



Teresa Beck, Simon Gawlok and HiFlow<sup>3</sup> team





### Introduction



- parallel finite element software
- developed by EMCL (Engineering Mathematics and Computing Lab) of Prof. Heuveline, IWR, University of Heidelberg
- 12 years of development and experience
- open source: LGPLv3-License



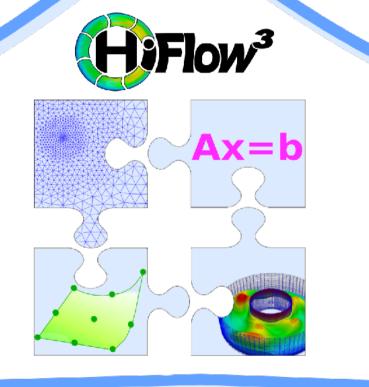
### A modular approach

#### Mesh

- 2D: triangles, quads
- 3D: tetrahedrons, hexahedrons
- unstructured meshes
- h-refinement

#### **Finite Element Spaces**

- Lagrange Finite Elements
- arbitrary polynomial degree
- p-refinement



#### Linear Algebra toolbox

- matrix and vector structures
- · linear and nonlinear solvers
- preconditioners

#### **User defined application**

- PDE
- assembly of matrices and vectors
- postprocessing
- visualization



### **Interfaces and Backends**



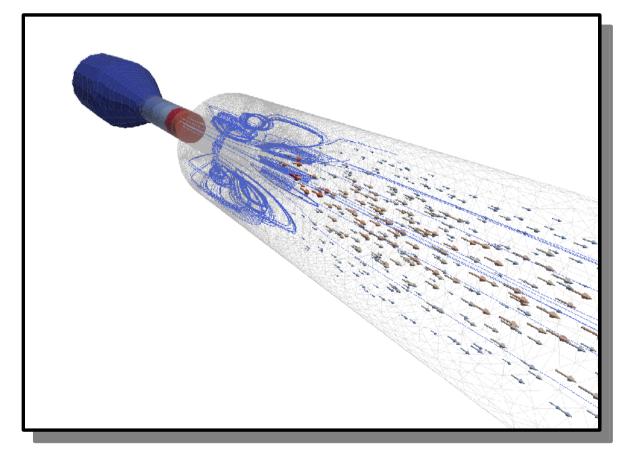
- interfaces to various toolkits: METIS, MUMPS, ATLAS, MKL BLAS, HDF5, CLAPLACK, MKL LAPACK, CUDA, OpenCL, GaussQ, ILU++, OpenMP, UMFPACK
- backends for matrix and vector node-level implementation: CUDA, OpenMP, naive, OpenCL, ...
- **parallelism** introduced on three levels:
  - distributed memory parallelization: MPI
  - shared memory parallelization: **OpenMP**
  - accelerators: CUDA, OpenCL



### **Performance and Scalability**

#### Nozzle benchmark:

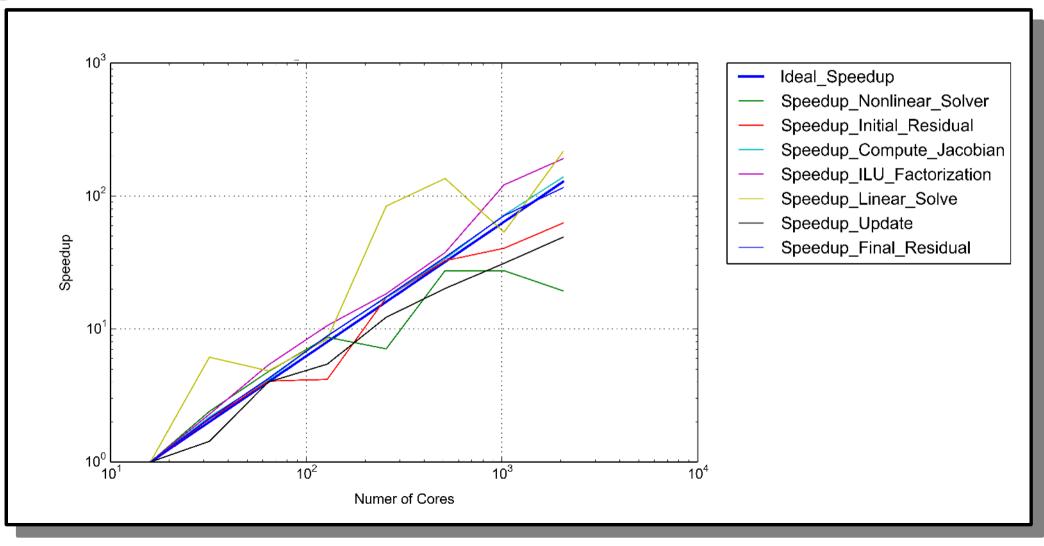
- Incompressible Navier-Stokes equations
- Reynolds number approx. 500
- Discretization with P2/P1 elements
- about 4 Mio. unknowns
- Block preconditioning with ILU++
- GMRES iterative linear solver
- Newton method





### **Performance and Scalability**

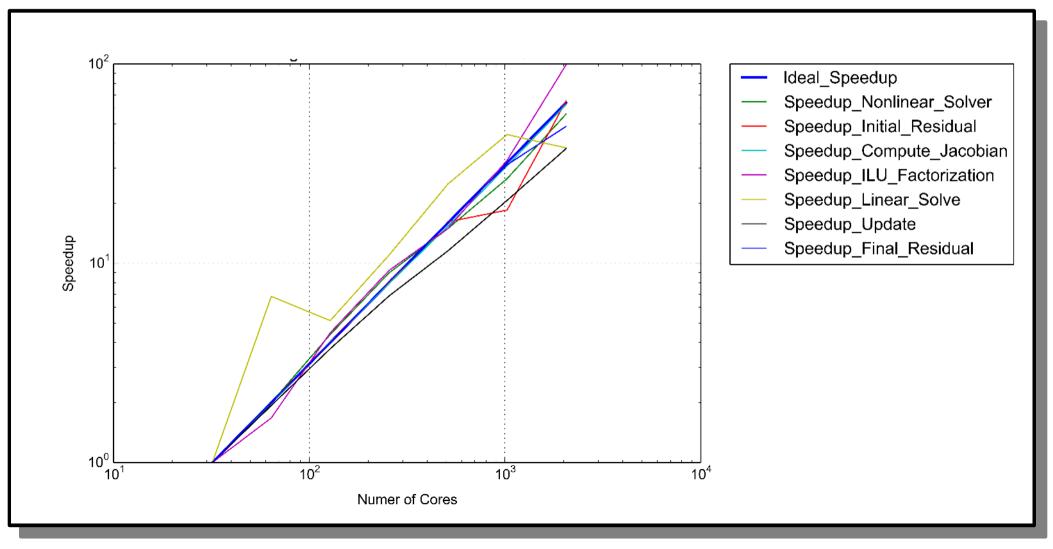
Scaling of Nozzle benchmark on JUROPA, FZ Jülich





## Performance and Scalability

Scaling of Nozzle benchmark on JUQUEEN, FZ Jülich

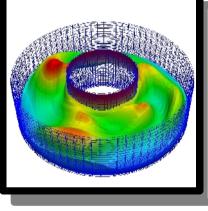






### **Fields of Application** amongst others:

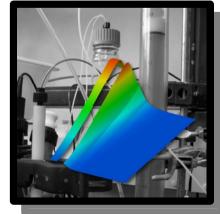
**Environmental Sciences** Baroclinic Wavetank



#### **Medical Engineering Aortic Blood** Flow



**Biochemistry** Chromatographic **System** 



**Environmental Sciences** Tropical **Cyclones** 





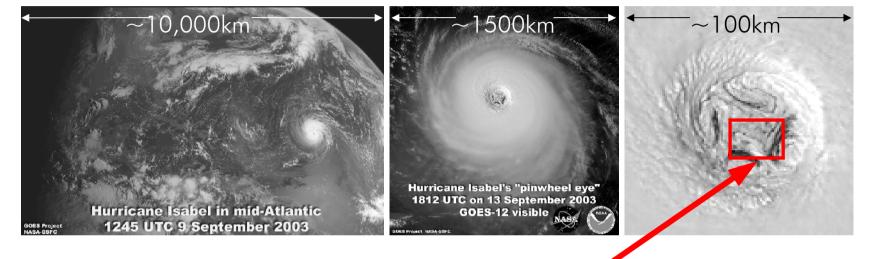
### **Goal Oriented Adaptivity**

**For Tropical Cyclones** 

### **DFG** MetStröm

#### Goal

 prediction of storm tracks and intensity



### Challenges for the modeling

- multi-scale problem
- Which regions and which processes are relevant?

**Approach:** goal-oriented adaptivity in space and time

**Reference**: Baumann, M., *Numerical Simulation of Tropical Cyclones using Goal-Oriented Adaptivity,* Phd-Thesis, Karlsruhe Institute of Technology, 2011

### **Goal Oriented Adaptivity For Tropical Cyclones**

# Implementation *highlights* with

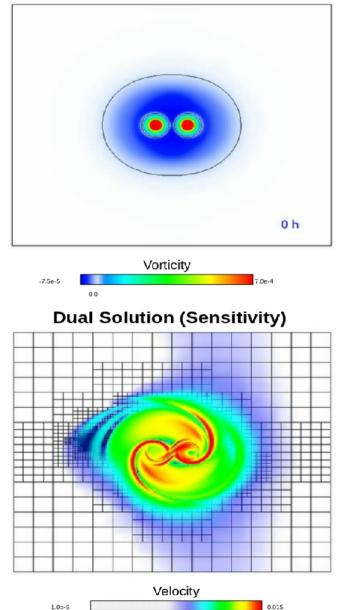


- finite element discretizations in space/time (Q2-Q1/cGP(1))
- $-h/\Delta t$ -adaptivity in space/time
- adaptivity guided by goal-oriented error estimators
  - computation of dual solution
  - higher-order interpolation
  - mesh adaptation strategy
- preconditioning with ILU++
- simulations with up to 10 Mio. unkowns in 3D

**Reference**: Baumann, M., *Numerical Simulation of Tropical Cyclones using* Goal-Oriented Adaptivity, Phd-Thesis, Karlsruhe Institute of Technology, 2011



**Primal Solution** 



### **Release 1.4**



- available from 11/07/2014
- maintenance release streamlined and standardized version
- new features
  - generic interfaces for Matrices and Vectors
  - additional postprocessing abilities
  - support for geometric search
  - evaluation of solution at arbitrary points
  - extended support for single precision
- two new tutorials
- improved examples



Universität

Heidelberg

Zukunft. Seit 1386.

### Outlook



- available from autumn 2014
- new parallel I/O concept
  - based on **XDMF** (eXtensible Data Model and Format) and
    - HDF5 (hierarchival data format)
  - enables using the same parallel I/O data format for both visualization and checkpointing

#### – new module Stochastic FEM

- model uncertainties in physical problems
- support of specialized solvers and preconditioners

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Data Structures	Files	Directories	Q- Search
Gelting Starled Quickly			
learn best is very individ having somebody explai Whereas most of the doc towards those who want	ual. For some n things work comentation h to get their ha	eading documentation s better. Many people pro- tere is a reference to the c ands dirty right away. It is	I ways to go about this task, and how we is the most efficient way to learn, for others, fer riving out the use of a tool themselves, capabilities of HiFlow, this page is geared meant as a guide into the reference will need to accomplish basic tasks.
<ul> <li>How do I create</li> <li>How do I assemi</li> <li>How can I treat e</li> <li>What is a function</li> </ul>	ble the linear ssential bou	system? Indary conditions?	
How do I create a m	iesh?		
to define the vertices and	cells directly st use a Mesh	y in the code, and then us Builder object. This object	a especially suited to simple geometries, is is refinement to increase the number of cts lets the user define vertices and cells,
written to files, which car (".inp") format created by	then be read AVS, and the	d into HiElow. The suppor e unstructured grid format	Is to create descriptions of meshes that are ted file formats is the well-known UCD is ".vtu" and ".pvtu" defined in the VTK on read_mesh_from_file().
files, one of which is to b	e read in on e	each process. Reading in	sh and associated data in a sequence of these files requires passing a pointer to a he sequential case, this parameter can be
the other processes, usin for parallel computation,	ig the function it is necessar	n partition_and_distribu ry to define a layer of gho	n one process, partition it, and distribute it to te(). Regardless of which method one uses, st cells for exchanging information on the he compute_ghost_cells() function
See also: mesh::MeshBull mesh::MeshDb\			



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HOMEPAGE	You are here: Show Cases is Barcolinic Wavetank		
NEWS			
MODULES	Simulation Of Baroclinic	Waves In A	
DOWNLOAD	Differentially Heated, Ro	tating Annulus	
DOCUMENTATION	We simulate thermally driven mult-scale flows in a		
FORUM	differentially heated, rotating annulus. With the help of such	relative height of 23°C isothermal surface	
SHOW CASES	a baroclinic wavetank, thermally driven waves can be generated, which can be seen as an idealized		
Aortic Blood Flow	representation of atmospheric or oceanic flows. Other than		
Soft Tissue	for most applications in meteorology, this scenario has a real laboratory experiment, that enables for a validation of		
Respiratory System	our HiFlow <sup>a</sup> simulation with experimental data. For pictures		
Baroclinic Wavetank	of the simulation results, see the gallery.		
Tropical Cyclones	Technical Details		
Urban Air Flow	Technical Details For this simulation we solve a fully coupled system of the		
Multiphysics Model Coupling	Incompressible Navier-Stokes equations under the	AND EFFERENCE FEETING	
ChromX	Boussinesq assumption, along with a convection diffusion		
Porous Media	equation for the heat transport, both in three dimensions. We use a mesh consisting of cubes with adapted sizes.		
Nozzle Benchmark	Linear finite elements are used for the pressure, quadratic	HEIGHT OF 23°C ISOTHERMAL SURFACE RELATIVE TO	
QUALITY	finite elements for the three velocity components and the temperature. The simulations were carried out with	HEIGHT OF THE WAVETANK. MESH IS DRAFTED AT THE INNER AND OUTER RINGS.	
LICENSE	2084604 degrees of freedom. The time-stepping is based		
TEAM	on the Grank-Nicolson scheme.		
LEGAL NOTICE	Further Information		
CONTACT	The simulations presented were executed on Juropa, FZ Juli	ch. For more details, please ask Teresa Beck or Martin	





# Thanks for ur attention!