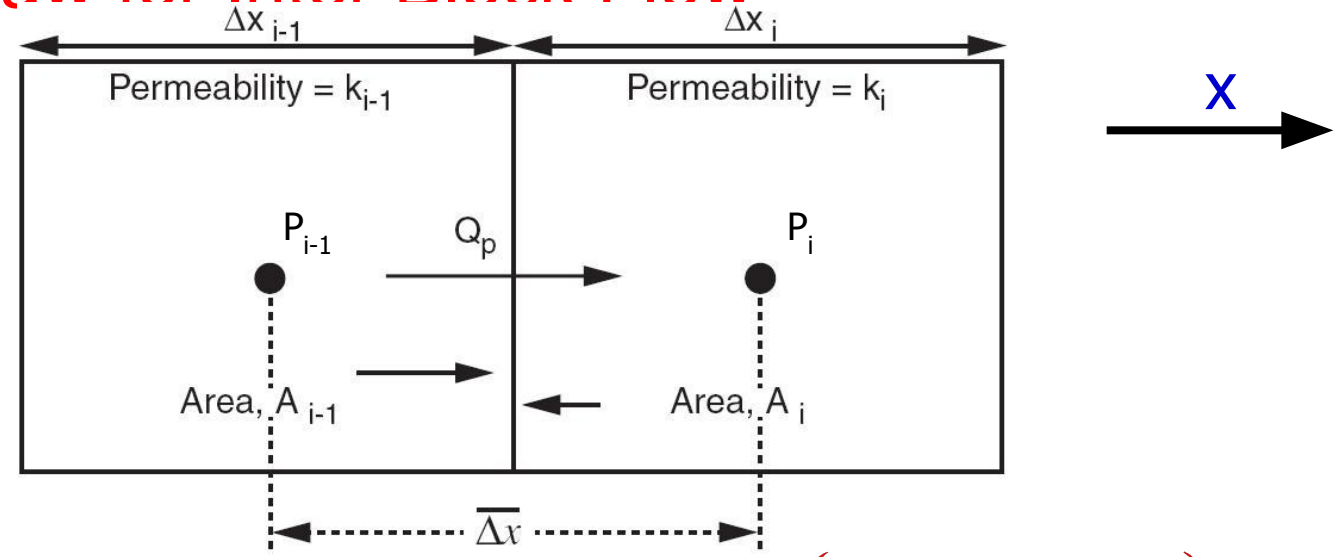


Outline

- Gridding in Reservoir Simulation
- Calculation of Block to Block Flows in Reservoir Simulators
- Wells in Reservoir Simulation

Calculation of Block to Block Flows in Reservoir Simulators

- Darcy Law for Inter Block Flow

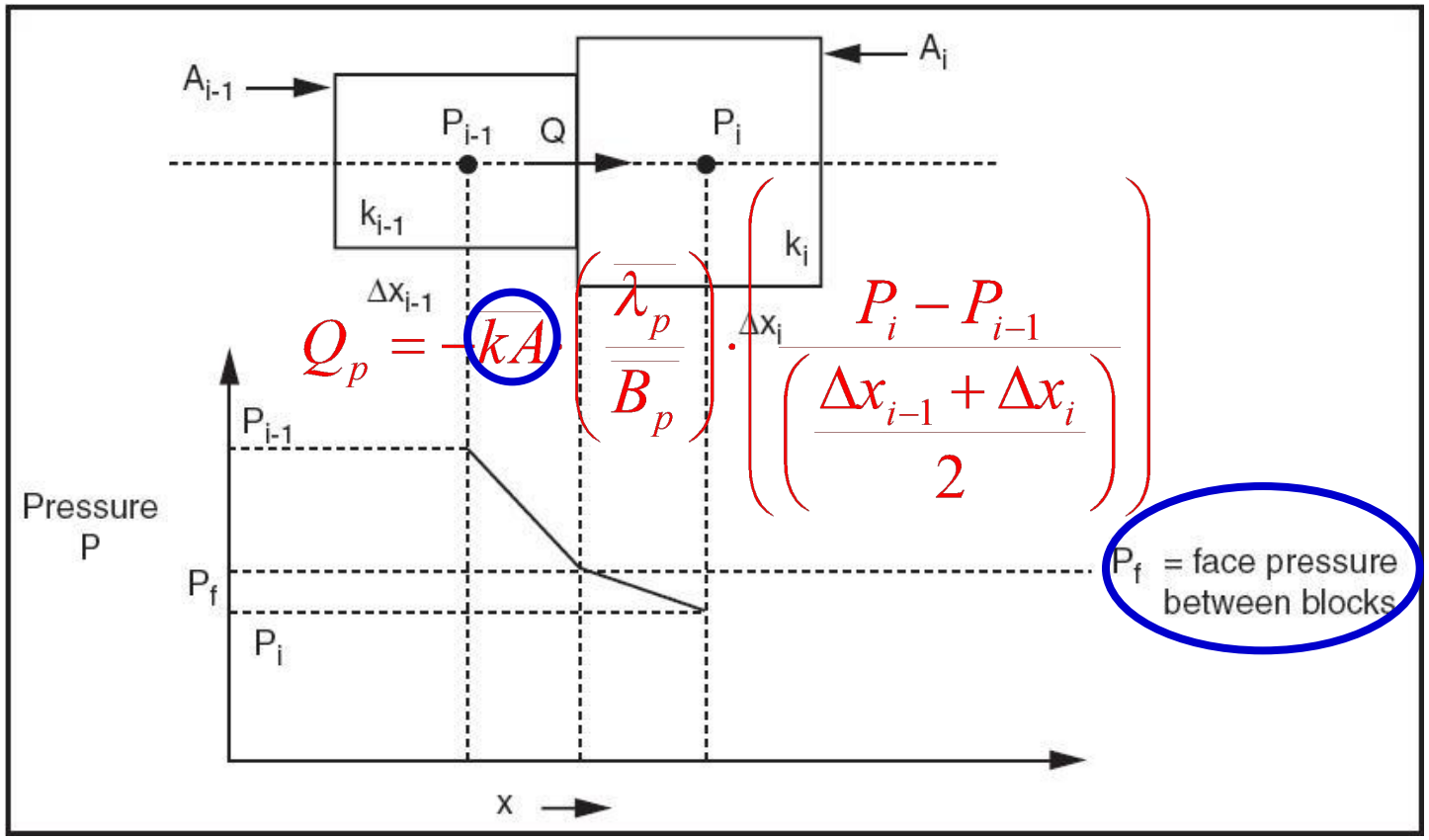


$$Q_p = -\overline{kA} \cdot \left(\frac{\overline{\lambda_p}}{B_p} \right) \cdot \left(\frac{\Delta P}{\Delta x} \right) = -\overline{kA} \cdot \left(\frac{\overline{\lambda_p}}{B_p} \right) \cdot \left(\frac{P_i - P_{i-1}}{\left(\frac{\Delta x_{i-1} + \Delta x_i}{2} \right)} \right)$$

?

Calculation of Block to Block Flows in Reservoir Simulators

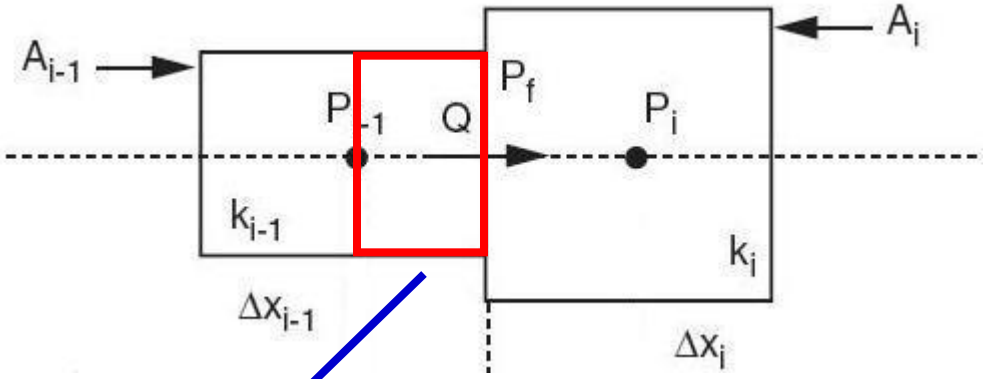
- Averaging k-A Product, $\overline{kA}$



Calculation of Block to Block Flows in Reservoir Simulators

- Averaging k-A Product, $\overline{kA}$

block i-1

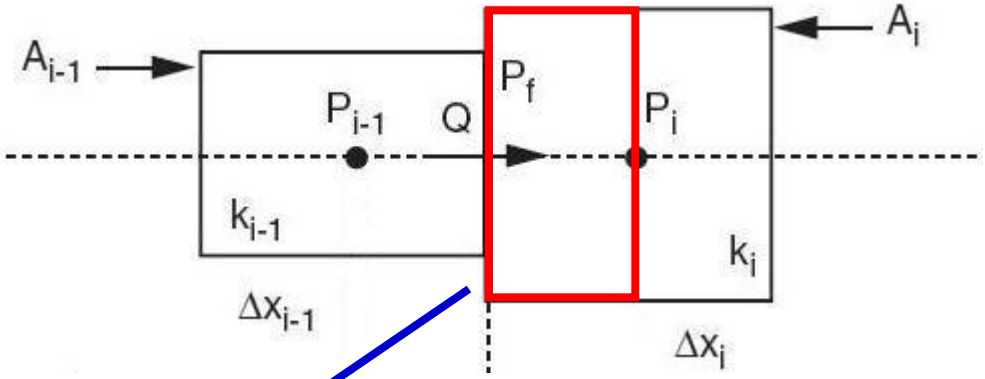


$$Q = -\frac{k_{i-1} \cdot A_{i-1}}{\mu} \cdot \left(\frac{P_f - P_{i-1}}{\frac{\Delta x_{i-1}}{2}} \right) \rightarrow \left(P_f - P_{i-1}\right) = -Q\mu \cdot \frac{\Delta x_{i-1}}{2} \cdot \left(\frac{1}{(k \cdot A)_{i-1}} \right)$$

Calculation of Block to Block Flows in Reservoir Simulators

- Averaging k-A Product, $\overline{kA}$

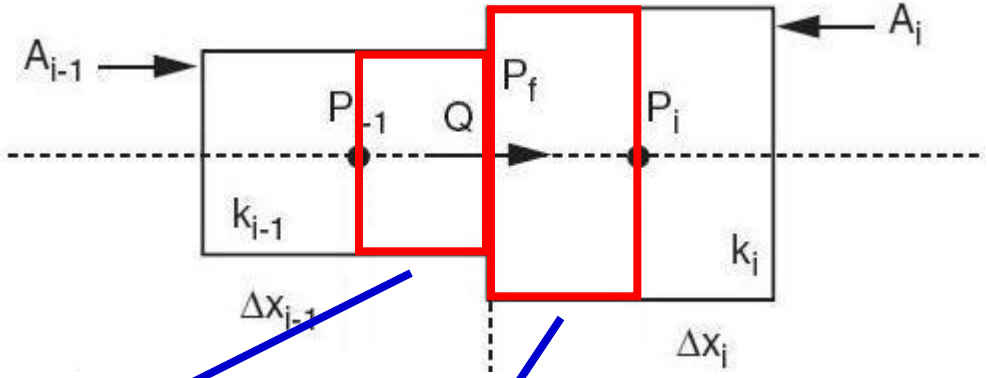
block i



$$Q = -\frac{k_i \cdot A_i}{\mu} \cdot \left(\frac{P_i - P_f}{\frac{\Delta x_i}{2}} \right) \rightarrow \left(P_i - P_f \right) = -Q\mu \cdot \frac{\Delta x_i}{2} \cdot \left(\frac{1}{(k \cdot A)_i} \right)$$

Calculation of Block to Block Flows in Reservoir Simulators

- Averaging k-A Product, $\overline{kA}$



$$\left(P_f - P_{i-1}\right) = -Q\mu \cdot \frac{\Delta x_{i-1}}{2} \cdot \left(\frac{1}{(k \cdot A)_{i-1}}\right)$$

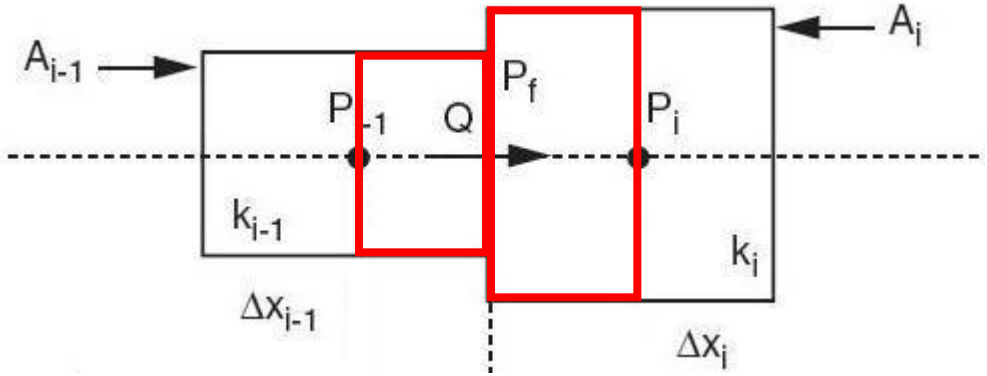
$$+$$

$$\left(P_i - P_f\right) = -Q\mu \cdot \frac{\Delta x_i}{2} \cdot \left(\frac{1}{(k \cdot A)_i}\right)$$

$$\rightarrow \quad \left(P_i - P_{i-1}\right) = -\frac{Q\mu}{2} \cdot \left(\frac{\Delta x_{i-1}}{(k \cdot A)_{i-1}} + \frac{\Delta x_i}{(k \cdot A)_i}\right)$$

Calculation of Block to Block Flows in Reservoir Simulators

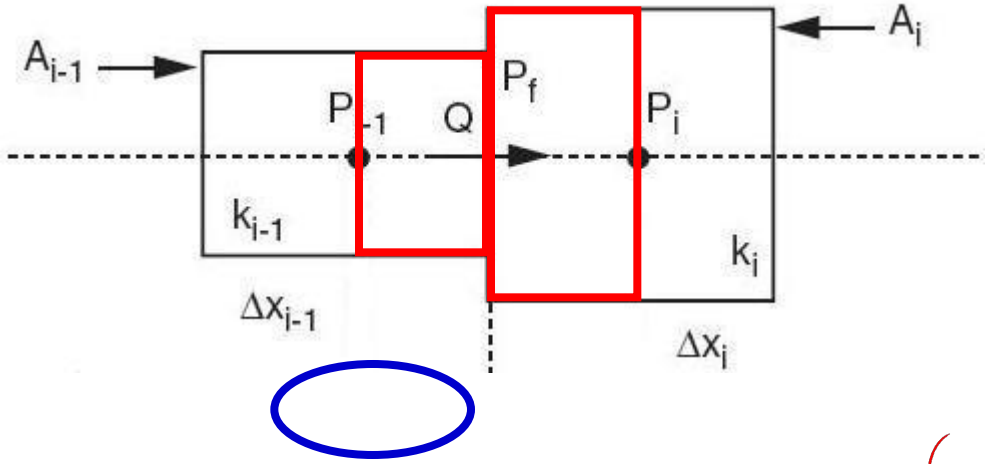
- Averaging k-A Product, $\overline{kA}$



$$Q = -\frac{1}{\mu}\cdot\left(\frac{2\left(P_i - P_{i-1}\right)}{\frac{\Delta x_{i-1}}{(k\cdot A)_{i-1}} + \frac{\Delta x_i}{(k\cdot A)_i}}\right) = -\frac{Q\mu}{2}\cdot\left(P_i - P_{i-1}\right)\cdot\left(\frac{\Delta x_{i-1}}{(k\cdot A)_{i-1}} + \frac{\Delta x_i}{(k\cdot A)_i}\right)$$

Calculation of Block to Block Flows in Reservoir Simulators

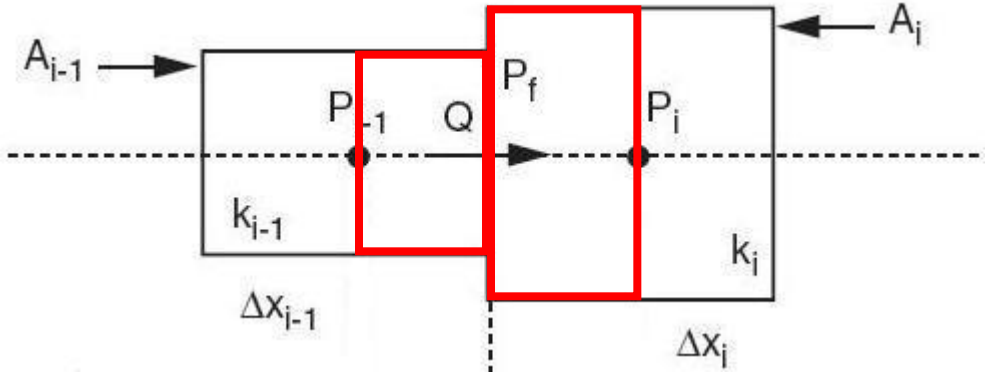
- Averaging k-A Product, $\overline{kA}$



$$Q = -\frac{\overline{kA}}{\mu}\cdot\left(\frac{P_i - P_{i-1}}{\frac{\Delta x_{i-1}+\Delta x_i}{2}}\right) \qquad \frac{1}{\mu}\cdot\left(\frac{2\cdot(P_i - P_{i-1})}{\frac{\Delta x_{i-1}}{(k\cdot A)_{i-1}}+\frac{\Delta x_i}{(k\cdot A)_i}}\right) \qquad \frac{\overline{kA}}{\left(\frac{\Delta x_{i-1}+\Delta x_i}{2}\right)} = \left(\frac{2}{\frac{\Delta x_{i-1}}{(k\cdot A)_{i-1}}+\frac{\Delta x_i}{(k\cdot A)_i}}\right)$$

Calculation of Block to Block Flows in Reservoir Simulators

- Averaging k-A Product, $\overline{kA}$



$$\overline{kA} = \frac{\Delta x_{i-1} + \Delta x_i}{\left(\frac{\Delta x_{i-1}}{(k \cdot A)_{i-1}} + \frac{\Delta x_i}{(k \cdot A)_i}\right)} = \frac{2}{\left(\frac{\Delta x_{i-1}}{(k \cdot A)_{i-1}} + \frac{\Delta x_i}{(k \cdot A)_i}\right)\left(\frac{\Delta x_{i-1} + \Delta x_i}{2}\right)}$$

Harmonic average

Calculation of Block to Block Flows in Reservoir Simulators

- Averaging k-A Product, $\overline{kA}$

Harmonic average

$$Q_p = -\overline{kA}\left(\frac{\overline{\lambda_p}}{\overline{B_p}}\right)\cdot\left(\frac{P_i - P_{i-1}}{\left(\frac{\Delta x_{i-1} + \Delta x_i}{2}\right)}\right)$$

Calculation of Block to Block Flows in Reservoir Simulators

- Averaging Two-Phase Mobility, $\overline{\lambda}_p$

$$\overline{\lambda}_p = \frac{\overline{k}_{rp}}{\overline{\mu}_p}$$

$$Q_p = -\overline{k}A \cdot \left(\frac{\overline{\lambda}_p}{\overline{B}_p}\right) = -\overline{k}A \cdot \left(\frac{\overline{k}_{rp}}{\overline{\mu}_p \overline{B}_p}\right) \cdot \left(\frac{P_i - P_{i-1}}{\left(\frac{\Delta x_{i-1} + \Delta x_i}{2}\right)}\right)$$

$$\overline{\mu}_p = \frac{\mu_{i-1} + \mu_i}{2} \qquad \overline{B}_p = \frac{B_{i-1} + B_i}{2}$$

Arithmetic average

Calculation of Block to Block Flows in Reservoir Simulators

- Averaging Two-Phase Mobility, $\overline{\lambda}_p$

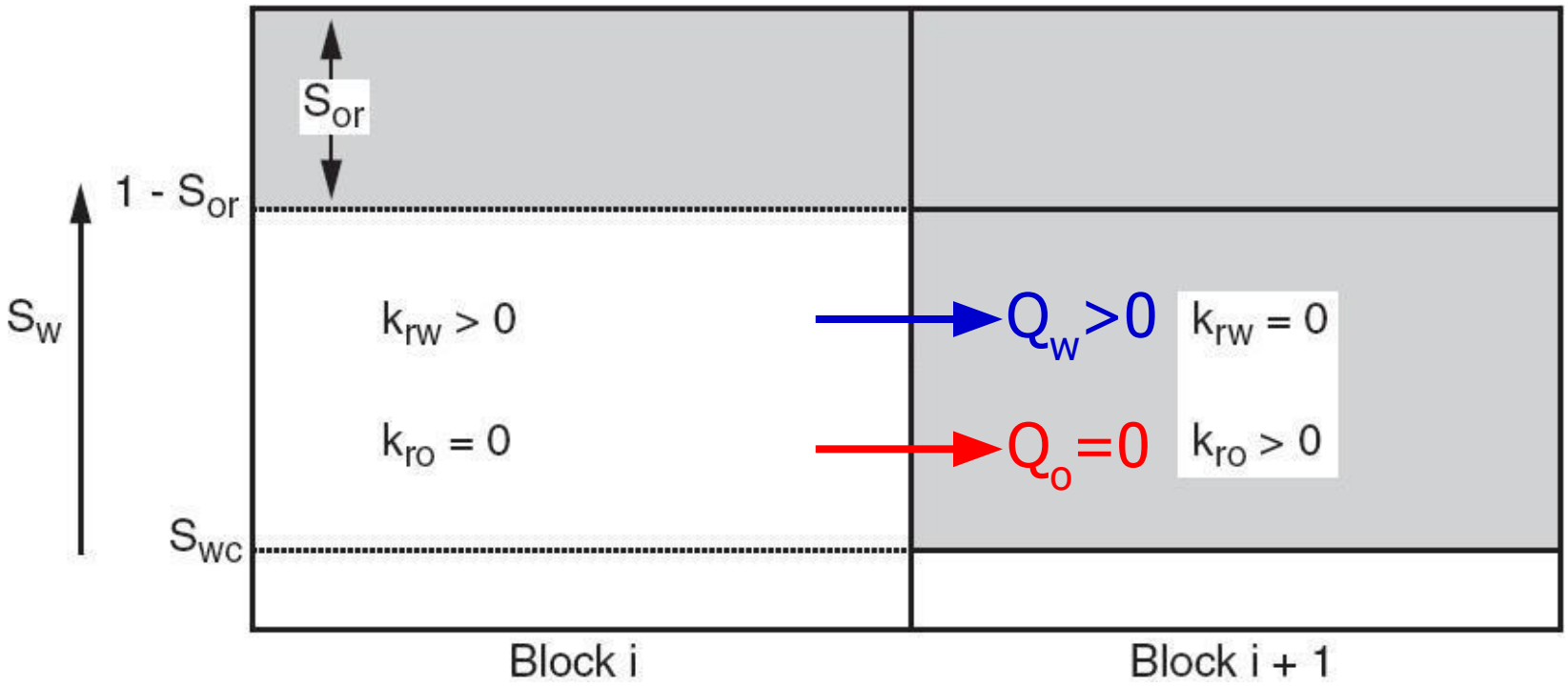
Harmonic average

$$Q_p = -\overline{kA} \cdot \left(\frac{\overline{k_{rp}}}{\mu_p \cdot B_p} \right) \cdot \left(\frac{P_i - P_{i-1}}{\left(\frac{\Delta x_{i-1} + \Delta x_i}{2} \right)} \right)$$

Arithmetic average

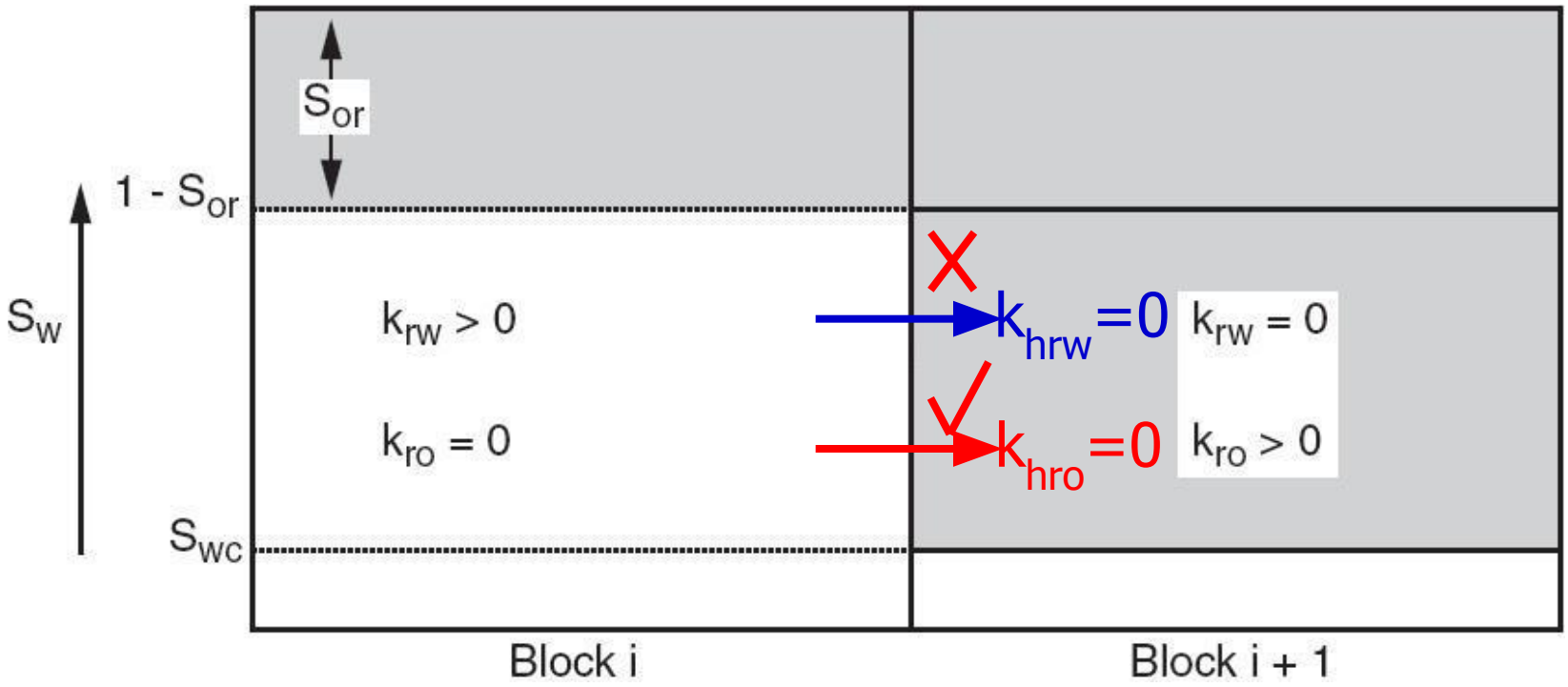
Calculation of Block to Block Flows in Reservoir Simulators

- Averaging Two-Phase Mobility, $\bar{\lambda}_p$
  - Physically



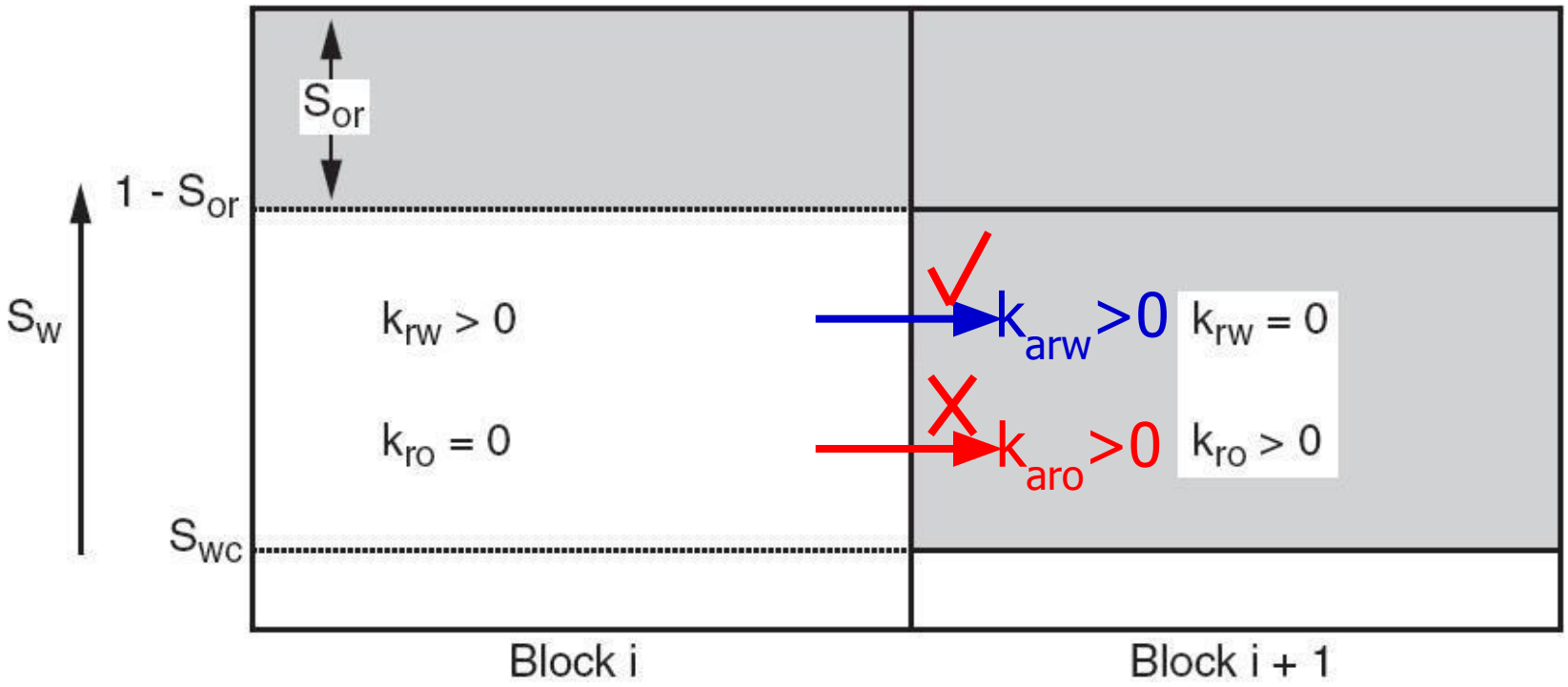
Calculation of Block to Block Flows in Reservoir Simulators

- Averaging Two-Phase Mobility, $\bar{\lambda}_p$
  - ~~Harmonic average (k_h) ?~~



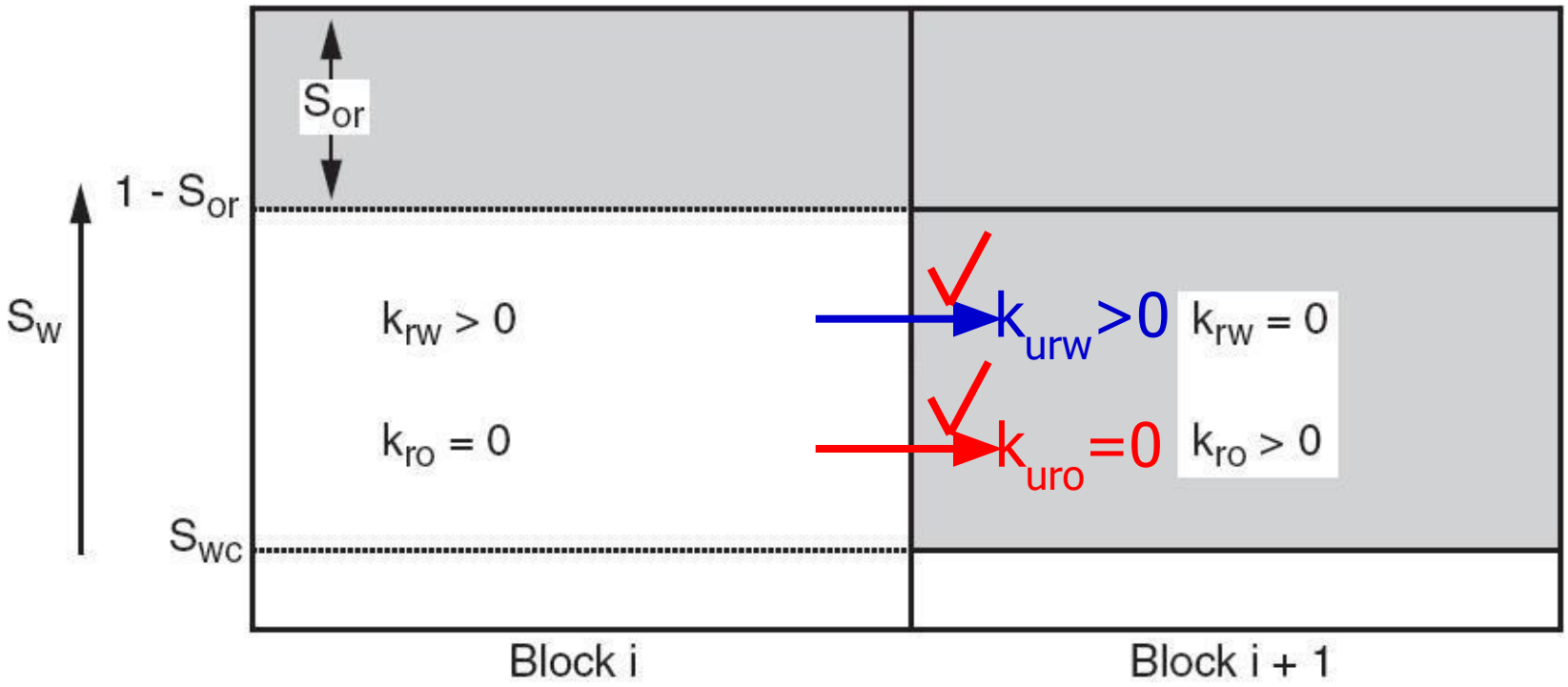
Calculation of Block to Block Flows in Reservoir Simulators

- Averaging Two-Phase Mobility, $\overline{\lambda}_p$
  - ~~Arithmetic average (k_a) ?~~



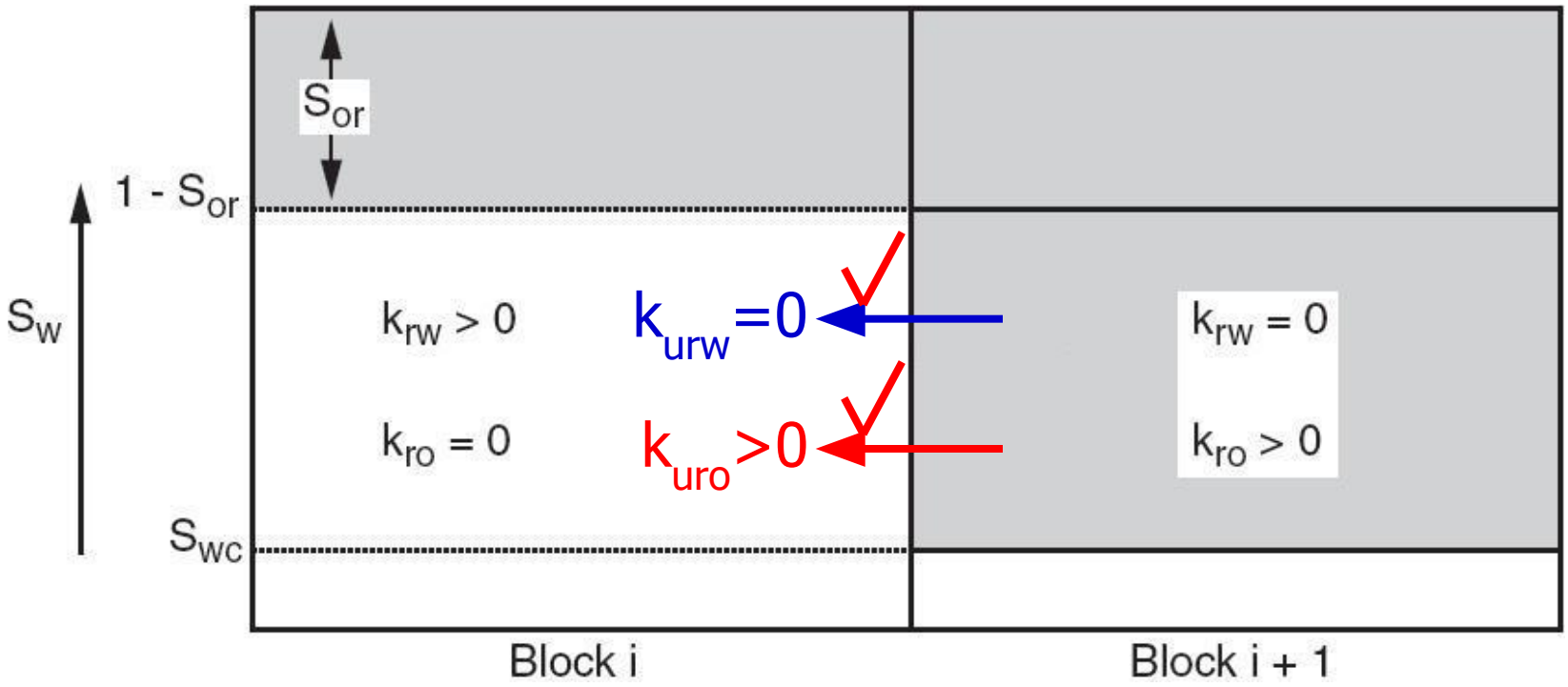
Calculation of Block to Block Flows in Reservoir Simulators

- Averaging Two-Phase Mobility, $\bar{\lambda}_p$
  - Upstream value ?



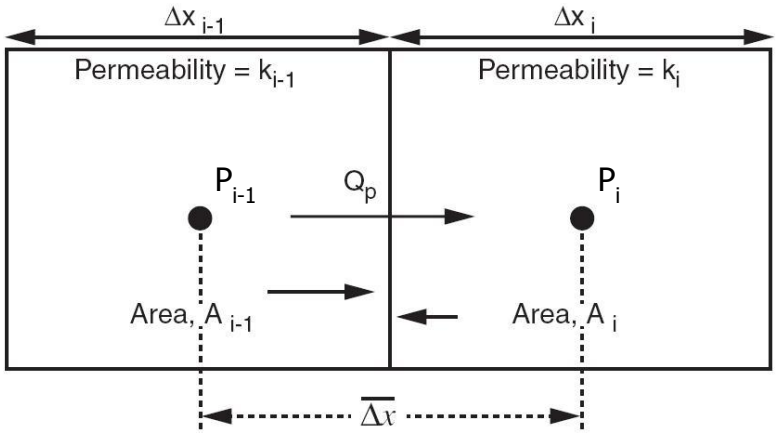
Calculation of Block to Block Flows in Reservoir Simulators

- Averaging Two-Phase Mobility, $\bar{\lambda}_p$
  - Upstream value ? ✓



Calculation of Block to Block Flows in Reservoir Simulators

- Summary



Harmonic average

Upstream value

$$Q_p = -\overline{kA} \cdot \left(\frac{\overline{k_{rr}}}{\overline{\mu_r} \cdot \overline{B_r}} \right) \cdot \left(\frac{\Delta P}{\Delta x} \right)$$

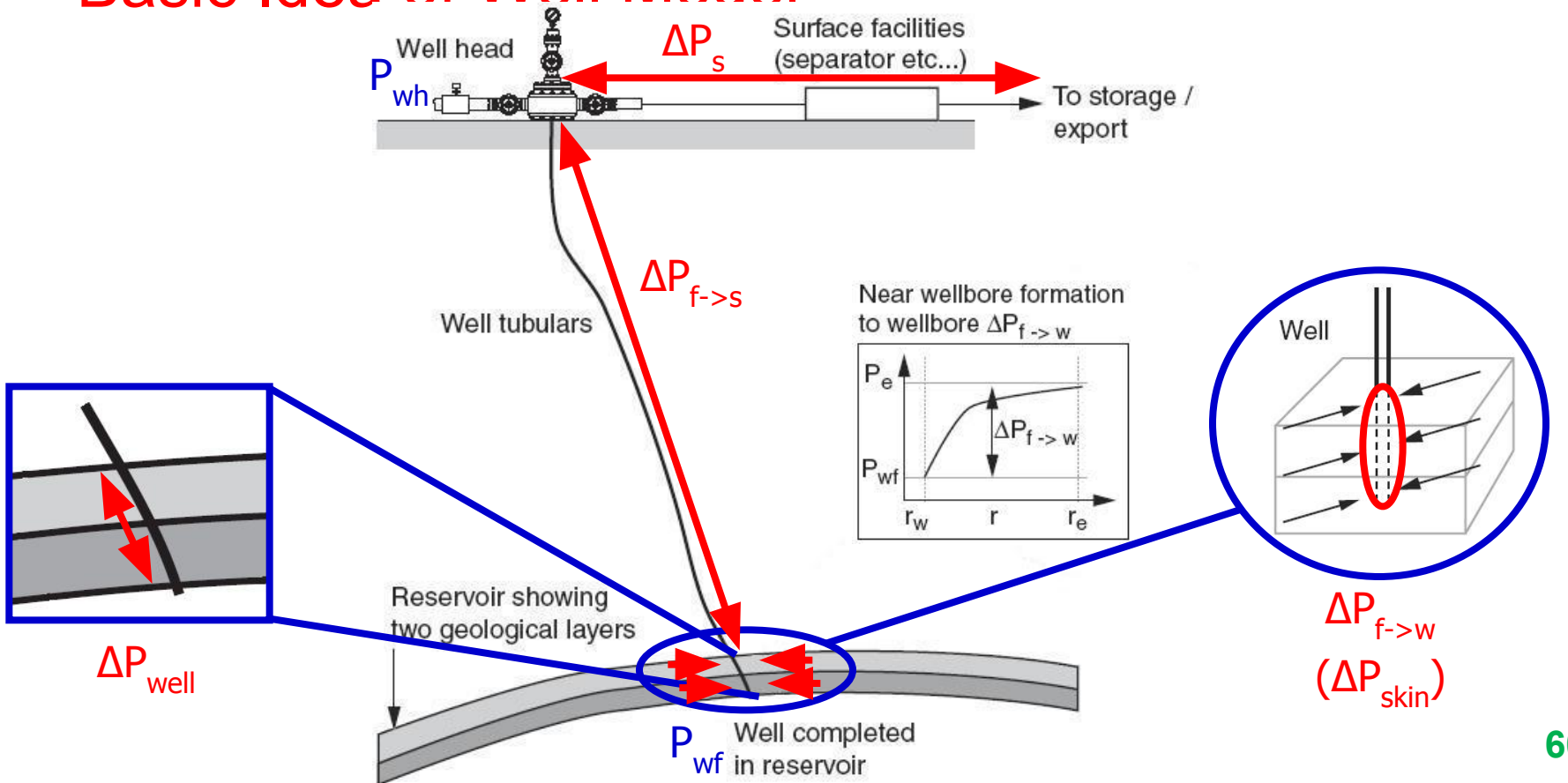
Arithmetic average

Outline

- Gridding in Reservoir Simulation
- Calculation of Block to Block Flows in Reservoir Simulators
- Wells in Reservoir Simulation

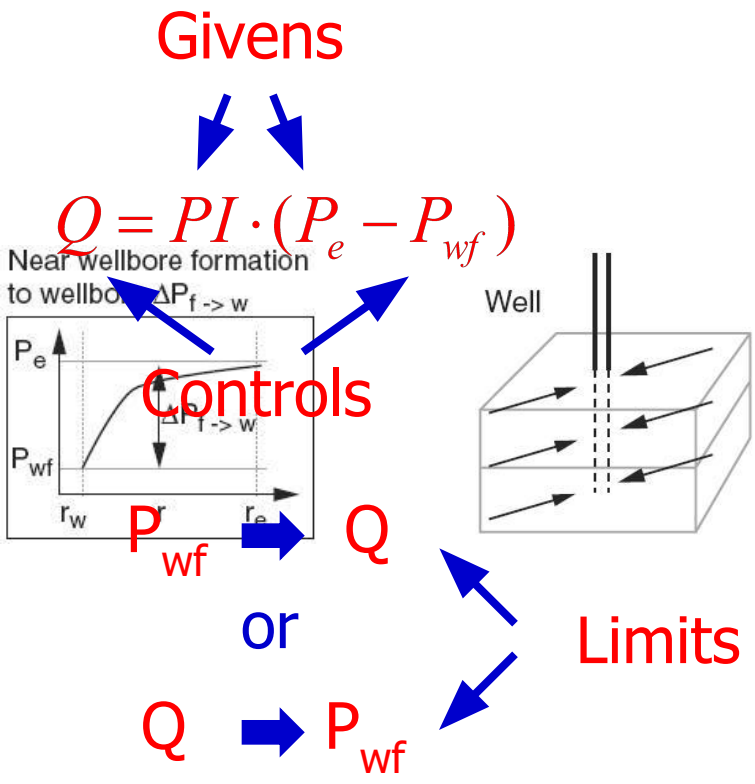
Wells in Reservoir Simulation

- Basic Idea of Well Model



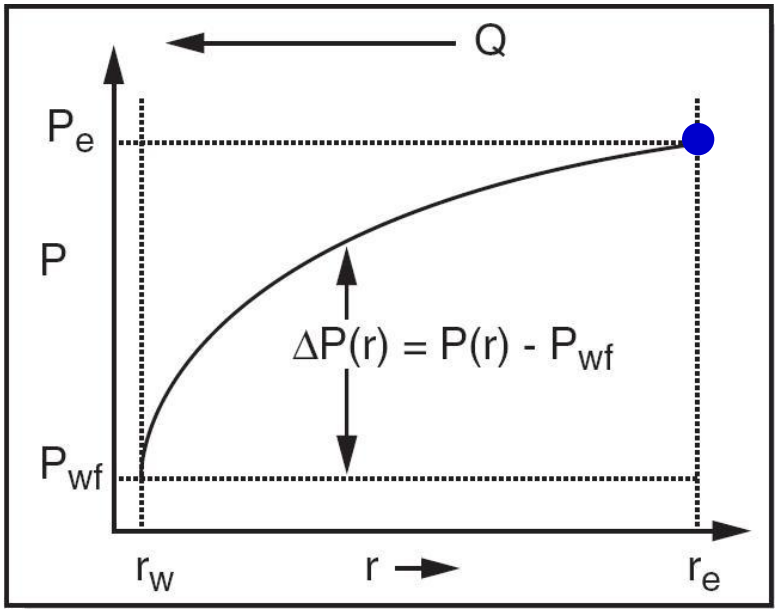
Wells in Reservoir Simulation

- Well Models for Single and Two Phase Flow



Wells in Reservoir Simulation

- Well Models for Single and Two Phase Flow



$$\Delta P(r) = P(r) - P_{wf} = \frac{Q\mu}{2\pi kh} \cdot \left(P_e - \ln P_{wf} \frac{r}{r_w} \right)$$

P=P_e at r_e:

$$P_e - P_{wf} = \frac{Q\mu}{2\pi kh} \ln \left(\frac{r_e}{r_w} \right)$$

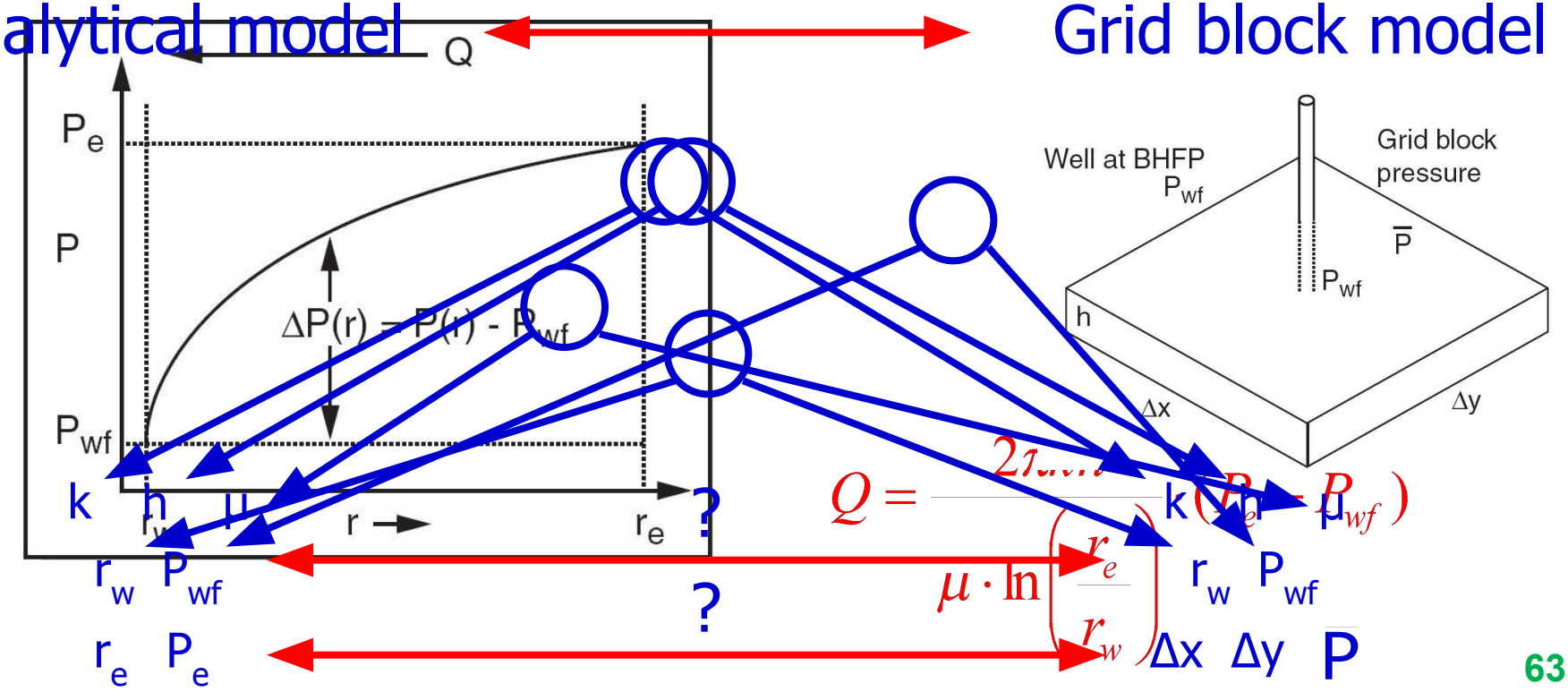
$$Q = \frac{2\pi kh}{\mu \cdot \ln \left(\frac{r_e}{r_w} \right)} \cdot (P_e - P_{wf})$$

Wells in Reservoir Simulation

- Well Models for Single and Two Phase Flow

Analytical model

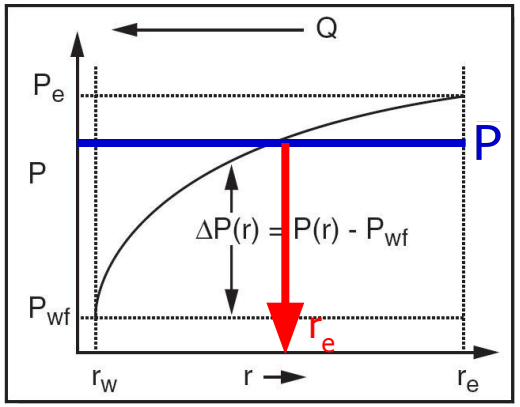
Grid block model



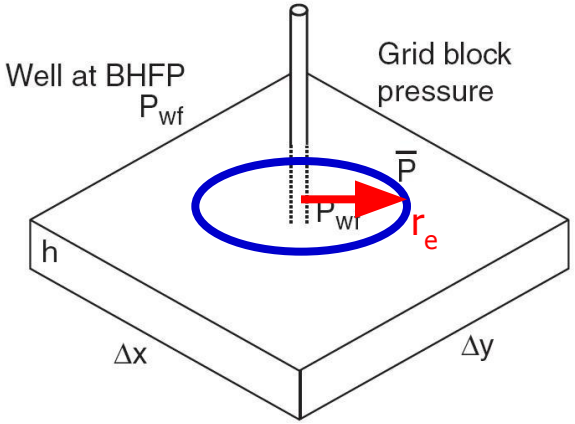
Wells in Reservoir Simulation

- Well Models for Single and Two Phase Flow

Analytical model ⟷ Grid block model



$$Q = \frac{2\pi k h}{\mu \cdot \ln\left(\frac{r_e}{r_w}\right)} \cdot (P_e - P_{wf})$$



r_e ? $\Delta x \ \Delta y$

P_e = $\bar{P}$

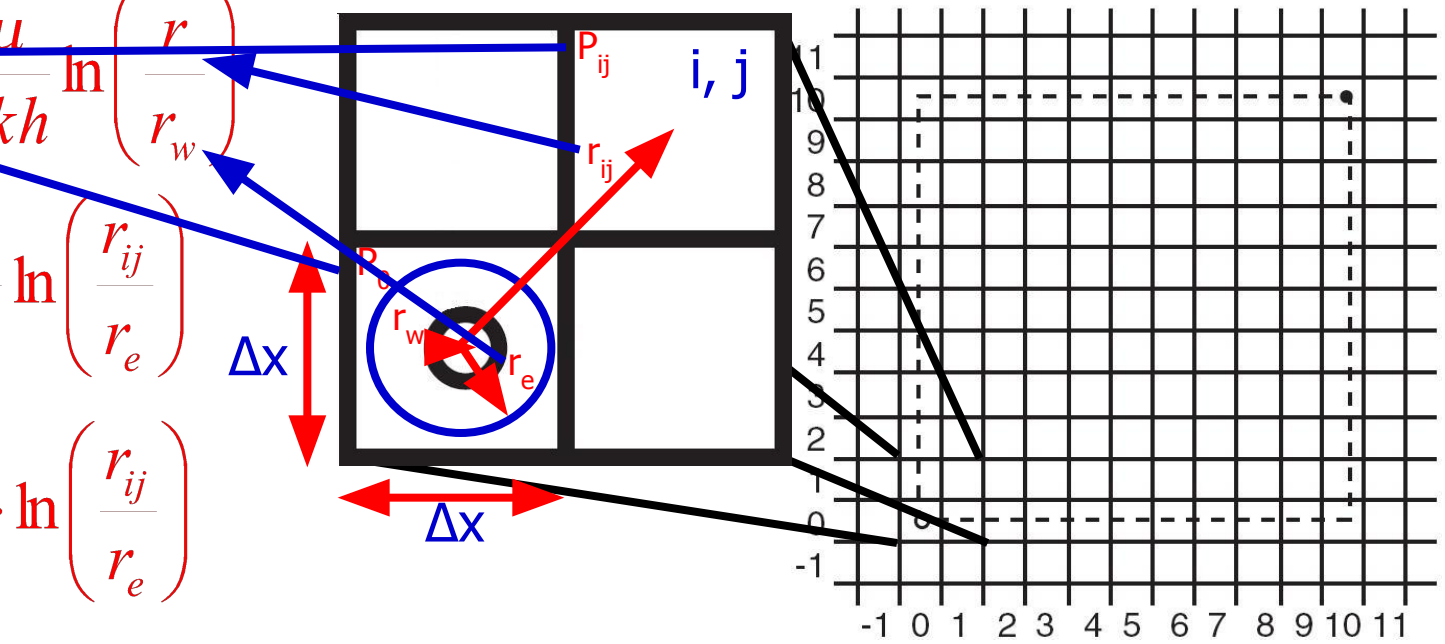
Wells in Reservoir Simulation

- Well Models for Single and Two Phase Flow
  - Peaceman Equivalent radius, r_e

$$P(r) - P_{wf} = \frac{Q\mu}{2\pi kh} \ln\left(\frac{r}{r_w}\right)$$

$$P_{ij} - P_o = \frac{Q\mu}{2\pi kh} \ln\left(\frac{r_{ij}}{r_e}\right)$$

$$\frac{P_{ij} - P_o}{\frac{Q\mu}{kh}} = \frac{1}{2\pi} \cdot \ln\left(\frac{r_{ij}}{r_e}\right)$$



Wells in Reservoir Simulation

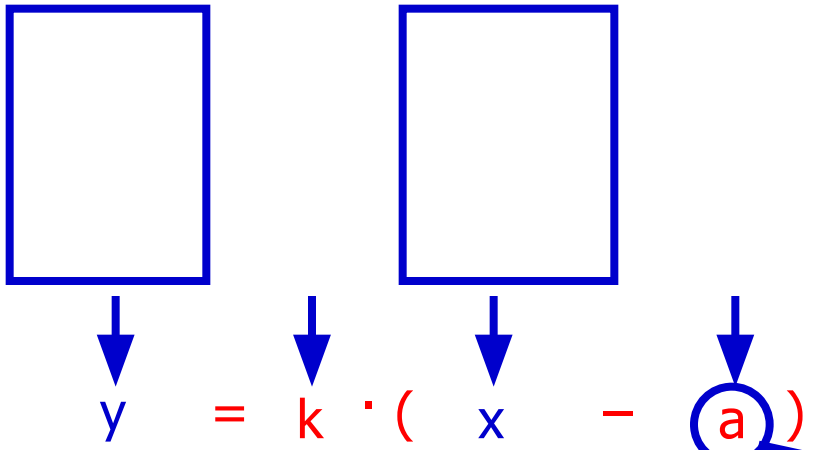
- Well Models for Single and Two Phase Flow
  - Peaceman Equivalent radius, r_e

$$\ln\left(\frac{r_{ij}}{r_e}\right) = \ln\left(\frac{r_{ij}}{\Delta x}\cdot\frac{\Delta x}{r_e}\right) = \ln\left(\frac{r_{ij}}{\Delta x}\right) - \ln\left(\frac{r_e}{\Delta x}\right)$$

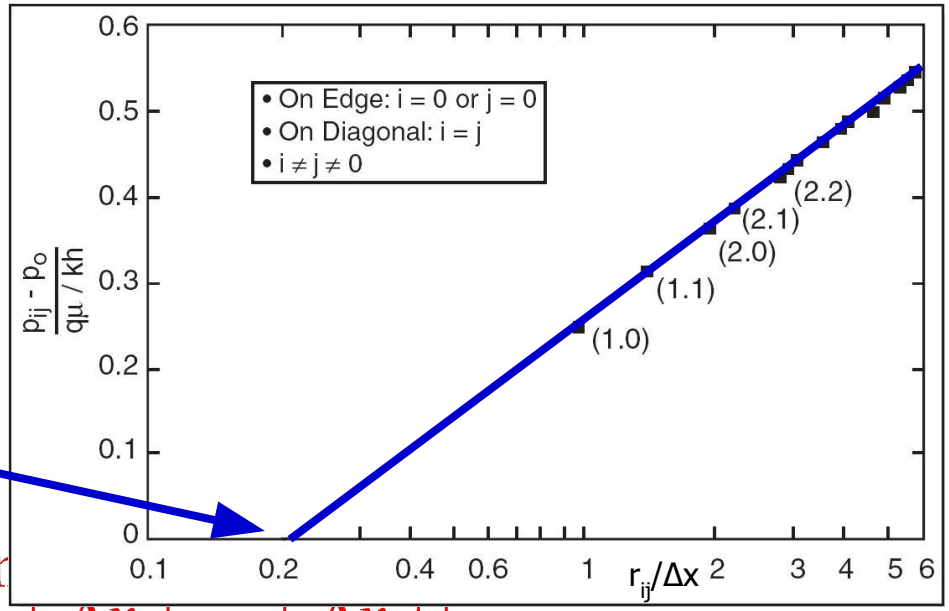
$$\frac{P_{ij}-P_o}{\frac{Q\mu}{kh}} = \frac{1}{2\pi}\cdot\ln\left(\frac{r_{ij}}{r_e}\right) \quad \frac{P_{ij}-P_o}{\frac{Q\mu}{kh}} = \frac{1}{2\pi}\cdot\left[\ln\left(\frac{r_{ij}}{\Delta x}\right) - \ln\left(\frac{r_e}{\Delta x}\right)\right]$$

Wells in Reservoir Simulation

- Well Models for Single and Two Phase Flow
  - Peaceman Equivalent radius, r_e



$$y = k \cdot (x - a)$$



$$\frac{r_e}{\Delta x} \approx 0.2 \rightarrow \frac{P_{ij} - P_o}{\frac{q\mu}{kh}} = \ln\left(\frac{0.2\Delta x}{r_w}\right)$$

Wells in Reservoir Simulation

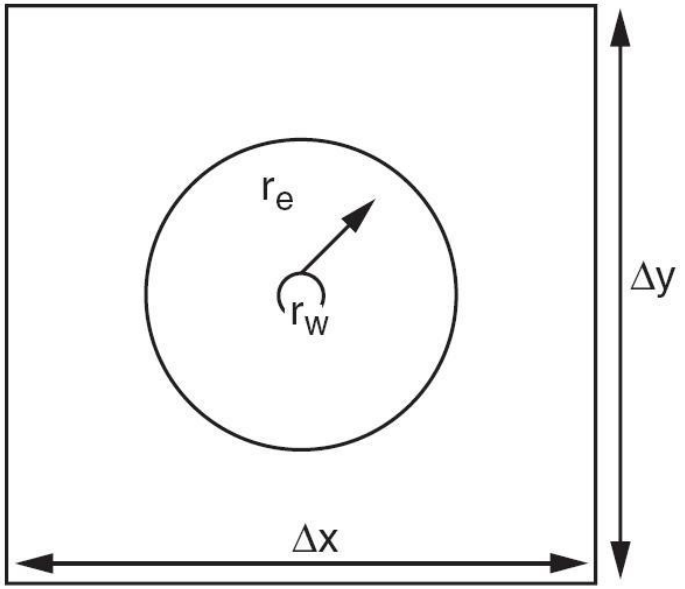
- Well Models for Single and Two Phase Flow
  - Peaceman Equivalent radius, r_e

$(\Delta x = \Delta y)$

$$r_e \approx 0.14\sqrt{\Delta x^2 + \Delta y^2}$$

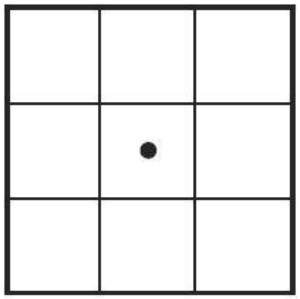
$(\Delta x \neq \Delta y)$

$$r_e \approx 0.2\Delta x$$

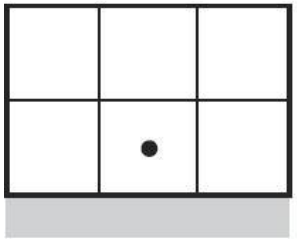


Wells in Reservoir Simulation

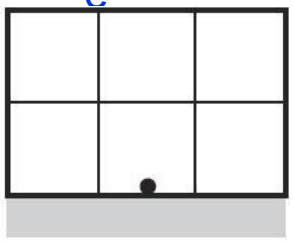
- Well Models for Single and Two Phase Flow
  - Peaceman Equivalent radius, r_e



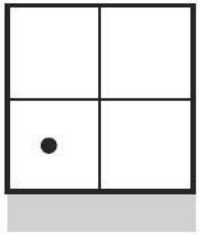
$r_e \approx 0.2\Delta x$



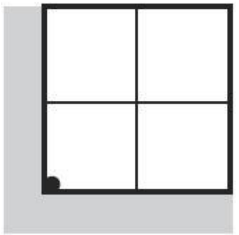
$r_e \approx 0.196\Delta x$



$r_e \approx 0.433\Delta x$



$r_e \approx 0.193\Delta x$



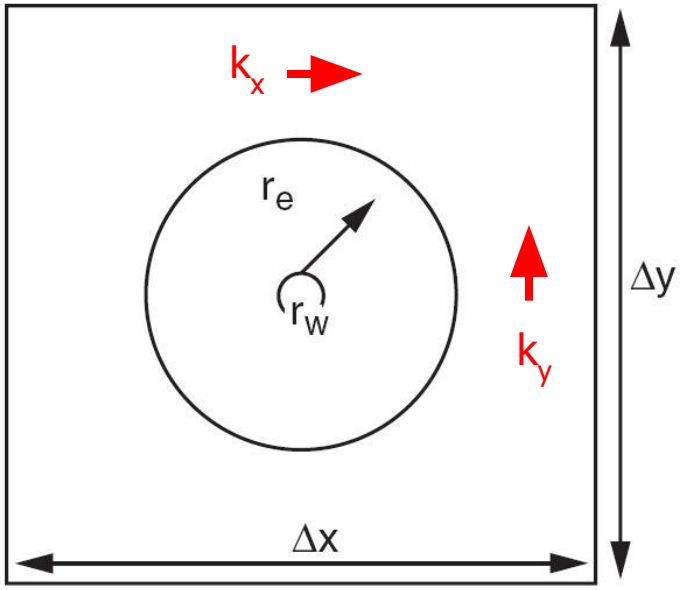
$r_e \approx 0.72\Delta x$

Wells in Reservoir Simulation

- Well Models for Single and Two Phase Flow
  - Peaceman Equivalent radius, r_e

($\Delta x \neq \Delta y$) ($k_x \neq k_y$)

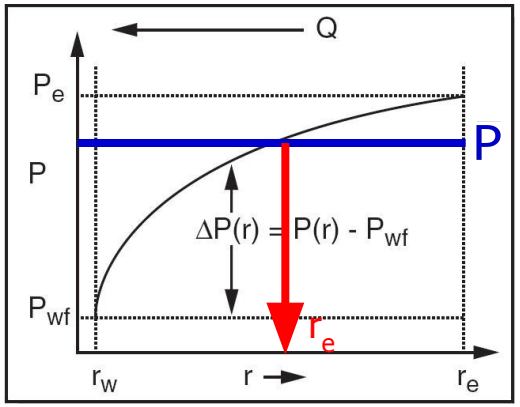
$$r_e \approx 0.28 \frac{\left[\left(\frac{k_y}{k_x}\right)\cdot \Delta x^2 + \left(\frac{k_x}{k_y}\right)\cdot \Delta y^2\right]^{\frac{1}{2}}}{\left(\frac{k_y}{k_x}\right)^{\frac{1}{4}} + \left(\frac{k_x}{k_y}\right)^{\frac{1}{4}}}$$



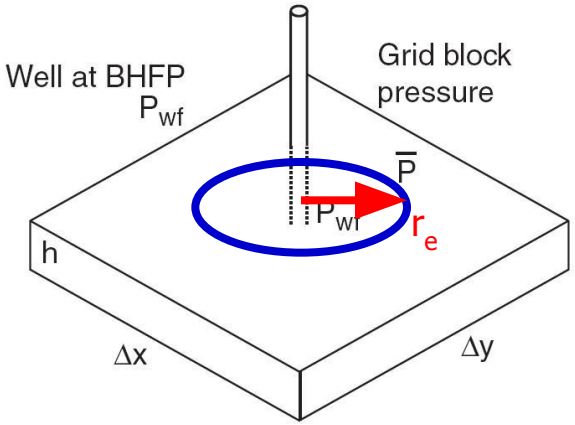
Wells in Reservoir Simulation

- Well Models for Single and Two Phase Flow

Analytical model ⟷ Grid block model



$$Q = \frac{2\pi k h}{\mu \cdot \ln\left(\frac{r_e}{r_w}\right)} \cdot (P_e - P_{wf})$$



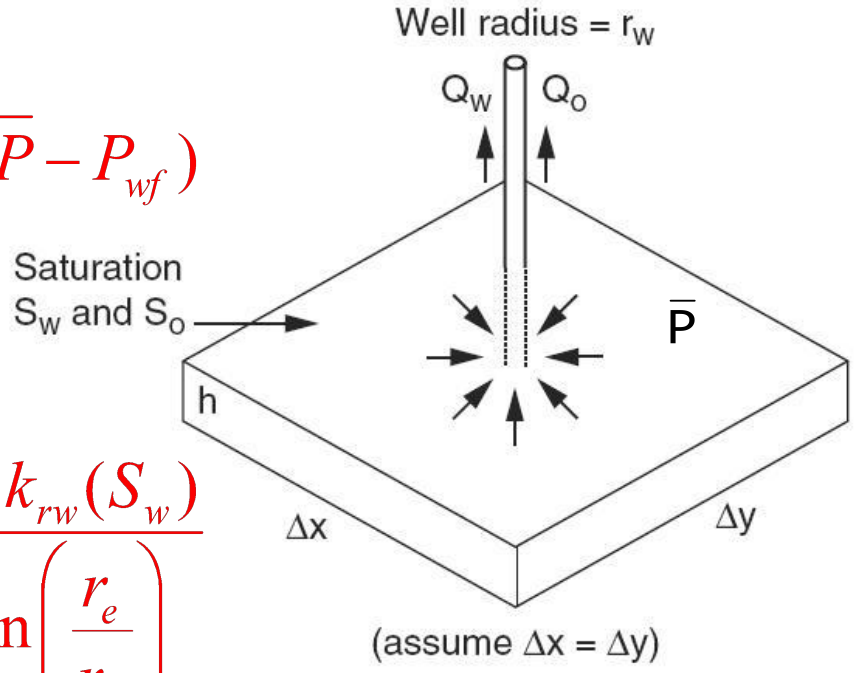
$r_e \stackrel{?}{=} 0.14\sqrt{\Delta x^2 + \Delta y^2}\ \Delta x\ \Delta y$

$P_e = \bar{P}$

Wells in Reservoir Simulation

- Well Models for Single and Two Phase Flow
  - Two phase flow

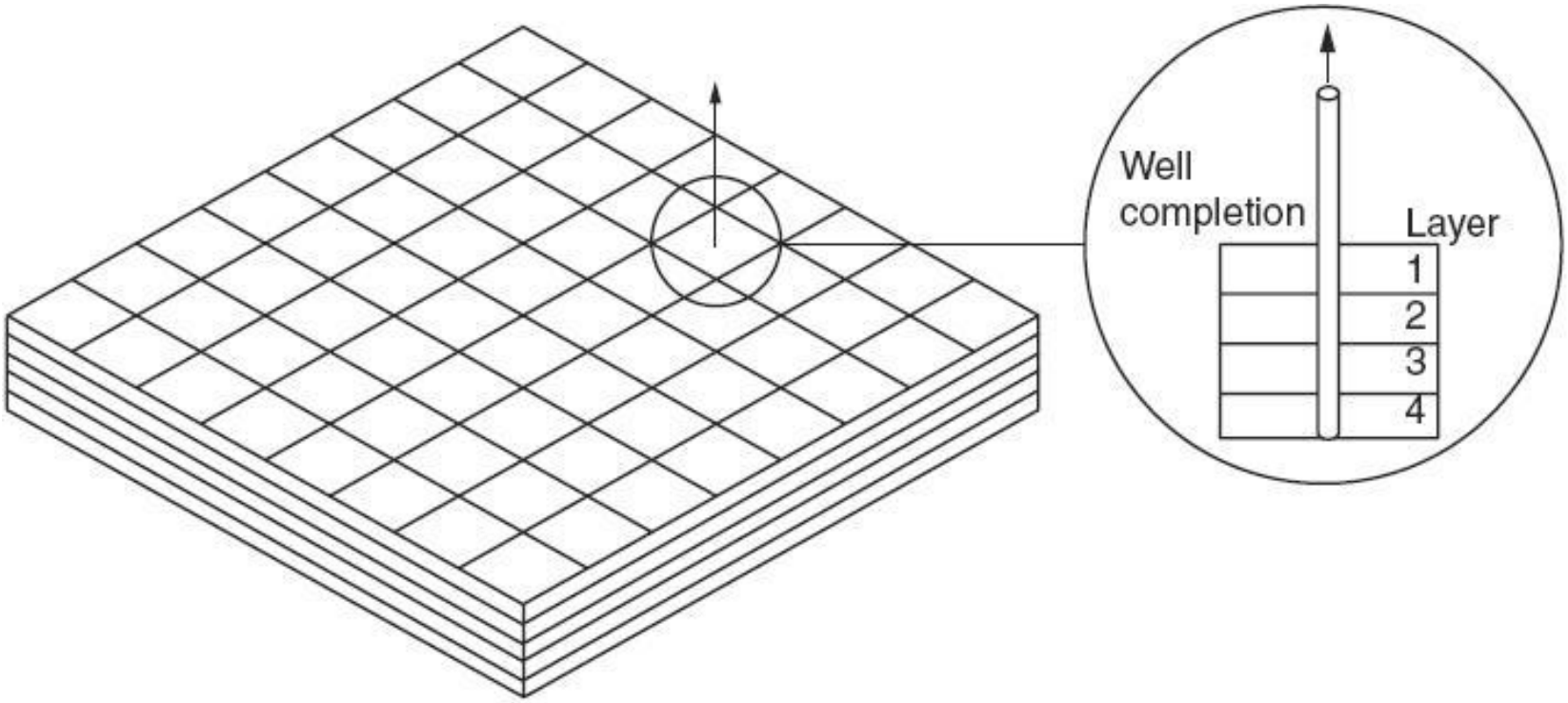
$$Q_o = PI_o \cdot (\overline{P} - P_{wf}) \qquad Q_w = PI_w \cdot (\overline{P} - P_{wf})$$



$$PI_o = \frac{2\pi kh \cdot k_{ro}(S_o)}{\mu_o \cdot \ln\left(\frac{r_e}{r_w}\right)} \qquad PI_w = \frac{2\pi kh \cdot k_{rw}(S_w)}{\mu_w \cdot \ln\left(\frac{r_e}{r_w}\right)}$$

Wells in Reservoir Simulation

- Well Modelling in a Multi-Layer System



Wells in Reservoir Simulation

- Well Modelling in a Multi-Layer System

For each layer (k=1..4)

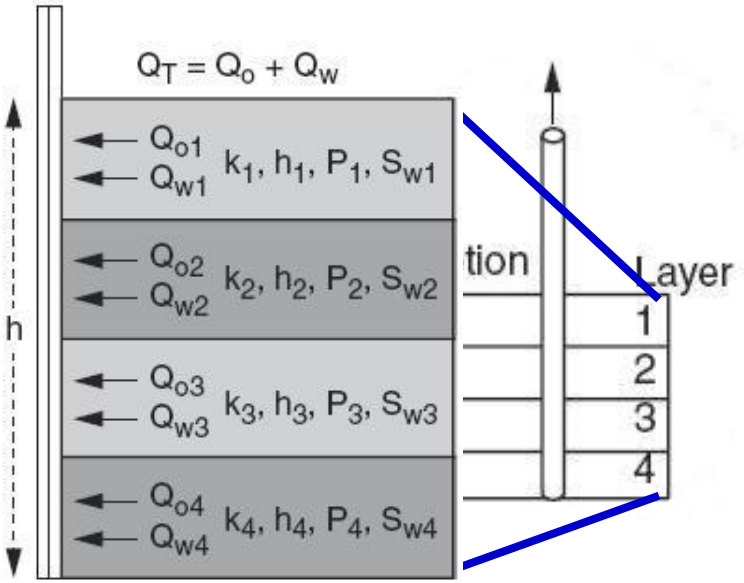
$$Q_{ok} = PI_{ok} \cdot (\overline{P_k} - P_{wfk})$$

$$+$$

$$Q_{wk} = PI_{wk} \cdot (\overline{P_k} - P_{wfk})$$

$$\Downarrow$$

$$Q_{Tk} = (PI_{ok} + PI_{wk}) \cdot (\overline{P_k} - P_{wfk})$$



$$PI_{ok} = \frac{2\pi (kh \cdot k_{ro}(\overline{S_o}))_k}{\mu_o \cdot \ln\left(\frac{r_{ek}}{r_w}\right)} \qquad PI_{wk} = \frac{2\pi (kh \cdot k_{rw}(S_w))_k}{\mu_w \cdot \ln\left(\frac{r_{ek}}{r_w}\right)}$$

Wells in Reservoir Simulation

- Well Modelling in a Multi-Layer System

For each layer (k=1..4)

$$Q_{ok} = PI_{ok} \cdot (\overline{P_k} - P_{wfk})$$

$$Q_{wk} = PI_{wk} \cdot (\overline{P_k} - P_{wfk})$$

$$Q_{Tk} = (PI_{ok} + PI_{wk}) \cdot (\overline{P_k} - P_{wfk})$$

Total

$$Q_o = \sum_{k=1}^{4} PI_{ok} \cdot (\overline{P_k} - P_{wfk})$$

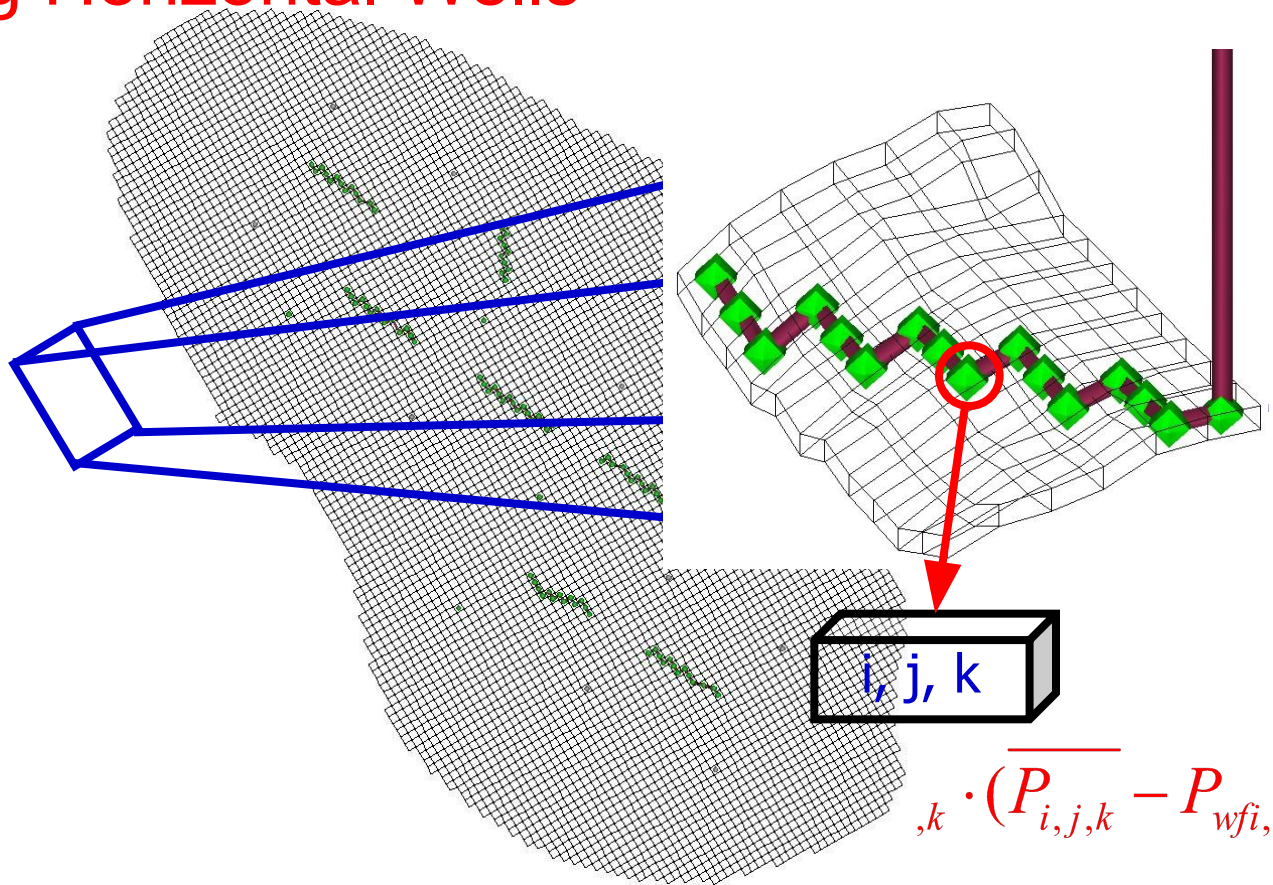
$$Q_w = \sum_{k=1}^{4} PI_{wk} \cdot (\overline{P_k} - P_{wfk})$$

$$Q_T = \sum_{k=1}^{4} (PI_{ok} + PI_{wk}) \cdot (\overline{P_k} - P_{wfk})$$

For simplicity $P_{wf1} = P_{wf2} = P_{wf3} = P_{wf4}$

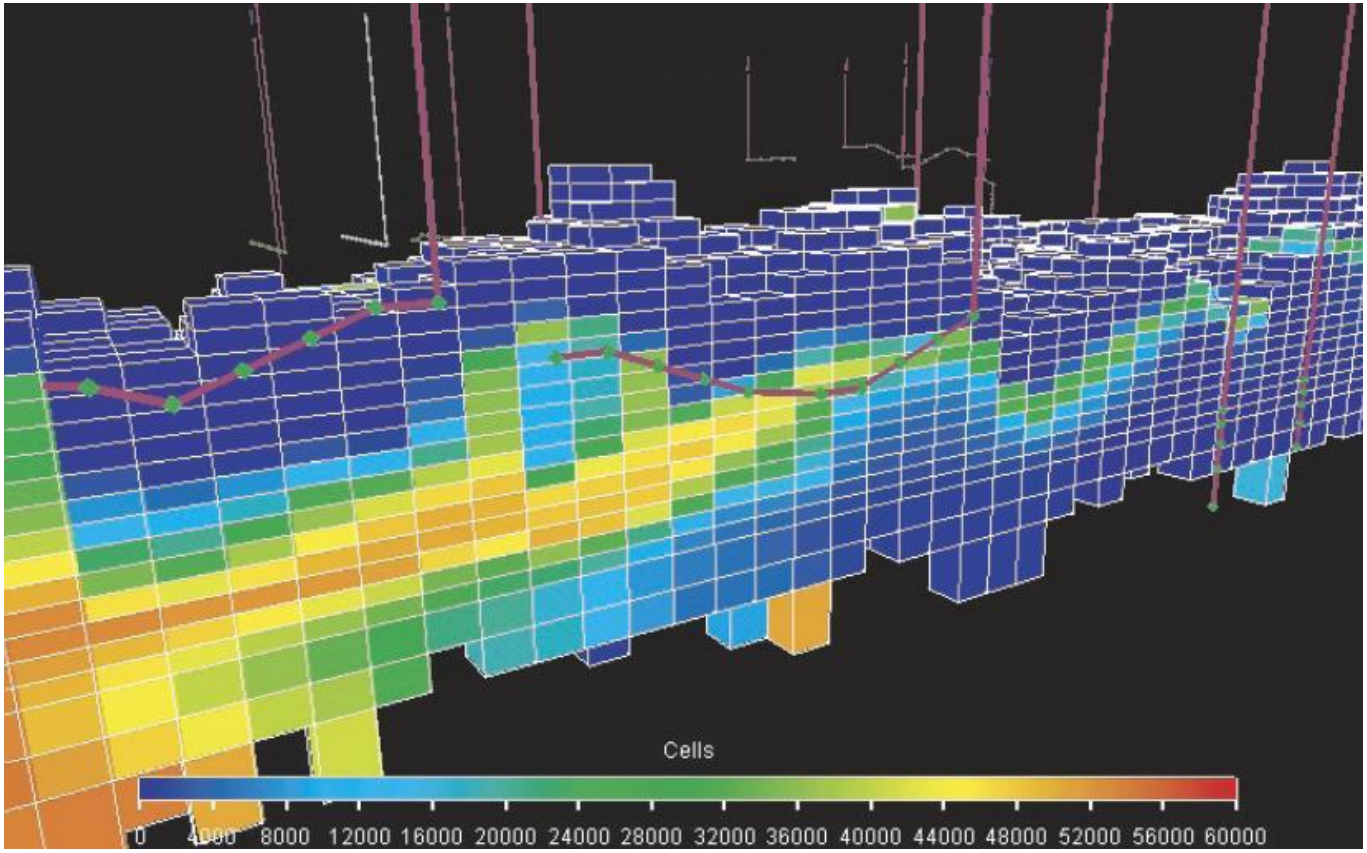
Wells in Reservoir Simulation

- Modelling Horizontal Wells



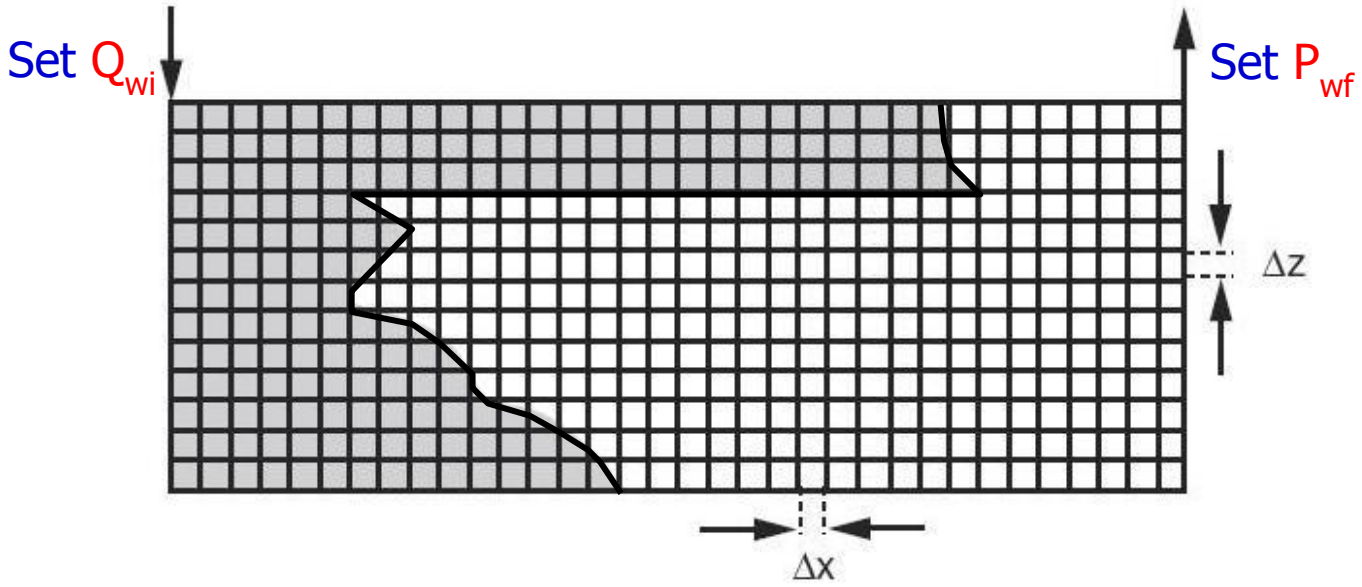
Wells in Reservoir Simulation

- Modelling Horizontal Wells



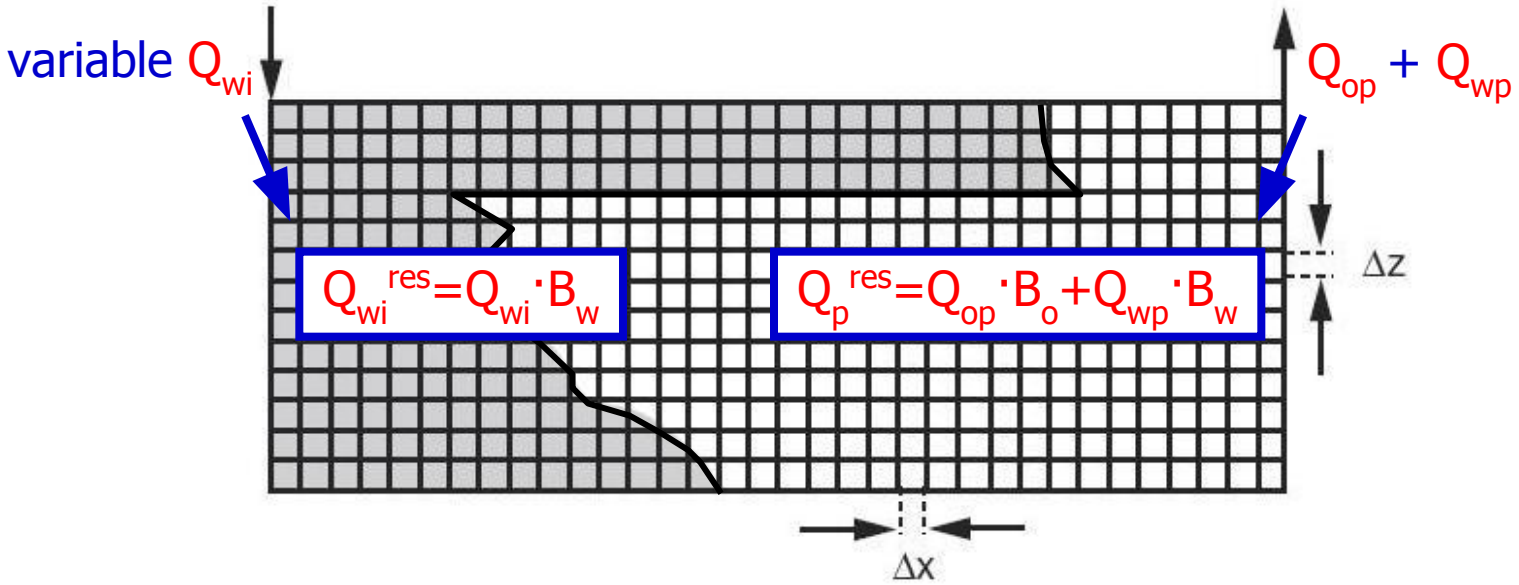
Wells in Reservoir Simulation

- Hierarchies of Wells and Well Controls
  - Well Controls
    - Rate constrained injection
    - Pressure constrained production



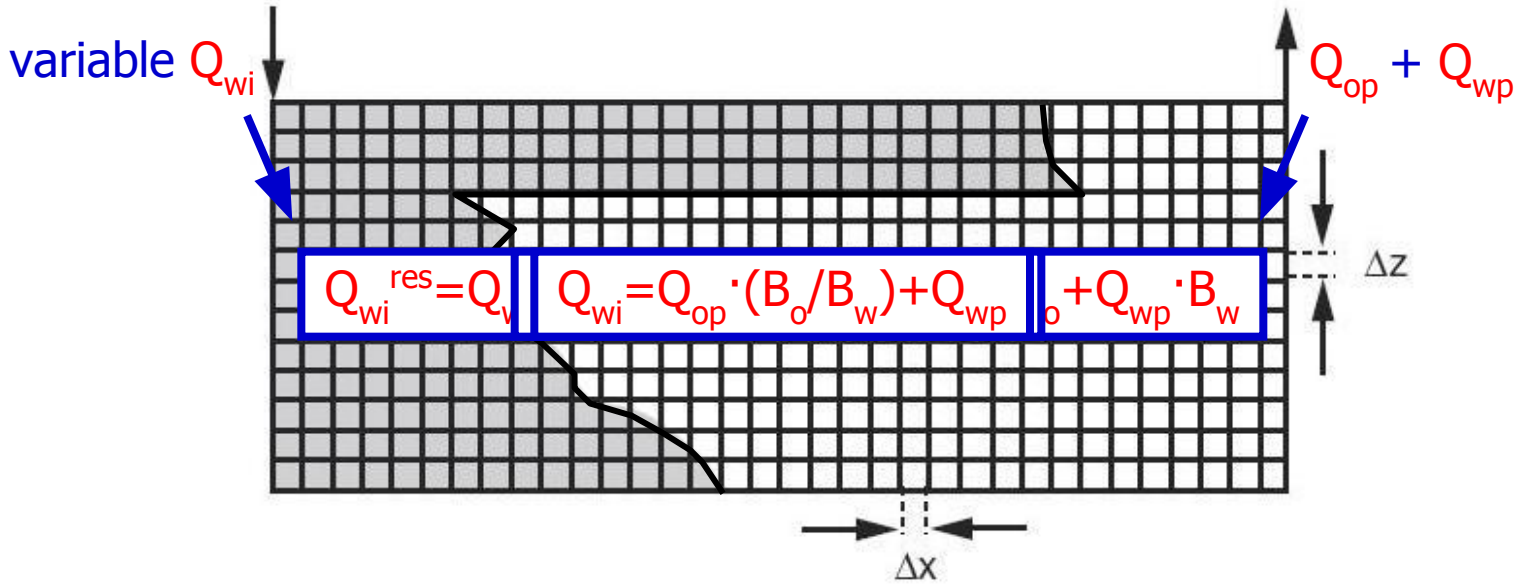
Wells in Reservoir Simulation

- Hierarchies of Wells and Well Controls
  - Well Controls
    - Rate or Pressure constrained production
    - Voidage replacement (injection)



Wells in Reservoir Simulation

- Hierarchies of Wells and Well Controls
  - Well Controls
    - Rate or Pressure constrained production
    - Voidage replacement (injection)



Thank you for attention!

Reservoir Simulation

Gridding and Well Modelling

Sergey Kurelenkov

2011