The State of MFEM

MFEM Community Workshop 2025

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LLNL

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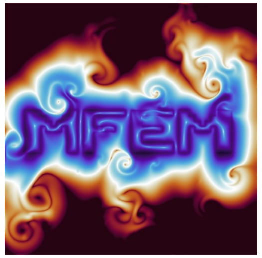
mfem

Lawrence Livermore National Laboratory

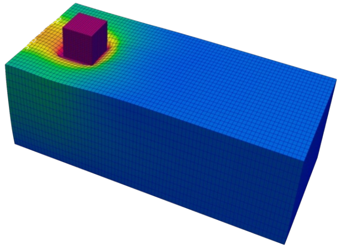
MFEM Finite Element Library

Cutting-edge algorithms for powerful applications on HPC architectures

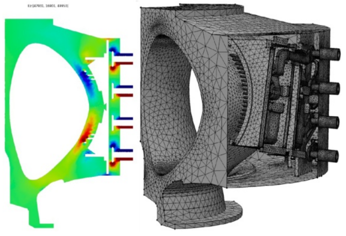
- **Flexible discretizations on unstructured grids**
  - Triangular, quadrilateral, tetrahedral and hexahedral meshes
  - Local conforming and non-conforming **AMR**, **mesh optimization**
  - Wide variety of finite element methods: Galerkin, DG, **IGA**, **DPG**, **HDG**…
- **High-order and scalable**
  - 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, many example codes and miniapps
  - Part of **SciDAC**, **ECP/CEED**, xSDK, OpenHPC, E4S, …



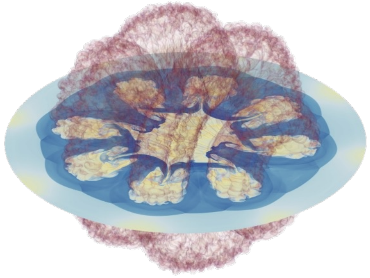
HDG convection-diffusion



Contact mechanics

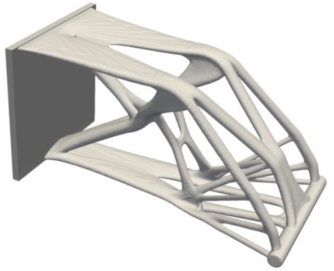


Core-edge tokamak



Compressible flow

Next-gen MRI



Topology Optimization

MFEM: A modular finite element methods library, CAMWA 2020

High-performance finite elements with MFEM, IJHPCA, 2024

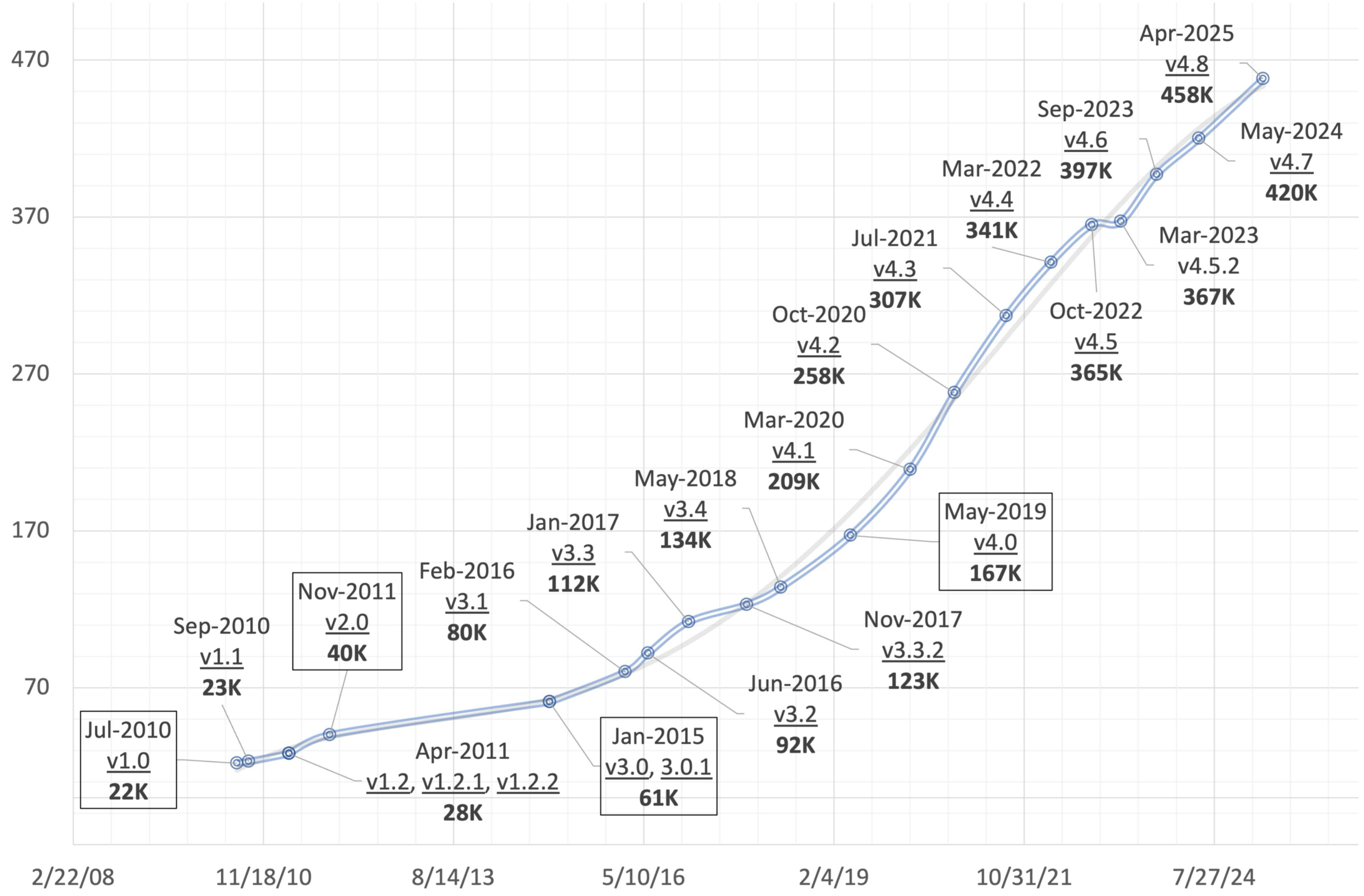
A Brief History

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 exascale computing developments: GPUs, partial assembly, matrix-free
- **2024 – El Capitan, Differentiable Simulations**

The Source Code is Growing

SLOC in MFEM releases over the last 15 years



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mfem-4.7.tgz	v4.7	May 2024	3.8M	420K	
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

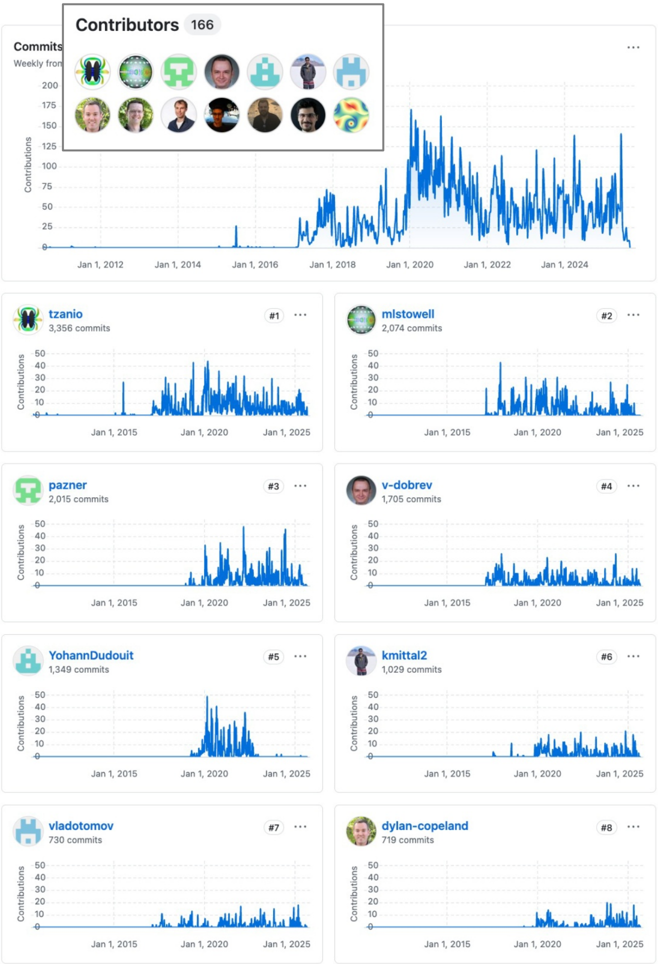
- **166** contributors
- **784** people in the mfem organization – *join to contribute* + *receive announcements*
- **1961** stars – *thank you!* Starred 2k

Downloads

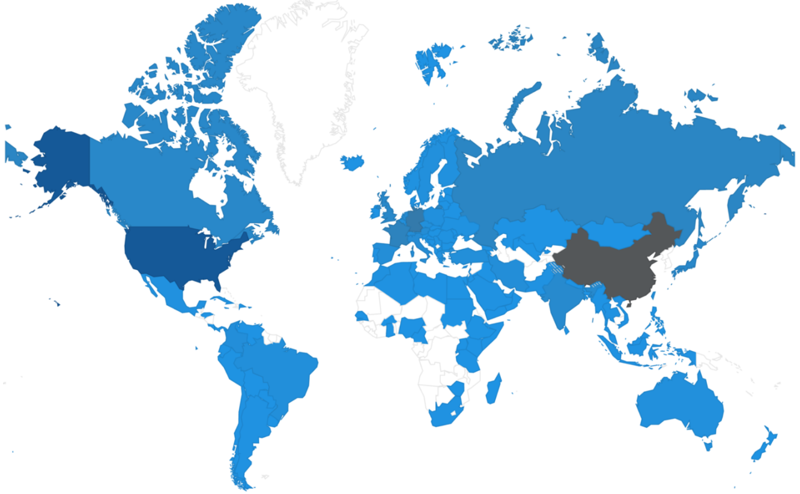
- **150+** unique visitors / day
- **200+** downloads + clones / day
- **100K+** / year
- **130** countries total

2025 Community Workshop

- **200+** researchers (**50+** in person)
- **100+** organizations
- **24** countries



Top contributors as of Sep 2025



MFEM has been downloaded from 130 countries

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

001	Aaron Fisher	*Lawrence Livermore National Laboratory*	fisher47@llnl.gov
002	Abdellatif Semmouri	*FST, Sultan Moulay Slimane University*	abd_semmouri@yahoo.fr
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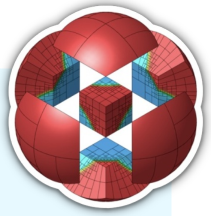
004	Abdesslam Ouaziz	*University Sidi Mohammed Ben Abdellah*	abdesslam.ouaziz1994@gmail.com
005	Achraf El Omari	*Hassan II University of Casablanca*	achraf.elomari-etu@etu.univh2c.ma
006	Achraf Zinihi	*aculty of Sciences and Technics, Moulay Ismail University of Mekne*	a.zinihi@edu.umi.ac.ma
007	Adel Babbah	*abdelmalek essadi university*	a.babbah@uae.ac.ma
008	Aditya Parik	*Utah State University*	aditya.parik@usu.edu
009	Adolfo Rodriguez	*Kappa Engineering*	adantra@gmail.com
010	Adrian Butscher	*Autodesk*	adrian.butscher@autodesk.com
011	Ahdia Achabbak	*Faculty of the science*	ahdia.achabbak@etu.uae.ac.ma
013	Alberto Padovan	*University of Illinois at Urbana-Champaign*	padovan3@illinois.edu
014	Alejandro Muñoz	*Universidad de Granada*	almuma@ugr.es
015	Alex Lindsay	*Idaho National Laboratory*	alexander.lindsay@inl.gov
016	Alexander Blair	*UK Atomic Energy Authority*	alexander.blair@ukaea.uk
017	Alexander Grayver	*ETH Zurich*	agrayver@ethz.ch

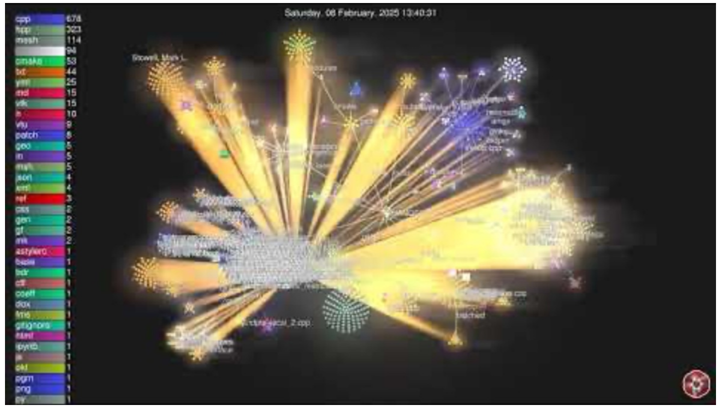
Community workshops have 200+ registrations

Latest Release Was a Team Effort

Version 4.8 stats



- Released **April, 2025**
- **11** months in development
- **36** contributors
- **212** PRs merged
- **284** issues closed
- **53K** new lines of code
- **2922** commits
- **Many new features:**
  - high-order pyramids
  - parallel p- and hp-refinement
  - nonuniform anisotropic AMR
  - field interpolation on GPUs
  - SubMesh extraction with AMR
  - many GPU improvements
  - proximal Galerkin eikonal example

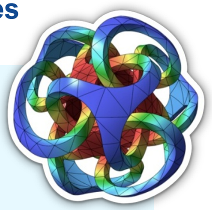


The making of mfem-4.8 video on YouTube

pazner 325 commits	tzanio 268 commits	helloworld922 194 commits
mlstowell 167 commits	najlkin 167 commits	kmittal2 142 commits
dylan-copeland 134 commits	artv3 117 commits	vladotomov 111 commits
v-dobrev 94 commits	adam-sim-dev 72 commits	cjvogl 61 commits
hughcars 57 commits	j-signorelli 40 commits	camierjs 35 commits

Top 15 contributors to the latest release

The mfem-4.8 CHANGELOG has 52 entries

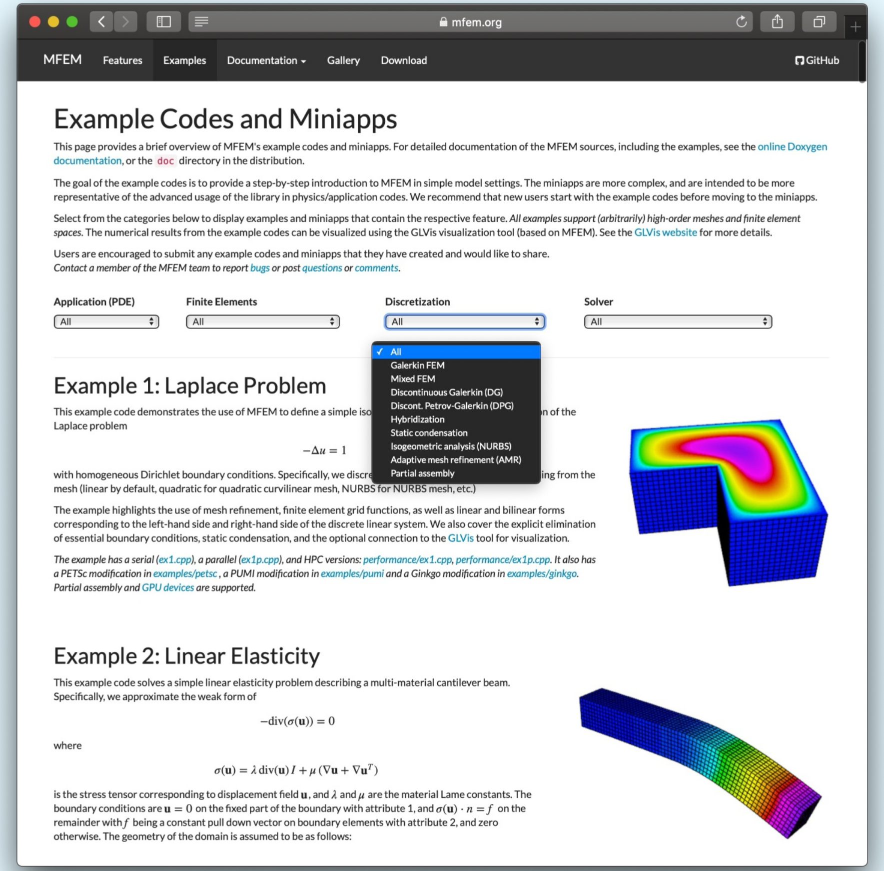


New GLVis release

- **glvis-4.4** released in May
- **New features:**
  - support for external color palettes
  - new optional palette sets
  - loading of MFEM data collections
  - up to 3D vector fields in 1D/2D
  - bugfixes and refactoring
- Updated **pyglvis**, glvis.org/live

Examples

The first stop for new users


mfem.org
MFEM Features Examples Documentation Gallery Download GitHub

Example Codes and Miniapps

This page provides a brief overview of MFEM's example codes and miniapps. For detailed documentation of the MFEM sources, including the examples, see the online Doxygen documentation, or the doc directory in the distribution.

The goal of the example codes is to provide a step-by-step introduction to MFEM in simple model settings. The miniapps are more complex, and are intended to be more representative of the advanced usage of the library in physics/application codes. We recommend that new users start with the example codes before moving to the miniapps.

Select from the categories below to display examples and miniapps that contain the respective feature. *All examples support (arbitrarily) high-order meshes and finite element spaces.* The numerical results from the example codes can be visualized using the GLVis visualization tool (based on MFEM). See the GLVis website for more details.

Users are encouraged to submit any example codes and miniapps that they have created and would like to share.
Contact a member of the MFEM team to report bugs or post questions or comments.

Application (PDE): All | Finite Elements: All | Discretization: All | Solver: All

All
Galerkin FEM
Mixed FEM
Discontinuous Galerkin (DG)
Discont. Petrov-Galerkin (DPG)
Hybridization
Static condensation
Isogeometric analysis (NURBS)
Adaptive mesh refinement (AMR)
Partial assembly

Example 1: Laplace Problem

This example code demonstrates the use of MFEM to define a simple iso... n of the Laplace problem

$$-\Delta u = 1$$

with homogeneous Dirichlet boundary conditions. Specifically, we discre... ing from the mesh (linear by default, quadratic for quadratic curvilinear mesh, NURBS for NURBS mesh, etc.)

The example highlights the use of mesh refinement, finite element grid functions, as well as linear and bilinear forms corresponding to the left-hand side and right-hand side of the discrete linear system. We also cover the explicit elimination of essential boundary conditions, static condensation, and the optional connection to the GLVis tool for visualization.

The example has a serial (ex1.cpp), a parallel (ex1p.cpp), and HPC versions: performance/ex1.cpp, performance/ex1p.cpp. It also has a PETSc modification in examples/petsc , a PUMI modification in examples/pumi and a Ginkgo modification in examples/ginkgo. Partial assembly and GPU devices are supported.

Example 2: Linear Elasticity

This example code solves a simple linear elasticity problem describing a multi-material cantilever beam. Specifically, we approximate the weak form of

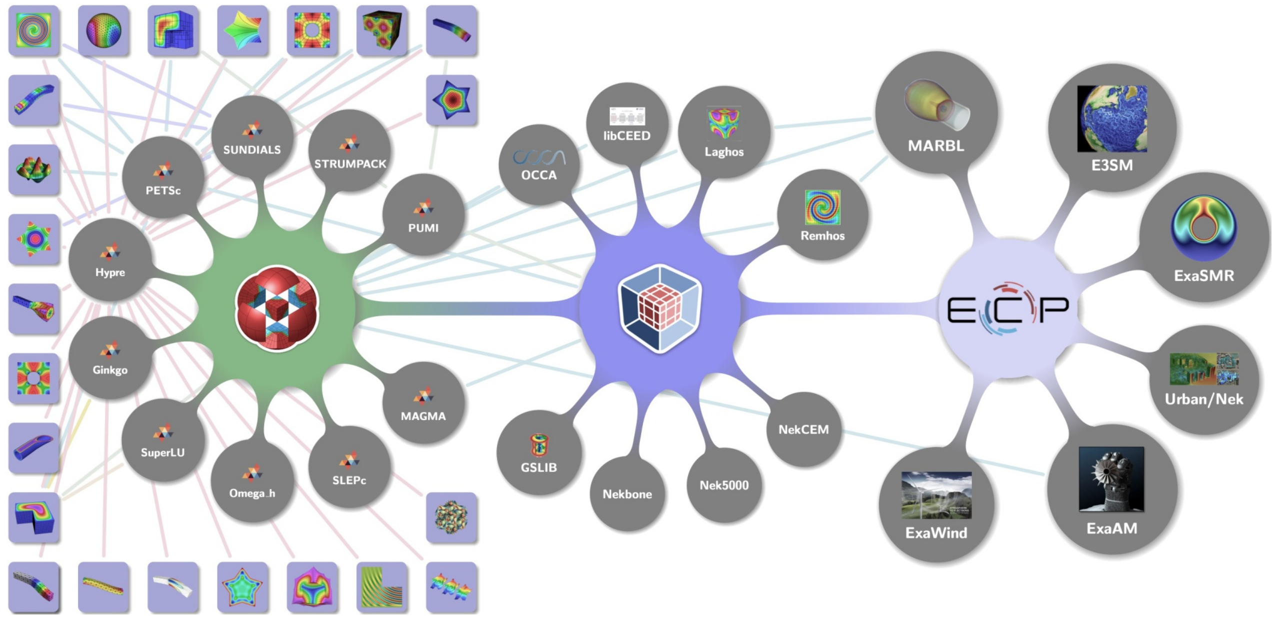
$$-\mathrm{div}(\sigma(\mathbf{u})) = 0$$

where

$$\sigma(\mathbf{u}) = \lambda\, \mathrm{div}(\mathbf{u})\, I + \mu\, (\nabla \mathbf{u} + \nabla \mathbf{u}^T)$$

is the stress tensor corresponding to displacement field $\mathbf{u}$, and λ and μ are the material Lame constants. The boundary conditions are $\mathbf{u} = 0$ on the fixed part of the boundary with attribute 1, and $\sigma(\mathbf{u}) \cdot n = f$ on the remainder with f being a constant pull down vector on boundary elements with attribute 2, and zero otherwise. The geometry of the domain is assumed to be as follows:

mfem.org/examples



- 40 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

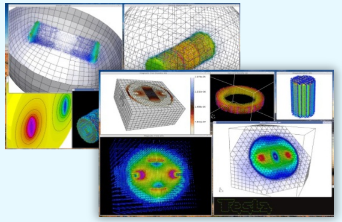
Miniapps

More advanced, ready-to-use physics solvers

Volta, Tesla, Maxwell and Joule Miniapps

Static and transient electromagnetics

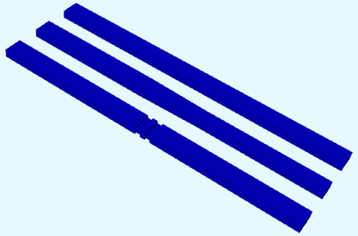
- **Volta** $-\nabla \cdot \epsilon \nabla \varphi = \rho - \nabla \cdot \vec{P}$
- **Tesla** $\nabla \times \mu^{-1} \nabla \times \vec{A} = \vec{J} + \nabla \times \mu^{-1} \mu_0 \vec{M}$



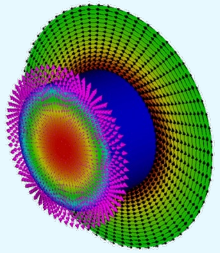
- **Maxwell** · *transient full-wave EM*

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

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



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



mfem.org/electromagnetics

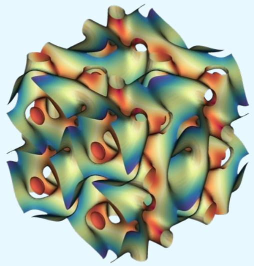
Navier Miniapp

Transient incompressible Navier-Stokes equations

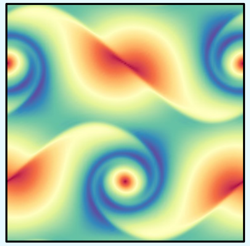
$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \nabla)\boldsymbol{u} - \nu \Delta \boldsymbol{u} + \nabla p = \boldsymbol{f}$$

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

- 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



3D Taylor-Green vortex, 7th order

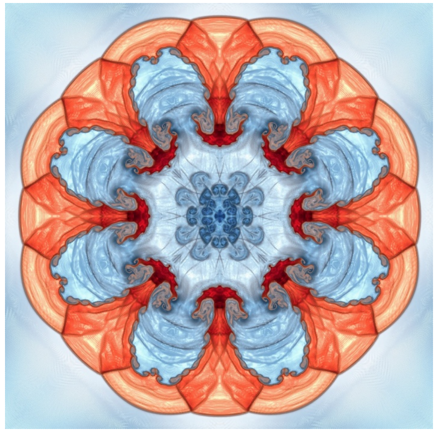


Double shear layer, 5th order, Re = 100000

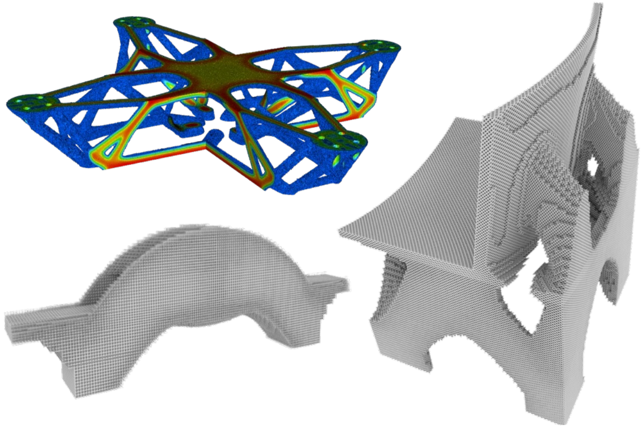
mfem.org/fluids

Applications

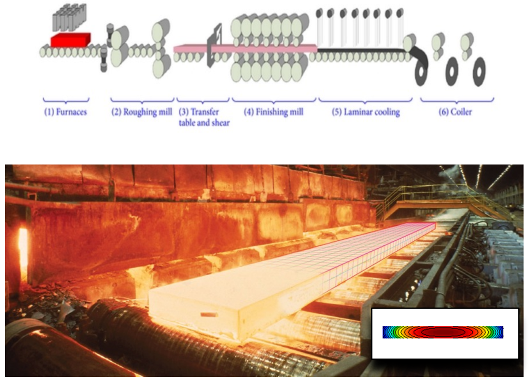
Some of the large-scale simulation codes powered by MFEM



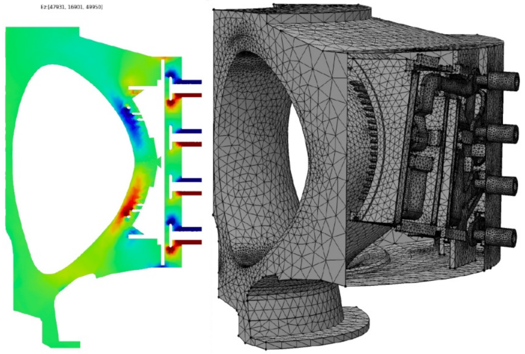
Inertial confinement fusion (BLAST, LLNL)



Topology optimization for additive manufacturing (LiDO, LLNL)



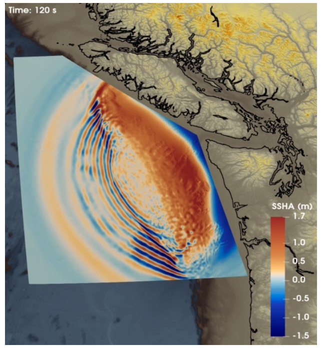
Hot strip mill slab modeling (U.S. Steel)



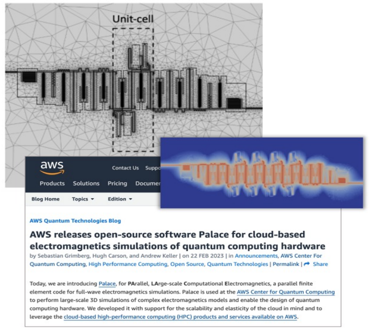
Core-edge tokamak EM wave propagation (SciDAC, PPPL)

Electric aircraft design (RPI)

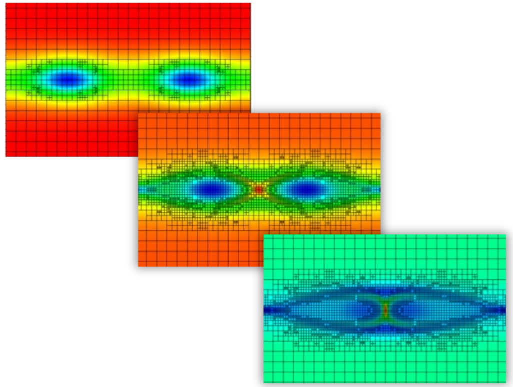
MRI modeling (Harvard Medical)



Tsunami warning (Cascadia, UT/UCSD)



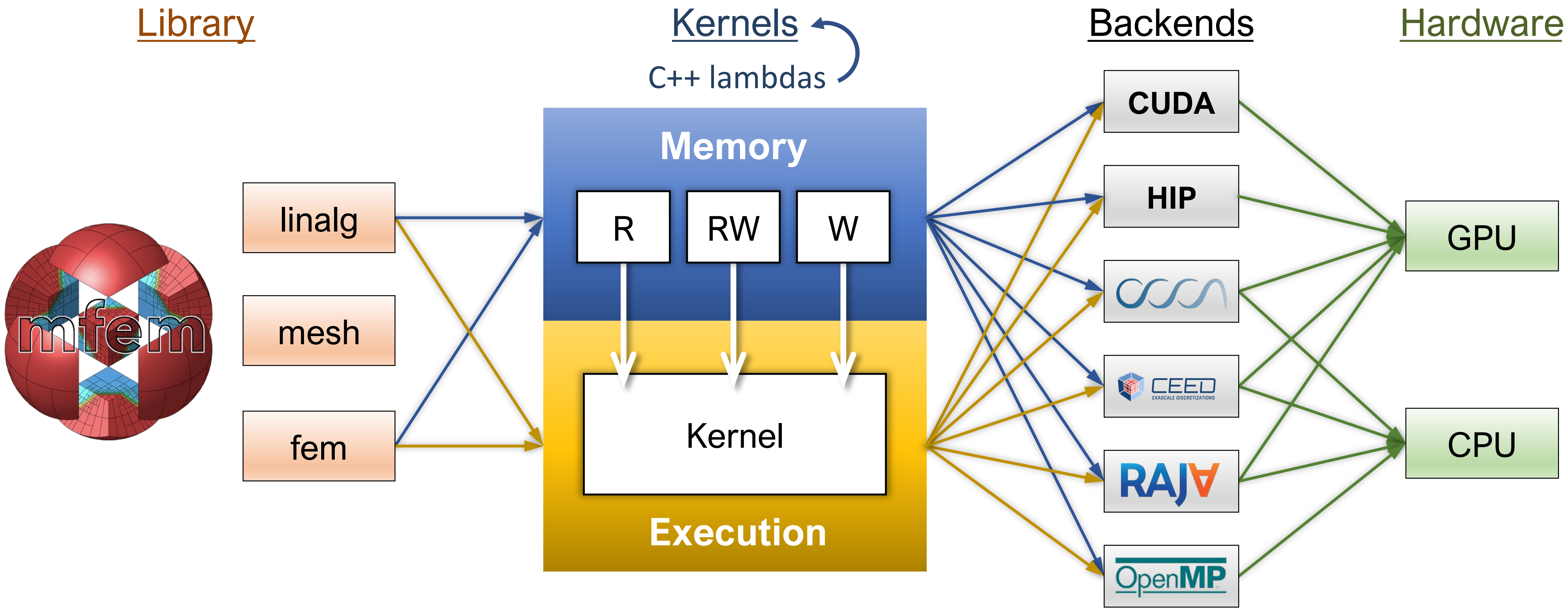
Quantum Computing Hardware (Palace, Amazon)



Adaptive MHD island coalescence (SciDAC, LANL)

GPU Support as a First-class Citizen

MFEM has provided GPU acceleration for over 6 years (since mfem-4.0)

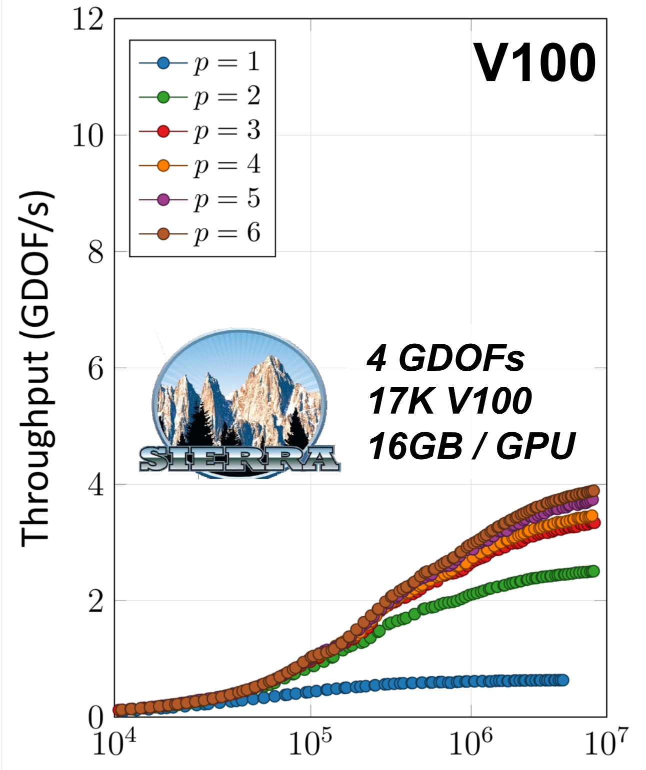


- Matrix-free partial assembly (PA)
- runtime-selectable backends
- ready for future hardware

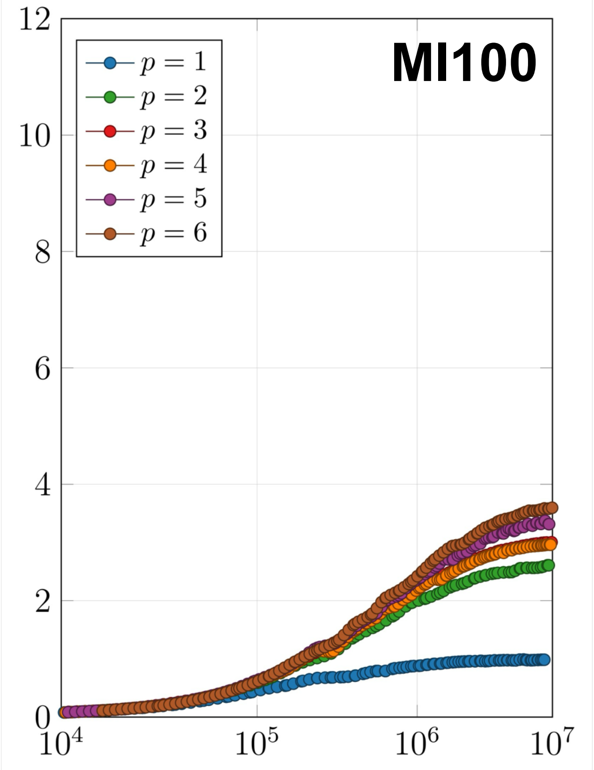
Performance-Portable GPU Finite Element Kernels

MFEM's results on the CEED bake-off problems are state-of-the-art

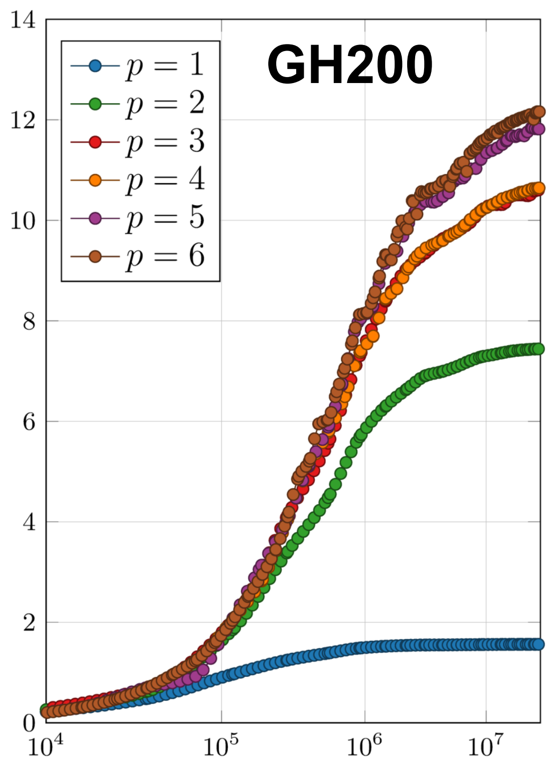
MFEM BP1 (atomics) @ V100



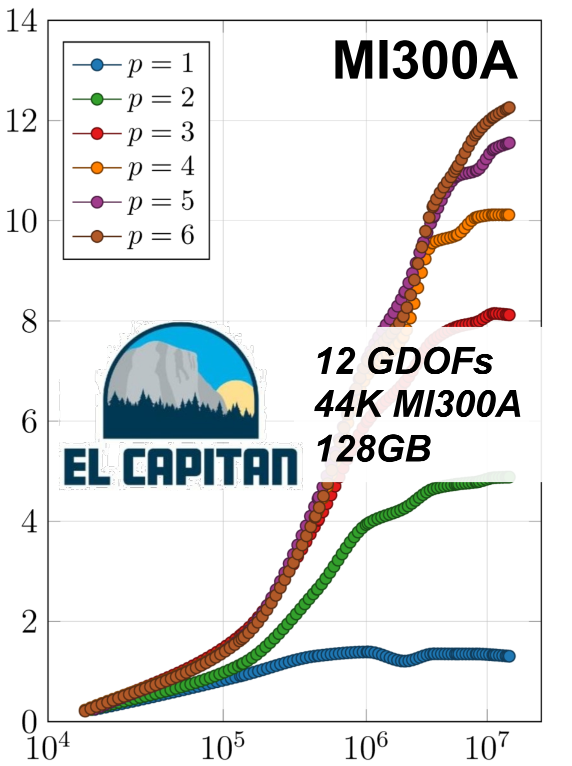
MFEM BP1 (atomics) @ MI100

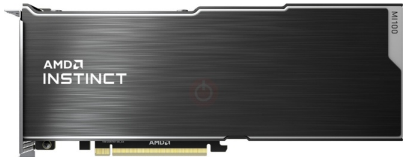


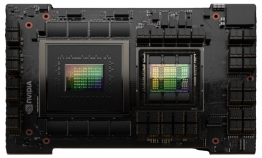
MFEM BP1 (atomics) @ GH200

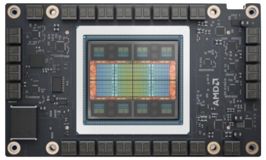


MFEM BP1 (atomics) @ MI300A





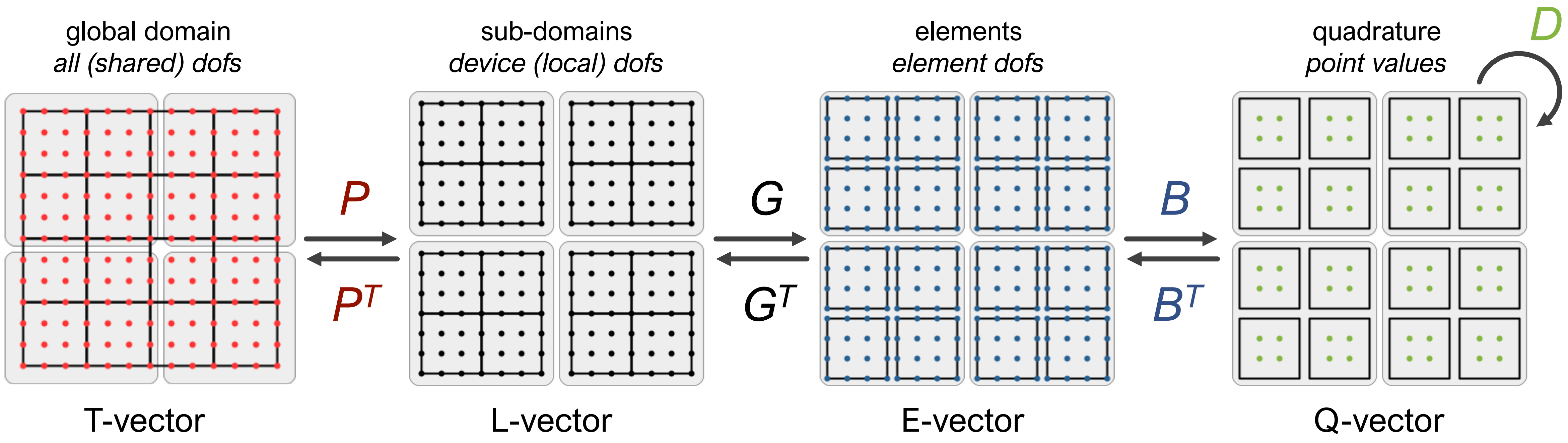




FEM Operator Decomposition + Partial Assembly for HPC

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

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

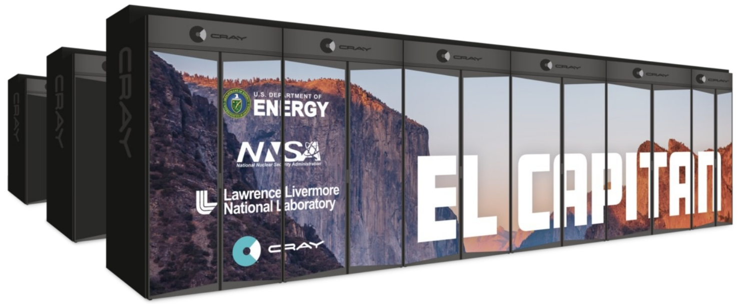


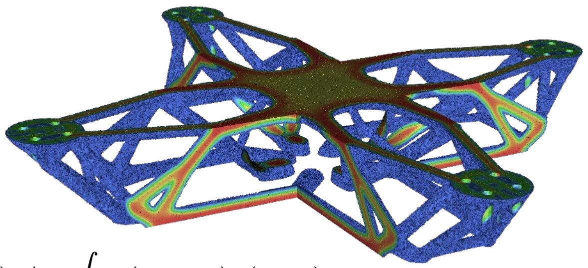
- **Partial assembly = store only D, evaluate B** NO ASSEMBLY REQUIRED
- **Optimal memory, near-optimal FLOPs compared to A**
- **Key for AMR, HO, GPUs**
- **Enables dFEM**

Roadmap for Next Year

Plans for FY26

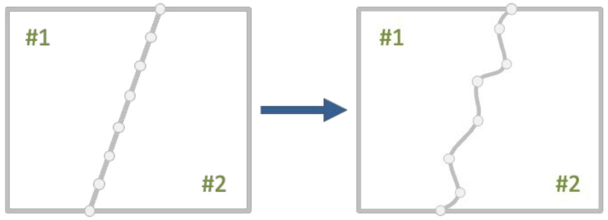
- **GPU computing**
  - Solver optimizations on El Capitan
  - Kernels using tensor/matrix cores
  - Mixed precision algorithms
- **Differentiable Simulations**
  - dFEM autodiff in next release
  - AD on GPU · Enzyme collaboration
  - ALE multi-physics · inverse design
- **R&D**
  - Meshing and discretizations for AI workflows
  - Efficient high-order methods on mixed meshes · including simplices
  - Improved field transfer · multiphysics coupling · particles support
- **New releases**
  - mfem-4.9 in Nov · switch to C++17 · initial dFEM in `mfem::future`
- **What would you like to see?**
  - Slack: #meet-the-team · GitHub: github.com/mfem/mfem/issues · Email: mfem@llnl.gov

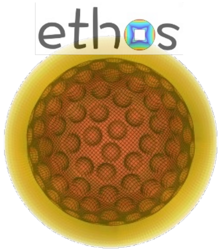




$$\langle F_D(u,\rho), v\rangle = \int_\Omega D(u,\nabla u,\rho)\cdot(v,\nabla v)$$

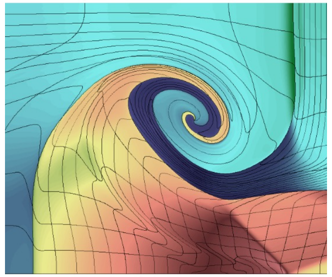
$$F_D(u,\rho) = T_v^{\mathrm{T}}\, D_\omega(T_u u, T_\rho \rho) \longrightarrow \frac{dF}{du}(u^*,\rho^*) = T_v^{\mathrm{T}}\, \partial_{\tilde u} D_\omega(\tilde u^*, \tilde \rho^*) T_u$$

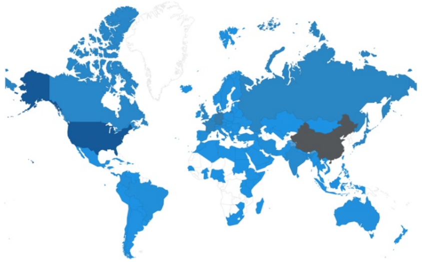




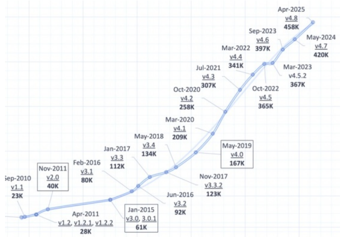
The state of MFEM is strong

- **Strong development team**
  - Pushing the boundaries of finite element R&D
  - Made a lot of progress last year
- **Awesome applications**
  - Both at DOE, industry and academia
  - Scaled to world's largest supercomputers
- **Growing community**
  - GitHub, workshop, tutorials
  - Users contribute back, become developers
- **The future is bright**
  - Exciting new directions
  - MFEM keeps growing and accelerating

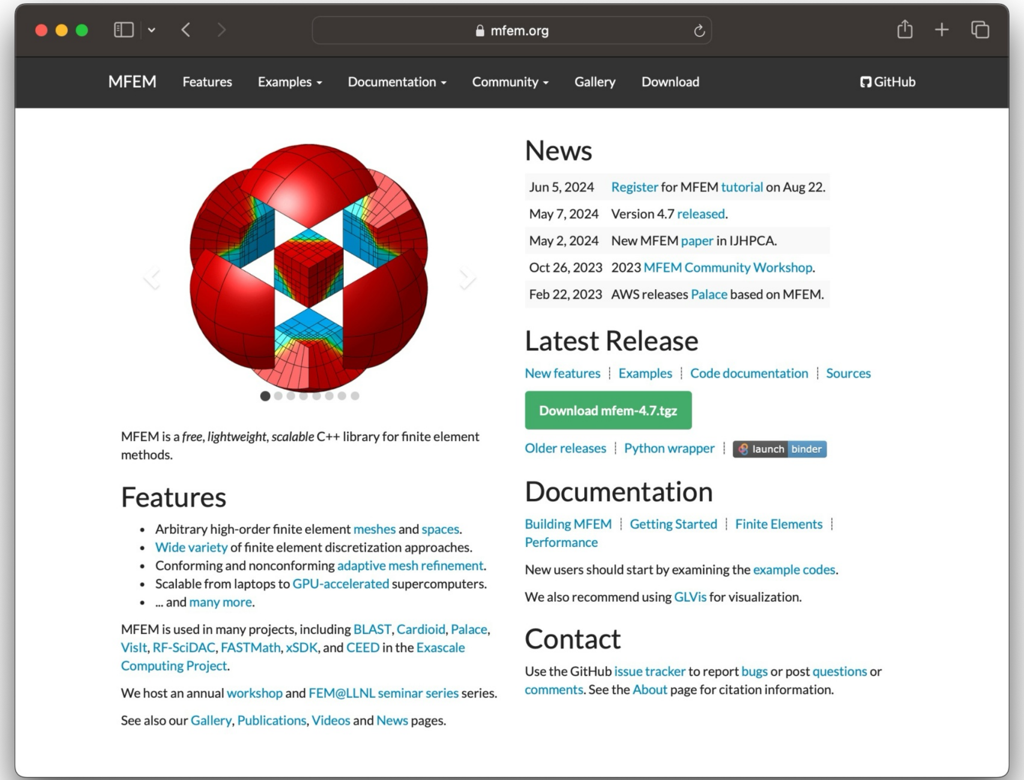




Differentiable Multiphysics Codes



MFEM Resources



Website:
mfem.org

Software:
github.com/mfem

Publications:
mfem.org/publications

Email:
mfem@llnl.gov

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