The State of MFEM

MFEM Community Workshop
October 26, 2023

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LLNL

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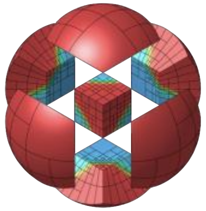
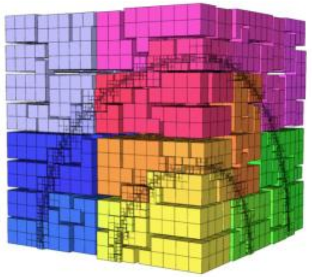
MFEM

Cutting-edge algorithms for powerful applications on HPC architectures

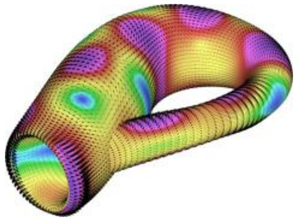
- **Flexible discretizations on unstructured grids**
  - Triangular, quadrilateral, tetrahedral and hexahedral meshes.
  - Local conforming and non-conforming AMR, mesh optimization.
  - Bilinear/linear forms for variety of methods: Galerkin, DG, DPG, …
- **High-order and scalable**
  - Arbitrary-order H1, H(curl), H(div)- and L2 elements.
  - Arbitrary order curvilinear meshes.
  - MPI scalable to millions of cores and GPU-accelerated.
  - Enables application development from laptops to exascale machines.
- **Built-in solvers and visualization**
  - Integrated with: HYPRE, SUNDIALS, PETSc, SLEPc, SUPERLU, …
  - AMG preconditioners for full de Rham complex, geometric MG
  - Support for GPU solvers from: HYPRE, PETSc, AmgX
  - Accurate and flexible visualization with VisIt, ParaView and GLVis
- **Open source**
  - Available on GitHub under BSD license. 100+ example codes and miniapps.
  - Part of FASTMath, ECP/CEED, xSDK, OpenHPC, E4S, …



High-order curved elements

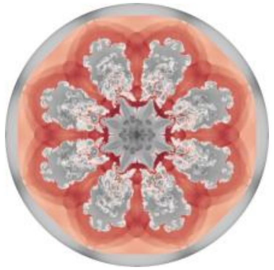


Parallel non-conforming AMR



Surface meshes

Heart modeling

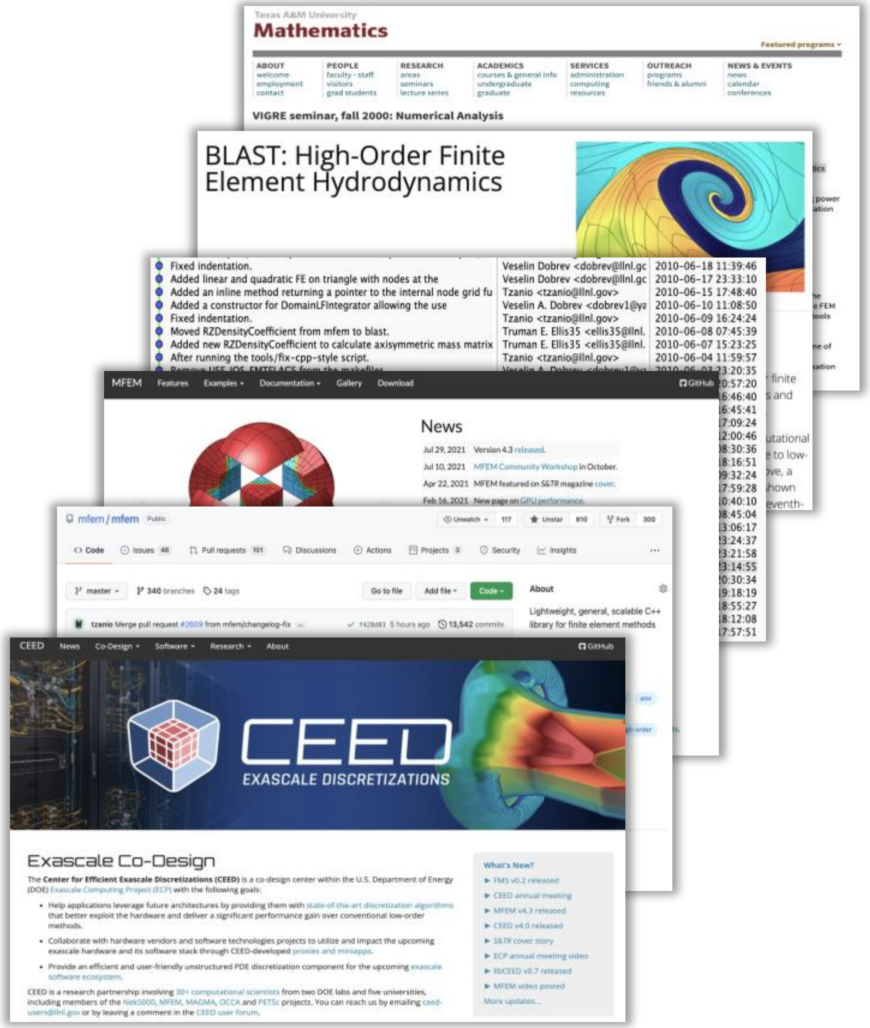


Compressible flow ALE simulations

A Brief History

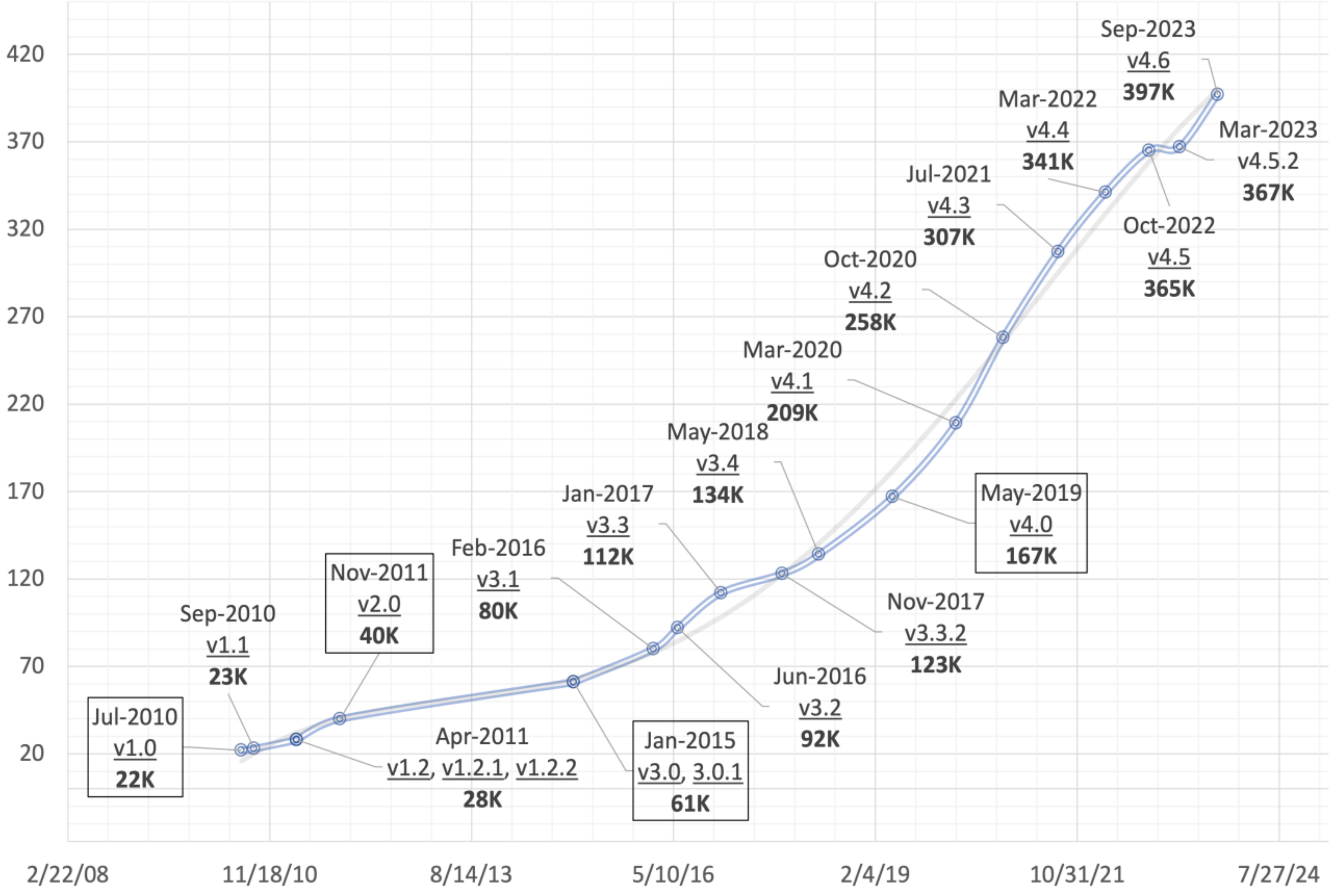
We’ve been doing this for a long time

- **2000 – “VIGRE seminar: Numerical Analysis,” Texas A&M University**
  - Research code: AggieFEM/aFEM
  - Some of the original contributors: **@v-dobrev**, **@tzanio**, **@stomov**
  - Used in summer internships at LLNL
- **2010 – BLAST project at LLNL**
  - Motivated high-order, non-conforming AMR and parallel scalability developments
  - MFEM repository created in May 2010
  - Some of the original contributors: **@v-dobrev**, **@tzanio**, **@rieben1**, **@trumanellis**
  - Project website **mfem.org** goes live in August 2015
- **2017 – Development moved to GitHub**
  - First GitHub commits in February 2017
  - Team expands to include many new developers at LLNL and externally
- **2017 – CEED project in the ECP**
  - Motivated partial assembly, GPU, and exascale computing developments



The Source Code is Growing

SLOC in MFEM releases over the last 13 years



mfem-4.6.tgz	v4.6	Sep 2023	3.6M	397K	
mfem-4.5.2.tgz	v4.5.2	Mar 2023	3.3M	367K	
mfem-4.5.tgz	v4.5	Oct 2022	3.3M	365K	
mfem-4.4.tgz	v4.4	Mar 2022	3.0M	341K	
mfem-4.3.tgz	v4.3	Jul 2021	2.8M	307K	
mfem-4.2.tgz	v4.2	Oct 2020	2.4M	258K	
mfem-4.1.tgz	v4.1	Mar 2020	7.9M	209K	
mfem-4.0.tgz	v4.0	May 2019	5.2M	167K	*GPU support*
mfem-3.4.tgz	v3.4	May 2018	4.4M	134K	
mfem-3.3.2.tgz	v3.3.2	Nov 2017	4.2M	123K	*mesh optimization*
mfem-3.3.tgz	v3.3	Jan 2017	4.0M	112K	
mfem-3.2.tgz	v3.2	Jun 2016	3.3M	92K	*dynamic AMR, HPC miniapps*
mfem-3.1.tgz	v3.1	Feb 2016	2.9M	80K	*fem ↔ linear system interface*
mfem-3.0.1.tgz	v3.0.1	Jan 2015	1.1M	61K	
mfem-3.0.tgz	v3.0	Jan 2015	1.1M	61K	*non-conforming AMR*
mfem-2.0.tgz	v2.0	Nov 2011	308K	40K	*arbitrary order spaces, NURBS*
mfem-v1.2.2.tgz	v1.2.2	Apr 2011	240K	28K	
mfem-v1.2.1.tgz	v1.2.1	Apr 2011	240K	28K	
mfem-v1.2.tgz	v1.2	Apr 2011	240K	28K	*MPI parallelism based on hypre*
mfem-v1.1.tgz	v1.1	Sep 2010	166K	23K	
mfem-v1.0.tgz	v1.0	Jul 2010	160K	22K	*initial release*

The Community is Growing

GitHub, downloads, and workshop stats

GitHub

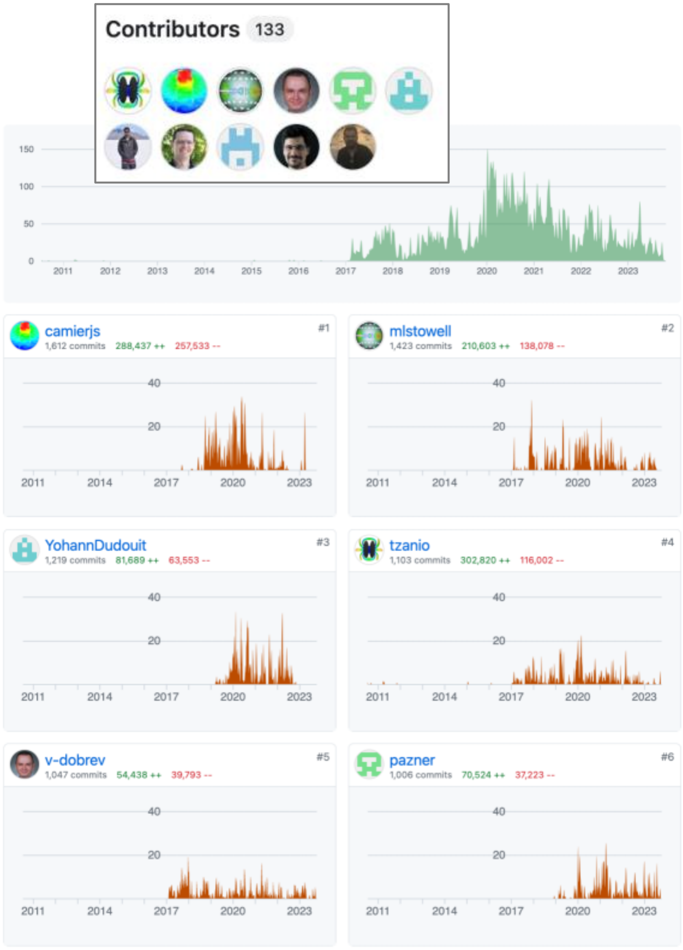
- **133** contributors
- **250** lines of code / day
- **629** people in the mfem organization – *join to contribute* + *receive announcements*
- **150** unique visitors / day
- **1390** stars – *thank you!*

Downloads

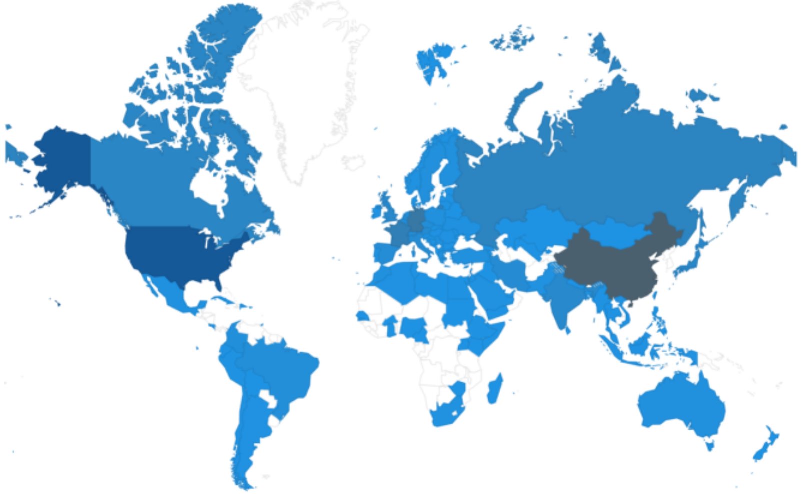
- **250** downloads + clones / day · **91K** / year
- **115** countries total

2023 Community Workshop

- **272** researchers
- **134** organizations
- **33** countries



Top contributors as of Oct 2023



MFEM has been downloaded from 115 countries

mfem.org **MFEM Community Workshop** *October 2023*

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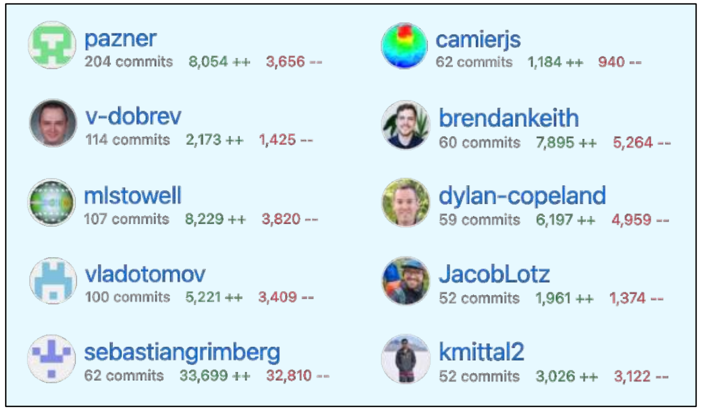
2022 Community workshop had 258 registrations

Latest Releases Were Team Efforts

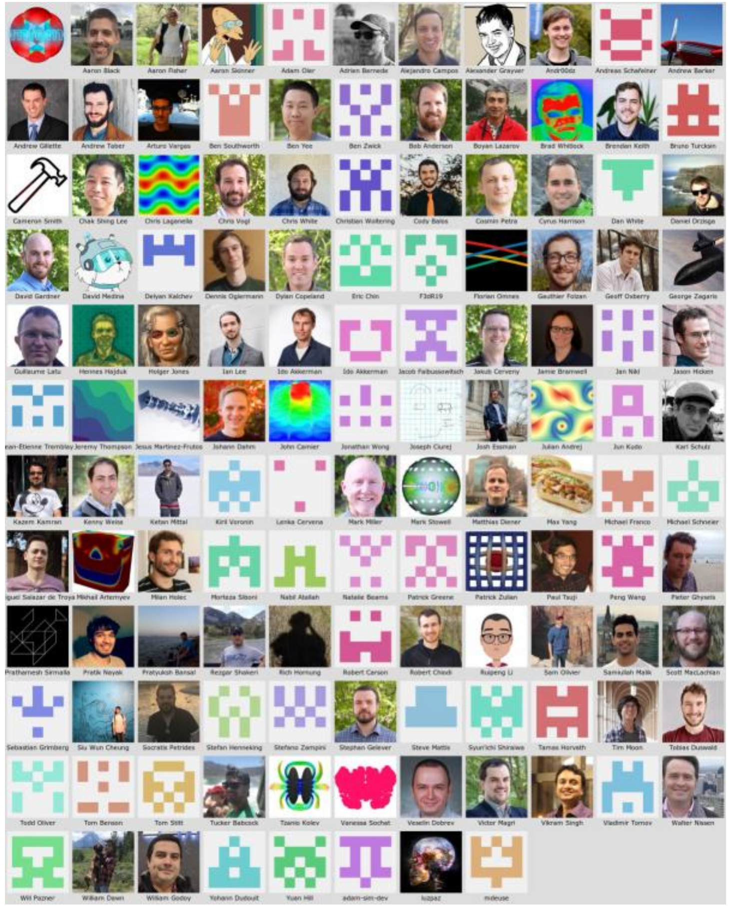
Versions 4.5.2 + 4.6 stats

- Released **Mar + Sep, 2023**
- **11** months in development
- **39** contributors
- **234** PRs merged
- **243** issues closed
- **58K** new lines of code
- **2180** number of commits
- **Many new features:**
  - NURBS + TMOP meshing improvements
  - new H(div) matrix-free solver
  - SubMesh support for H(curl) and H(div)
  - HIP support for PETSc, SUNDIALS
  - stochastic PDEs, k-d tree, ultraweak DPG



Top 10 contributors to the last releases

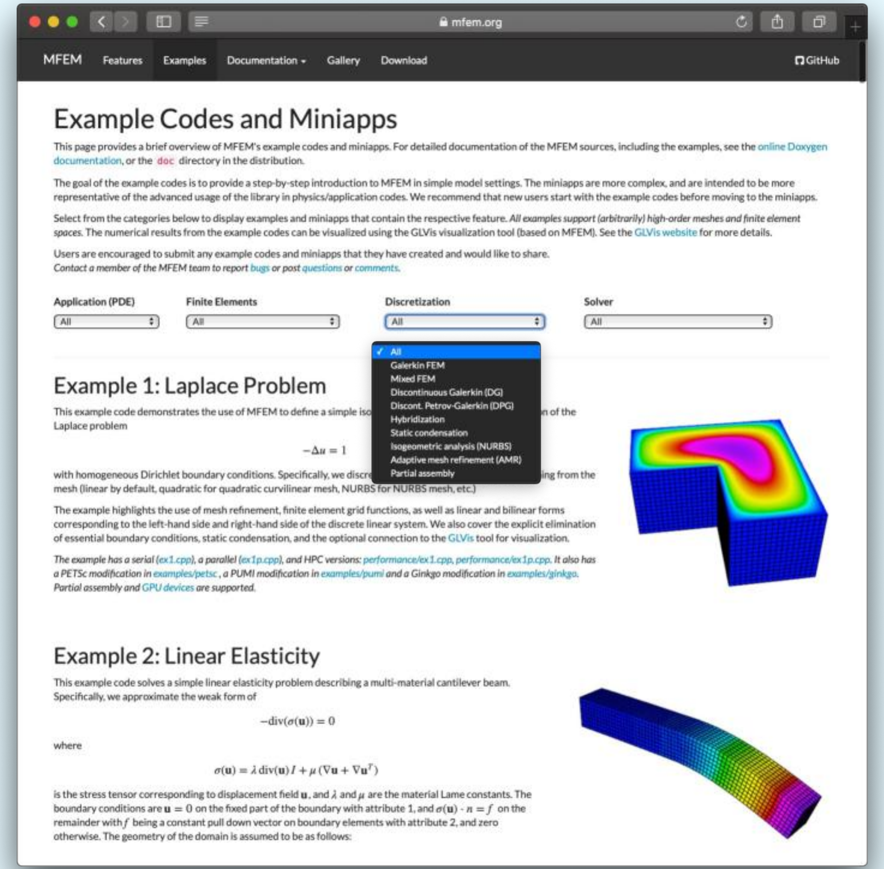
The mfem-4.5.2+4.6 CHANGELOG has 45 entries



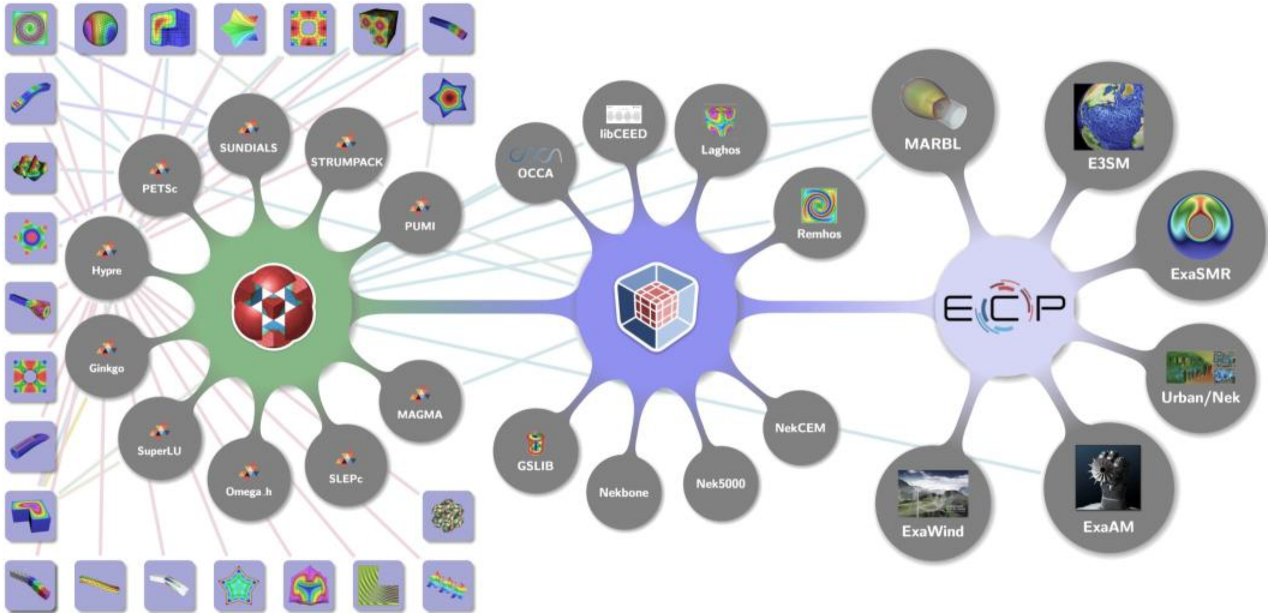
MFEM contributors on GitHub

Examples

The first stop for new users



mfem.org/examples



- 38 example codes, most with both serial + parallel versions
- Tutorials to learn MFEM features
- Starting point for new applications
- Show integration with many external packages, miniapps

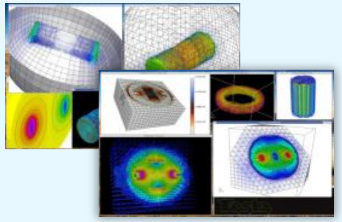
Miniapps

More advanced, ready-to-use physics solvers

Volta, Tesla, Maxwell and Joule Miniapps

Static and transient electromagnetics

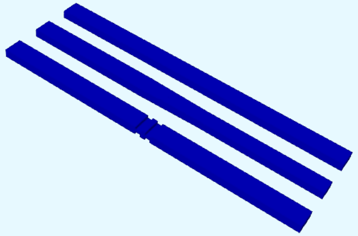
- **Volta** $-\nabla \cdot \epsilon \nabla \varphi = \rho - \nabla \cdot \vec{P}$
- **Tesla** $\nabla \times \mu^{-1} \nabla \times \vec{A} = \vec{J} + \nabla \times \mu^{-1} \mu_0 \vec{M}$



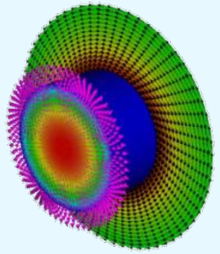
- **Maxwell** · *transient full-wave EM*

$$\frac{\partial(\epsilon \vec{E})}{\partial t} = \nabla \times (\mu^{-1} \vec{B}) - \sigma \vec{E} - \vec{J}$$

$$\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E}$$



- **Joule** · *transient magnetics + Joule heating*
- Arbitrary order elements + meshes
- Adaptive mesh refinement



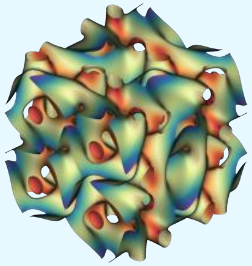
mfem.org/electromagnetics

Navier Miniapp

Transient incompressible Navier-Stokes equations

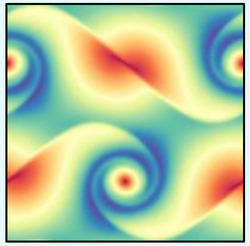
$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \nabla)\boldsymbol{u} - \nu \Delta \boldsymbol{u} + \nabla p = \boldsymbol{f}$$

$$\nabla \cdot \boldsymbol{u} = 0$$



3D Taylor-Green vortex, 7th order

- Arbitrary order elements
- Arbitrary order curvilinear mesh elements
- Adaptive IMEX (BDF-AB) time-stepping algorithm up to 3rd order
- State-of-the-art HPC performance
- GPU acceleration
- Convenient user interface

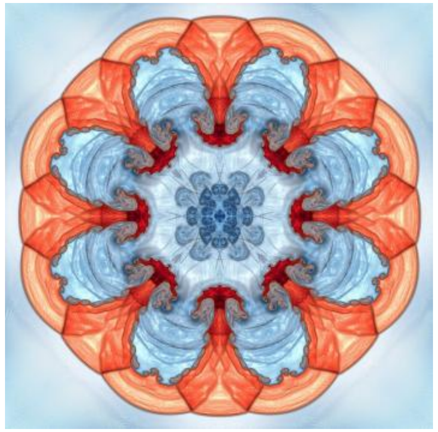


Double shear layer, 5th order, Re = 100000

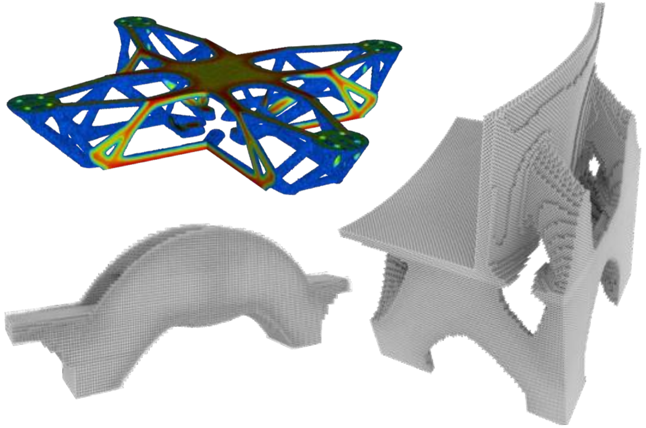
mfem.org/fluids

Applications

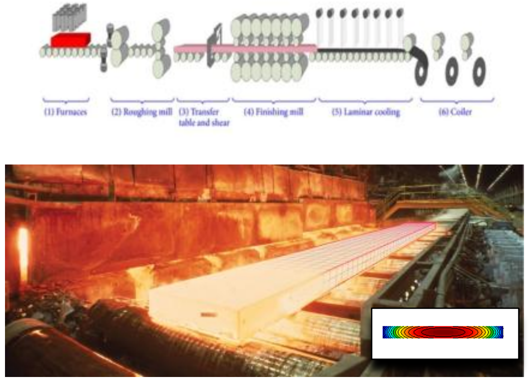
Some of the large-scale simulation codes powered by MFEM



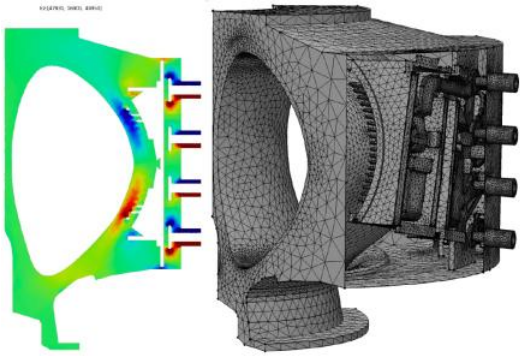
Inertial confinement fusion (BLAST, LLNL)



Topology optimization for additive manufacturing (LiDO, LLNL)



Hot strip mill slab modeling (U.S. Steel)

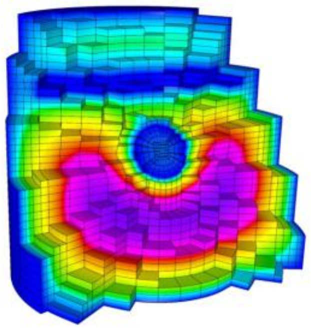


Core-edge tokamak EM wave propagation (SciDAC, RPI)

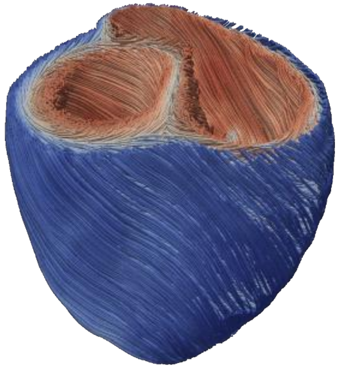
Electric aircraft design (RPI)

MRI modeling (Harvard Medical)

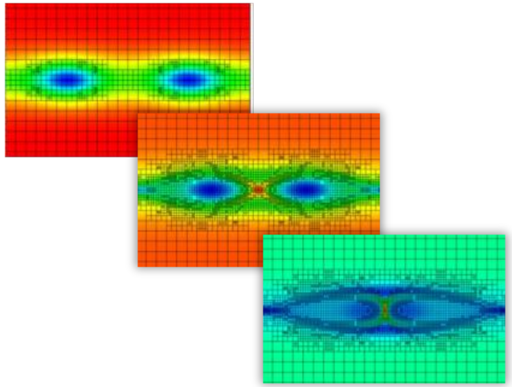
coreform



NURBS meshing and IGA (Coreform LLC, SBIR)



Heart modeling (Cardioid, LLNL/IBM)

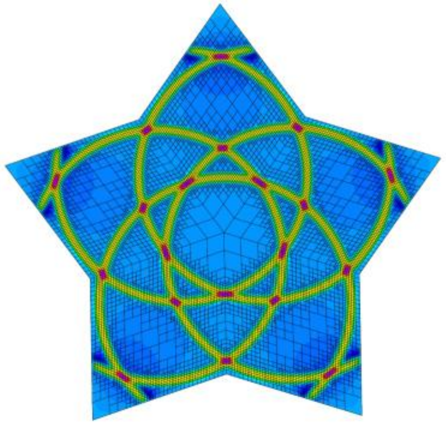


Adaptive MHD island coalescence (SciDAC, LANL)

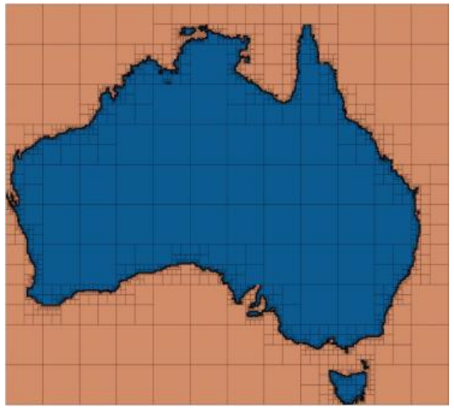
Adaptive Mesh Refinement

MFEM’s unstructured AMR infrastructure

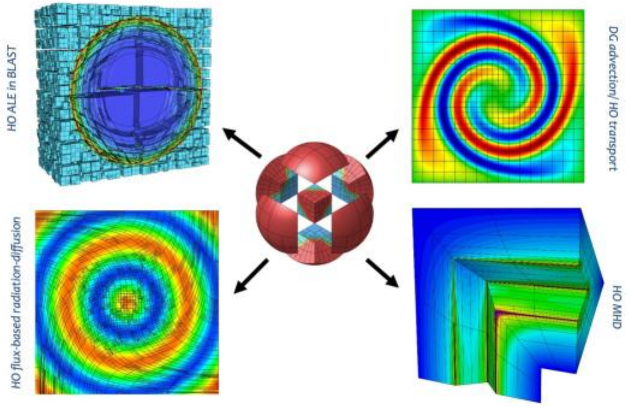
- **AMR on library level**
  - Conforming local refinement on simplex meshes
  - Non-conforming refinement for quad/hex meshes
  - Initial hp-refinement
- **General approach**
  - Any high-order finite element space, H1, H(curl), H(div), on any high-order curved mesh
  - 2D and 3D ∙ hexes, prisms, tets
  - Arbitrary order hanging nodes
  - Anisotropic refinement
  - Derefinement
  - Serial and parallel, including parallel load balancing
  - Independent of the physics
  - Easy to incorporate in applications



Example 15



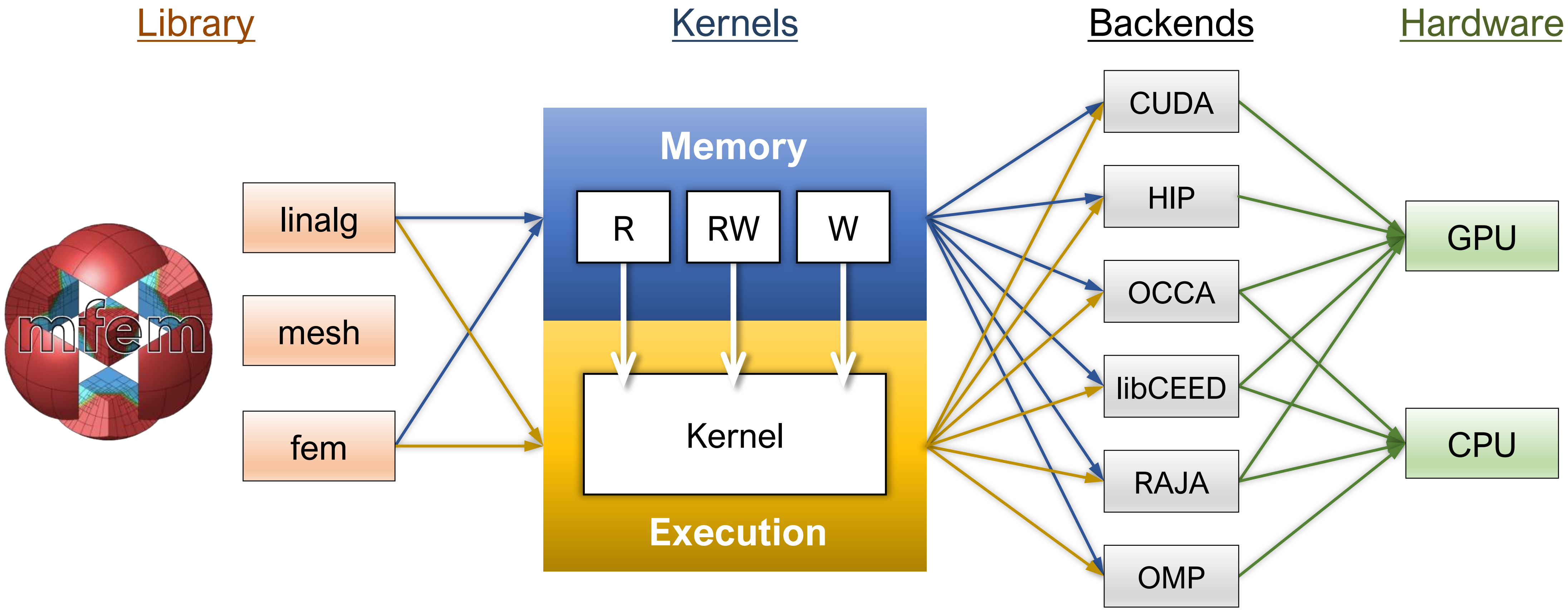
Shaper miniapp



Same AMR algorithms can be applied to a variety of high-order physics

GPU Support

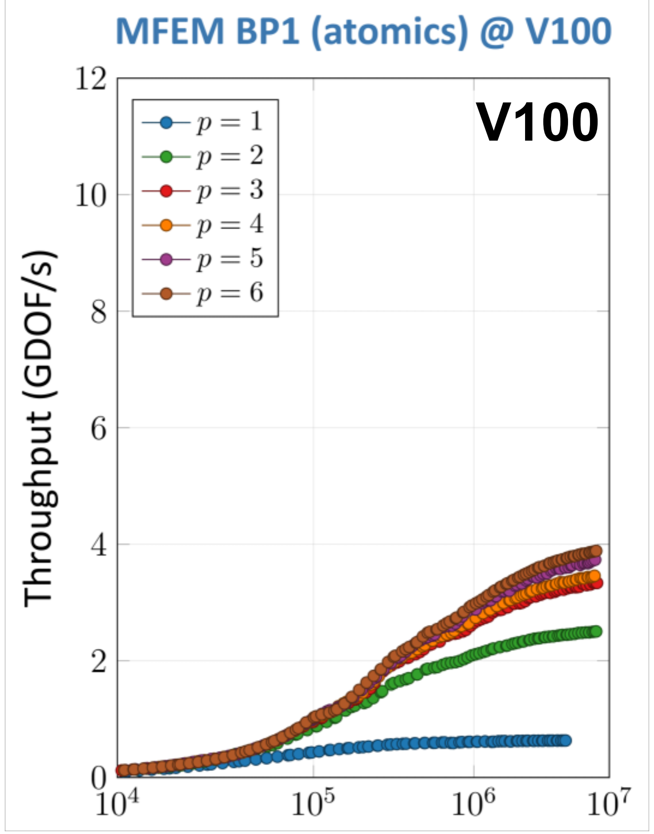
MFEM has provided GPU acceleration for over 5 years (since mfem-4.0)

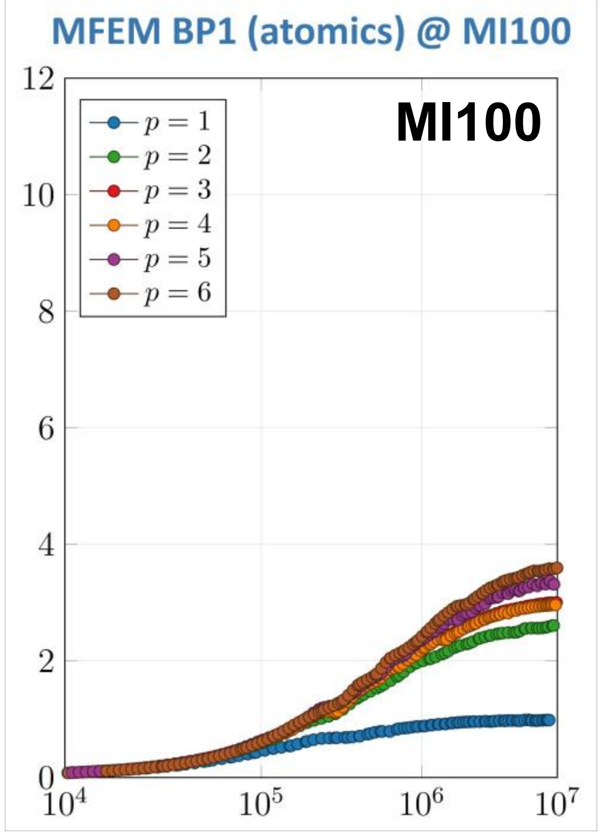


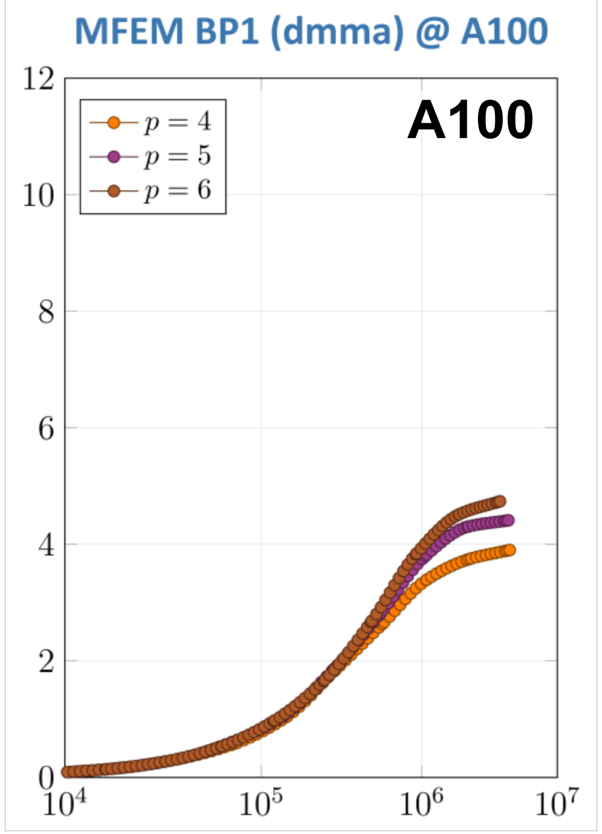
- **Backends are runtime selectable, can be mixed**
- **Coming soon: support for Intel/SYCL**

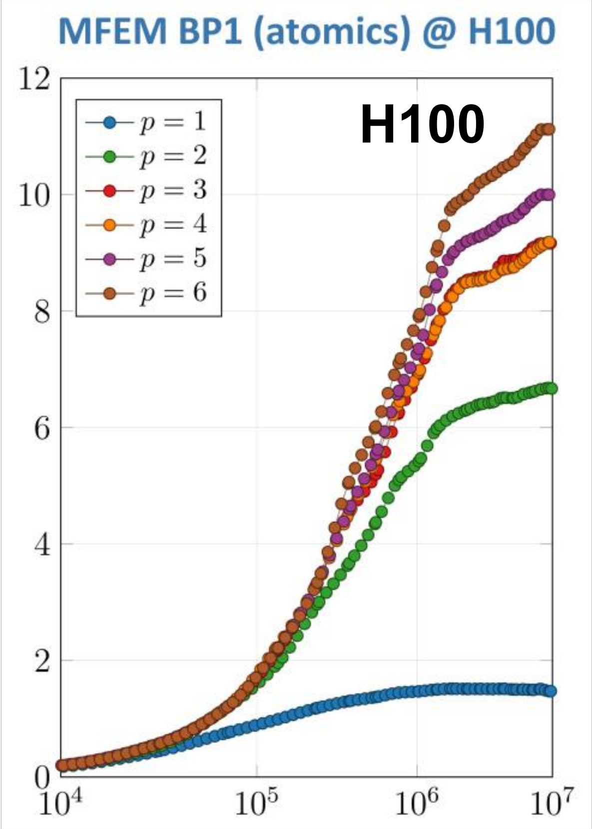
GPU Support

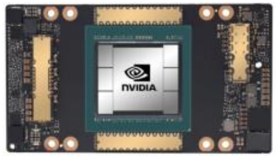
Recent GPU kernel improvements in MFEM







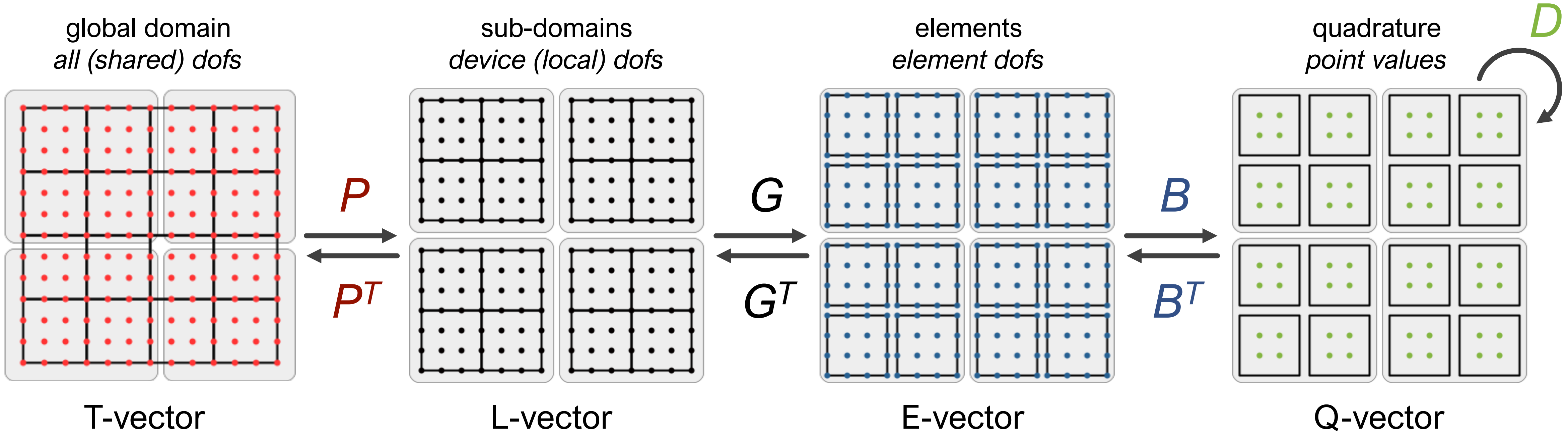




FEM Operator Decomposition + Partial Assembly

Decompose A into parallel, mesh, basis, and geometry/physics parts

$$A = P^T G^T B^T D B G P$$

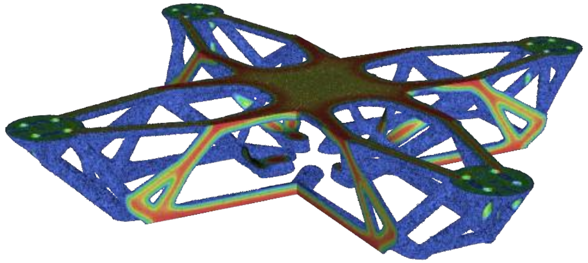


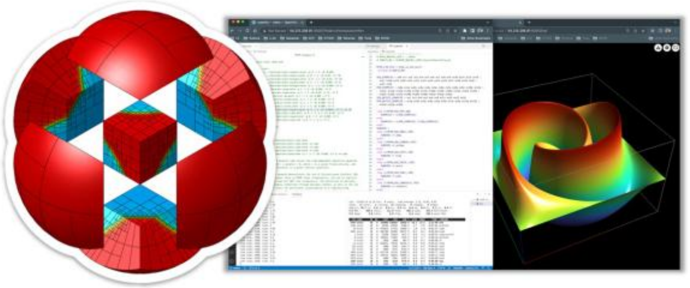
- **Partial assembly = store only D, evaluate B**
- **Optimal memory, near-optimal FLOPs compared to A**
- **AD-friendly**
- **MFEM + Enzyme**

Roadmap for Next Year

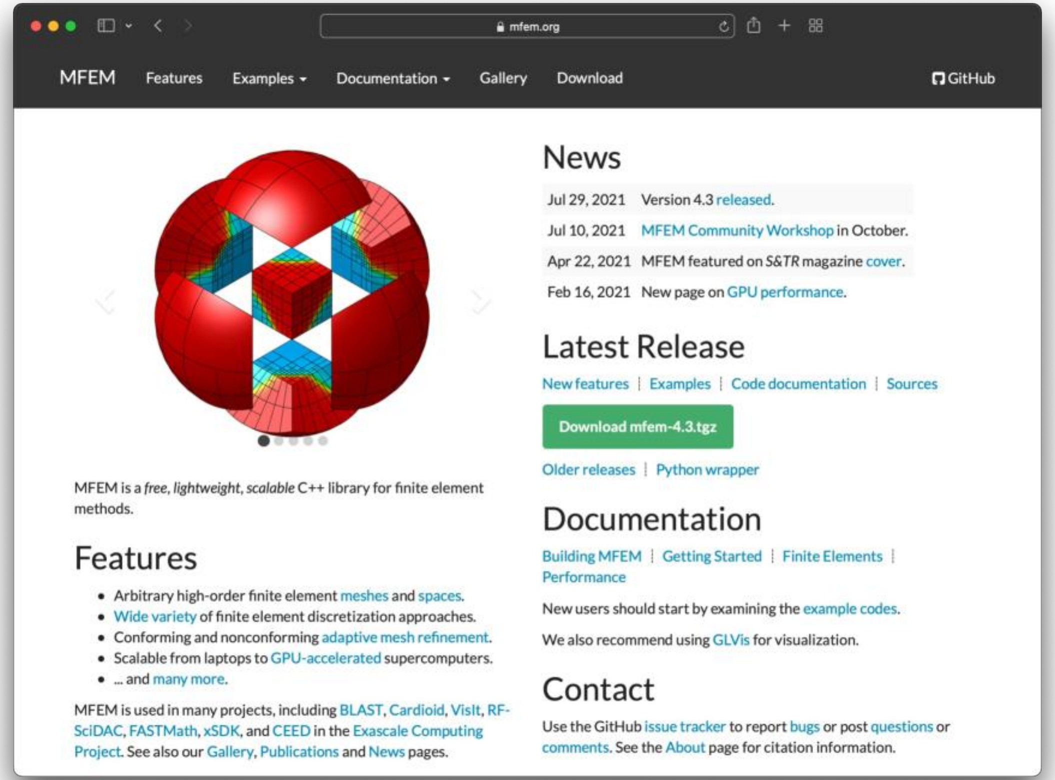
Plans for FY24

- **GPU support**
  - Performance on AMD GPU: Frontier + El Capitan
  - Continued GPU porting and performance improvements
- **Applications**
  - Automatic differentiation · Design optimization
  - Compressible and incompressible flow
  - Fusion: both magnetic and ICF
  - Contact · 4D · mixed meshes · new collaborations
- **Code quality**
  - Improve documentation, testing
  - Additional examples + miniapps
- **New releases**
  - v4.7 in Mar · start work on v5.0 – *expect breaking changes!*
- **What would you like to see?**
  - Slack: [#meet-the-team]() · GitHub: [github.com/mfem/mfem/issues]() · Email: [mfem@llnl.gov]()





MFEM Resources



Website:
mfem.org

Software:
github.com/mfem

Publications:
mfem.org/publications

Email:
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- Contact us with questions + feedback
- Contribute to the code
- Explore our publications

Thank you from the MFEM team at LLNL!

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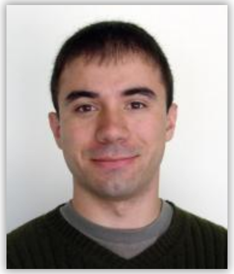

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