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Combining FEniCS and MFront Code Generation Tools for Nonlinear Mechanics

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Binding two code-generation tools

FEniCS : a code-generation software package for automated solution of **partial differential equations**

$$\int_{\Omega} \nabla \mathbf{u} : \nabla \mathbf{v} \, dx - \int_{\Omega} p \operatorname{div} \mathbf{v} \, dx + \int_{\Omega} q \operatorname{div} \mathbf{u} \, dx = \int_{\Omega} \mathbf{f} \cdot \mathbf{v} \, dx$$

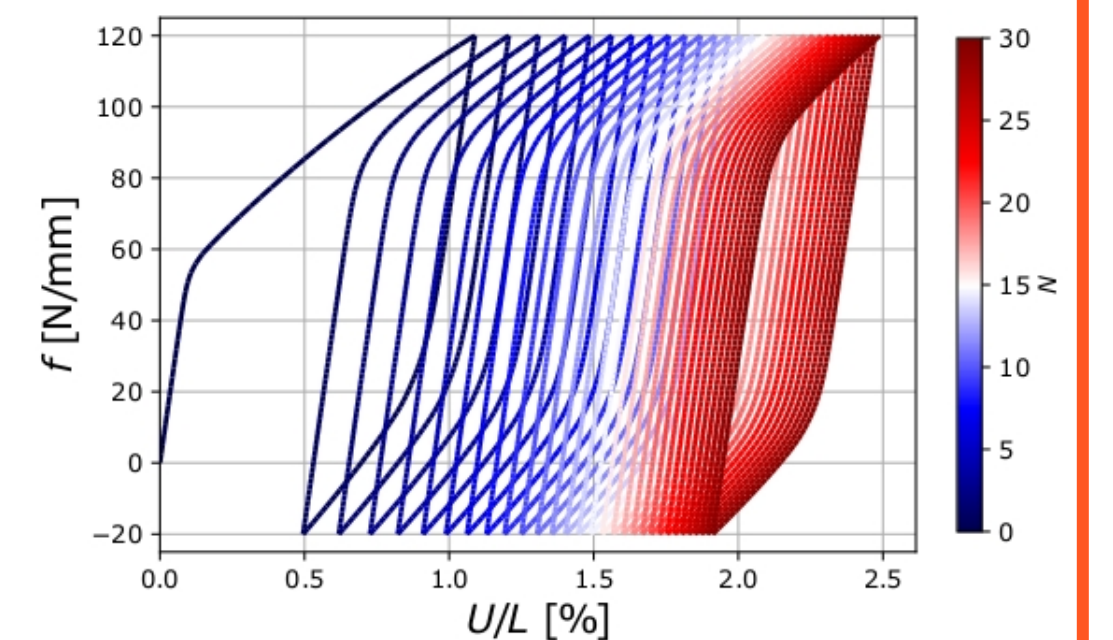
MFfront : a code-generation tool for complex **material constitutive laws**

$$\Delta \varepsilon, \sigma_n, \mathbf{Y}_n \rightarrow \boxed{\text{MFfront}} \rightarrow \sigma_{n+1}, \mathbf{Y}_{n+1}, \frac{\partial \sigma}{\partial \Delta \varepsilon}$$

Non-linear material constitutive laws

e.g. elasto-viscoplasticity, damage, ductile fracture usually formulated as a set of **non-linear equations** at the **material point level** => **implicit stress/strain relation, history-dependent**

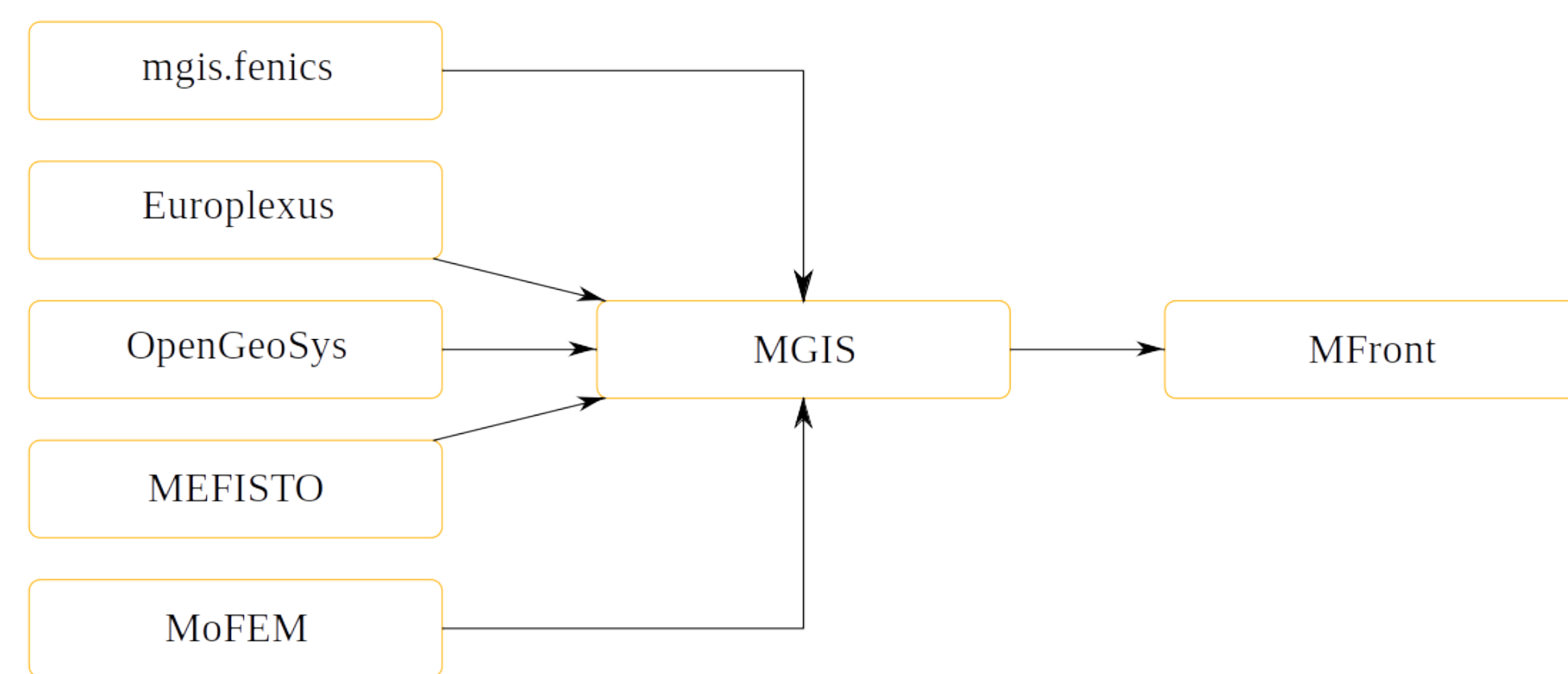
Implementation should also return the **tangent operator**



A Python package in the MGIS project

MFfront Generic Interface Support project

A generic interface between Mfront and (FE, FFT...) solvers
 Bindings : C, Fortan, Python, Julia



within FEniCS

$$F(\mathbf{v}) = \int_{\Omega} \boldsymbol{\sigma}(\mathbf{u}) \cdot \delta \mathbf{g}(\mathbf{v}) \, dx - L(\mathbf{v}) = 0 \quad \forall \mathbf{v} \in V$$

$$a_{\text{tangent}}(\mathbf{u}, \mathbf{v}) = \int_{\Omega} \delta \mathbf{g}(\mathbf{v}) \cdot \mathbb{T} \cdot \delta \mathbf{g}^j(\mathbf{u}) \, dx$$

Stress and **tangent blocks** represented by "Quadrature" functions => not optimal but not intrusive

The only metadata **not provided** by MGIS is how the gradients (e.g. strain) relate to the unknown fields (e.g. displacement)

The user is required to provide this link using UFL expressions (**registration**)

```
mat_prop = {"YoungModulus": E, "PoissonRatio": nu, "Hardening": H, "YieldStrength": sig0}
material = mf.MFrontNonlinearMaterial("src/libBehaviour.so",
                                       "IsotropicLinearHardeningPlasticity", hypothesis="plane_strain",
                                       material_properties=mat_prop)
u = Function(V, name="Displacement")
problem = mf.MFrontNonlinearProblem(u, material, quadrature_degree=2, bcs=bc)
problem.register_gradient("Strain", sym(grad(u)))
```

Monolithic thermo-elastoplasticity

Generalized behaviour

displacement + temperature

```
1 @DSL DefaultGenericBehaviour;
2 @Behaviour HeatTransferPhaseChange;
3
4 @Gradient TemperatureGradient VT;
5 VT.setGlossaryName("TemperatureGradient");
6
7 @Flux HeatFlux j;
8 j.setGlossaryName("HeatFlux");
9
10 @StateVariable real h;
11 h.setEntryName("Enthalpy"); //per unit of volume
12
13 @AdditionalTangentOperatorBlock djdT;
14 @AdditionalTangentOperatorBlock dh/dT;
```

$$\varepsilon^{\text{el}} = \varepsilon^{\text{to}} - \varepsilon^{\text{p}} - \varepsilon^{\text{th}}$$

$$\boldsymbol{\sigma} = \lambda \operatorname{tr}(\varepsilon^{\text{el}}) \mathbf{I} + 2\mu \varepsilon^{\text{el}}$$

$$s = \frac{C_{\varepsilon}}{T_{\text{ref}}}(T - T_{\text{ref}}) + \frac{\kappa}{\rho} \operatorname{tr}(\varepsilon^{\text{el}})$$

$$\mathbf{j} = -k \nabla T$$

$$\int_{\Omega} \boldsymbol{\sigma}_{n+1} : \nabla^s \hat{\mathbf{u}} \, dx = \int_{\partial \Omega} \mathbf{T} \cdot \hat{\mathbf{u}} \, dS \quad \forall \hat{\mathbf{u}}$$

$$\int_{\Omega} (\rho T_{\text{ref}} \frac{s_{n+1} - s_n}{\Delta t} - \mathbf{j}_{n+1}) \hat{T} \, dx = - \int_{\partial \Omega} q \hat{T} \, dS \quad \forall \hat{T}$$

```
Vue = VectorElement("CG", mesh.ufl_cell(), 2) # displacement finite element
Vte = FiniteElement("CG", mesh.ufl_cell(), 1) # temperature finite element
V = FunctionSpace(mesh, MixedElement([Vue, Vte]))

v = Function(V)
(u, Theta) = split(v)
problem = mf.MFrontNonlinearProblem(v, material, quadrature_degree=2, bcs=bcs)
problem.register_gradient("Strain", sym(grad(u)))
problem.register_gradient("TemperatureGradient", grad(Theta))
problem.register_external_state_variable("Temperature", Theta + Tref)
```

```
sigsig = problem.get_flux("Stress")
j = problem.get_flux("HeatFlux")
s = problem.get_state_variable("EntropyPerUnitOfMass")
prproblem.initialize()

s_s_old = s.copy(deepcopy=True)
v_v_ = TestFunction(V)
u_u_, T_ = split(v_v_) # Displacement and temperature test functions
eps_eps_ = problem.gradients["Strain"].variation(v_v_)
mech_resid = dot(sig, eps_eps_) * problem.dx
th_thermal_resid = (rho * Tref * (s - s_old) / dt + T_ - dot(j, grad(T_))) * problem.dx
prproblem_residual = mech_resid + thermal_resid
prproblem.compute_tangent_form()
```

Logarithmic strain plasticity

Hencky strain measure + elasto-plastic behaviour

$$H = \frac{1}{2} \log(\mathbf{F}^T \cdot \mathbf{F})$$

$$H = H^e + H^p$$

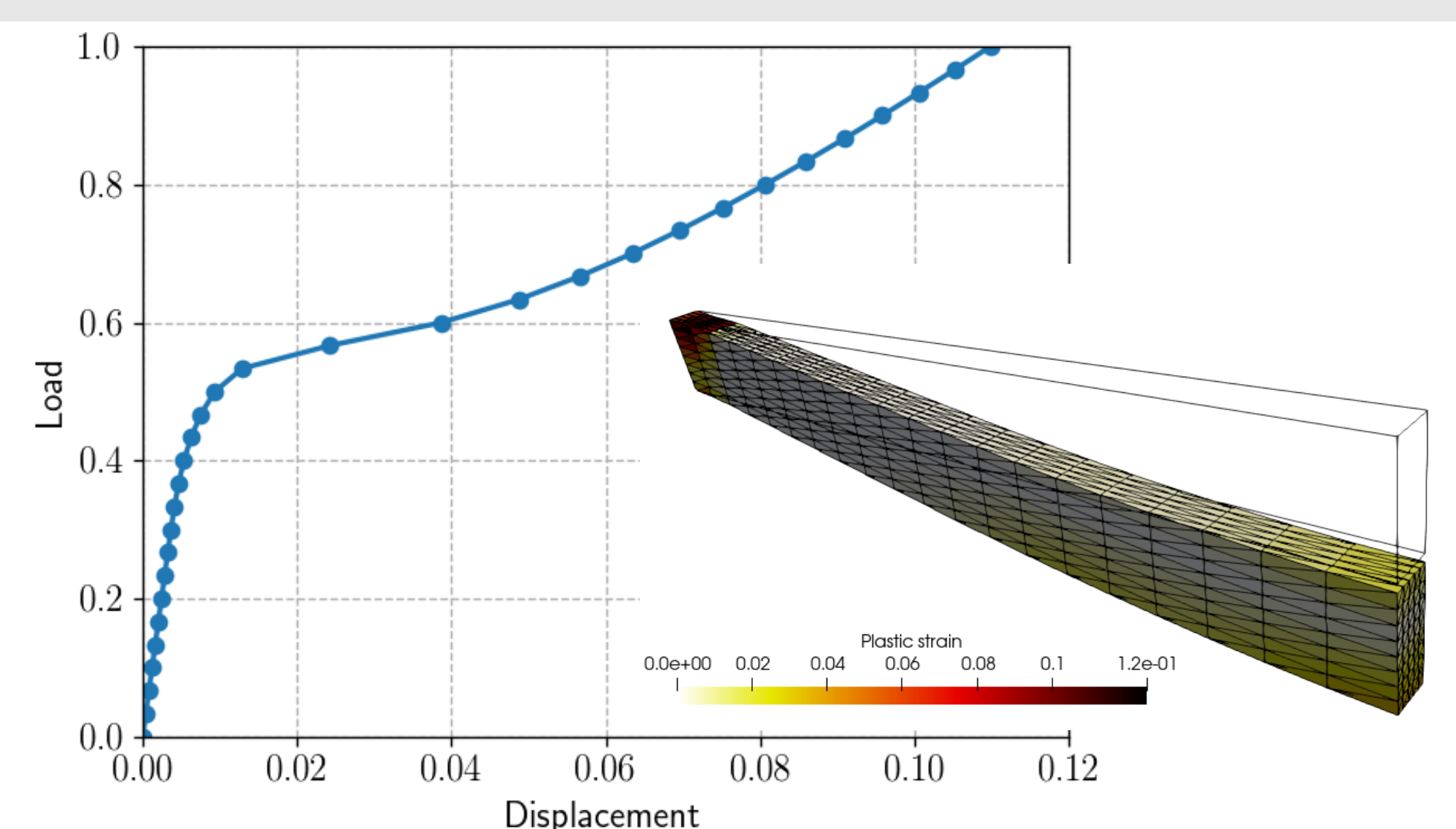
$$\mathbf{T} = \mathbb{C} : H^e$$

$$f(\mathbf{T}) = \|\mathbf{T}\| - (\sigma_0 + H_p) \leq 0$$

$$\dot{H}^p = \dot{\rho} \frac{\mathbf{T}}{\|\mathbf{T}\|}, \quad \dot{\rho} \geq 0$$

```
1 @DSL Implicit;
2
3 @Behaviour LogarithmicStrainPlasticity;
4
5 @StrainMeasure Hencky;
6
7 @Brick StandardElastoViscoPlasticity{
8   stress_potential: "Hooke" {
9     young_modulus: 210e9,
10    poisson_ratio: 0.3
11  },
12  inelastic_flow: "Plastic" {
13    criterion: "Mises",
14    isotropic_hardening: "Linear" {H: 500e6,
15                               Ro: 250e6}
16  };
17 };
```

```
material = mf.MFrontNonlinearMaterial("./src/libBehaviour.so", "LogarithmicPlasticity")
problem = mf.MFrontNonlinearProblem(u, material, bcs=bc)
problem.set_loading(dot(selfweight, u)*dx)
problem.register_gradient("DeformationGradient", Identity(3)+grad(u))
```



Conclusion

Working binding between FEniCS and MFfront
 Complex behaviours with very limited syntax, extension to generalized behaviours

Perspectives: better solution with dolfin-x, ExternalOperator ?