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Employing Model Reduction for Uncertainty Visualization in the Context of CO_2 Storage Simulation

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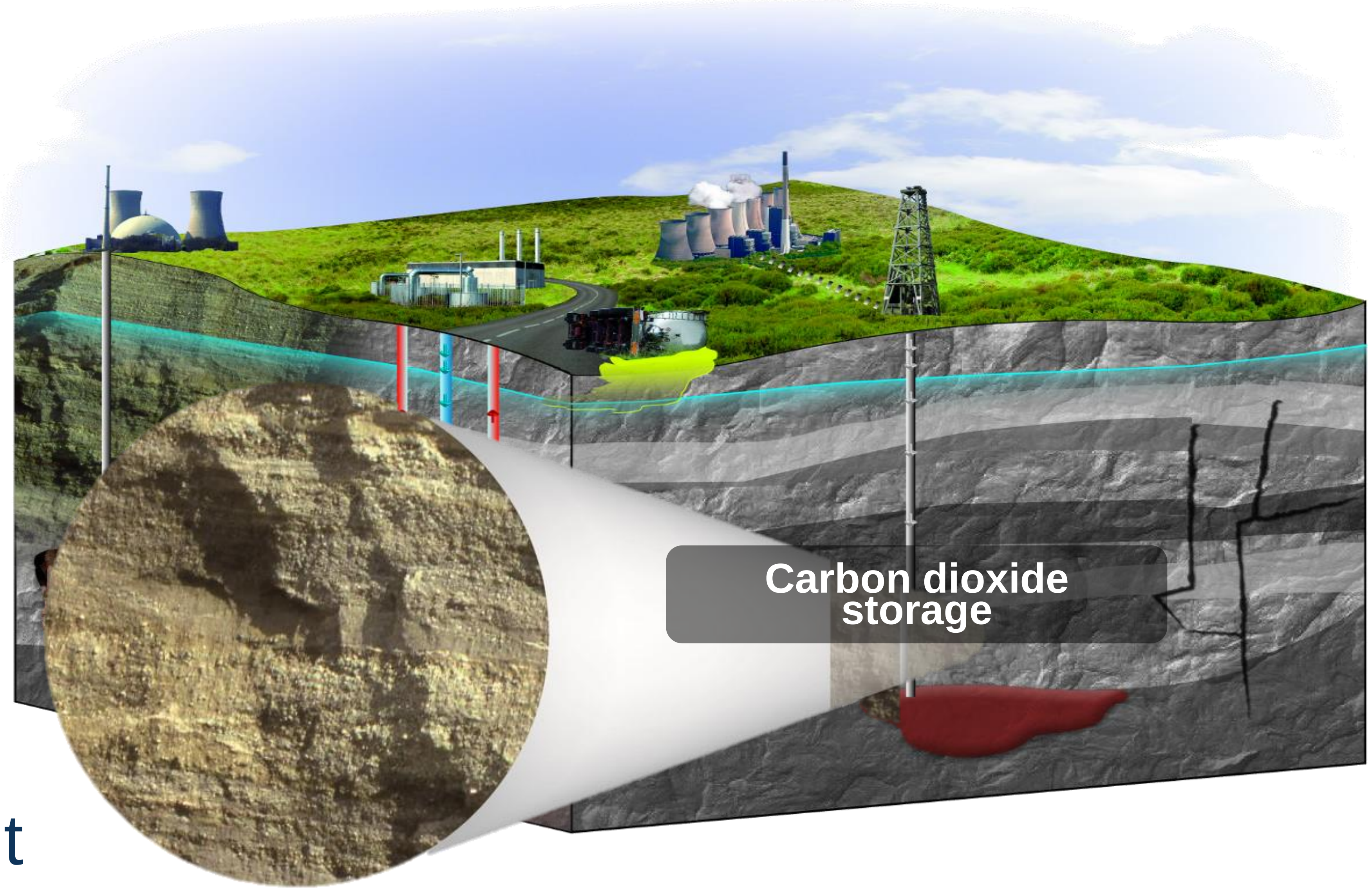
Problem setting - underground CO_2 storage

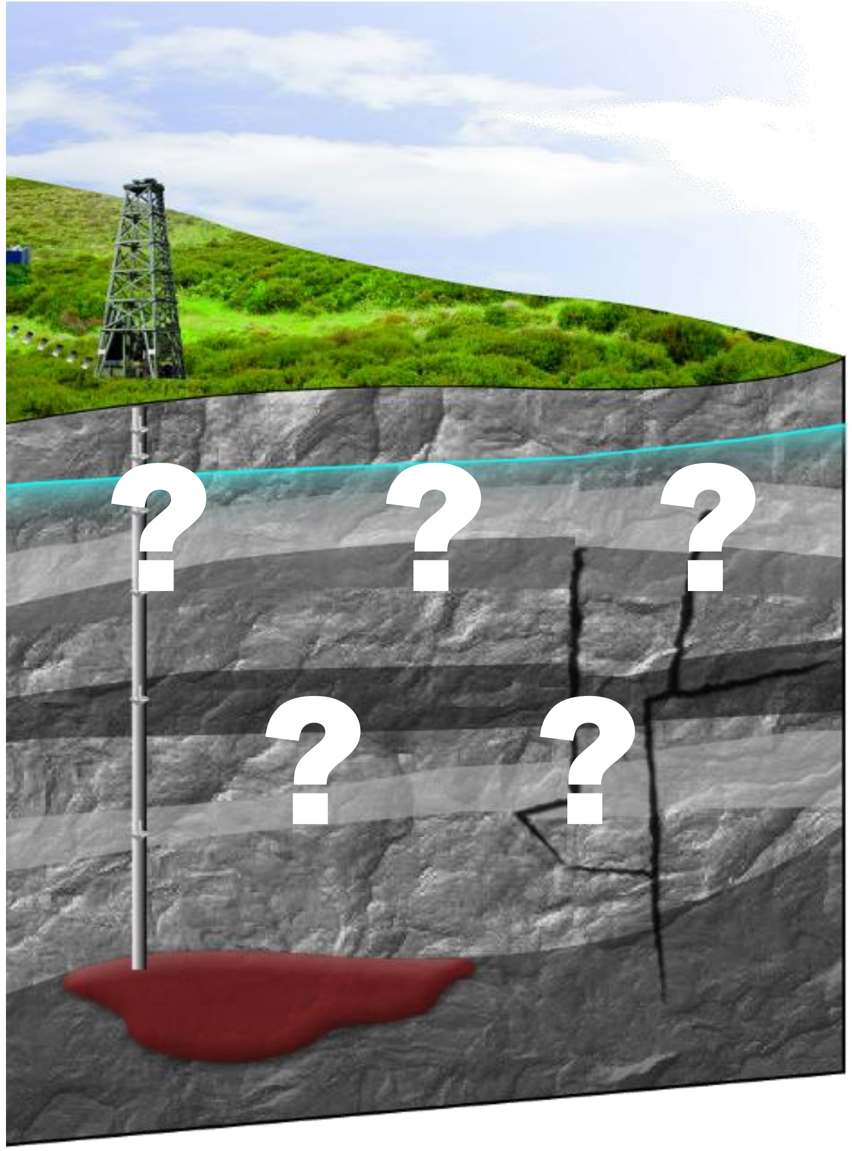
- Decision making
  - Controversial
  - Impact vs risks
  - Public opinion

- Experiments
  - difficult, expensive
  - only small scale, e.g., porosity tests
- Simulations are important



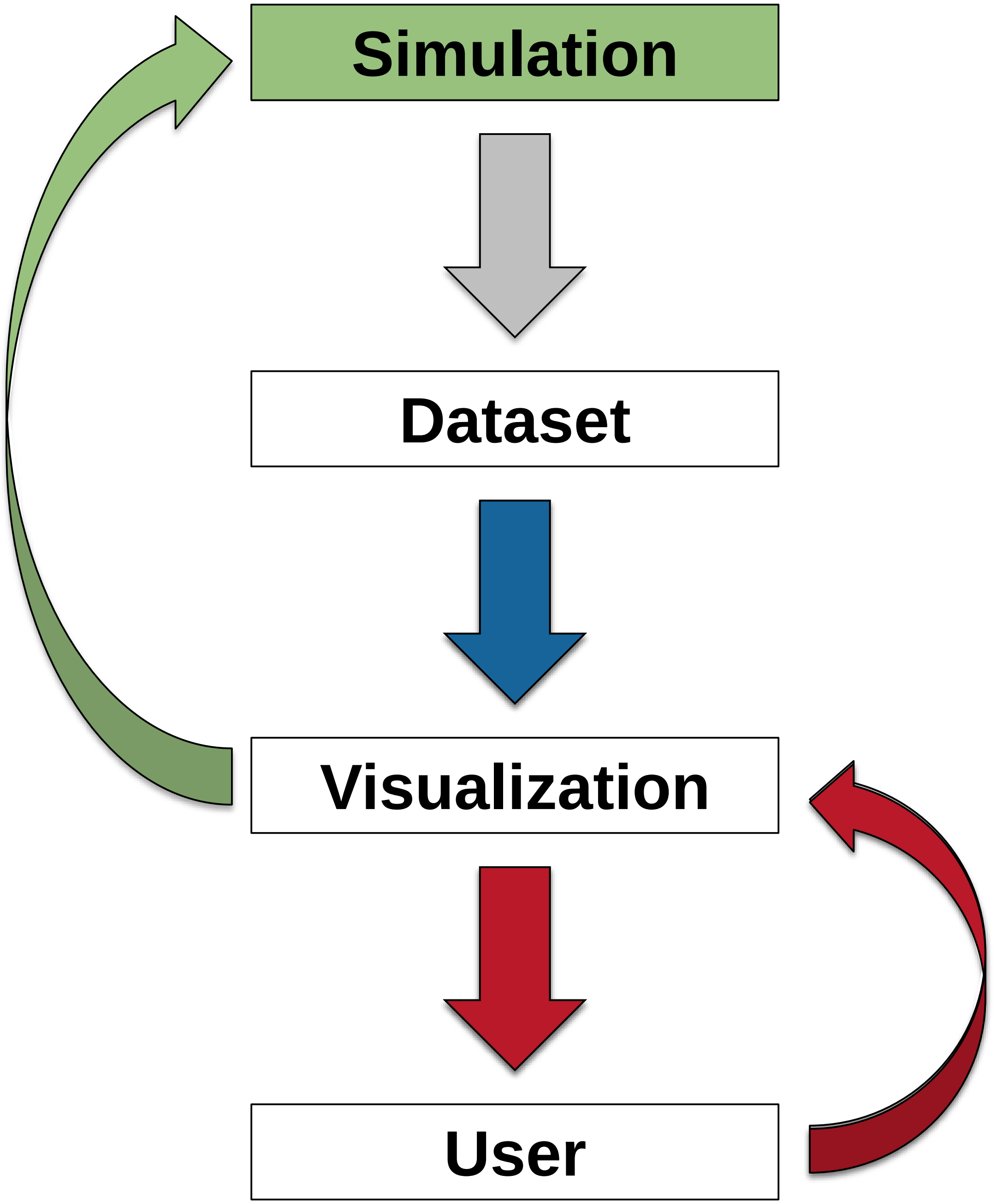
Simulation

- Modeling of storage site
  ➡ hard to obtain real site conditions
- Uncertain parameters
  - Boundary pressure
  - Barriers
  - …
- Monte Carlo approach



Uncertainty visualization

- Ensemble data
  - Detailed analysis
  - Large, visual overload
- Stochastic data (mean, std. dev. etc.)
  - Smaller data, less visual load
  - Aggregated
- Steering
  - Interactivity on model level
  - Fast simulation, often inaccurate
  - Aggregation expensive
- Possible to get all good properties?
- Stochastic model reduction!



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Polynomial chaos expansion (PCE)

- Approximation of model dependence on input
- Original PCE – Gaussian distribution of input [Wiener 1938]
- Arbitrary polynomial chaos (aPC) [Oladyshkin 2011]
  - Generalization
  - Incorporation of real probability distributions
- Stochastic quantities “for free”: mean, standard deviation
  - Different evaluation of PCE data
  - Aggregation of ensemble not required

PCE details

- Model response: projection on polynomial basis [Ashraf 2013]

$$\Gamma(\boldsymbol{x}, t, \Theta) \approx \sum_{i=1}^{n_c} c_i(\boldsymbol{x}, t) \cdot \Pi_i(\Theta)$$

space, time   input param

Γ - model response
$\boldsymbol{x}$ - spatial position
t - time
$\Theta = [\theta_1, \ldots, \theta_n] - n$ input parameters
n_c - number of expansion terms
c_i - expansion coefficients
Π_i - polynomials for input parameters Θ

- More details in [Oladyshkin 2012]

Computation of PCE data

- Different techniques to obtain expansion coefficients c_i
  - Intrusive techniques – modification of simulation code
  - Non-intrusive techniques – simulation is black box
- Here: non-intrusive – probabilistic collocation method (PCM)
- n_c simulation runs
- collocation points from most probable region of input parameter distribution

$$n_c = \frac{(d+n)!}{d!\,n!}$$

here: $n_c = \frac{(2+4)!}{2!4!} = 15$

$$\Gamma_c - \sum_{i=1}^{n_c} c_i \Pi(\Theta_c) = 0$$

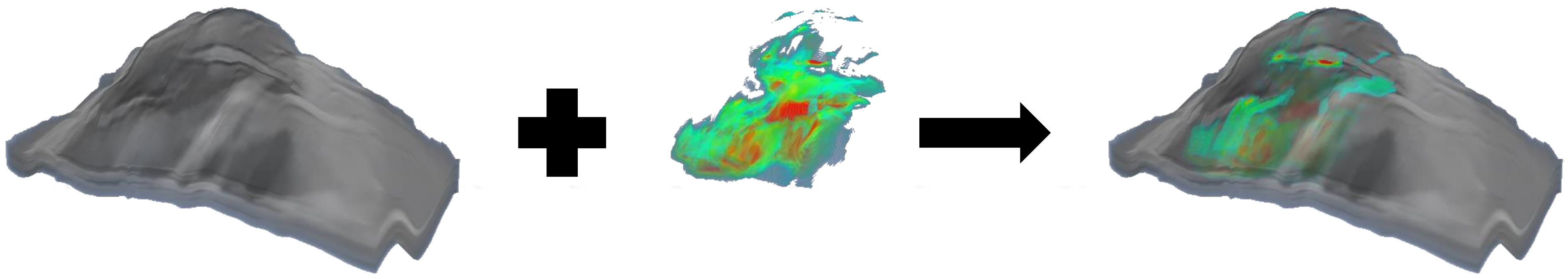
Γ_c - response values
Θ_c - collocation points

PCE data and visualization

- Field of expansion coefficients
- Evaluate polynomials with coefficients and input parameters to obtain result

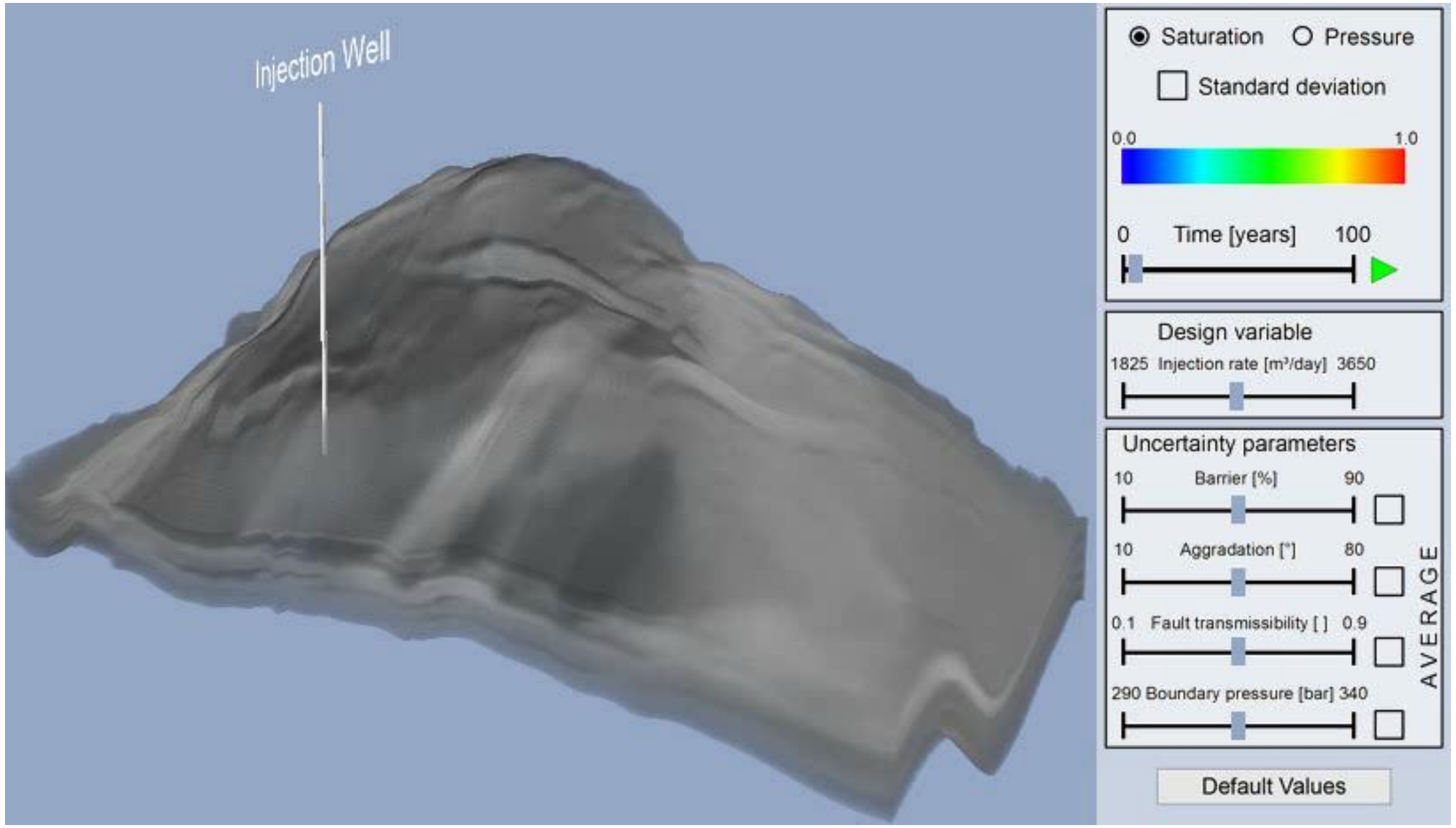
$$\Gamma(\boldsymbol{x}, t, \Theta) \approx \sum_{i=1}^{n_c} c_i(\boldsymbol{x}, t) \cdot \Pi_i(\Theta) \qquad \Pi_i(\Theta) = a_{0,i} + a_{1,i}\theta_n + a_{2,i}\theta_n^2 \ldots$$

- PCE data on GPU, standard ray casting approach
- 40 fps on middle class machine (818 x 466 viewport)



Visualization

- Different quantities
  - CO_2 Saturation
  - Pressure
  - Std. deviation
- Interactivity
  - View settings
  - Time series
  - Input parameters
- Averaging of parameters
- Rainbow color map – engineers like it ;-)



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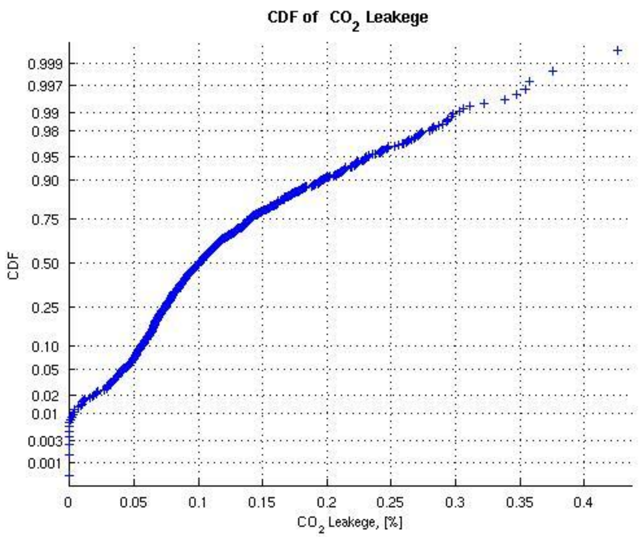
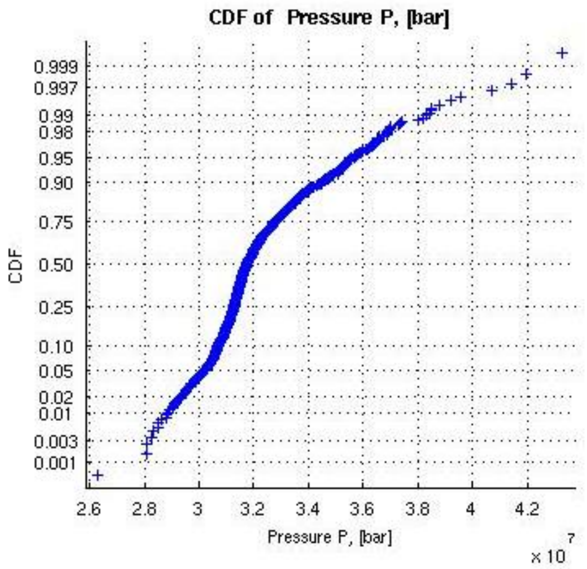
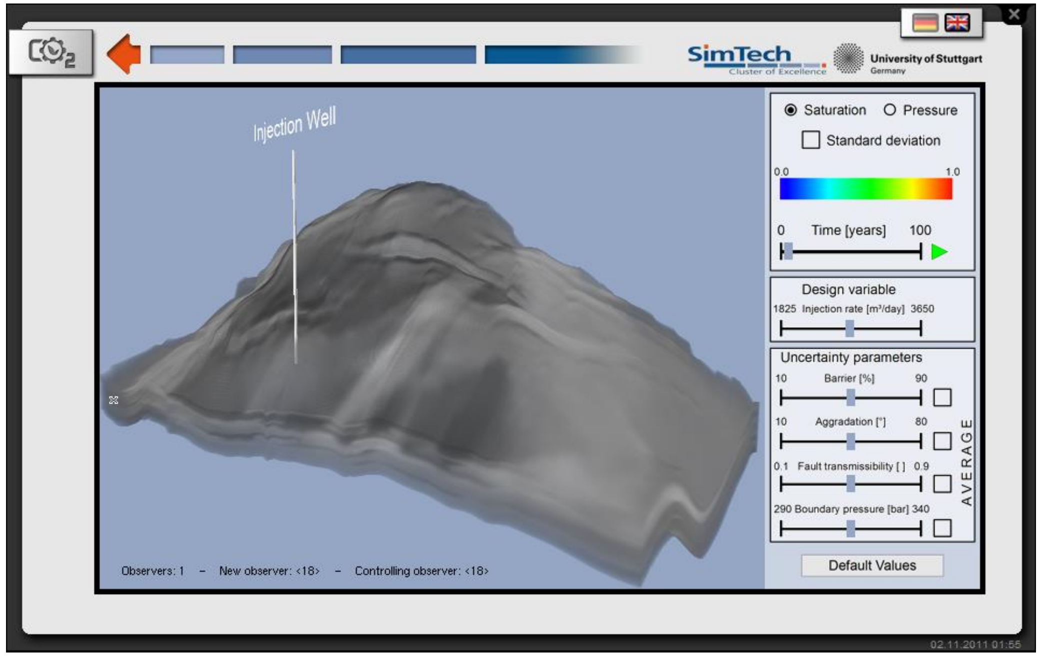
Experiences

- Experts
  - Standard: static snapshots, ROIs, Plots ➡ no interactivity
  - Now: interactive exploration







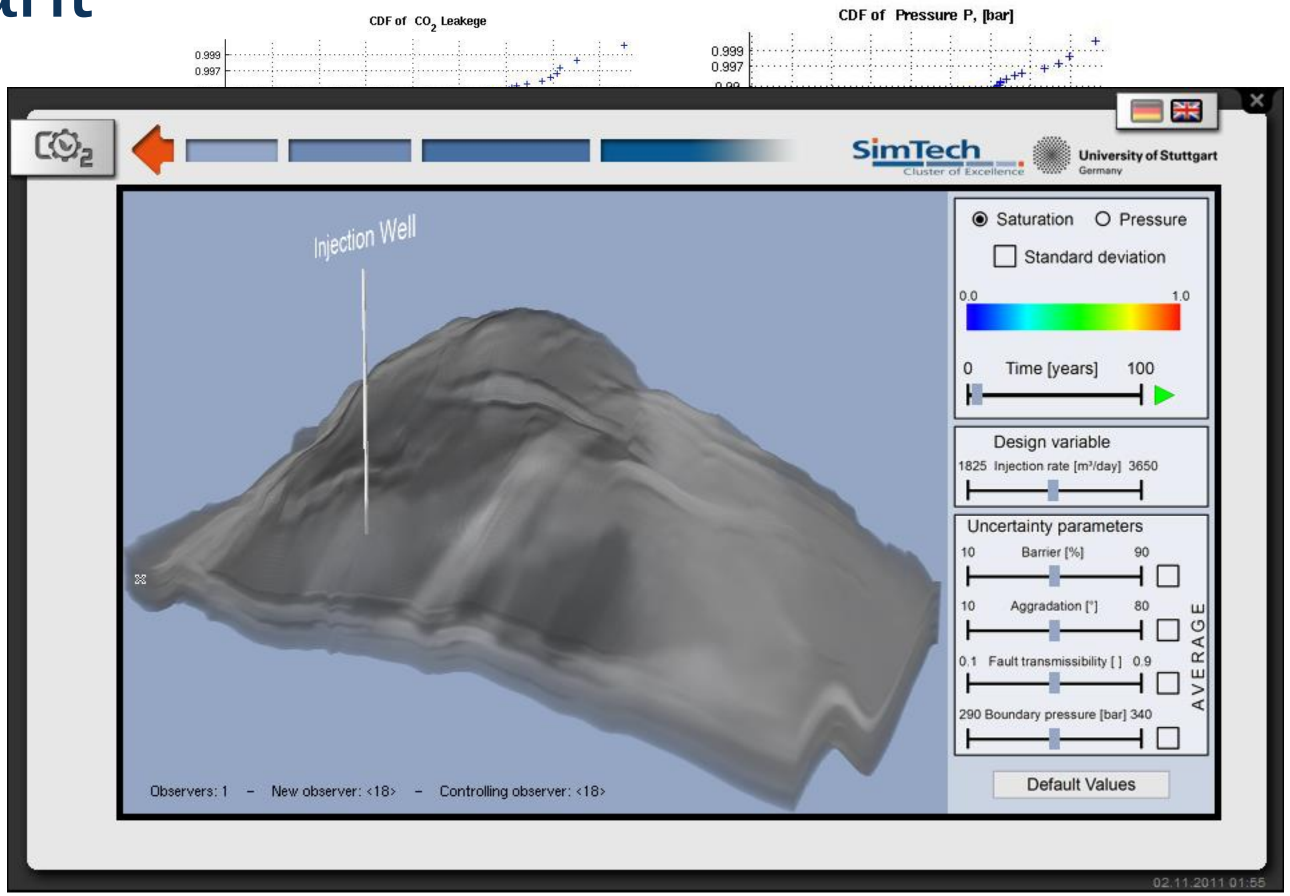
- Public
  - Open house events
  - Visitors played with application
  - Initiated discussion about technology
  - However: no direct relation to peoples’ everyday life

Decision making

- Trade-off: accuracy vs simplicity
- Interactivity on model level important
- Experts
    - Explore model
    - Deeper understanding
- Non-experts
    - Simple visualization
    - Simple interface
    - Interactivity
- Decision communication?

Do it!

65%



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Conclusion

- PCE is interesting tool
- Full ensemble accessible by visualization
- PCE approaches potential basis for novel uncertainty visualization techniques
- Increasing number of PCE applications, e.g., emergency management simulations
- Interactive visualization useful for experts and public

Thank you. Questions?

References:

[Ashraf 2013] M. Ashraf, S. Oladyshkin, and W. Nowak. *Geological storage of CO2: Application, feasibility and efficiency of global sensitivity analysis and risk assessment using the arbitrary polynomial chaos*. International Journal of Greenhouse Gas Control, 19(0):704–719, 2013.

[Oladyshkin 2011] S. Oladyshkin, H. Class, R. Helmig, and W. Nowak. *A concept for data-driven uncertainty quantification and its application to carbon dioxide storage in geological formations*. Advances in Water Resources, 34(11):1508–1518, 2011.

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