NIST Additive Manufacturing Fatigue and Fracture Project: Facilities and Capabilities

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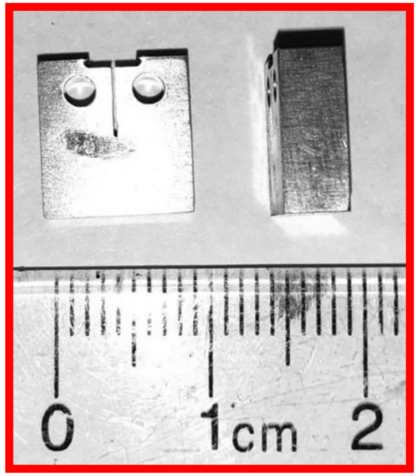
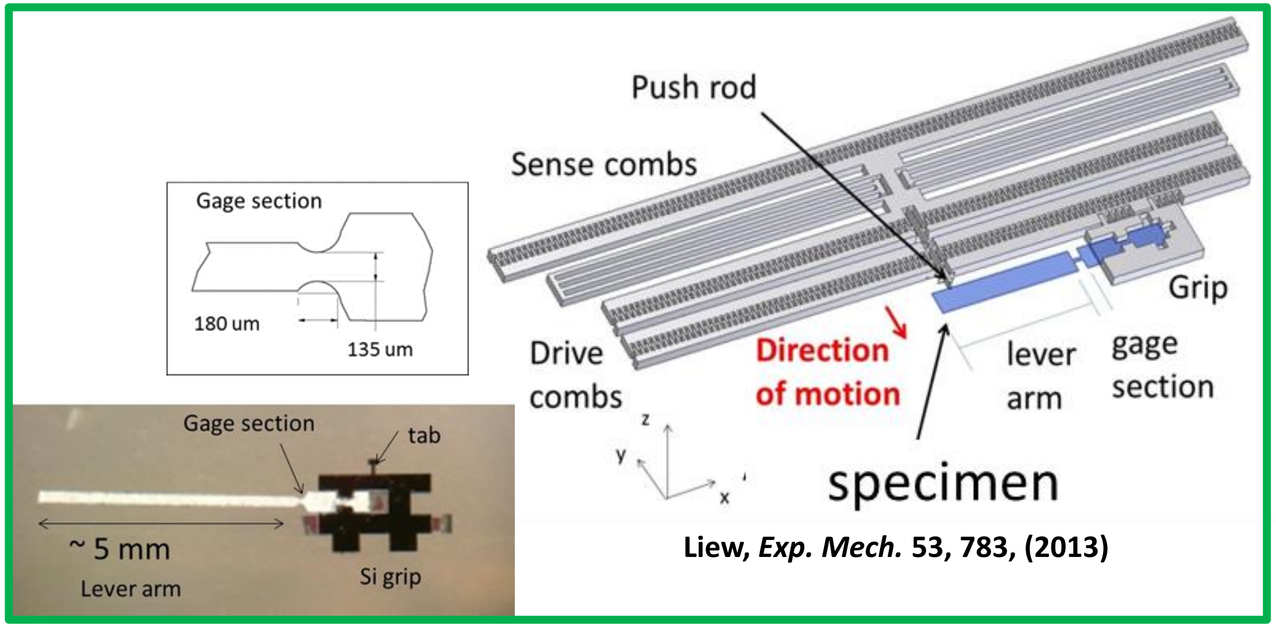
<u>Mechanical Testing</u> Facilities and Capabilities

- **<u>Standard Size</u>** Specimens
  - E.g. quasi-static tension/compression, high-cycle fatigue, low-cycle fatigue, fatigue crack growth rate (FCGR), rotating bending fatigue, instrumented Charpy, fracture toughness, etc
  - Digital Image Correlation (DIC)
  - High temperature, Low temperature (**liquid helium 4°K**), environmental (including **pressurized hydrogen**)
  - Microhardness and Nanoindentation with mapping capabilities
- **<u>Milli-scale</u>** Specimens
  - E.g. Quasi-static tension, small punch, **FCGR**
- **<u>MESO-scale</u>** specimens using table-top testing instruments
  - gauge section dimensions: hundreds of µm to several mm, and with larger grip sections
  - Tensile tests at strain rates from 0.001/s to 1/s
  - Shear tests at strain rates 0.001/s to 30/s
  - **In-situ tensile tests in x-ray computed tomography (XCT) and scanning electron microscope (SEM)**
- **<u>MICRO-scale</u>** specimens using table-top testing instruments
  - gauge section dimensions: tens of µm to 100 µm, and with larger grip sections
  - **Tensile tests on theta-specimens**
- **<u>MICRO-scale</u>** specimens using MEMS test instruments
  - **Bending fatigue tests**
  - Potential: high-throughput testing; in-situ environmental testing

Gaither, *JMR* 26, 2575 (2011).

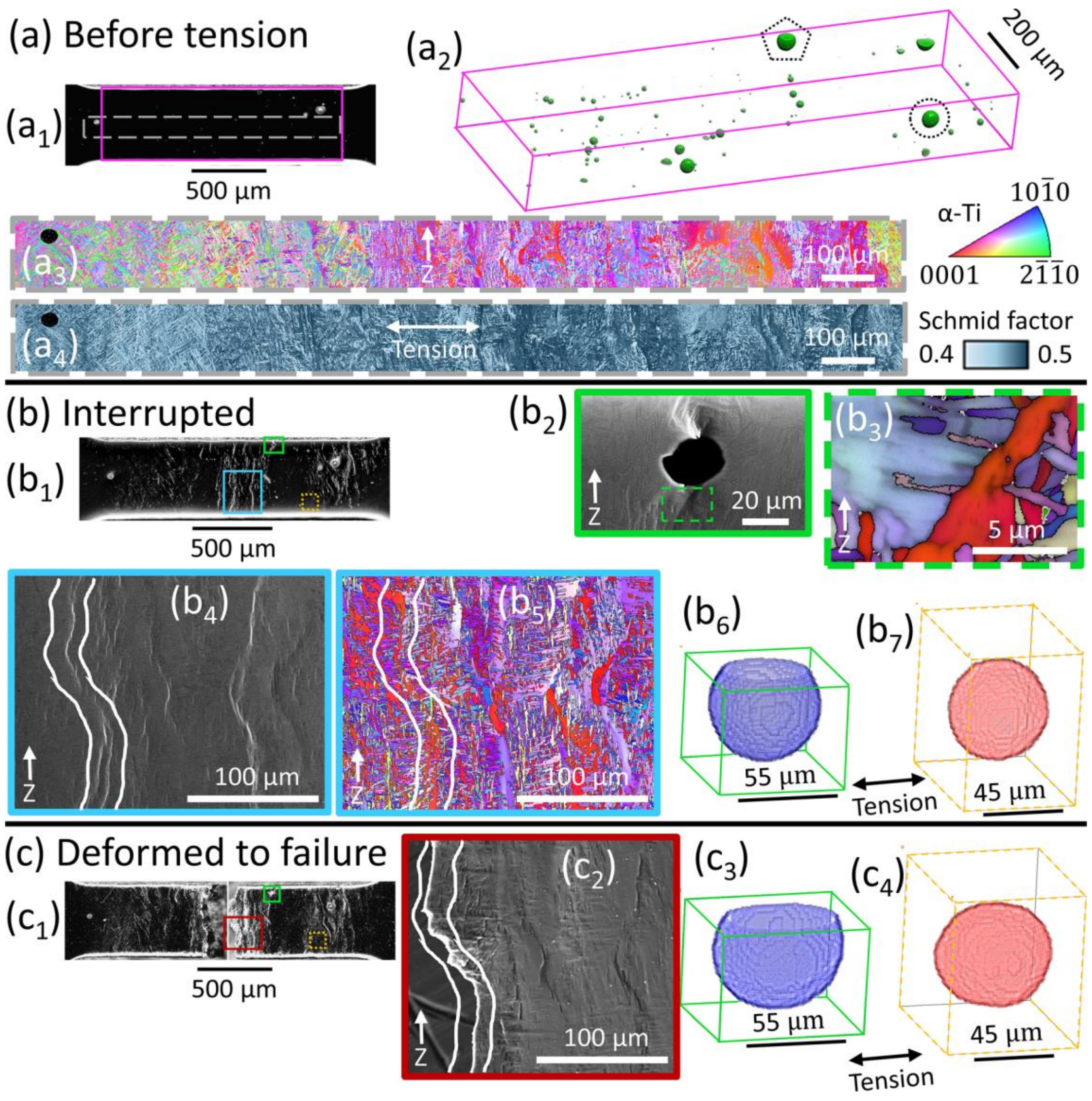




Liew, *Exp. Mech.* 53, 783, (2013)

Meso-scale Mechanical Testing for AM Metals

- Small-scale mechanical testing shows great promise in measuring AM microstructural heterogeneities at appropriate length scales
  - And when extracting specimens from AM components with small features
- Important to couple with microstructure characterization (e.g. SEM-EBSD, XCT)
- NIST has expertise in developing these techniques
- MESO-scale specimens using table-top testing instruments
  - gauge section dimensions: hundreds of μm to several mm, and with larger grip sections
  - Tensile tests at strain rates from 0.001/s to 1/s
  - Shear tests at strain rates 0.001/s to 30/s

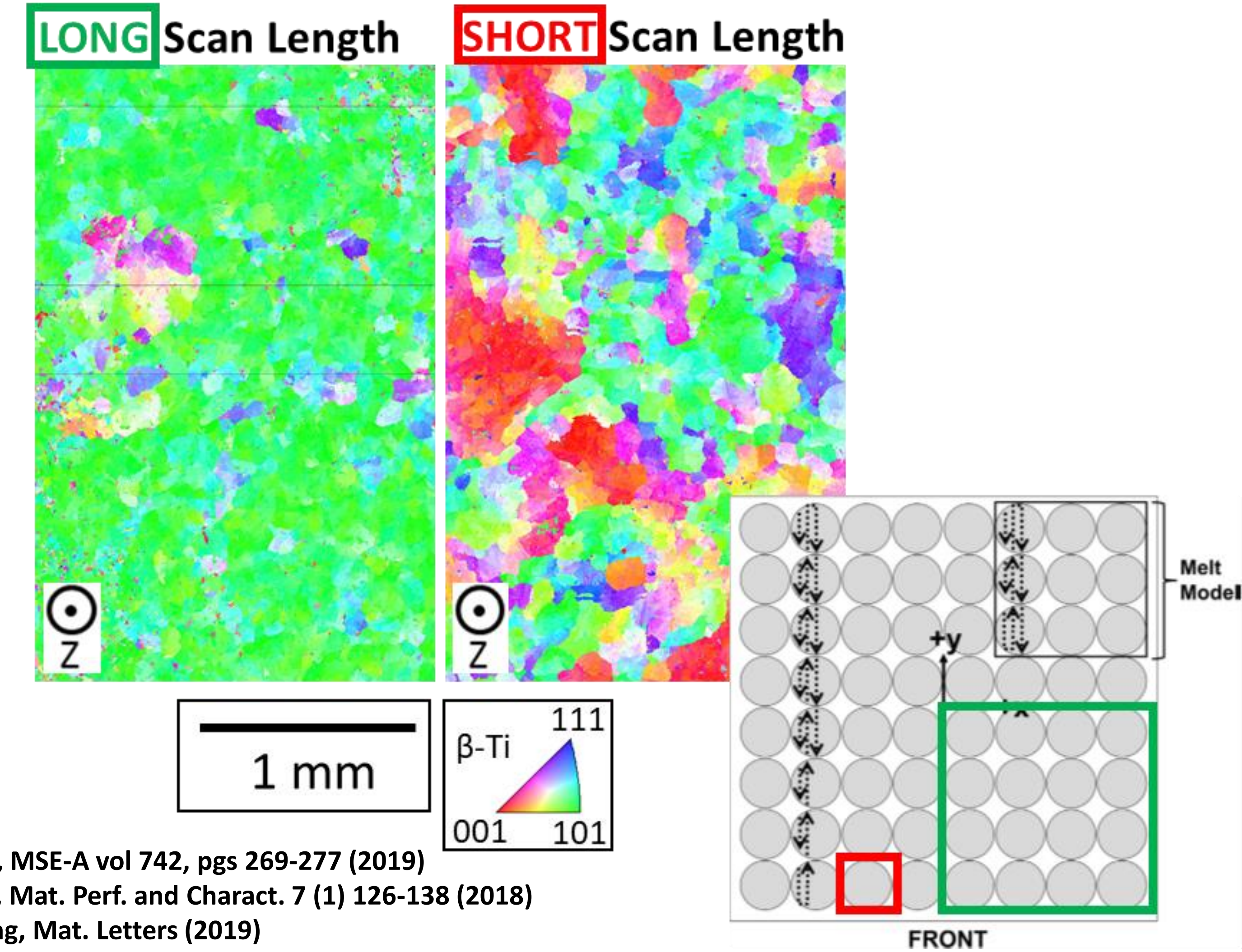


[1] Benzing, *Exp. Mech.* (2019)

Microstructure Characterization Facilities and Capabilities

- Optical Microscopy
  - Stereomicroscopy
- Optical Profilometry
  - Scanning white-light interferometry
- Scanning Electron Microscopy (SEM)
  - Focused ion beam (FIB)
  - Electron dispersive spectroscopy (EDS)
  - Large-area electron backscatter diffraction (EBSD)
  - Transmission-SEM (t-SEM)
- Scanning Transmission Electron Microscopy (STEM)
  - Electron energy-loss spectroscopy (EELS)
- Atomic Force Microscopy (AFM)
  - Scanning kelvin probe force microscopy (SKPFM)
- Atom Probe Tomography (APT)
  - Commercial APT
  - Extreme-UV APT

Large-area EBSD of AM titanium showing process-based texture variation



[1] Hrabe, MSE-A vol 742, pgs 269-277 (2019)
[2] Lucon, Mat. Perf. and Charact. 7 (1) 126-138 (2018)
[3] Benzing, Mat. Letters (2019)

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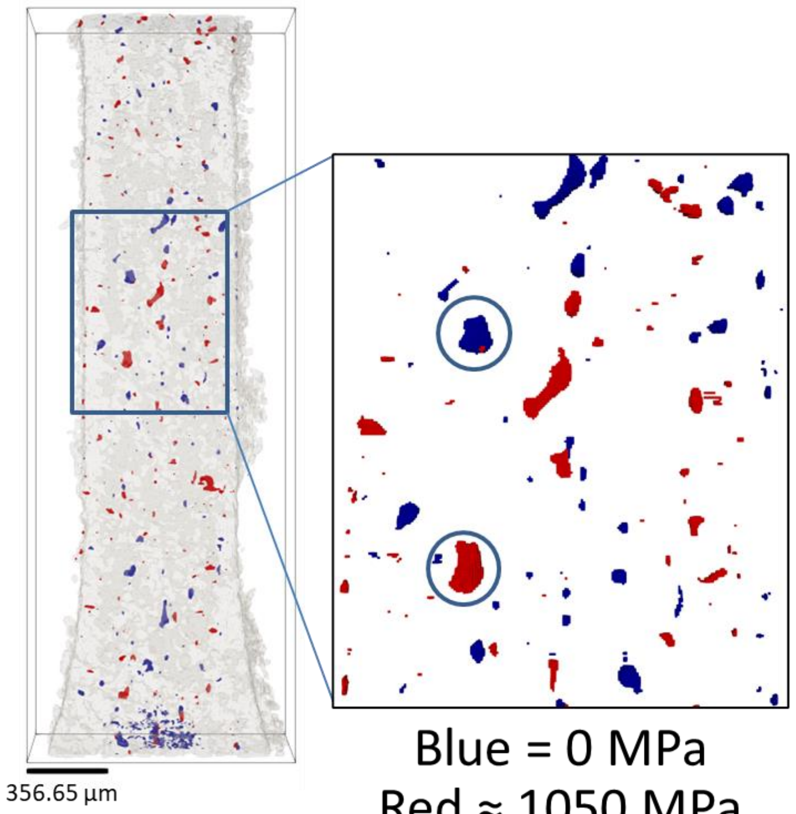
Nondestructive Evaluation Facilities and Capabilities

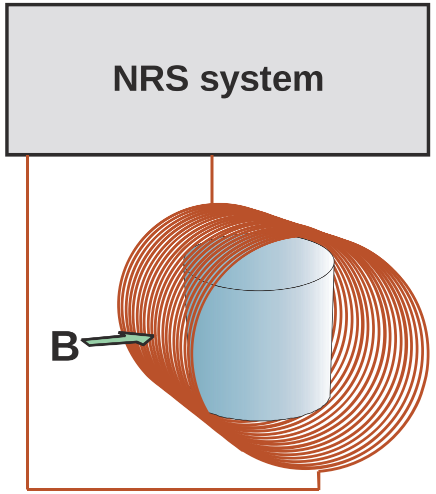
- **X-ray Computed Tomography (XCT)**
  - Two commercial XCT systems
  - Northstar has higher power to analyze larger specimens but with lower resolution (20µm voxel edge length)
  - Zeiss Xradia has lower power that limits specimen size but with better resolution (1µm voxel edge length)
  - In-situ tension/compression testing during XCT (loads <500N)

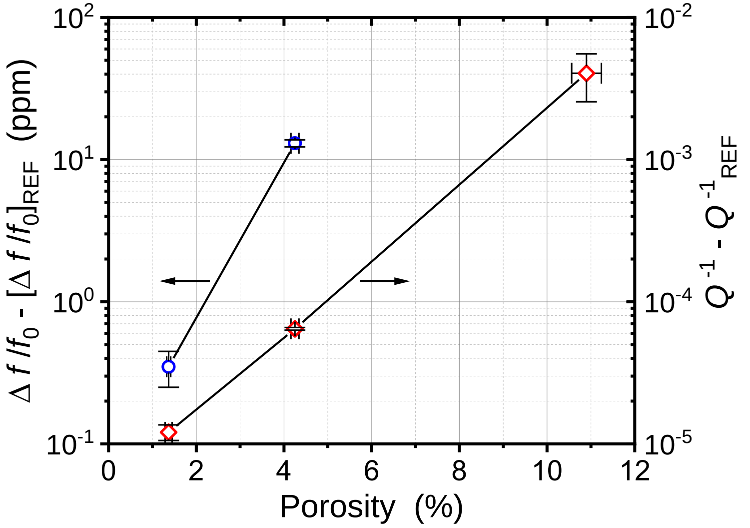
In-situ XCT mechanical testing, showing pores under zero load and 1050 MPa (past yield) in AM IN718 (Kafka, ICAM, 2021)



Blue = 0 MPa
Red ≈ 1050 MPa

- **Acoustics**
  - Unique Nonlinear Reverberation Spectroscopy (NRS) system that provides ultra-precise noncontacting measurements of acoustic nonlinearity and loss.
  - Unique system for noncontacting resonant acoustic measurements of metals from 100 K to 1100 K.
  - Resonant Ultrasound Spectroscopy (RUS) for measurement of complete acoustic spectra
  - Scanning acoustic microscopy

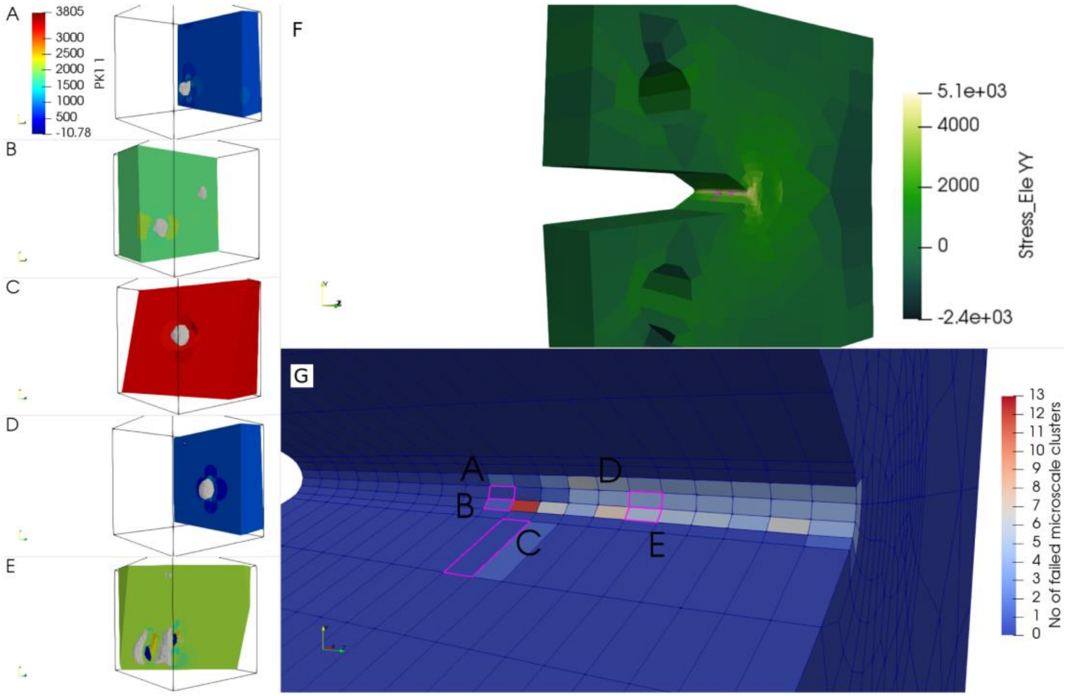




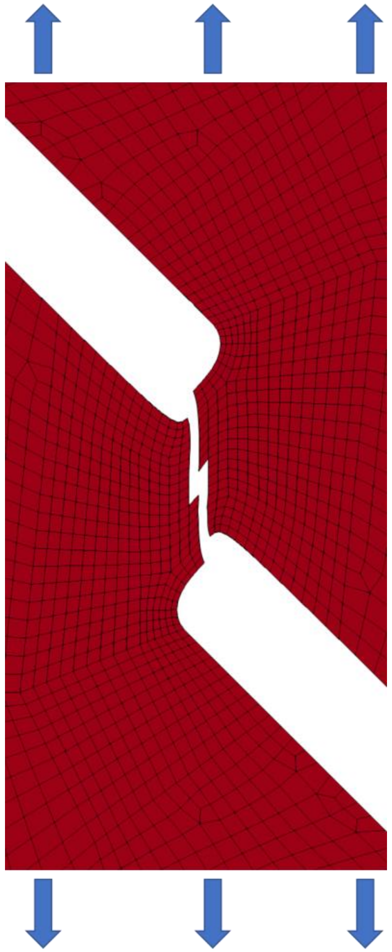
Resonant acoustic nonlinearity and loss in AM stainless steel. [W. Johnson *et al.*, AIP Conference Proceedings 2102, 020008 (2019)]

Computational Facilities and Capabilities

- Facilities
  - High-performance computer clusters for parallel computing, artificial intelligence, and general numerical methods.
  - Limited to about 128 processing cores and 2 GB to 4GB of RAM per node
- Capabilities
  - Finite element methods
  - Computational solid mechanics
  - Reduced order modeling
  - Metal plasticity
  - Damage mechanics
  - Contact-impact problems
  - Modal analysis
  - Crystal plasticity
  - Multi-scale modeling
  - Fracture mechanics
  - Fatigue life prediction.



Concurrent multiscale model for fracture initiation with varying microstructures [1]



Simulating fracture in a shear-type sheet metal specimen using a shear-modified GTN model [2]

[1] Kafka et al. (2021). Image-based multiscale modeling with spatially varying microstructures from experiments: Demonstration with additively manufactured metal in fatigue and fracture. *Journal of the Mechanics and Physics of Solids*, *150*, 104350.
[2] Moser et al. (2017). Predicting Ductile Fracture in Double-Sided Incremental Forming. *CIRP Annals Conference*

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