Geostatistics and Reservoir Simulation

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Dmitry Koroteev

2005 2006 2007 2008 2009 2010 2011 2012 2013 2014

Research Associate
Schlumberger R&E

Research Scientist
Schlumberger R&E

Senior Research Scientist
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Research Program Manager
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PhD, Chemical Physics
Lomonosov Moscow State University

Founder and CEO
Digital Petroleum

2014 2015 2016 2017 2018 2019

Department Head
Gazpromneft STC

Acting Research Director
Schlumberger R&E

Assistant Professor
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2 CEUs, Big Data
Massachusetts Institute of Technology

Projects

Schlumberger

- Acoustics for Hydraulic Fracture Monitoring
- Electrokinetics for Well Logging
- Digital Rock

Gazprom Neft

- Technology Strategy for E&P

Schlumberger

- Big Data Strategy for Production Technologies

Skoltech

- 9 AI related projects for Gazprom Neft
- 7 Internal R&D efforts for Machine Learning in E&P

The course

- Originally developed in 2017 by Ebrahim Fathi, assistant professor, West Virginia University
- Re-developed after student feedback session in 2018 by Dmitry Koroteev, Stanislav Ursegov and Denis Orlov
- Re-developed after student feedback session in 2019 by Dmitry Koroteev, Denis Orlov and Mohammad Ebadi

Instructors			Teaching assistant

Dmitry Koroteev

Denis Orlov

Mohammad Ebadi

Mohammad Ebadi

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The course: Schedule

Session	Date	Lecturer	Subject	Room
1	27 Mar 2019	Dmitry Koroteev	Intro to Reservoir Simulations	407
2	28 Mar 2019	Dmitry Koroteev	Intro to Reservoir Simulations	407
3	29 Mar 2019	Mohammad Ebadi	PVT	407
4	3 Apr 2019	Mohammad Ebadi	PVT	407
5	4 Apr 2019	Mohammad Ebadi	PVT	407
6	5 Apr 2019	Mohammad Ebadi	PVT	407
7	10 Apr 2019	Dmitry Koroteev	Reservoir Simulations on Practice	407
8	11 Apr 2019	Dmitry Koroteev	Reservoir Simulations on Practice	407
9	12 Apr 2019	Denis Orlov	History Matching	407
10	17 Apr 2019	Denis Orlov	History Matching	407
11	18 Apr 2019	Dmitry Koroteev	Geostatistics	407
12	19 Apr 2019	Dmitry Koroteev	Geostatistics	407
13	24 Apr 2019	Dmitry Koroteev	Geostatistics	407
14	25 Apr 2019	Denis Orlov	Sequential Gaussian Simulations	407
15	26 Apr 2019	Denis Orlov	Sequential Gaussian Simulations	407
16	15 May 2019	Dmitry Koroteev	Uncertainty Modelling	407
17	16 May 2019	Dmitry Koroteev	Uncertainty Modeling	407
18	17 May 2019	Project Preparation		407
19	22 May 2019			407
20	23 May 2019	Project Presentations		407
21	24 May 2019			407
22	29 May 2019			407
23	30 May 2019			407
24	31 May 2019			407

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Reference Books & Materials

- Course Notes and Technical Papers
- Inverse Theory for Petroleum Reservoir Characterization and History Matching (Dean S. Oliver; Albert C. Reynolds; Ning Liu)
- Pyrcz, M.J., and Deutsch, C.V., Geostatistical Reservoir Modeling, Oxford University Press, New York, second edition, 2014, 433 pages
- Basic Applied Reservoir Simulation, T. Ertekin, J.H. Abou-Kassem and G.R. King. SPE Textbook Series Vol. 7, 2001

Homework Assignment Policy:

- Homework's are due at the beginning of the class on due date
- Homework is to be submitted in soft copy to Mohammad.Ebadi@Skoltech.ru
- Each homework assignment must include:
  - Statement of the problem
  - Solution with sample calculations and conclusions

Mark Distribution

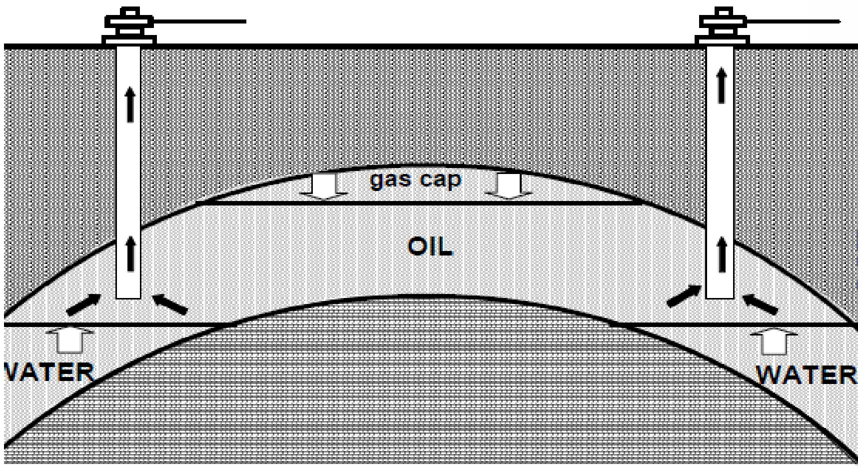
→Homework Assignments 70%

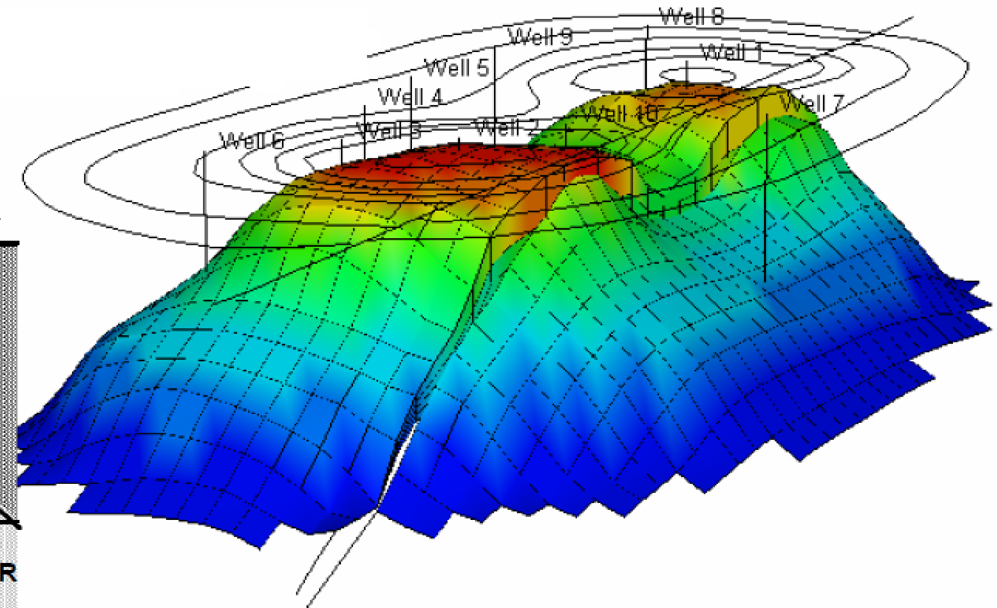
→Project/Exam 30%

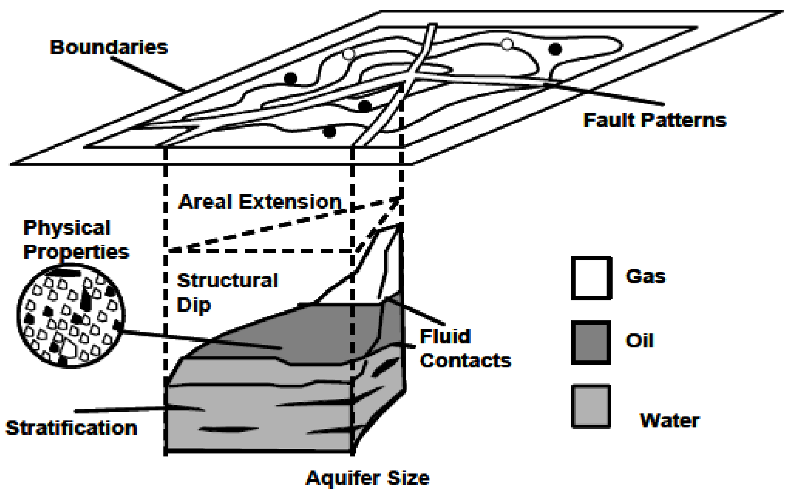
Homework Assignments & Project (individual work/individual report)

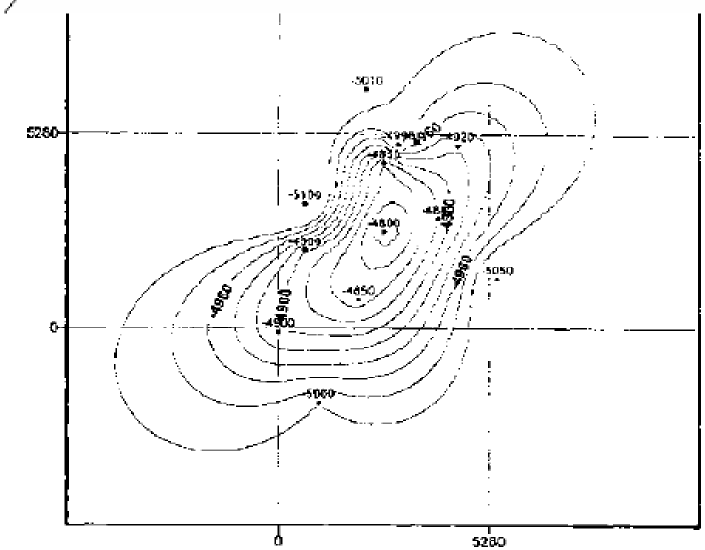
86–100 → A
71–85 → B
61–70 → C
56–60 → D
51–55 → E
≤ 50 → F

Intro to Reservoir Modeling









Application of Geostatistics in Petroleum Engineering

- Generating high resolution rock property maps for reservoir simulation purposes
- Uncertainty analysis and risk management for economic decisions
- Upscaling reservoir properties

What is Reservoir Simulation?

- Reservoir Engineers use different means to study and **analyze reservoir performance (History matching) and predict future production.**
- Reservoir performance is a function of its behavior with **pressure and time.**
- Reservoir Simulation is a blend of:
  - Engineering
  - Physics
  - Chemistry
  - Mathematics
  - Numerical analysis
  - Computer programming, and engineering experience and practice.
- Reservoir Simulation is a powerful technique **for reservoir management** and refers to the construction and operation of a model whose (hopefully) approaches that of a reservoir under actual reservoir condition.
- It allows the engineer to predict reservoir performance – provided it is used correctly – under different scenarios.
- The kind of reservoir simulators that are used today on digital computers are not the only tools an engineer has used to mimic the behavior of real reservoirs.

Type of Simulators

- Physical: involves building a prototype in the laboratory and reproduce the physical and chemical processes
- Mathematical:
  - Analytical
    - Well Testing Equations (Diffusivity Equation)
    - Decline Curves
    - Material Balance Equations
  - Numerical
  - Data Driven
  - Hybrid

Numerical Reservoir Flow Simulation

Physical Models:

- useful in visualizing the flow processes and develop mathematical models for the flow.
  - problem: lack generality – we need to modify the physical model for each reservoir under study.
- very expensive to build and run.

Physical vs Numerical Models:

- Numerical models must describe what physically takes place in the reservoir.
- In cases where we cannot model the reservoir physically

Analytical Models

Material Balance Equation (MBE)

Tank Model

→ Isotropic -> $K_x = K_y = K_z$

→ Homogeneous Reservoir -> φ, Kro, Krw, Krg, So, Sw, Sg, Bo, Bg, Rso, μo, μg are same throughout the tank

MBE is a powerful tool for reservoir performance analysis, particularly when there is negligible pressure difference (i.e. pressure gradient) in the reservoir.

Analytical Models

Diffusivity Equation

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial p}{\partial r}\right) = \frac{\phi\mu c}{k}\frac{\partial p}{\partial r}$$

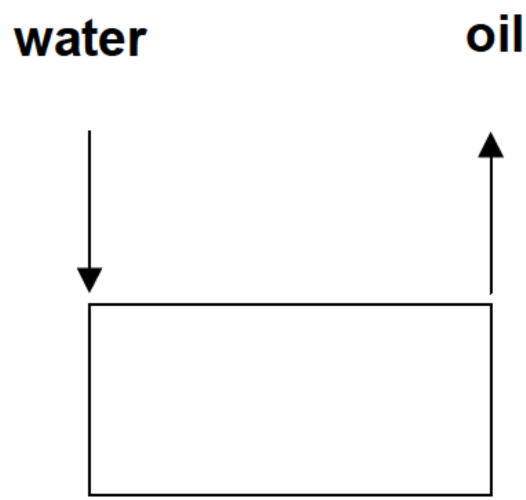
$\frac{\phi\mu c}{k}$ is a hydraulic Diffusivity

Solution of diffusivity equation gives the pressure distribution in the reservoir at different times.

Numerical Simulators

Conceptually, a reservoir numerical simulator model consists a series of tanks, which are connected with one another.

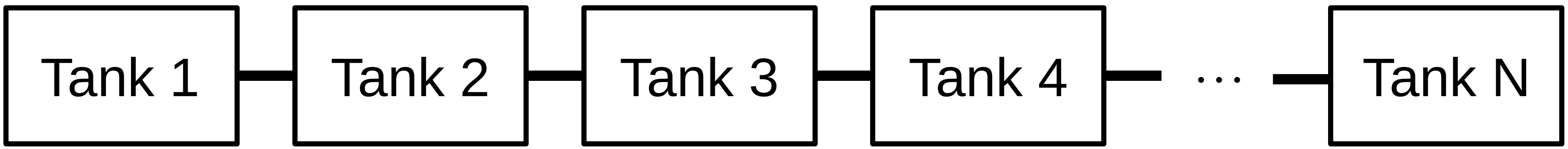
Reservoir being water flooded



Sw increases to the right with time

Numerical Simulators

The tanks still obey physical laws (specially the conservation of mass);



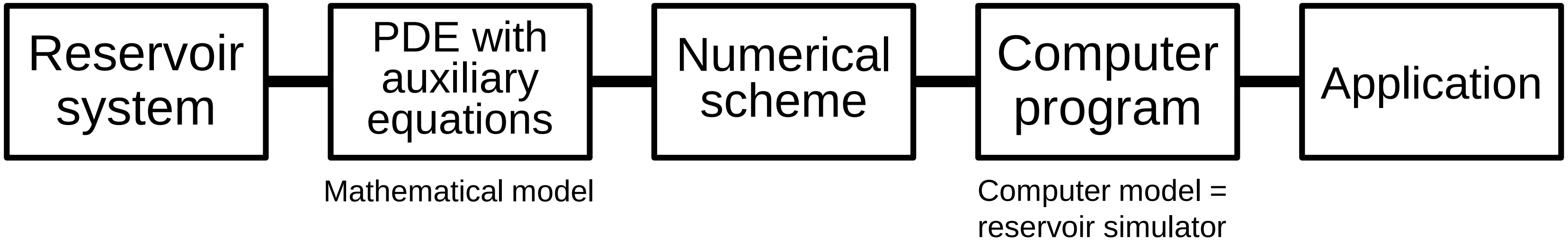
- → What it is different from the tank model for MBE, is that now is possible to allow for fluid to flow from one part of the reservoir (for example, “Tank 1”) to another point (for example “Tank 2”).
- → There is pressure difference in each tank and consequently there is fluid flow.
- → Reservoir Simulators: computer programs that solve the equations for heat and mass flow in porous media, subject to appropriate initial and boundary conditions

Mathematical Models

- Mathematically, a reservoir numerical model is consisted of equations describing the physical laws, including conservation of mass and momentum & energy, as well as laws governing the behavior (i.e. flow of fluids in our case)
- A complete set of PDE and auxiliary conditions, which describe the flow pressures in the reservoir.
- PDE's are derived from:
  - Conservation laws
  - Physical principles (Darcy's Law)
- The number and type of equations to be solved depends on:
  - Geological characteristics of the reservoir (single or double porosity)
  - Characteristics of the oil, and Rock and Fluid interactions
  - Oil recovery process to be modeled.

Mathematical Models

Solution of the mathematical system of equations requires knowledge of reservoir properties (i.e., permeability, porosity), fluid PVT properties, rock and fluid interactions and reservoir well geometry.



Reservoir description is seldom known with any degree of accuracy - usually obtained from geological and geophysical data as well as well test data and **geostatistical** description.

Mathematical Models

Mathematical Models contain three main sources of error:

→ Inaccuracy of input data;

→ Truncation error – introduced when we approximate our original PDE's using a Finite Difference or Finite Element Scheme;

→ Round off error of the machine on which we solve our equations.

Note:

The main advantage of a reservoir simulator is the ability to inexpensively produce the reservoir and a variety of different operating conditions.

Thus the optimum strategy for producing the reservoir can be determined without equipment investment and without actually producing any oil.

Historical Developments - Reservoir Simulators – "Timeline"

Traditional Reservoir Engineering (1930 - …)

- Computations with slide rules and mechanical calculators;
- Representation of reservoir by a single block;
- 1-D analytical solutions for linear two-phase flow and radial single-phase flow.

Early Reservoir Simulation (1955 – 1970)

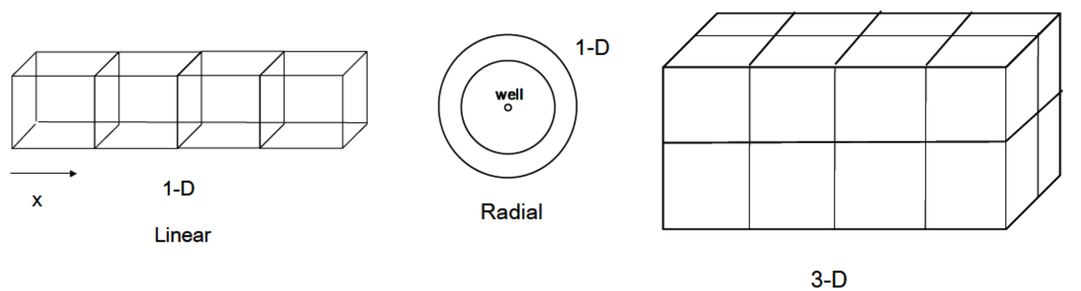
- Computations with digital computers;
- Primarily developed and used in research labs;
- Primary limitation was computer speed and storage;
- Limited ability to handle large systems of nonlinear equations;
- Poor reliability and lack of confidence in technology;
- High cost of development and use.

Modern Reservoir Simulation (1970 - …)

- High level of confidence in technology;
- Steady decrease in hardware cost;
- Large number of blocks with local grid refinement and irregular shape;
- Efficient methods for solving nonlinear equations;
- Robust methods for solving large systems of linear equations;
- Multicomponent fluid description and improvements in the handling of wells;
- Improvements in the understanding of complicated processes;
- Use of graphics and workstations and availability of supercomputers.

Different Reservoir Models (Simulators)

- **Singe-phase vs multi-phase simulators**
- Multiphase can also be subdivided into black oil, compositional and thermal simulators. Using one-phase or multi-phase depends on which flow process(es) is taking place in the reservoir being studied.



- Mostly 3-D. Linear predominates in fractured reservoirs while radial predominates near the wellbore. Hence, we can setup equations combining both linear and radial geometry. No single flow model occurs in the reservoir. What occurs in the reservoir is a combination of several geometrical simulator models
- Currently, many reservoir simulators are developed with incorporation of “fractures” describing the interaction of the reservoir with its surroundings structures (such as subsidence, leakage of fluids from reservoir to ground water zones)

How the Simulators are Used

Forecasting of reservoir performance

- →Sensitivity studies for evaluating reservoir development options (EOR process selection)
- →Evaluation of field pilots and scale-up
- →Full field studies for depletion planning at various stages of field development (number and location of wells, injection/production rates, composition of producing fluids, etc.)
- →Reservoir management
- →Assessment of uncertainty in forecasting reservoir performance

Improving reservoir description through history matching

- →Identification of major flow units and barriers
- →Identification of near well rock properties

Analysis of experiments

- →Relative permeability
- →Minimum miscibility pressure
- →Core displacement tests

Understanding of flow mechanisms

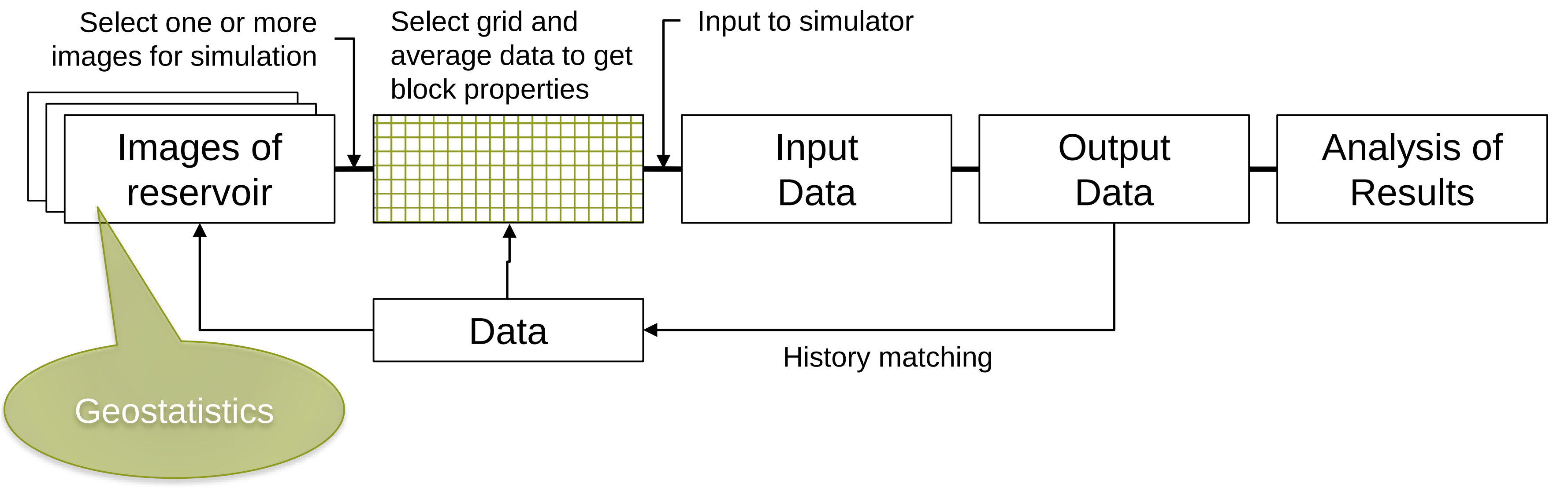
- →Unstable displacements
- →Flow in heterogeneous media
- →Block effective properties
- →Matrix/fracture transfer

Development of simple models and correlations

- →Coning
- →Cyclic steam injection
- →Steam displacement
- →Inflow performance relationships (IPR's)

Modeling Concepts

The basic steps required for a reservoir simulation study are:



In general, an engineer interested in doing a reservoir simulation study would follow the following steps:

- Develop study objectives
- Develop or select an appropriate simulator
- Review, collect and estimate appropriate data
- Make preliminary runs to establish model parameters and limitations
- Match available history
- Predict performance under different operating scenarios
- Analyze results and prepare a report
- Plan additional work

In carrying out a simulation study of a reservoir, the usual procedure involves

- Definition of a geological model for the reservoir, and the aquifer if present, in terms of: geometry, depth, zonation, spatial distribution of reservoir rock properties,
- Configuration of the most appropriate gridding for subdivision of the reservoir into blocks
- Specifications of thermodynamic properties of reservoir fluids
- Rock and fluid interactions including the definition of relative permeabilities and capillary pressure curves
- Initialization of the model with the assignment of real initial values of reservoir pressure, temperature, water-oil and gas contacts
- Introduction of production and injection wells and their operational constraints
- “History Matching” or replication of the production history of the reservoir, if it has one
- The model is run, with each well being assigned its actual record of production or injection, the calculated pressures, WORs, GORs at each well are compared with measured data where available;
- The reservoir description and model parameters can be verified within reasonable limits and the model is re-run as measuring until a satisfactory match with actual production is obtained.
- Prediction of reservoir behavior under future development programs could then be performed

Why Use Simulators?

- No other way to solve the problem
- Cheaper or more reliable than other methods
- Complement other more traditional techniques
- Increase profitability through improved reservoir management
- Assess economic and technical risks through sensitivity studies
- Enhance credibility with third parties
- Predict consequences of reservoir development and management decisions
- Establish relative merits of alternative operating strategies
- Resolve arbitration and utilization disputes
- Monitor reservoir performance
- Respond to safety, environmental and regulatory concerns
- Improve communication among interested parties
- Train engineers and operators
- Choose the optimum EOR scheme for a given reservoir
- Assess the impact on ultimate recovery of changing to a different EOR scheme
- Establish data needs during various stages of field development
- Assess the impact of assumptions on the analysis of well tests
- Optimize well location and well completion
- Assess possible advantages of horizontal wells over vertical wells
- Troubleshooting

Options and Features of Modern Reservoir Simulators

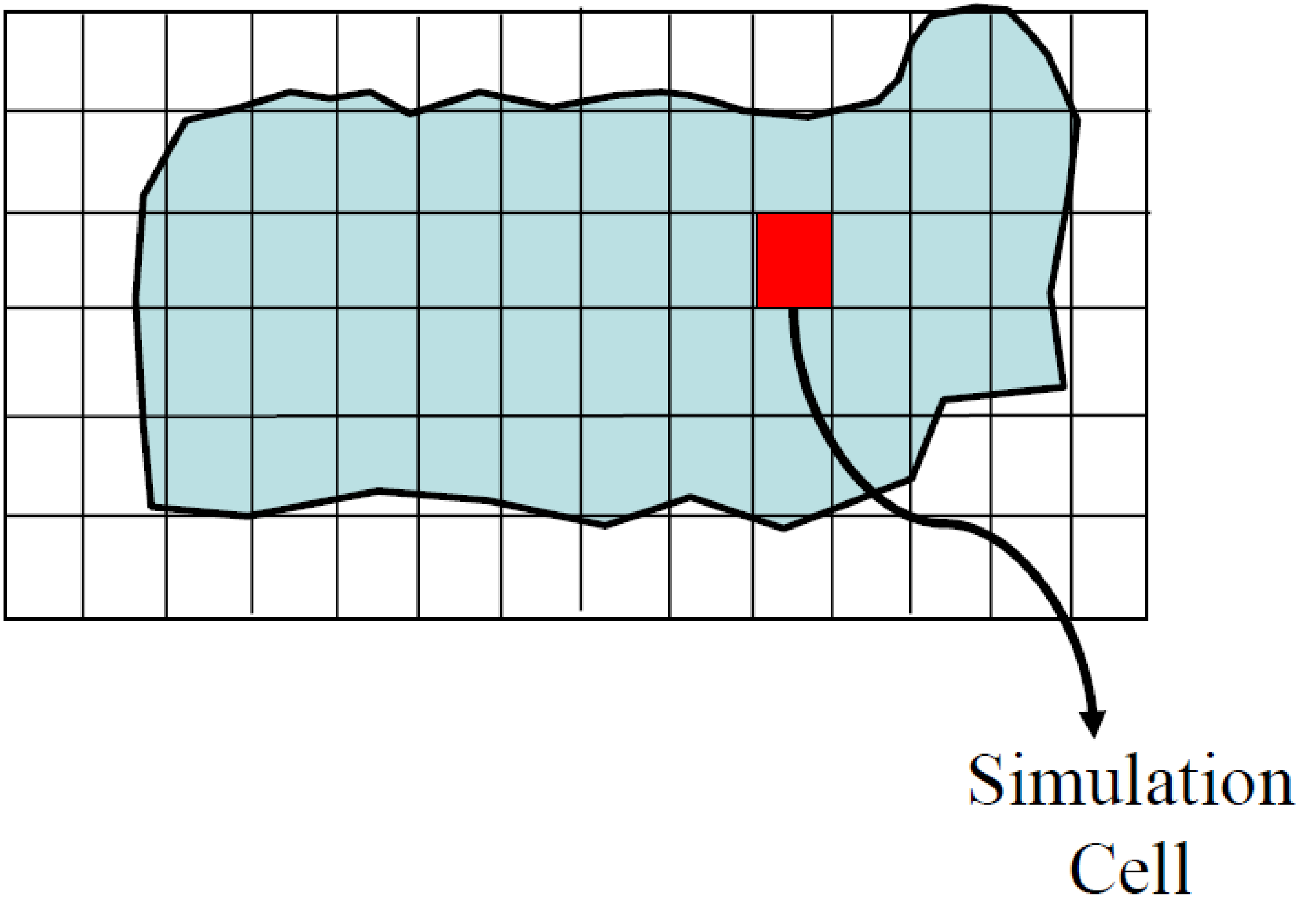
- Preprocessors
- Postprocessors
- Phase and component
- Gridding options
- Solution Techniques
- Well control
- Group control
- Injection control
- Shale gas production control
- Cross flow between zones
- Non-Darcy effects
- Initialization
- Aquifer models
- Pseudo-functions
- Control of simulator performance

The development of a reservoir simulator broadly follows the following steps:

- →Define the problem with partial differential equations and appropriate initial and boundary conditions
- →Convert the PDEs to (algebraic) finite difference equations
- →Apply the finite-difference equations to the "discretized" reservoir
- →Solve the equations to determine the behavior of the reservoir

- →The partial differential equations are derived using Darcy's Equation, Equation of Conservation of Mass, Momentum, energy and the Equation of State.

Mathematical Model – Discretization Concept



Mathematical Model – Discretization Concept

Functions of the Simulation Grid:

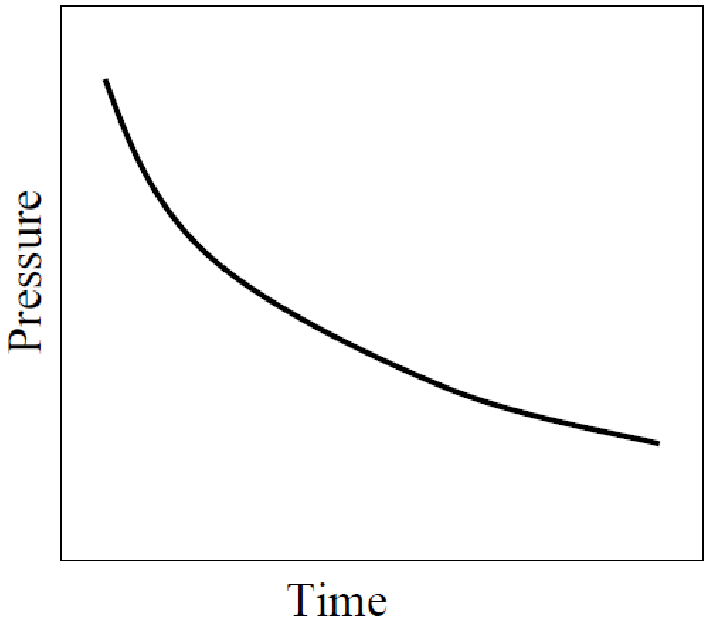
→ Description of the variation of properties in space

→ Approximation in space of the differential equations:

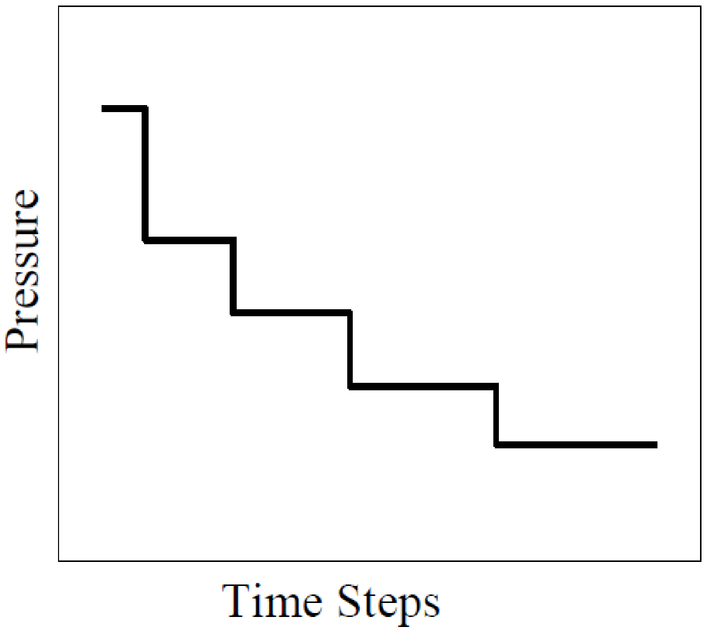
$$\frac{\partial p}{\partial x} \approx \frac{\Delta p}{\Delta x}$$

→ Posting of results

Mathematical Model – Discretization Concept



Pressure Variation
with time in the
reservoir



Pressure Variation
with time in the
simulator

Mathematical Model – Internal Grid Representation

Properties and Variables vs. Nodes and Connections

	Properties	Variables
Nodes	Centre of gravity Pore volume compressibility	Fluid pressure Fluid saturation
Connections	transmissibilities	Fluid flow

Software Available

Builder	EarthVision	FloGrid
GeoSim	Geolink	Geostat
Gocad	Grid	Gridgenr
Gridstat	Gviz	Heresim
Irap RMS	Isatis	Mapper
Open-GL	Petrel	Property 3D
ResMod	ResScale	ResView
Shapes	SigmaView	SimGrid
SimUp	SolidGeo	StatMod
Storm	Stratmodel	SureGrid

Reservoir Simulation Evolution Theory

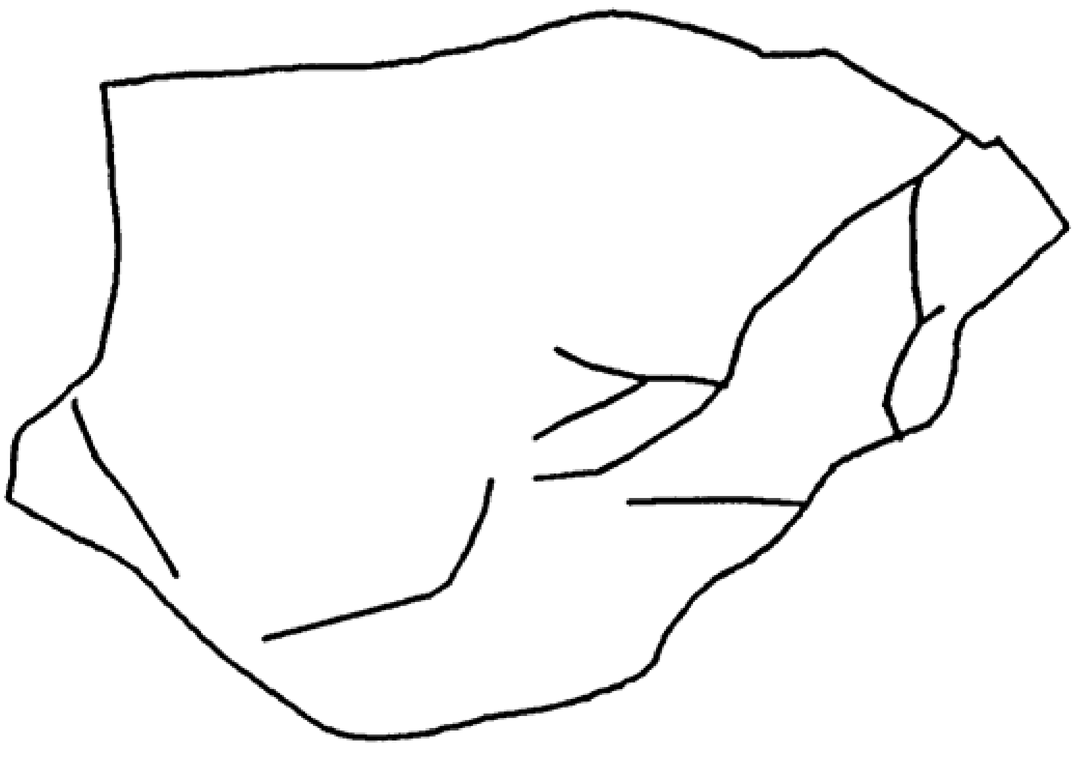
Introduction - Two Remarking Trends:

- *In Reservoir Characterization:*
  - Migration from 2D to 3D
  - Methodologies
- *In Simulation:*
  - Use of more Flexible Grids

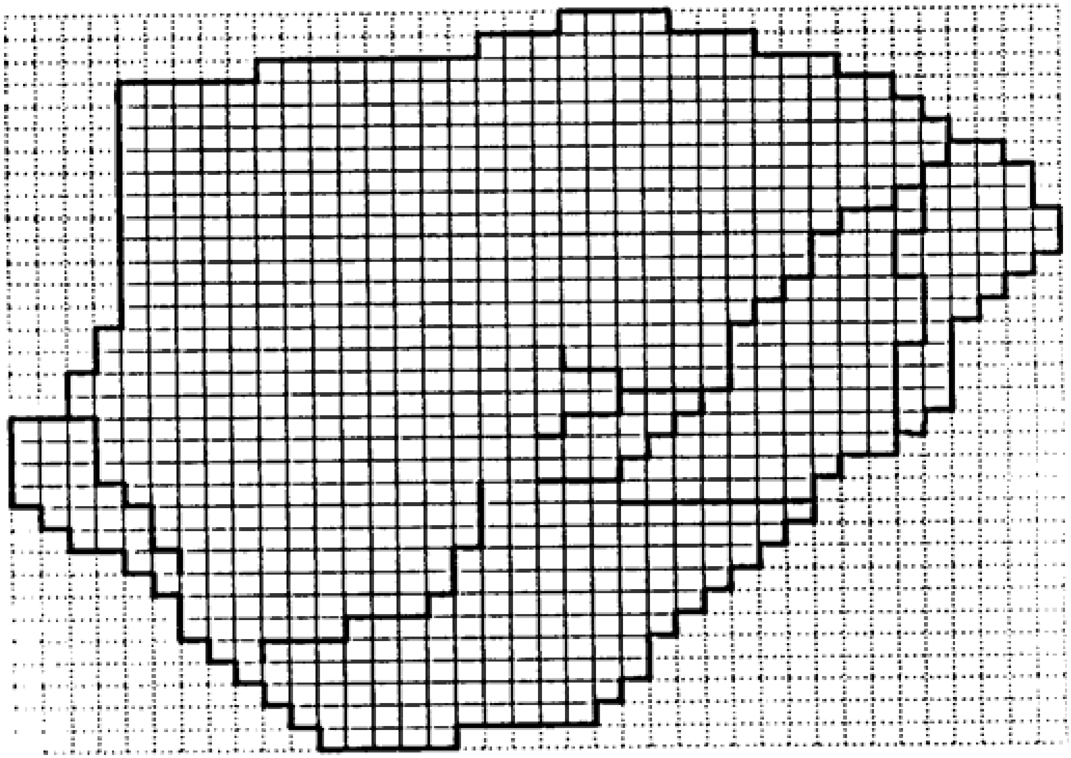
Grid Formats Objectives

- →Adequate Strategies to the Specification of Volumetric Grids in Integrated Studies
- →Strategies to the transference of information between Characterization Grids and Simulation Grids (Geometrical Approach x Topological Approach)
- →Better Representation of the Fault Geometry in Reservoir Simulation Models
- →Development of Upscaling Techniques

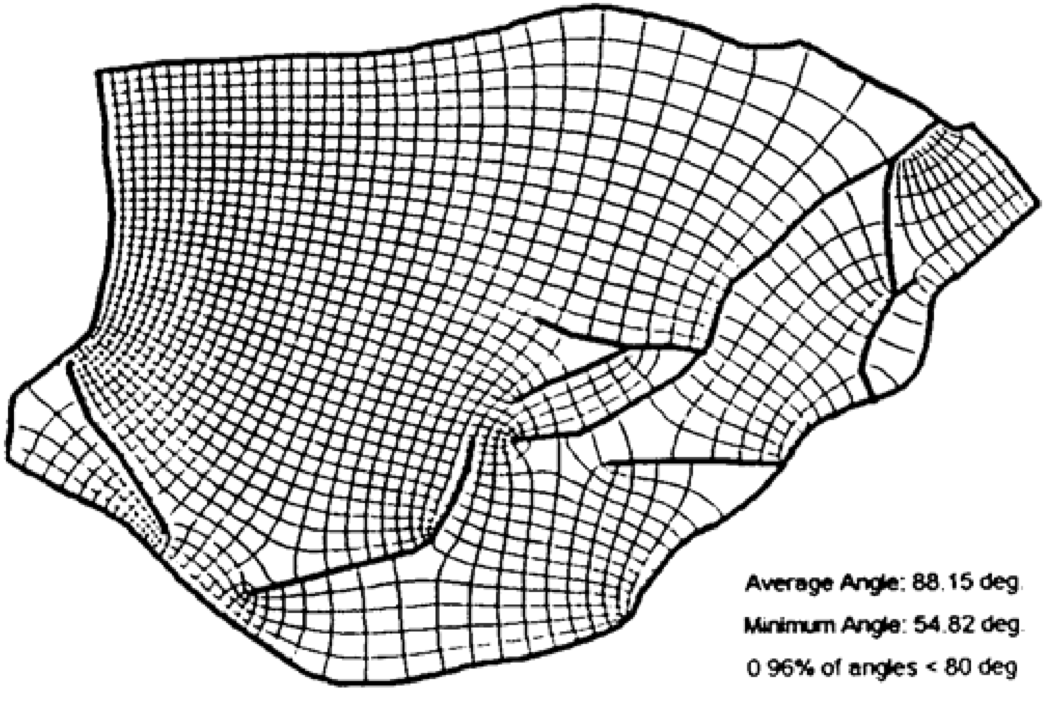
Base Map to Simulation Grid Examples [Hales, 96]



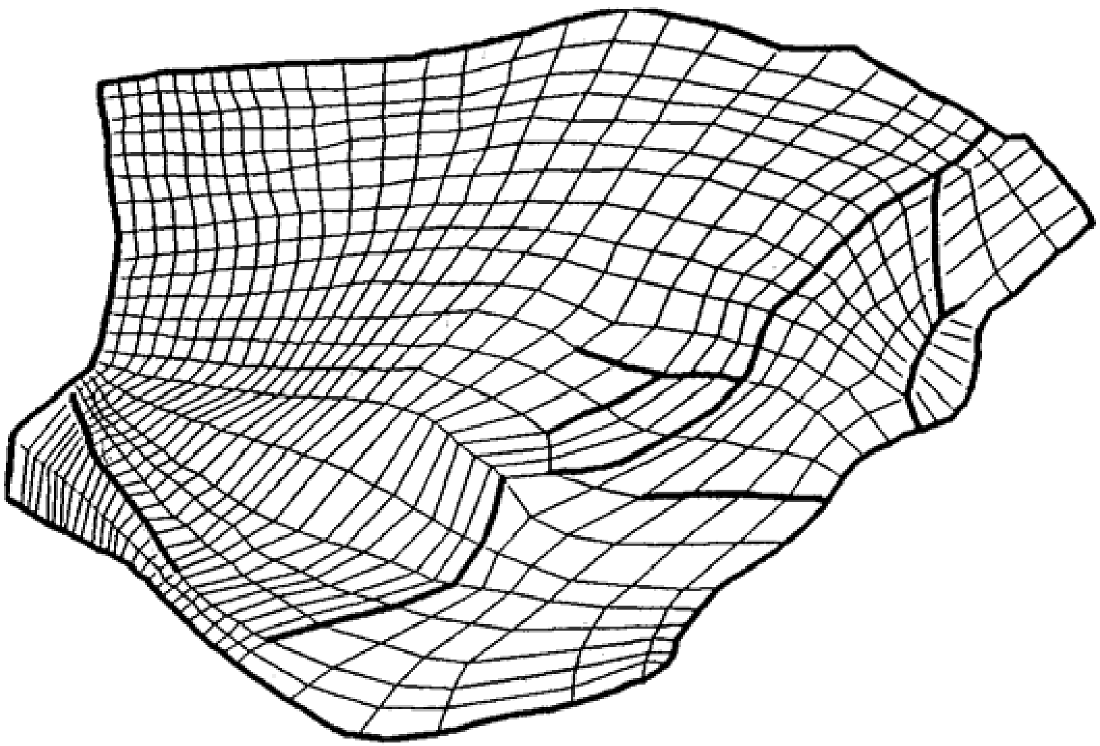
Cartesian Grid Example [Hales, 96]



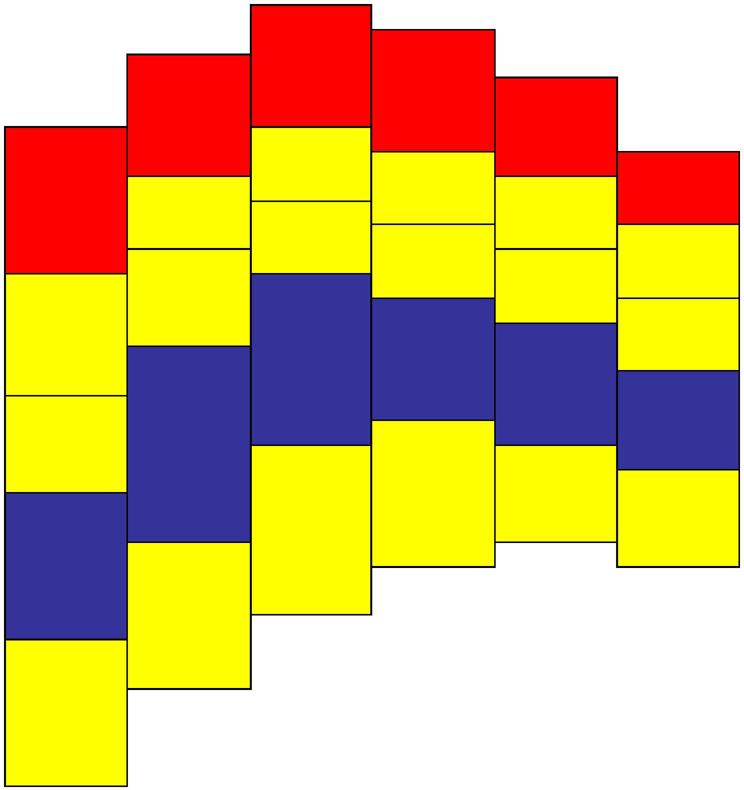
Orthogonal Curvilinear Grid Example [Hales, 96]

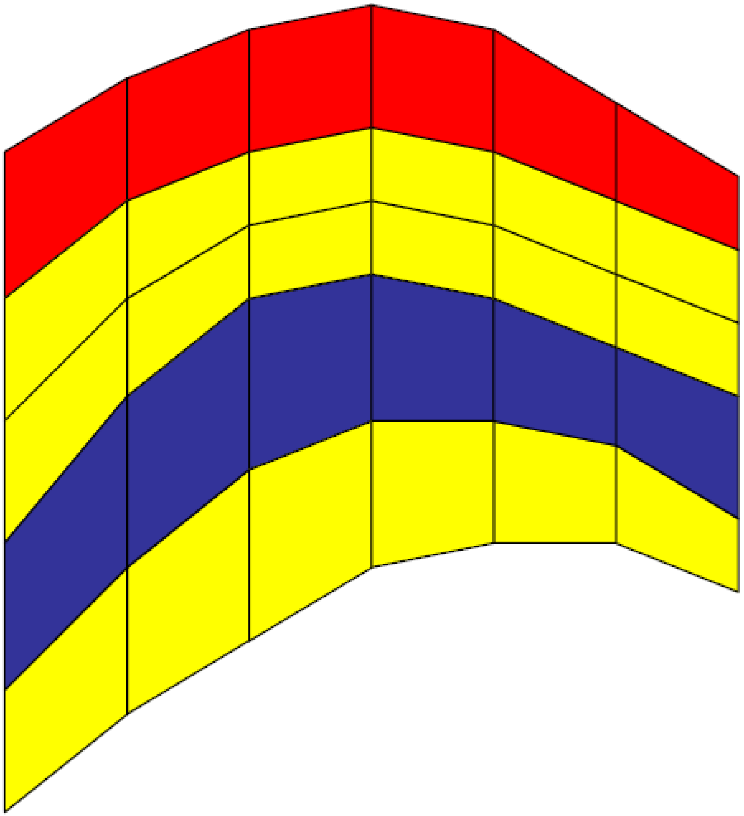


Corner Point Grid Example [Hales, 96]



Grids to Flow Simulation





Traditional Block-Centered Grid (Type 3 Grid)

XY Orthogonal Corner Point Grid (Type 4 Grid)