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Fully Coupled Geomechanics and Discrete Flow Network Modeling of Hydraulic Fracturing for Geothermal Applications

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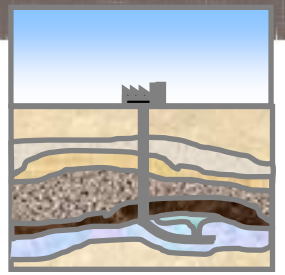
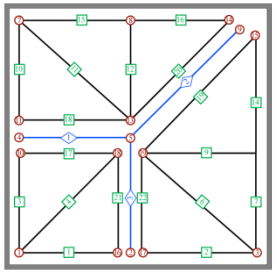
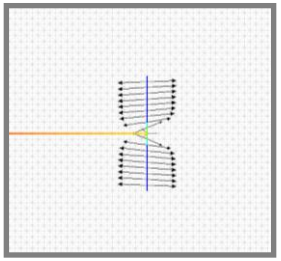
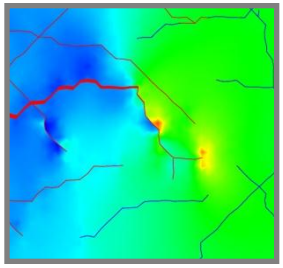
Outline

- Problem statement and general approach
- Important modules of the simulator
- Simulating interaction between fractures:
  - Cross vs. offset
- Simulating complex fracture network

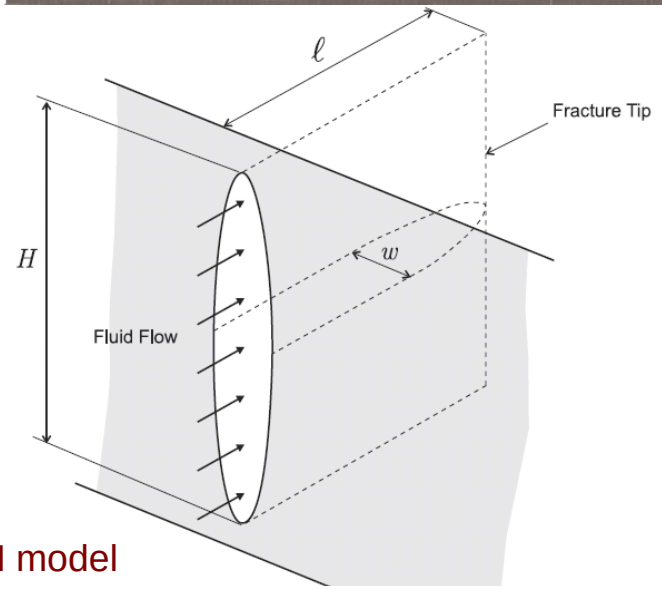




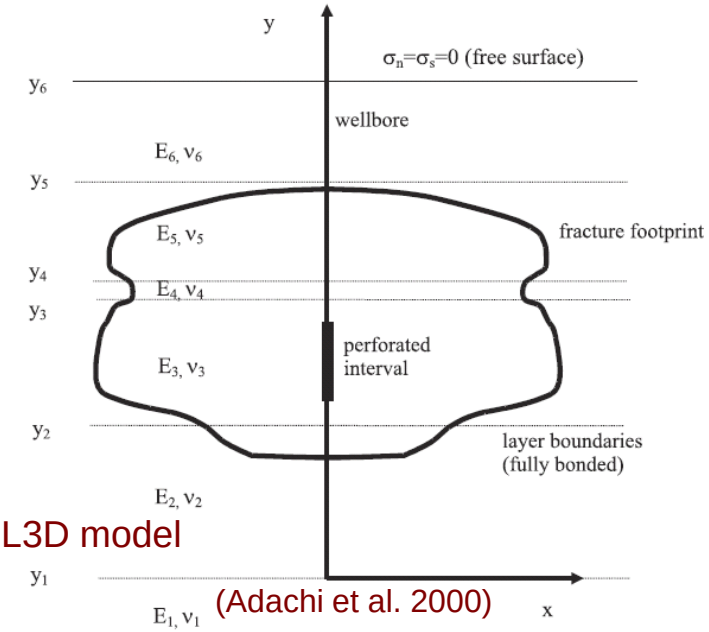




Fracture systems and available hydraulic fracturing models

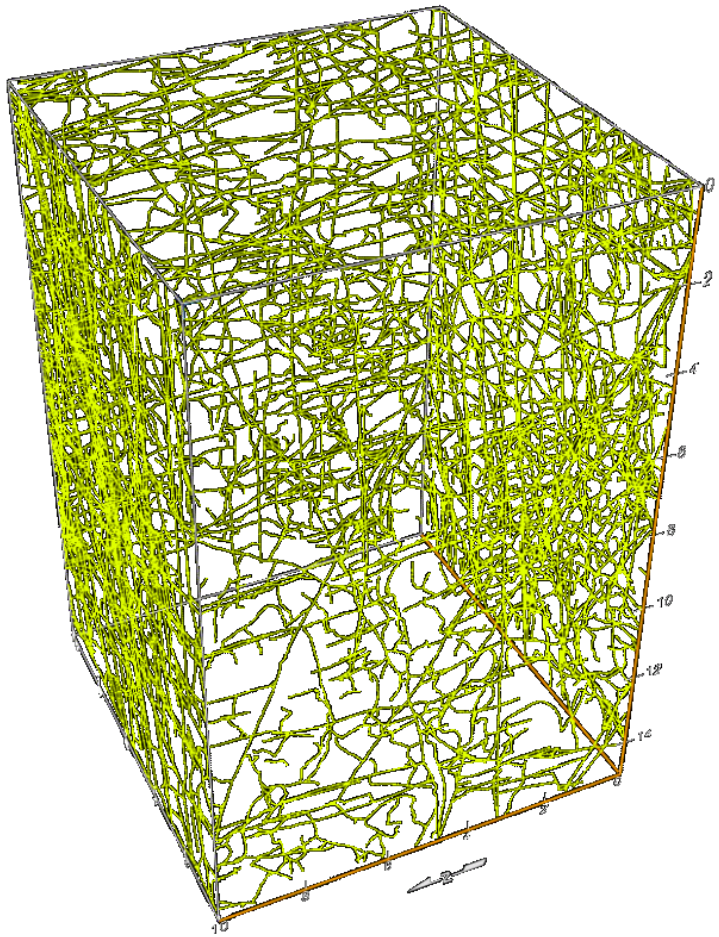


PKN model



PL3D model

(Adachi et al. 2000)



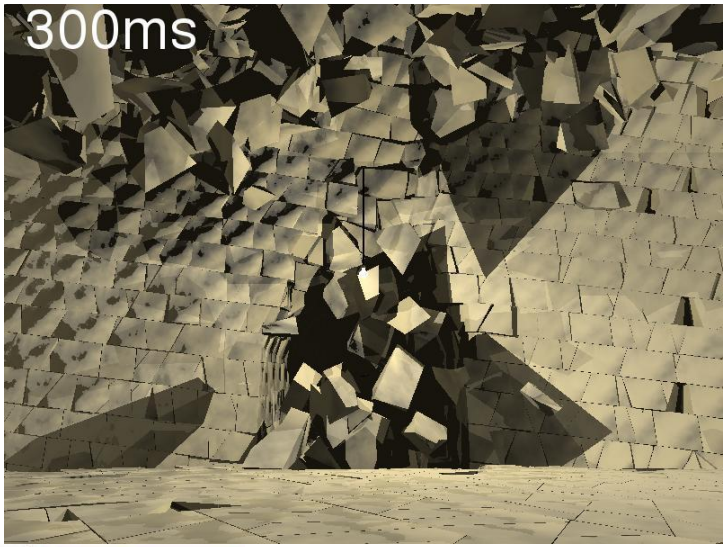
(Large Block Test, Yucca Mountain. Wagoner, 2000)

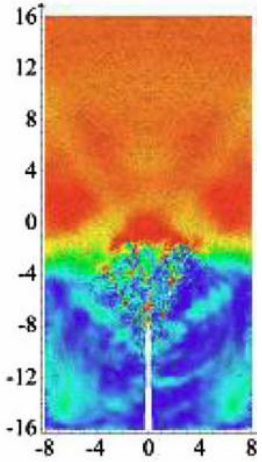
Research Goal

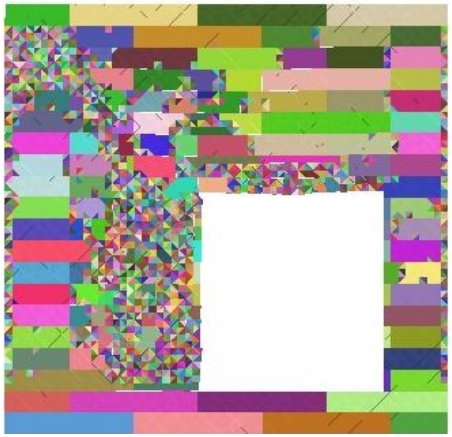
- Develop simulator for EGS stimulation
- Important mechanisms governing hydraulic fracturing
  - Discrete fracture flow
  - Fracturing in formation
  - Interactions between fractures
- Evaluate enhancement strategies for different EGS scenarios

Platform of Development

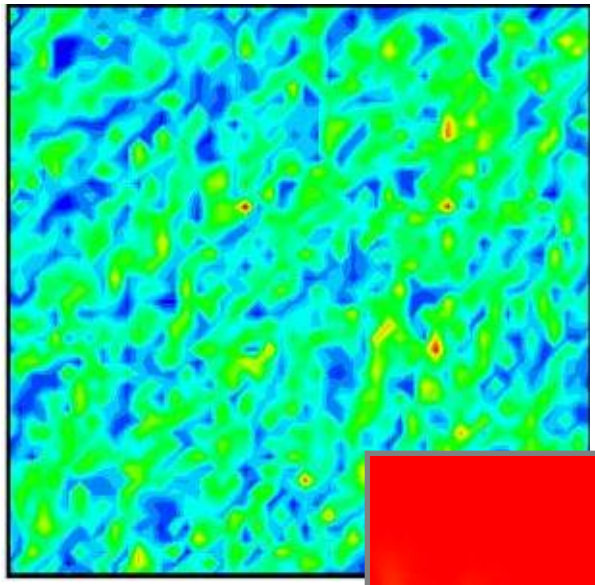
LDEC Livermore Distinct Element Code

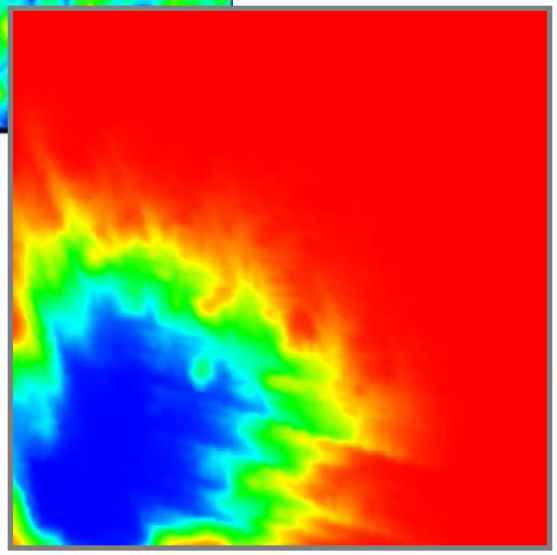






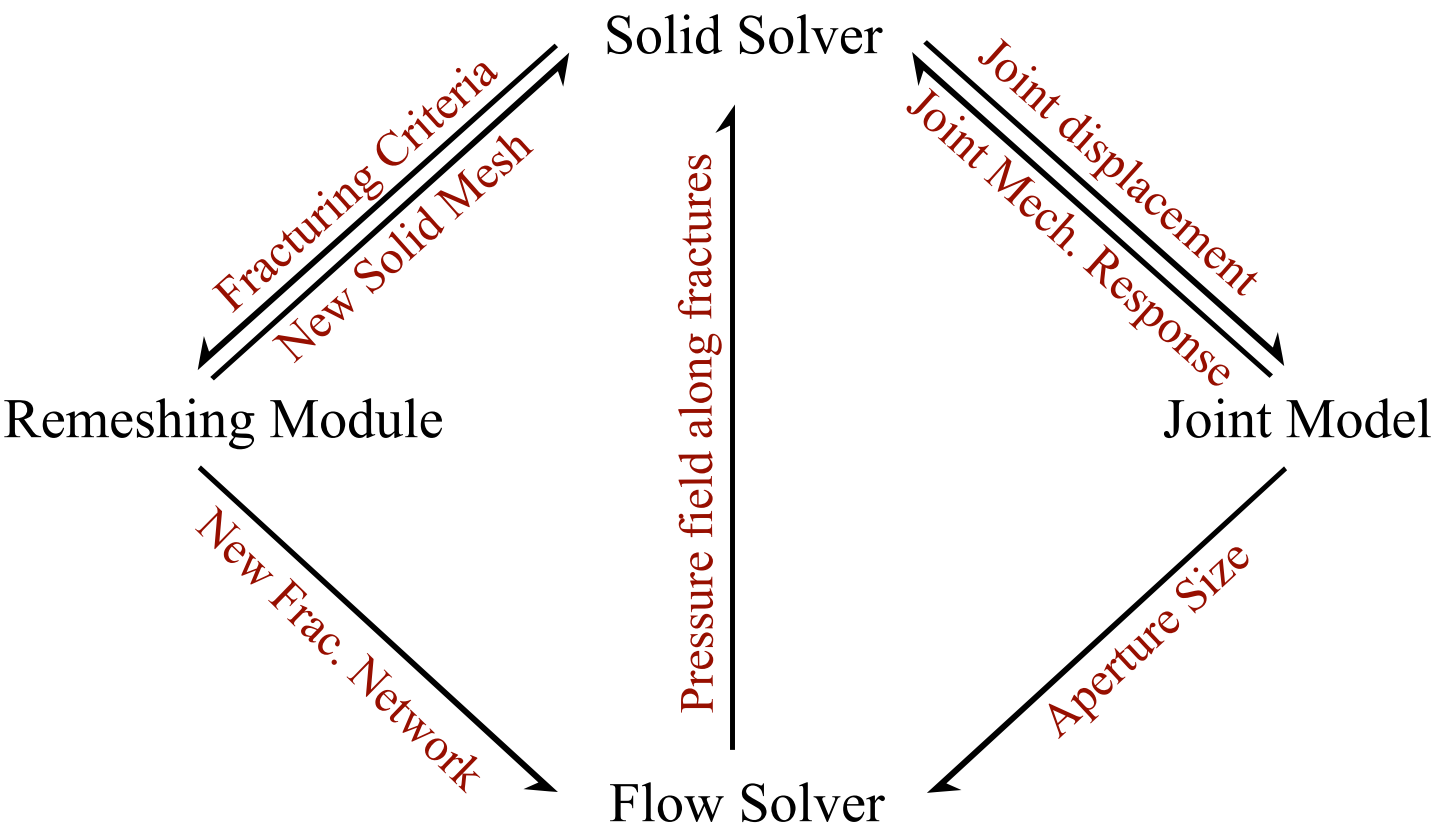
NUFT Non-isothermal Unsaturated Flow





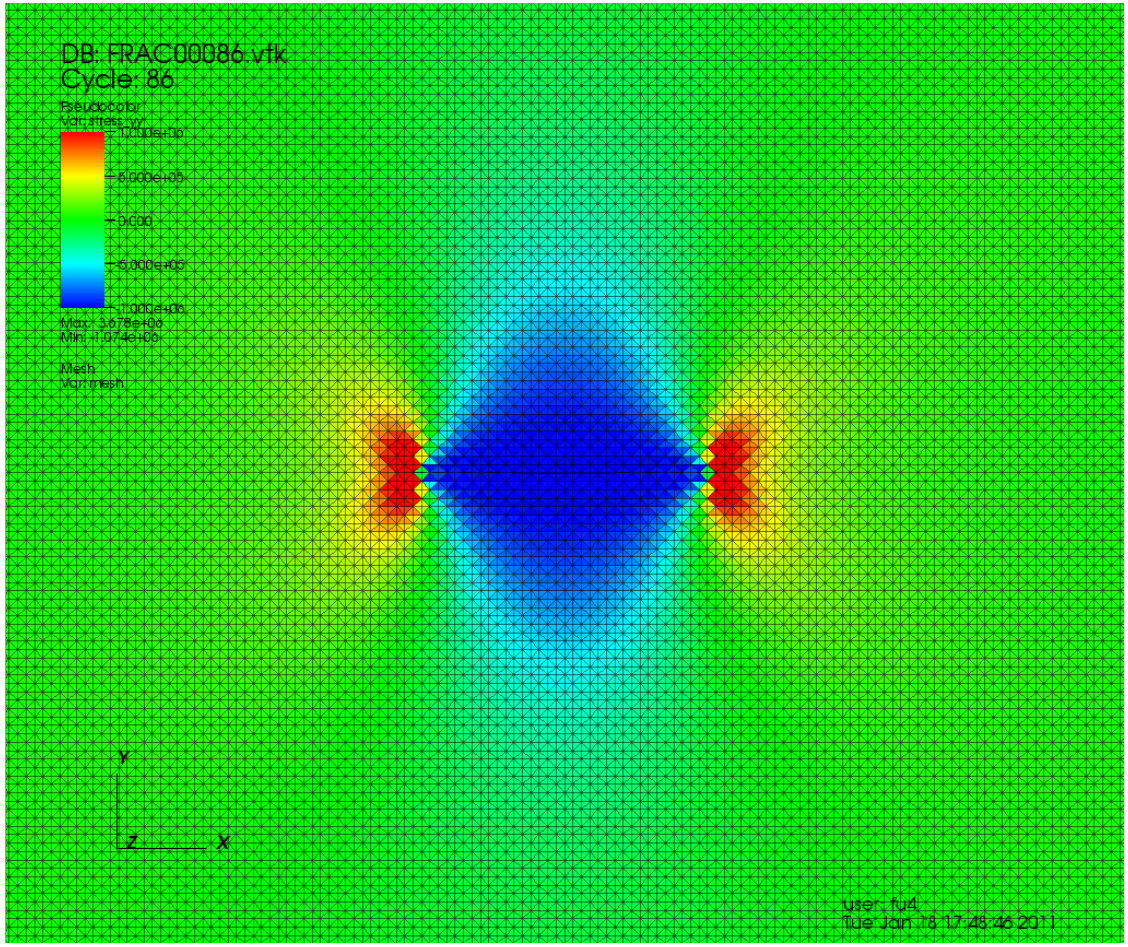
Images from previous applications, for conceptual demonstration only.

Hydraulic Fracture Simulator: Framework



Important Components

- Solid solver – Explicit finite element engine



Important Components

- Flow solver – Finite volume method

$$\kappa_{ij} = \frac{\alpha_{ij}^3}{6\mu(L_i + L_j)}$$

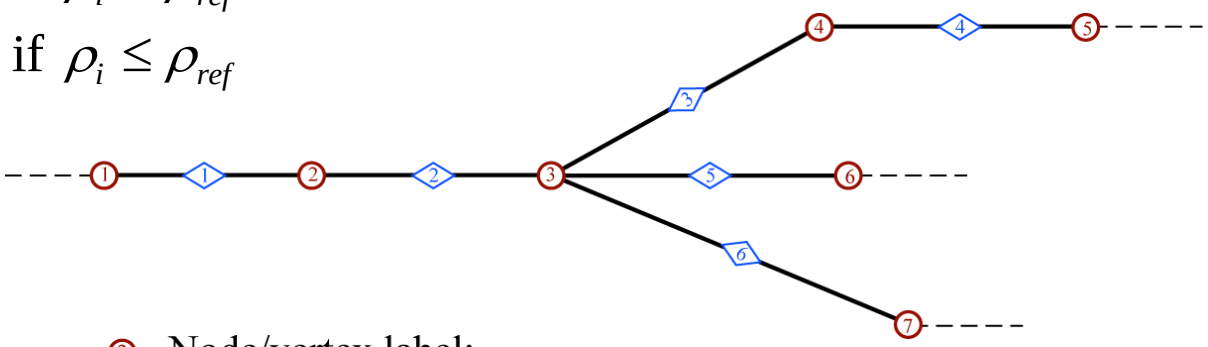
$$\alpha_{ij}^3 = \frac{\alpha_i^3 \alpha_j^3 (L_i + L_j)}{\alpha_i^3 L_j + \alpha_j^3 L_i}$$

$$\dot{V}_{ij} = \kappa_{ij}(P_i - P_j)$$

$$P_i = \begin{cases} K(\rho_i / \rho_{ref} - 1) & \text{if } \rho_i > \rho_{ref} \\ 0 & \text{if } \rho_i \le \rho_{ref} \end{cases}$$

Two mechanisms:

- Flow in fractures due to pressure gradient.
- Mass conservation with varying total fracture volume.



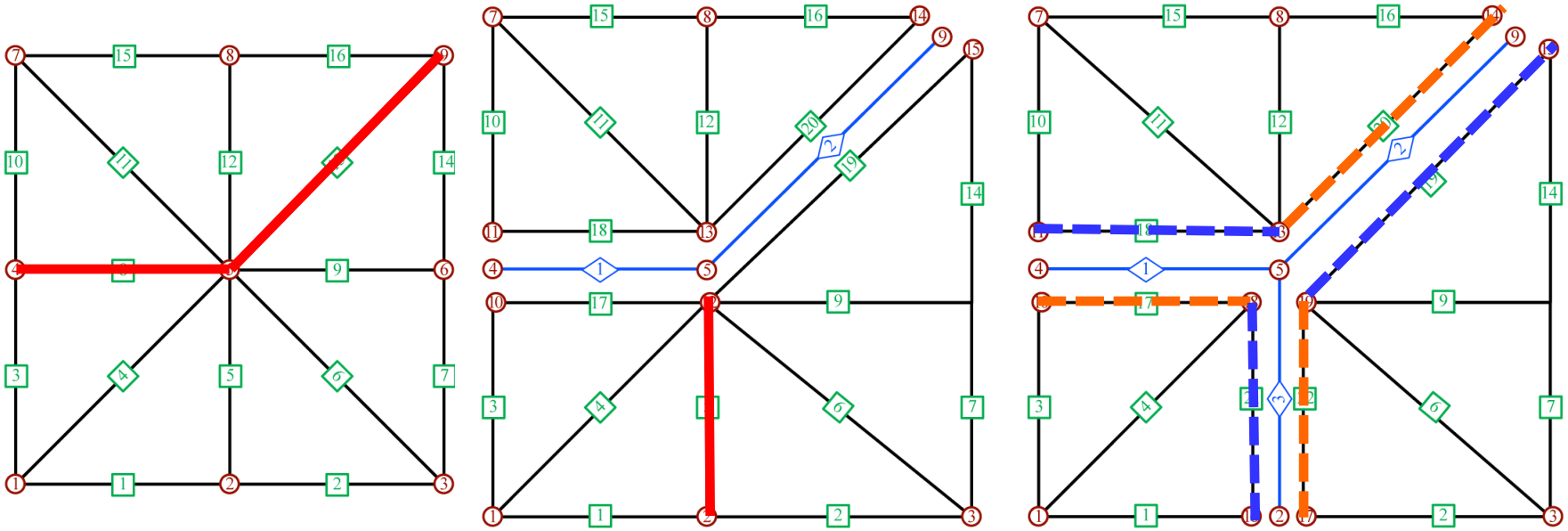
Important Components

- Fracturing criterion and adaptive remeshing

$$\sigma_n \geq \lambda T_0$$

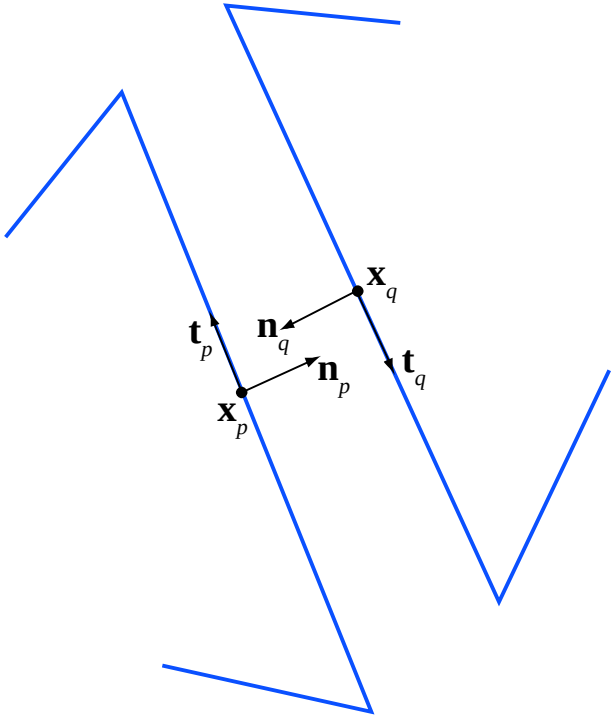
T_0 = tensile strength of rock;

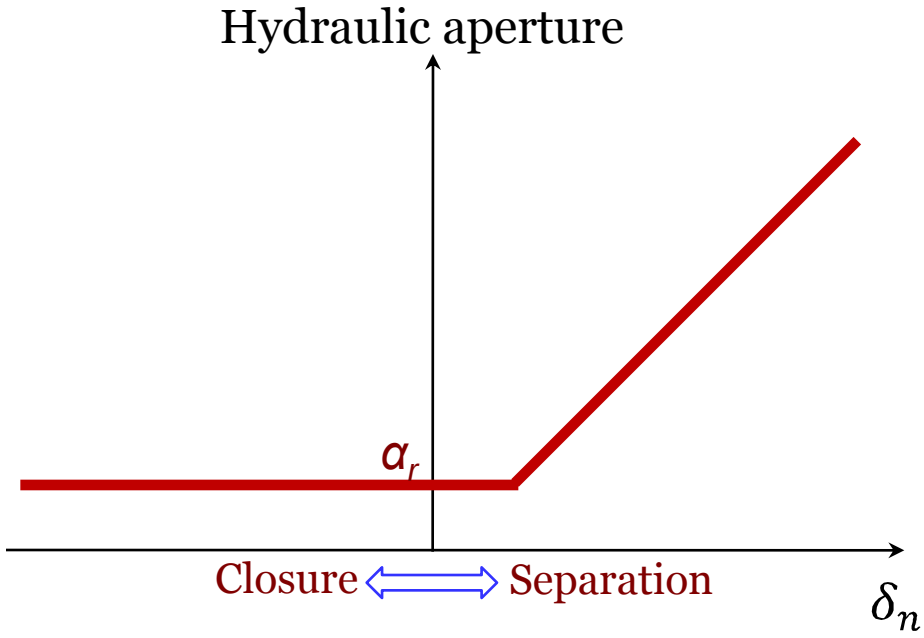
λ= correction factor.



Important Components

- Joint model





$$\delta_n = (\mathbf{x}_q - \mathbf{x}_p) \cdot \mathbf{n}_p \qquad \Delta F_n = K_n \dot{\delta}_n \Delta t$$

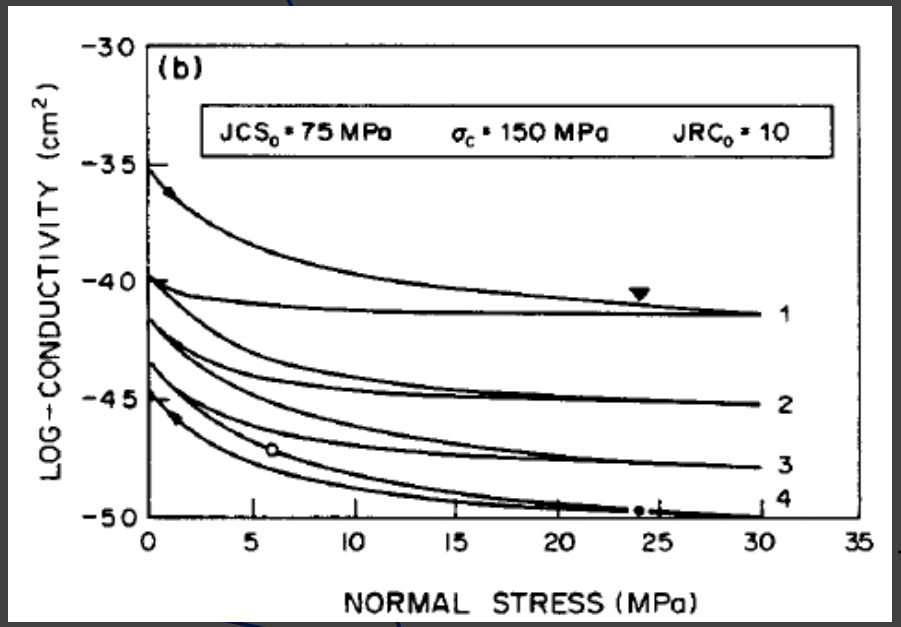
$$\delta_t = (\mathbf{x}_q - \mathbf{x}_p) \cdot \mathbf{t}_p \qquad \Delta F_t = K_t \dot{\delta}_t \Delta t$$

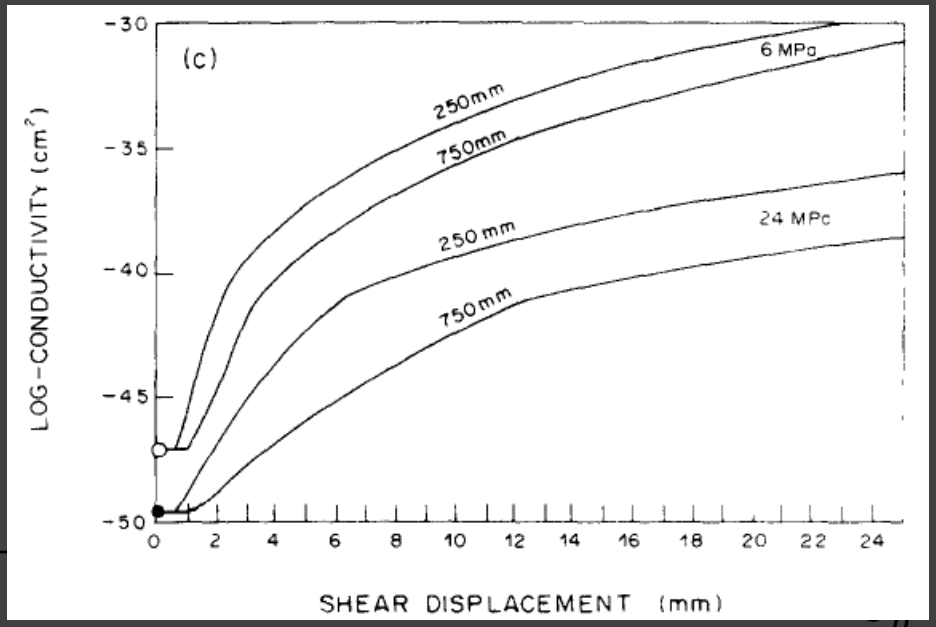
$$F_t \le F_n \tan\phi$$

$$\alpha = \begin{cases} \delta_n & \text{if } \delta_n > \alpha_r \\ \alpha_r & \text{if } \delta_n \le \alpha_r \end{cases}$$

Important Components

- Coupling between joint mechanical responses and conductivity.





$$\delta_n = (\mathbf{x}_q - \mathbf{x}_p) \cdot \mathbf{n}_p \qquad \Delta F_n = K_n \delta_n \Delta t$$

$$\delta_t = (\mathbf{x}_q - \mathbf{x}_p) \cdot \mathbf{t}_p \qquad \Delta F_t = K_t \delta_t \Delta t$$

$$\alpha = \begin{cases} \delta_n & \text{if } \delta_n > \alpha_r \\ \alpha_r & \text{if } \delta_n \le \alpha_r \end{cases}$$

Barton et al. (1985) Strength, deformation and conductivity coupling of rock joints.

Hydraulic Fracture Simulator: Framework

- Time stepping considerations

$$\Delta t_{solid\_crt} = L / c$$

3×10^{-4} s — Determines cost per step.

$$\Delta t_{flow\_crt} = \frac{6\mu}{K}\left(\frac{L_{ij}}{\alpha_{ij}}\right)^2$$

1×10^{-9} s — Determines num. of steps.

Hydraulic Fracture Simulator: Framework

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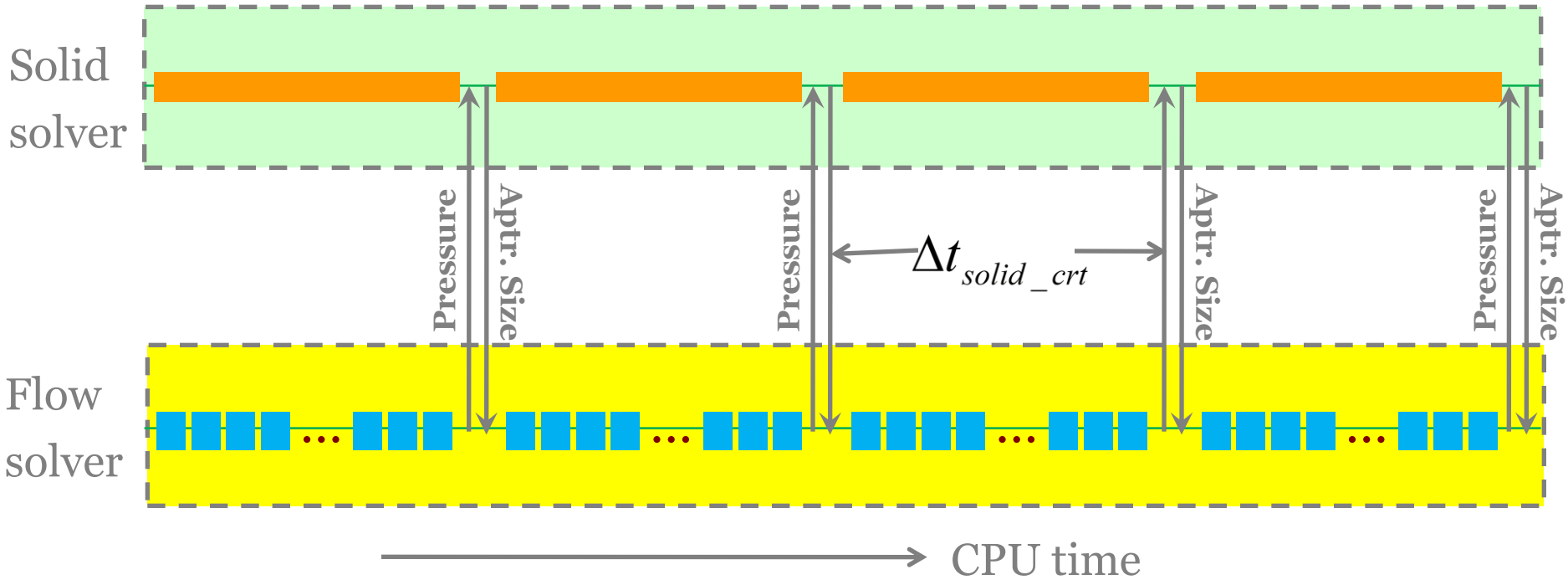
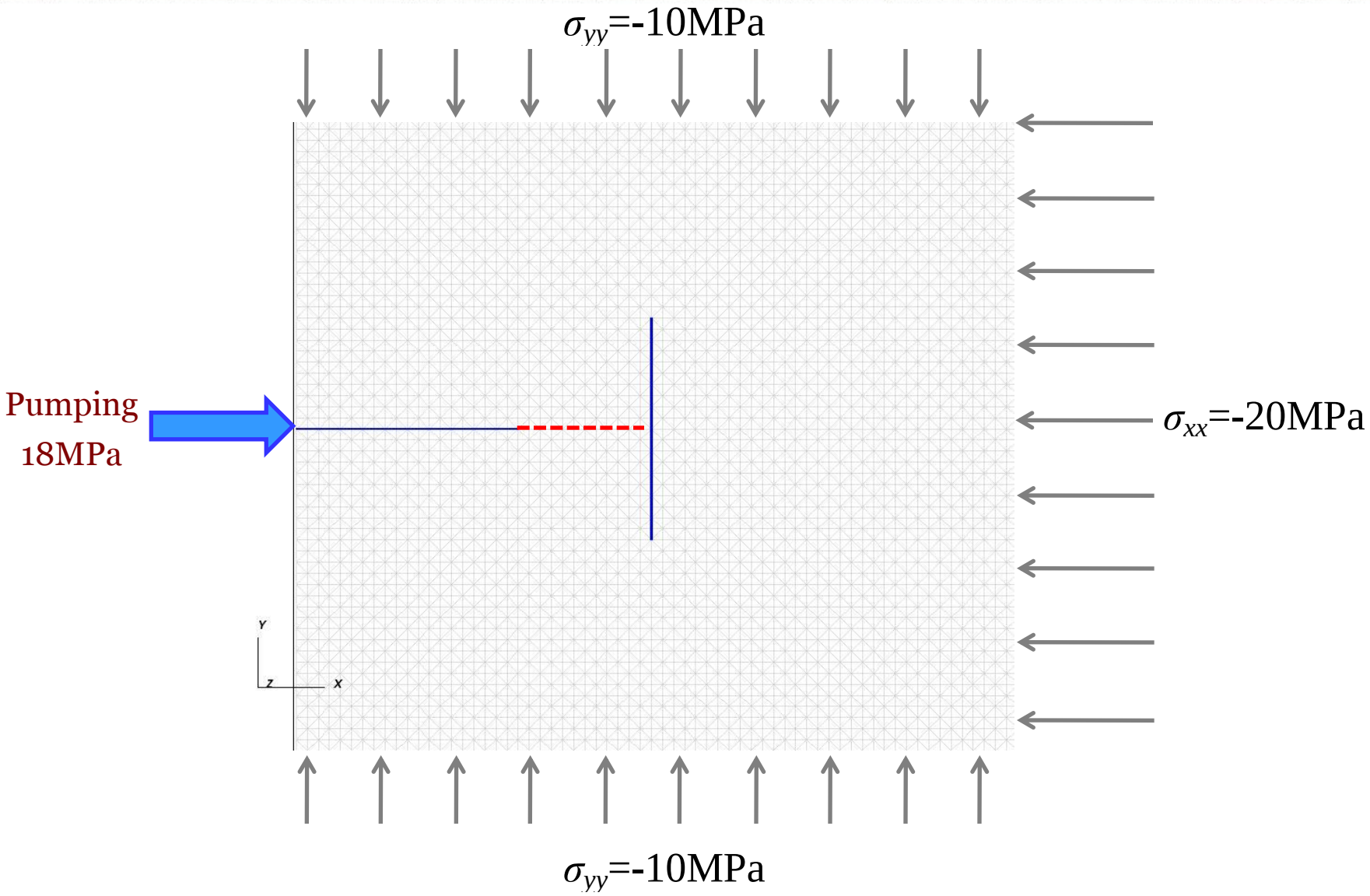


Interaction Between Propagating and Existing Fractures



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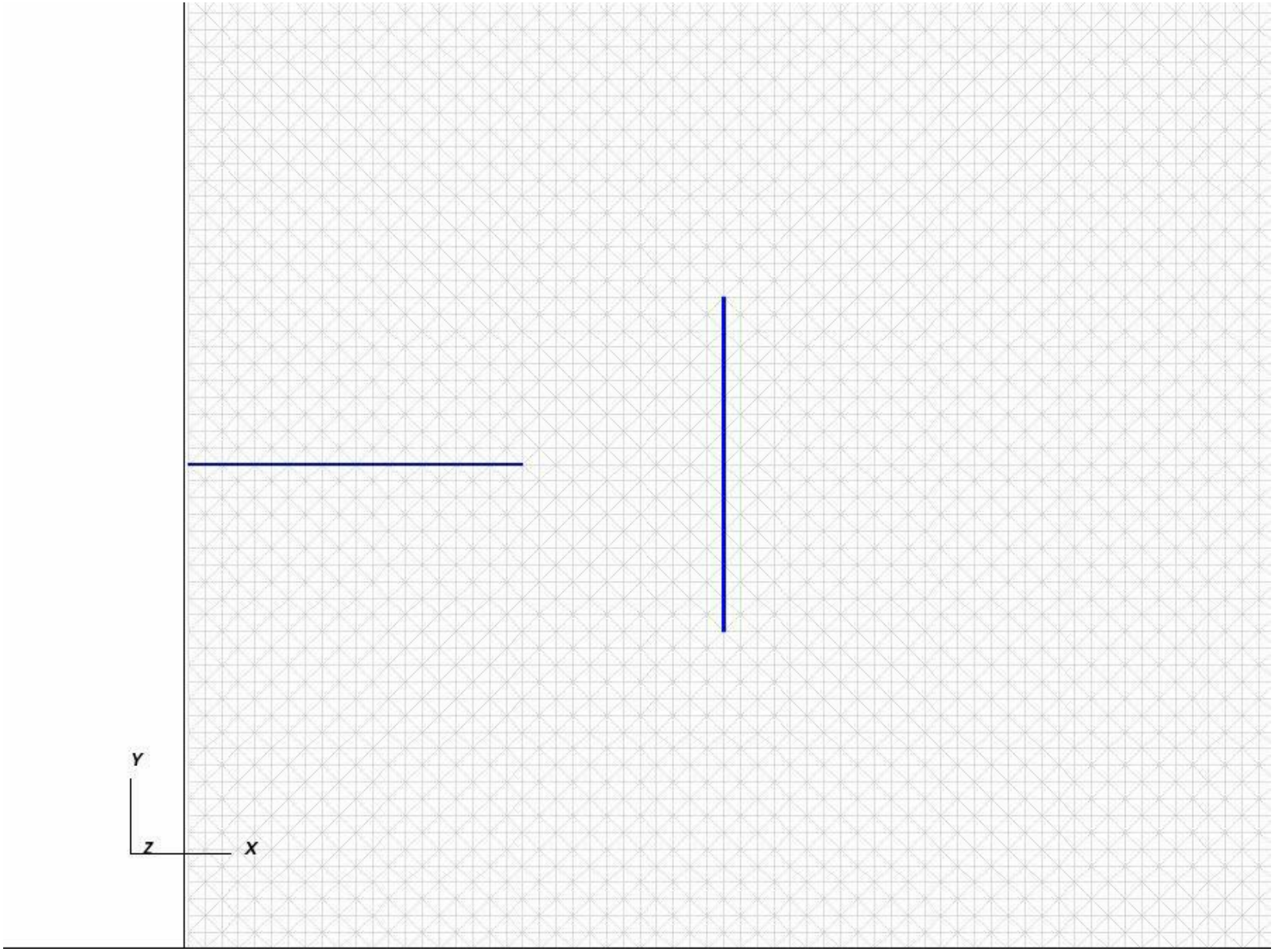

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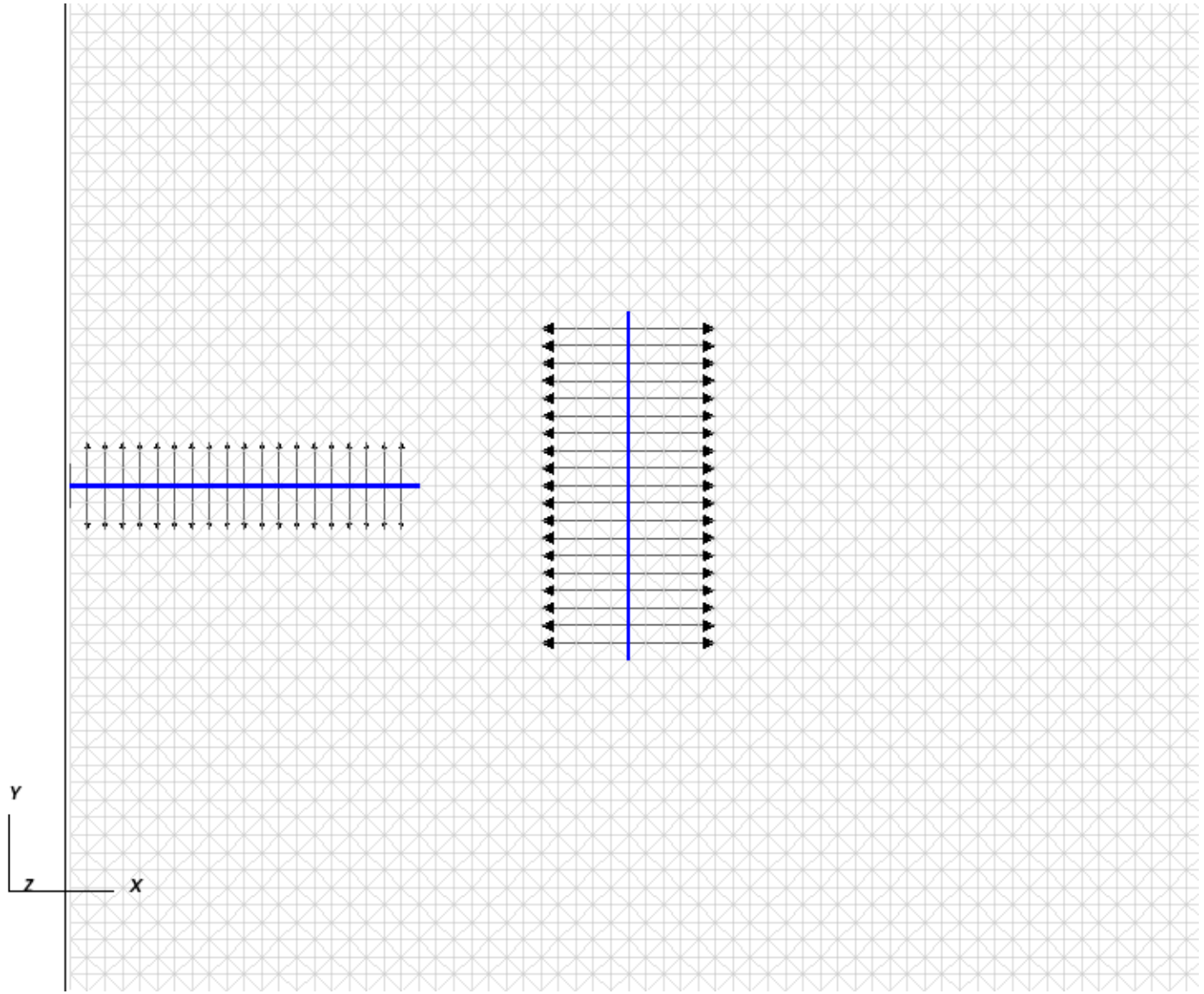

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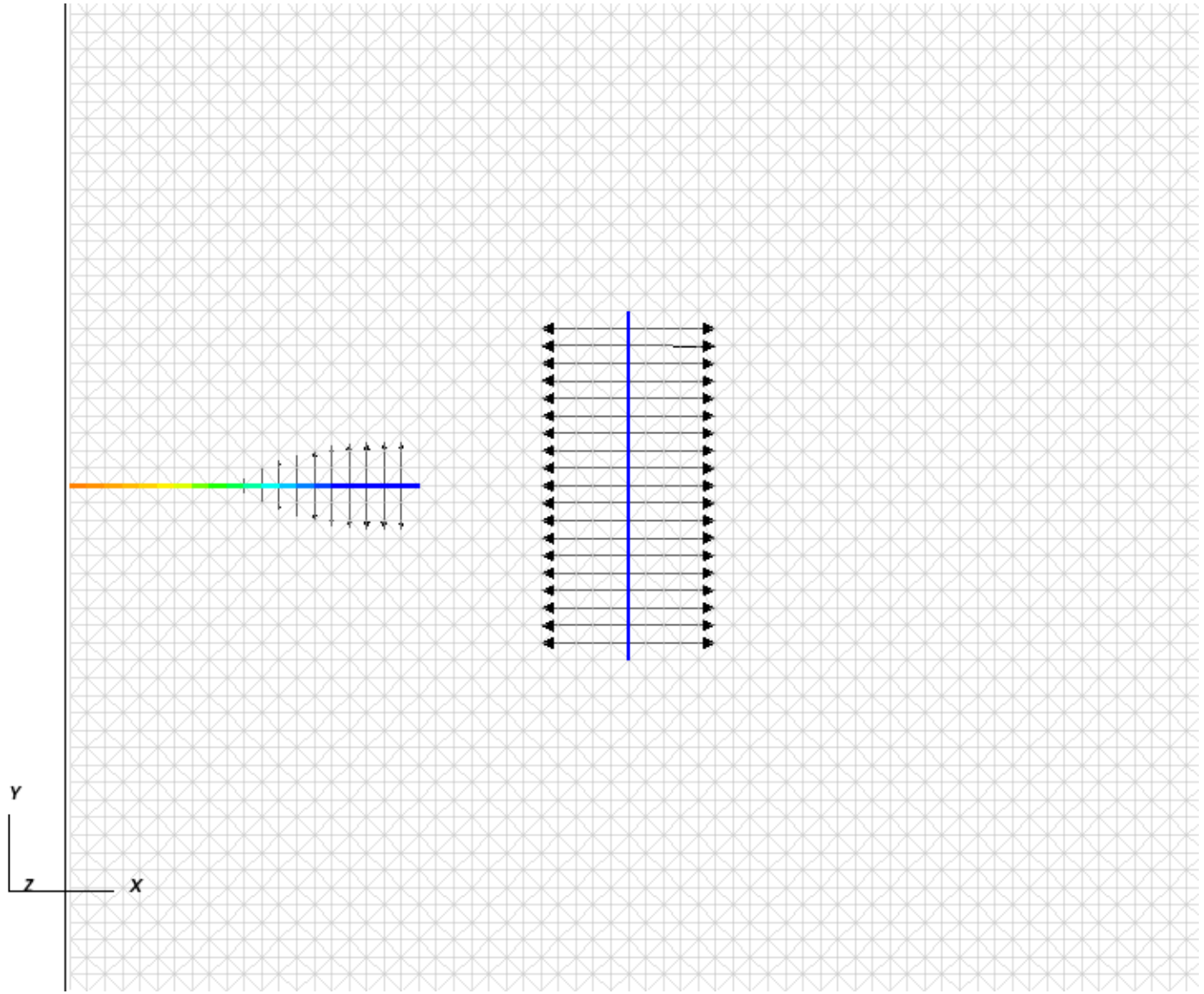

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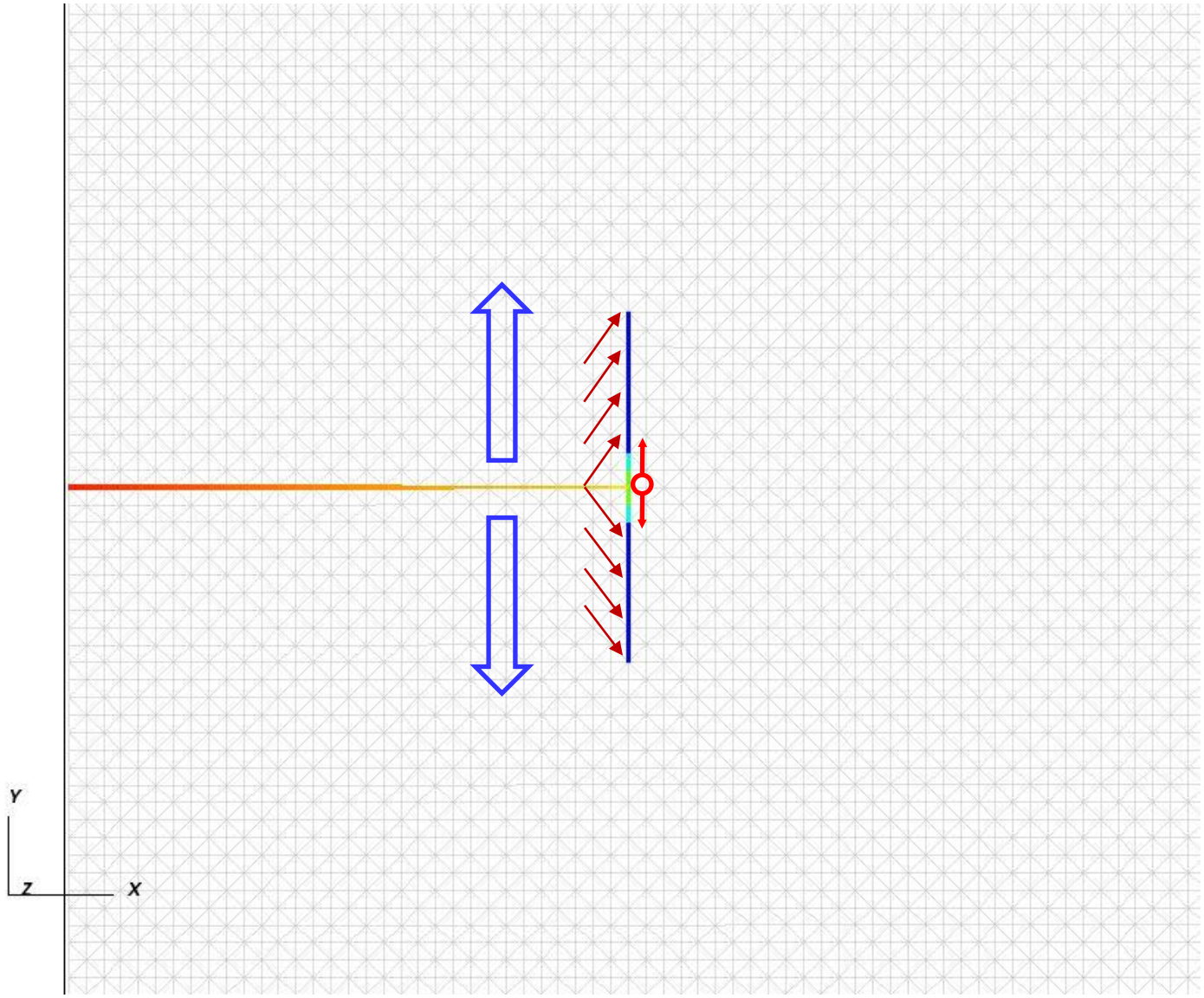

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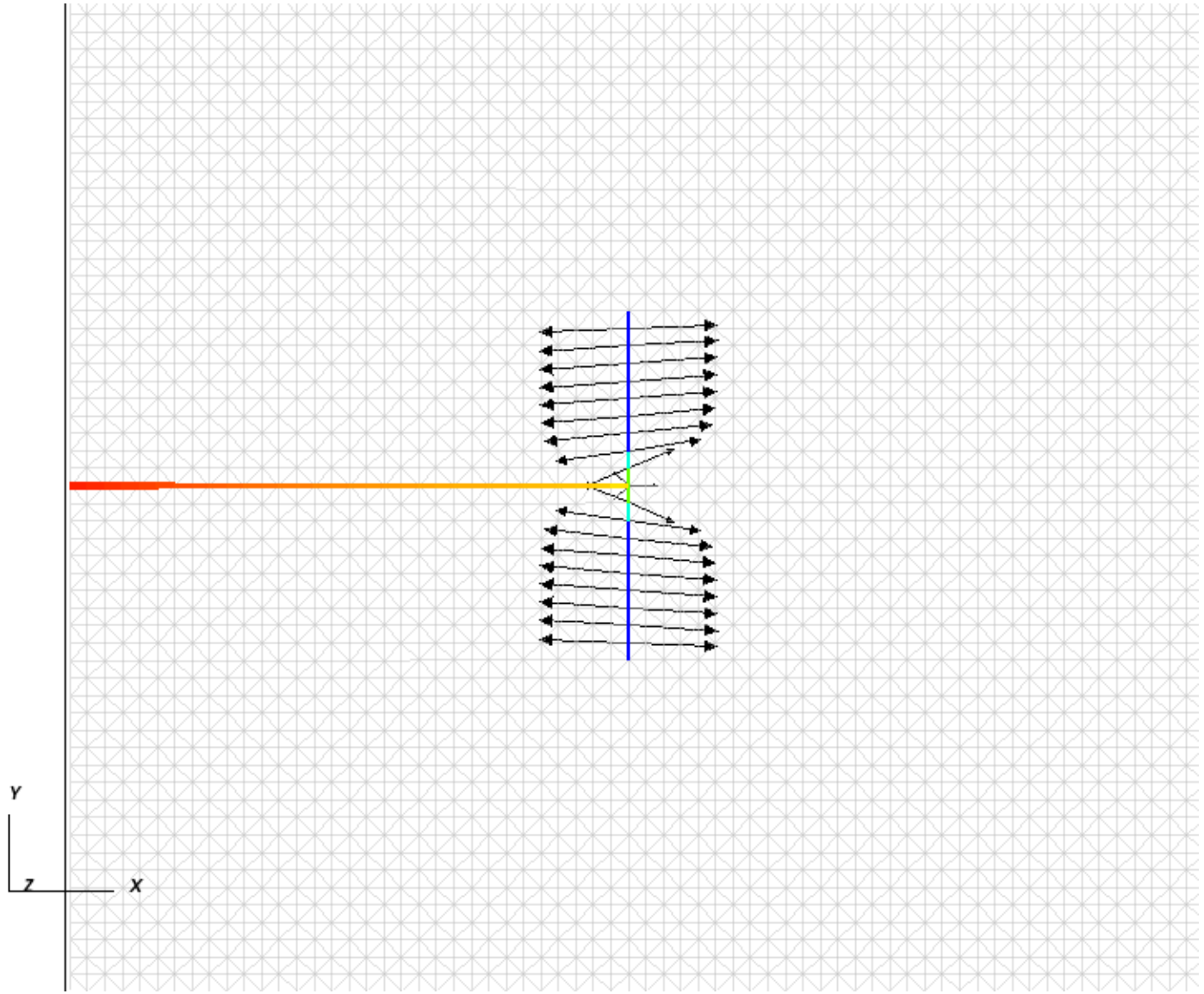

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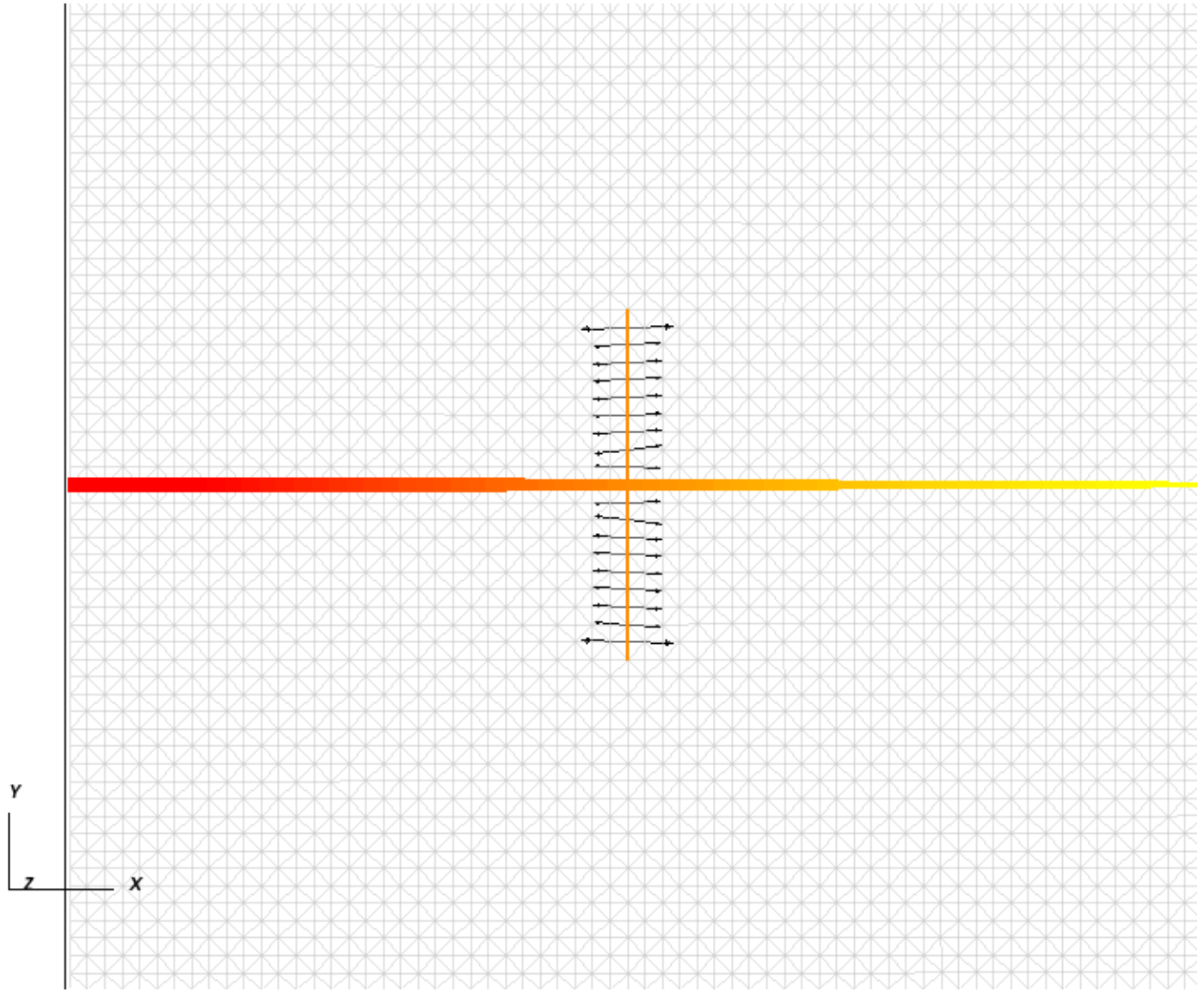

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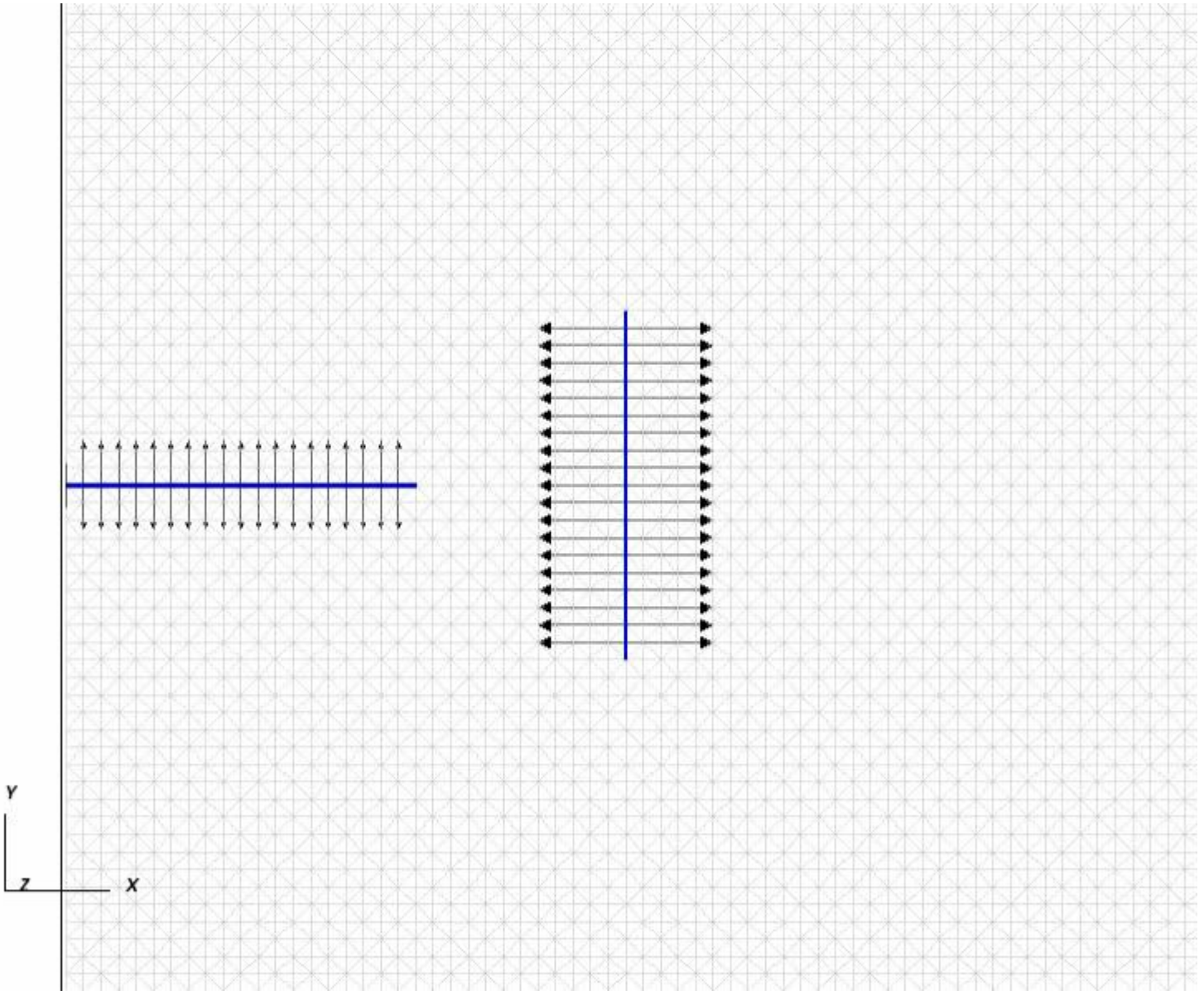

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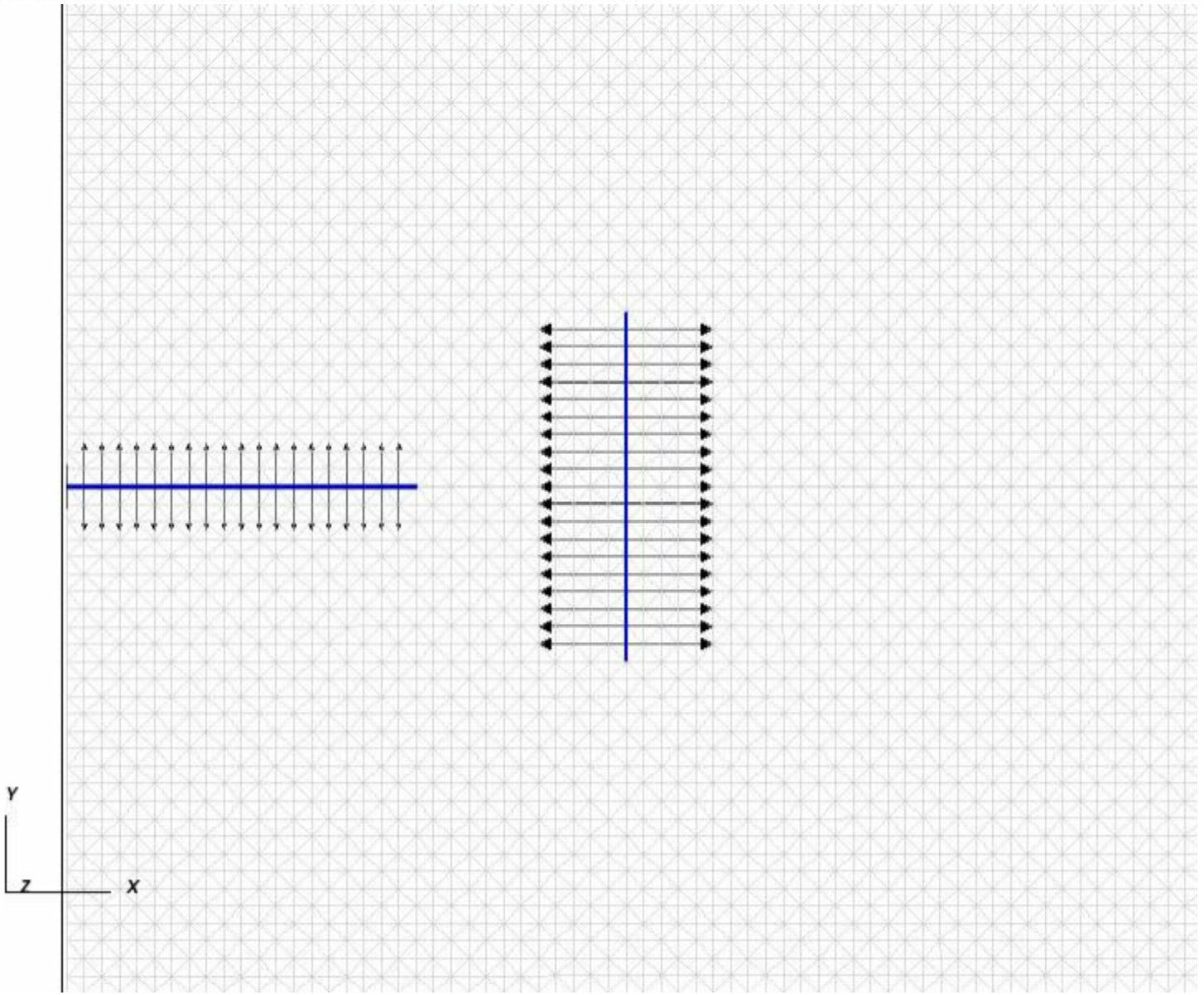

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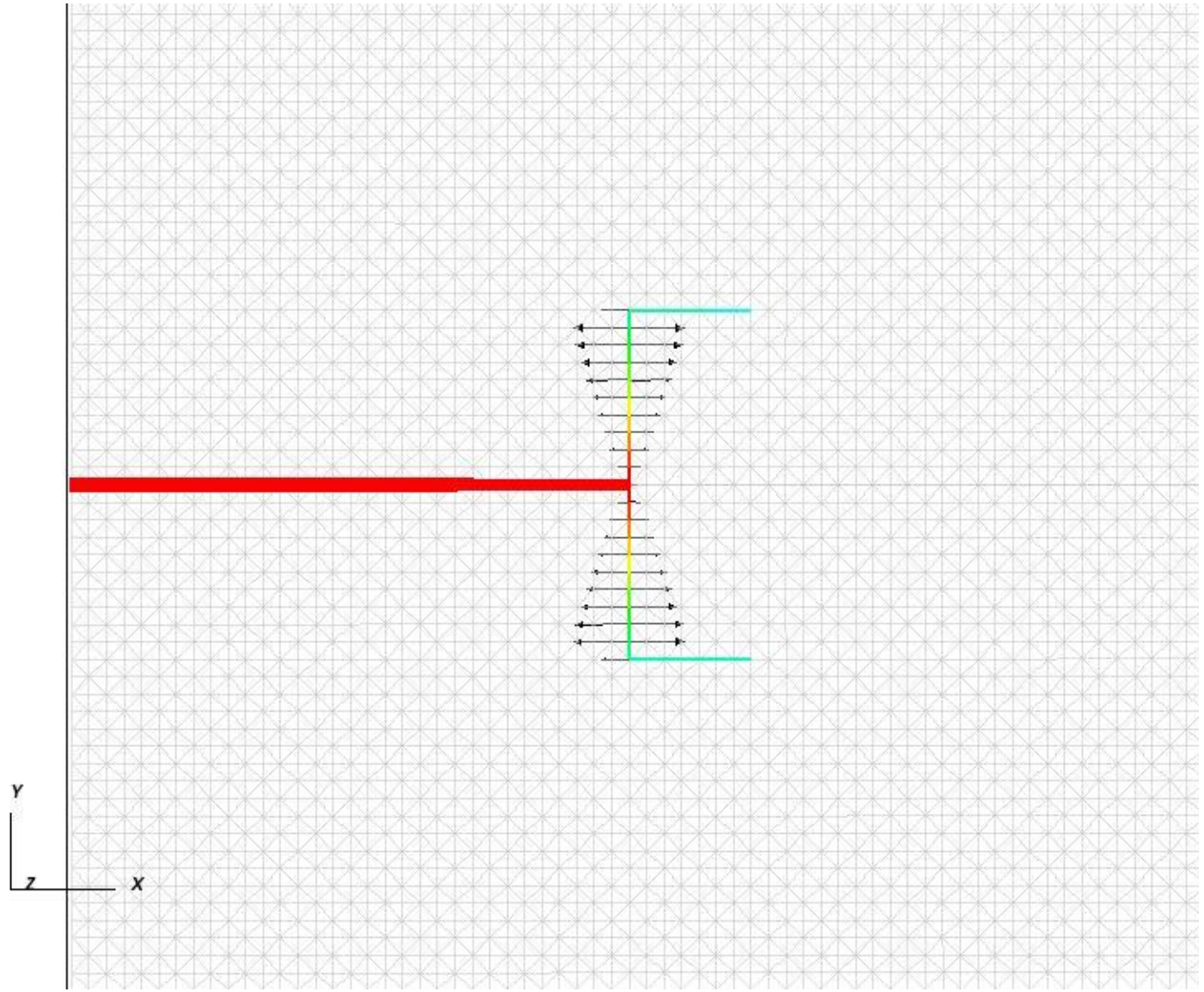
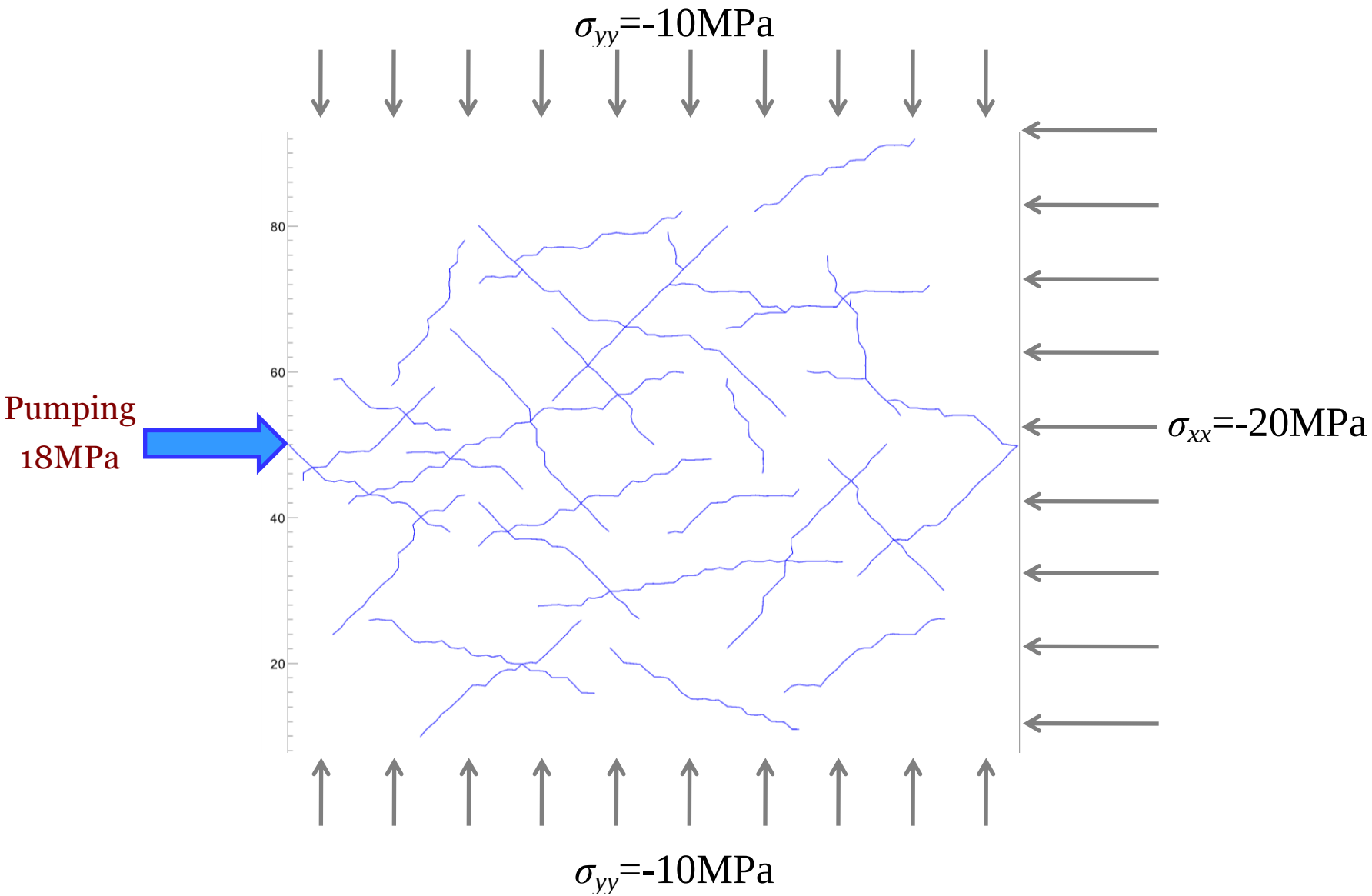
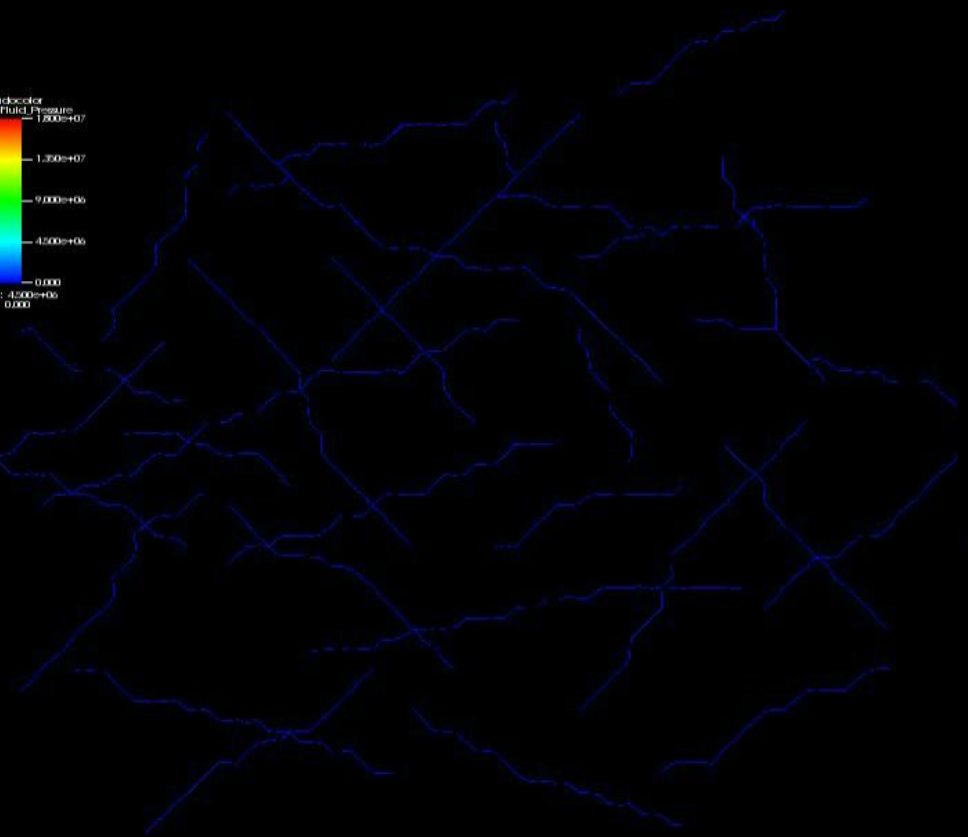


Stimulation of a Preexisting Fracture Network

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9.000e+06
4.500e+06
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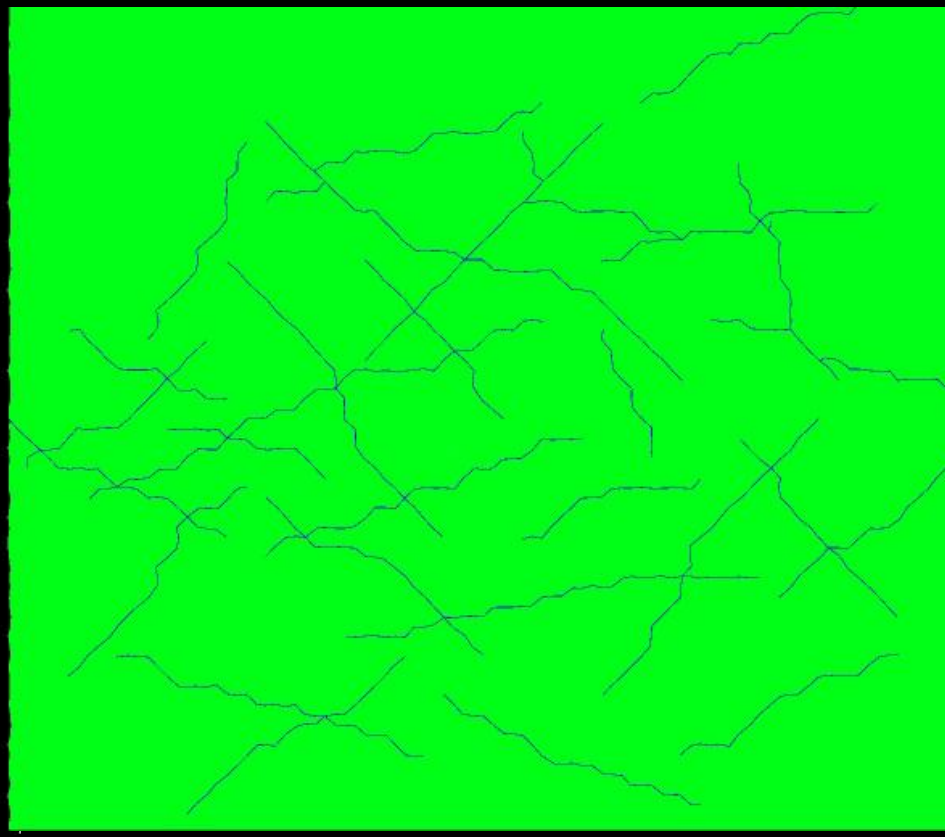
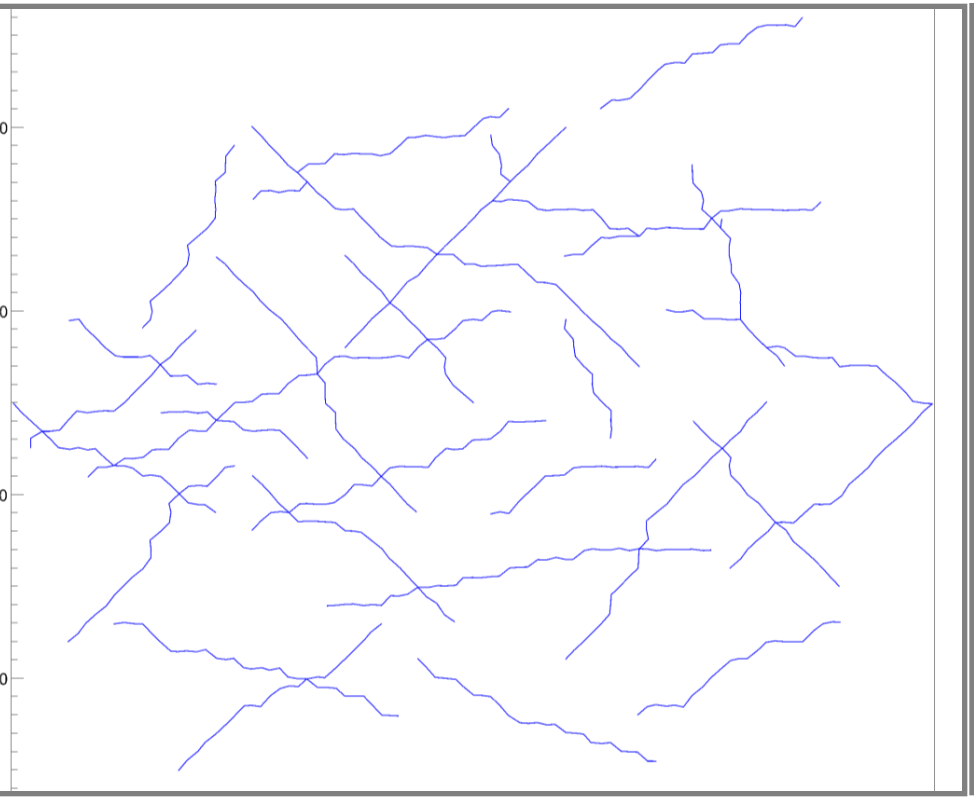
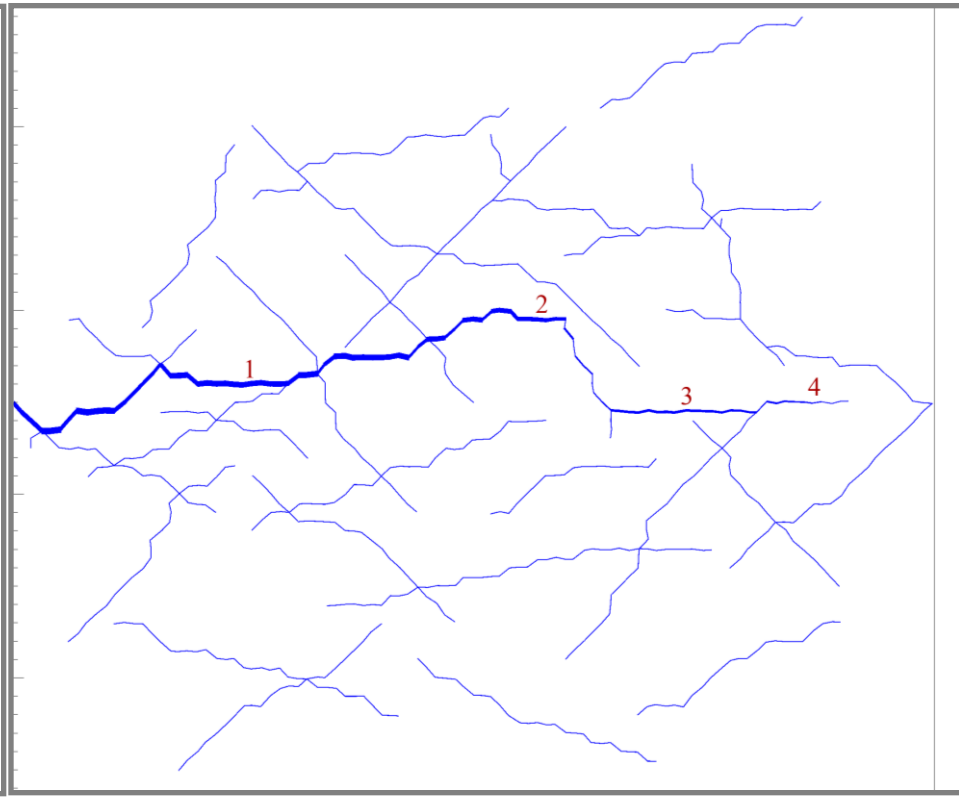


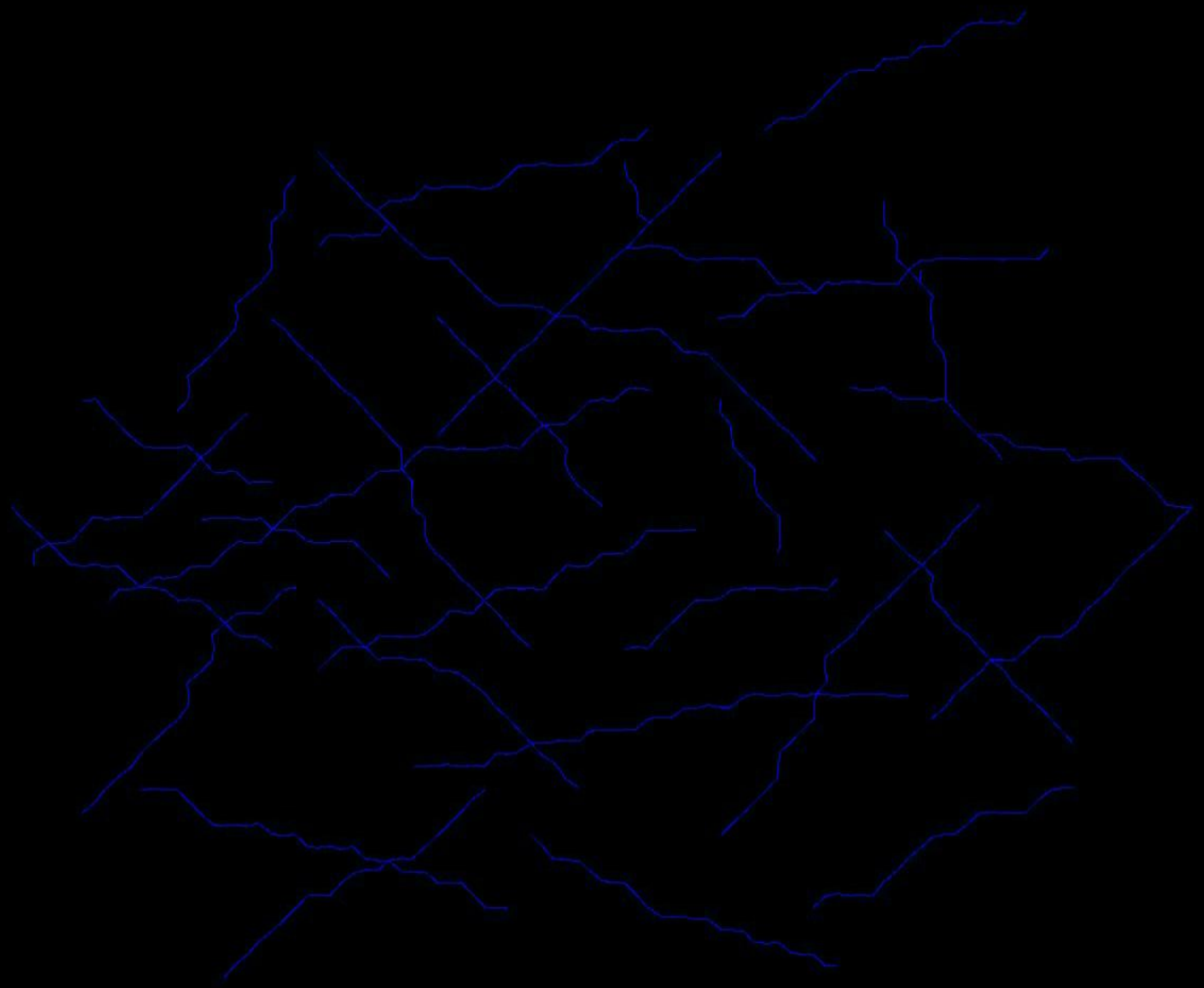
Stimulation of a Preexisting Fracture Network



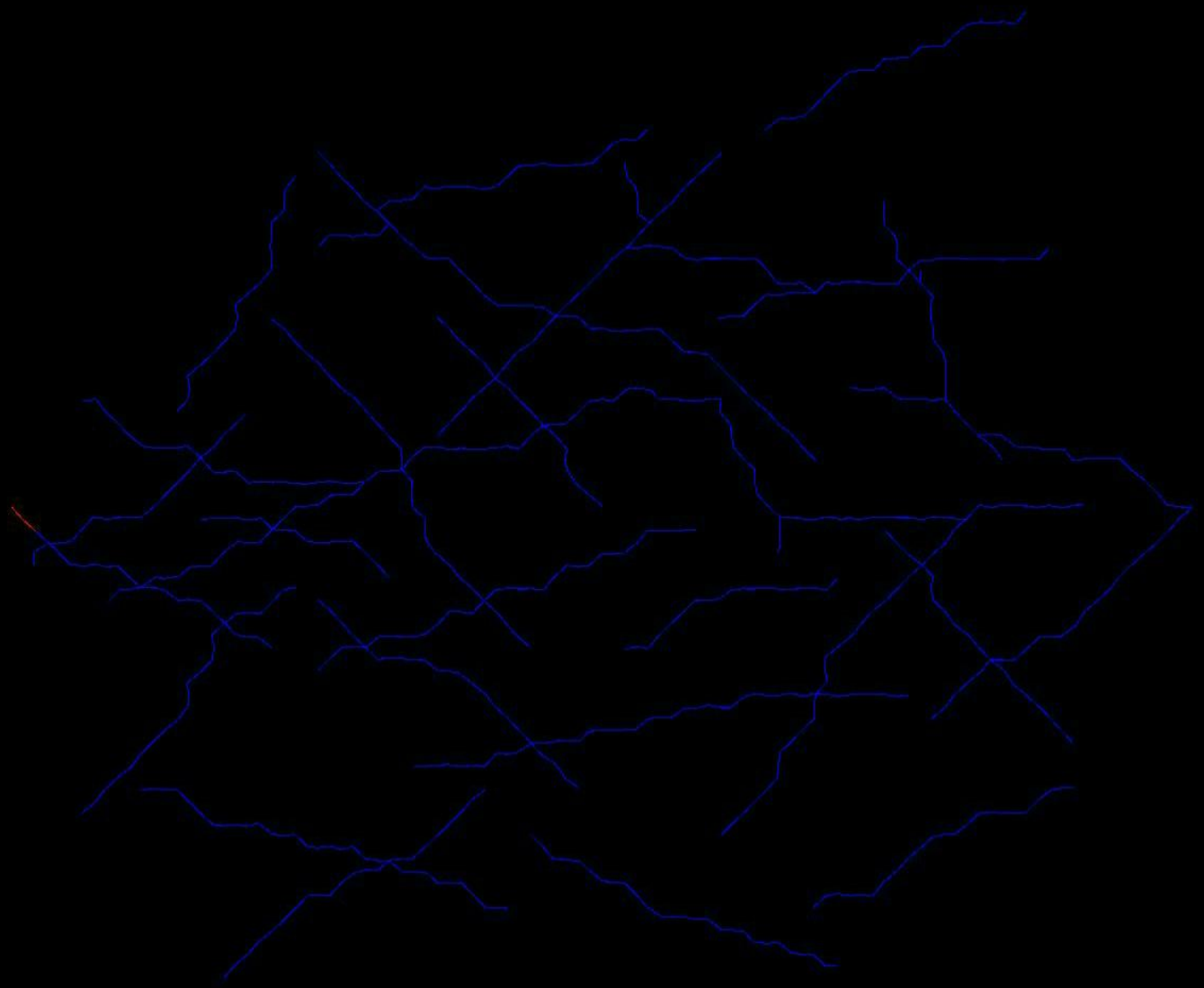
Original network



Enhanced network



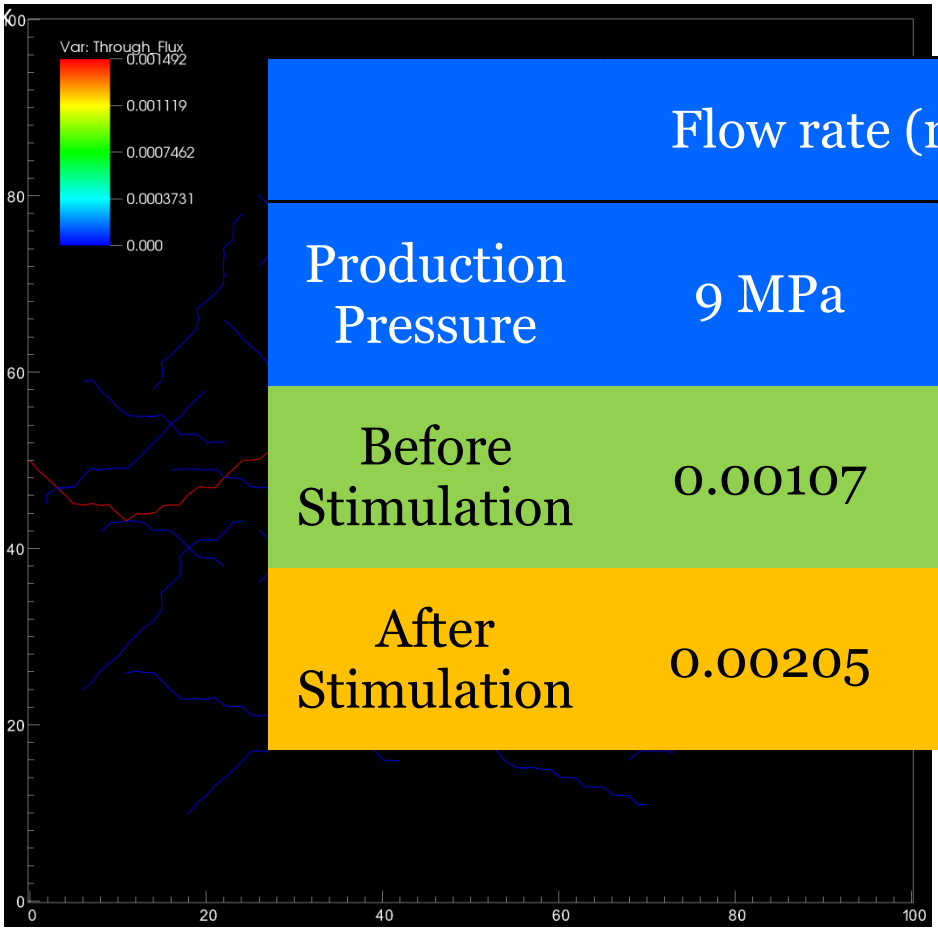
Permeability evaluation – original network
Color represents flow rates.



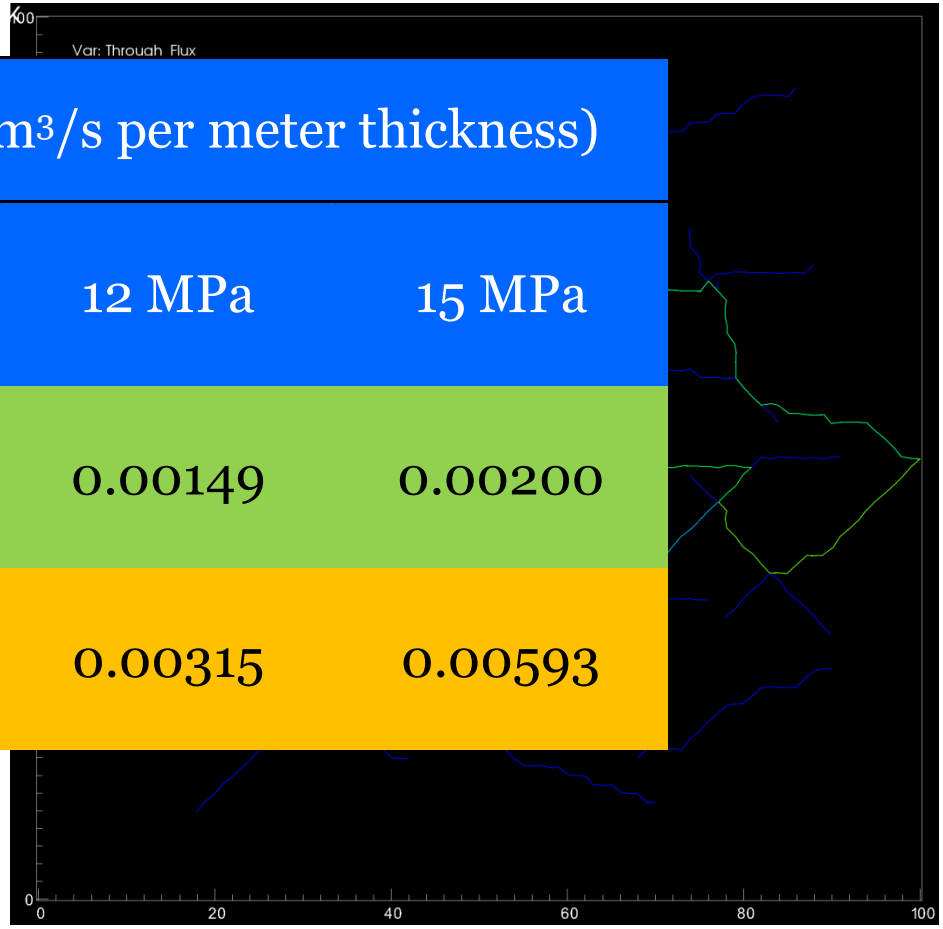
Permeability evaluation – enhanced network
Color represents flow rates.

Stimulation of a Preexisting Fracture Network

- Evaluate permeability enhancement due to stimulation



	Flow rate (m^3/s per meter thickness)		
Production Pressure	9 MPa	12 MPa	15 MPa
Before Stimulation	0.00107	0.00149	0.00200
After Stimulation	0.00205	0.00315	0.00593



Flow in original network

Flow in enhanced network

Concluding Remarks

- A simulator with full geomechanics – discrete flow network coupling has been developed at LLNL.
- A powerful platform for studying key mechanisms governing hydraulic fracturing in complex existing fracture network.
- A promising tool to evaluate candidate enhancement strategies.
- 3D parallel version with refined modules is being developed.

Acknowledgements

- This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.