Snap Buckling of a Constrained Photomechanical Switch Driven by Elastic Instability

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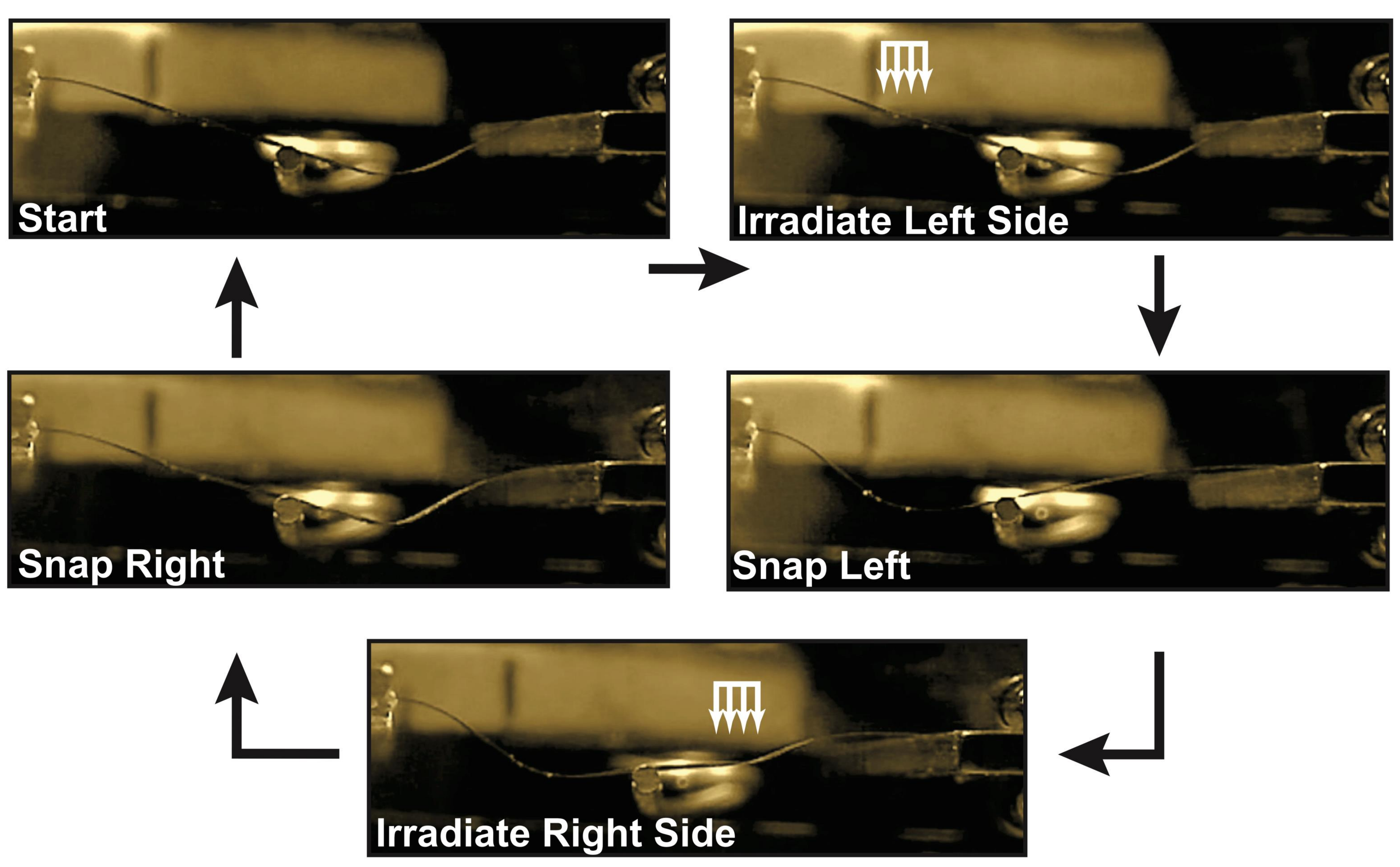
Introduction

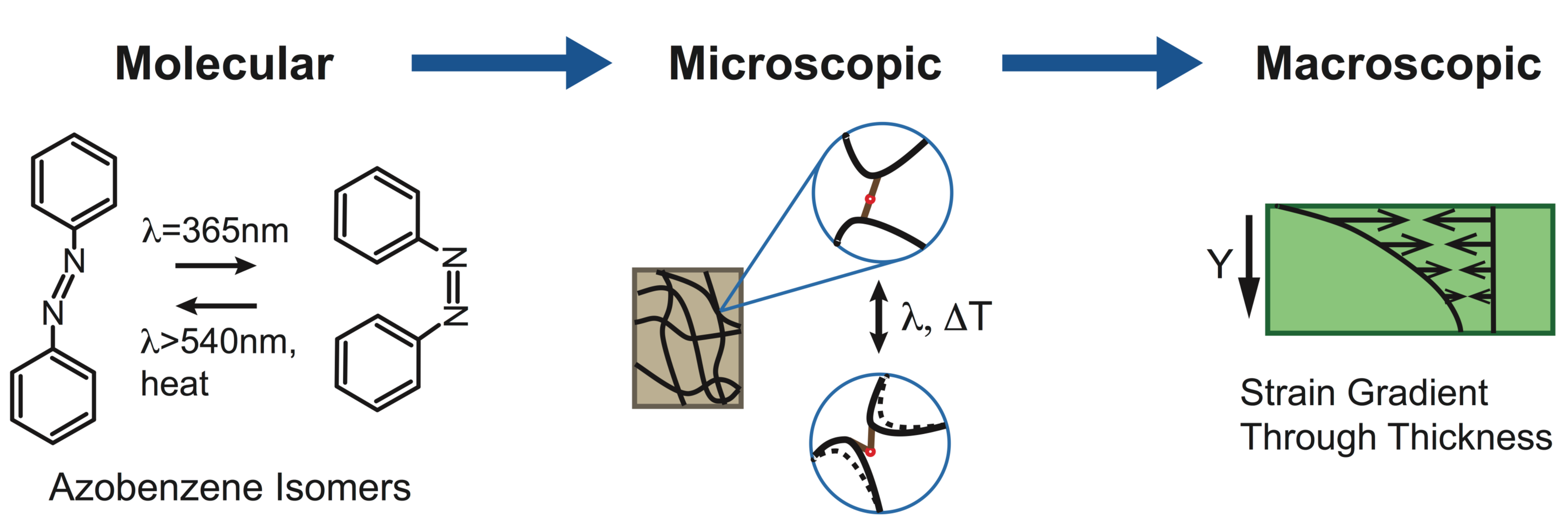
Photomechanical materials convert the energy in light to mechanical work. This class of materials represents a unique opportunity for wireless actuation and morphing surface technology. Challenges for realizing functional devices with these materials include: producing *controlled* complex motion, low power output, and degradation in actuator behavior with use. A typical strategy for producing complex motion is to engineer materials with various material anisotropies [1]. Recently we reported on a strategy for producing fast actuation rates (~10ms) and controlling positioning based in part on mechanical design concepts using snap-through of a photomechanical, buckled arch [2]. Herein we, propose that rational use of geometric contact points will lead to enhanced, controllable complex motion for a multi-position actuator.



Light is used to drive left-right, fast, snap buckling in arches utilizing a third contact point positioned near the arch midpoint. The actuator operates on the principle of storage and quick release of elastic energy. Once in an equilibrium configuration the actuator can hold its position without further energy input. The material shown is an azobenzene functionalized polyimide.

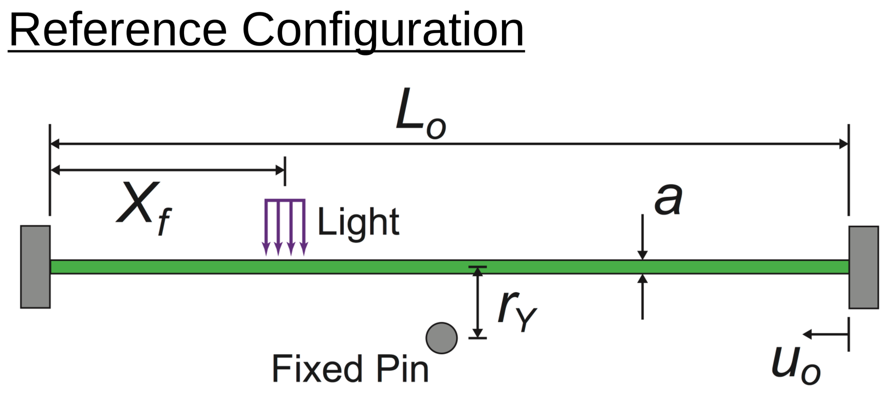
Background

Photomechanical materials based on azobenzene convert light energy to mechanical work via cooperative microscopic motion.



Formulation and Computational Methods

Reference Configuration



Inelastic Strains: Induced Photo-Strains

$$\varepsilon_{el} = \varepsilon - \varepsilon_{inel}$$

$$\varepsilon_{inel\_X} = \varepsilon_X^{ph} = I(X)\beta e^{-(a/2-Y)/d}$$

$$\varepsilon_{inel\_Y} = \varepsilon_Y^{ph} = \nu^{ph}\varepsilon_X^{ph}$$

Governing Equations

Equation of Motion

$$\rho\frac{\partial^2 \boldsymbol{u}}{\partial t^2} = \nabla\cdot[\boldsymbol{S}\cdot\boldsymbol{F}^T]$$

Constitutive Equation

$$\boldsymbol{S} = \boldsymbol{C}:\varepsilon_{el}$$

Strain-Displacement Relationship

$$\varepsilon = \frac{1}{2}[(\nabla\boldsymbol{u})^T + \nabla\boldsymbol{u} + (\nabla\boldsymbol{u})^T\nabla\boldsymbol{u}]$$

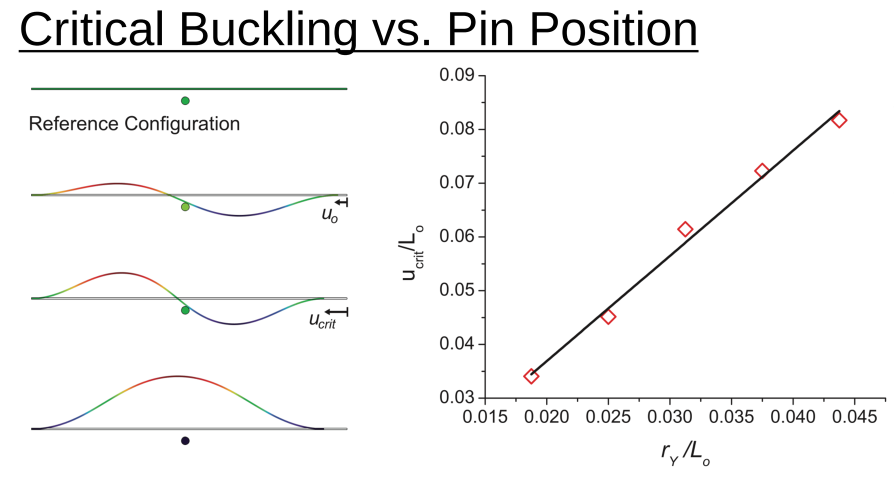
Simulation Details: Simulations were performed using the structural mechanics module of COMSOL Multiphysics. In this preliminary effort the material was modeled as a 2D, linearly elastic, solid with initial photo-induced strains. The BDF solver with the automatic Newton method was used to perform time dependent studies. Friction free contact surfaces were assigned between the bottom of the strip and the fixed pin. The ends were modeled as clamps with specified displacement allowed at the right end..

Parameter Definitions:

- L_o – original length of material strip
- a – thickness of strip
- X_f – focus point of collimated laser
- u_o – displacement of right end
- r_Y – vertical position of fixed pin
- $I(X)$ – Light intensity
- Material coordinates
  - $0 < X < L_o$
  - $-a/2 < Y < a/2$
- $\boldsymbol{u}$ – displacement vector
- $\boldsymbol{F}$ – deformation gradient
- $\boldsymbol{C}$ – Stiffness tensor
- $\boldsymbol{S}$ – 2nd Pioloa–Kirchoff stress tensor
- ν^{ph} – Photo Poission-like ratio
- ε_X^{ph} – Photo-induced strain
- β – Photo compliance
- ρ – Material density
- d – attenuation length of light

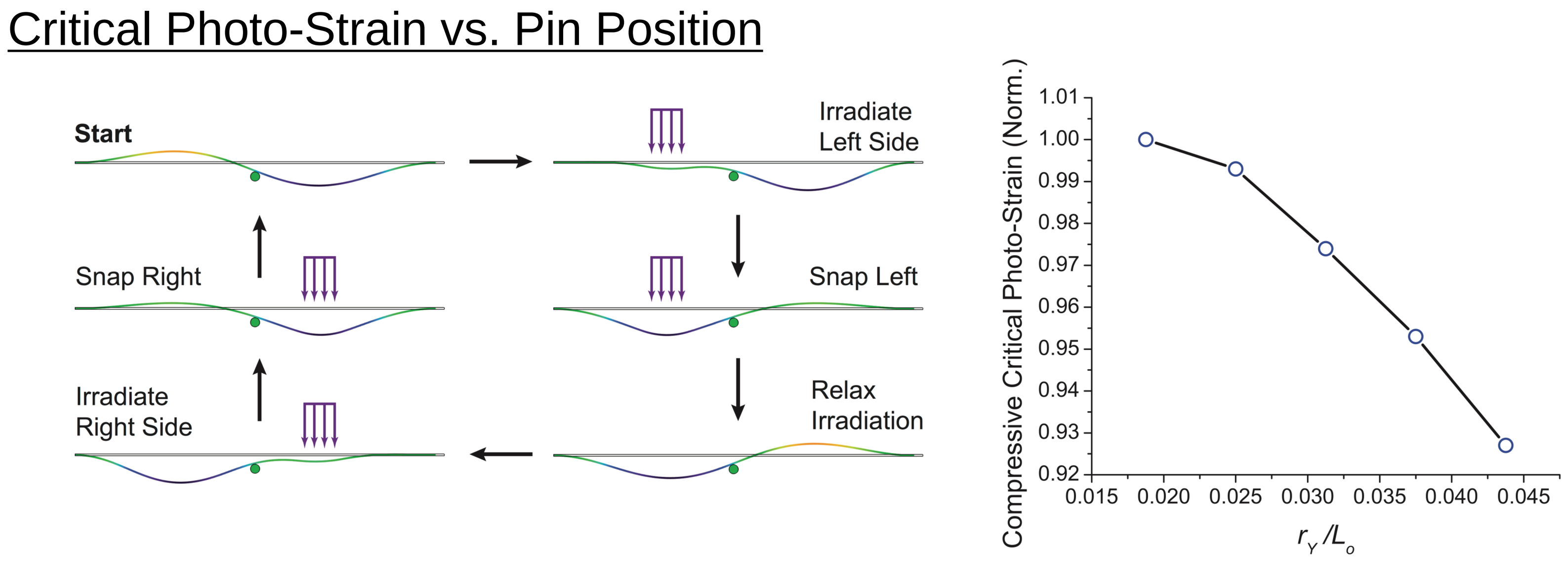
Results

Critical Buckling vs. Pin Position



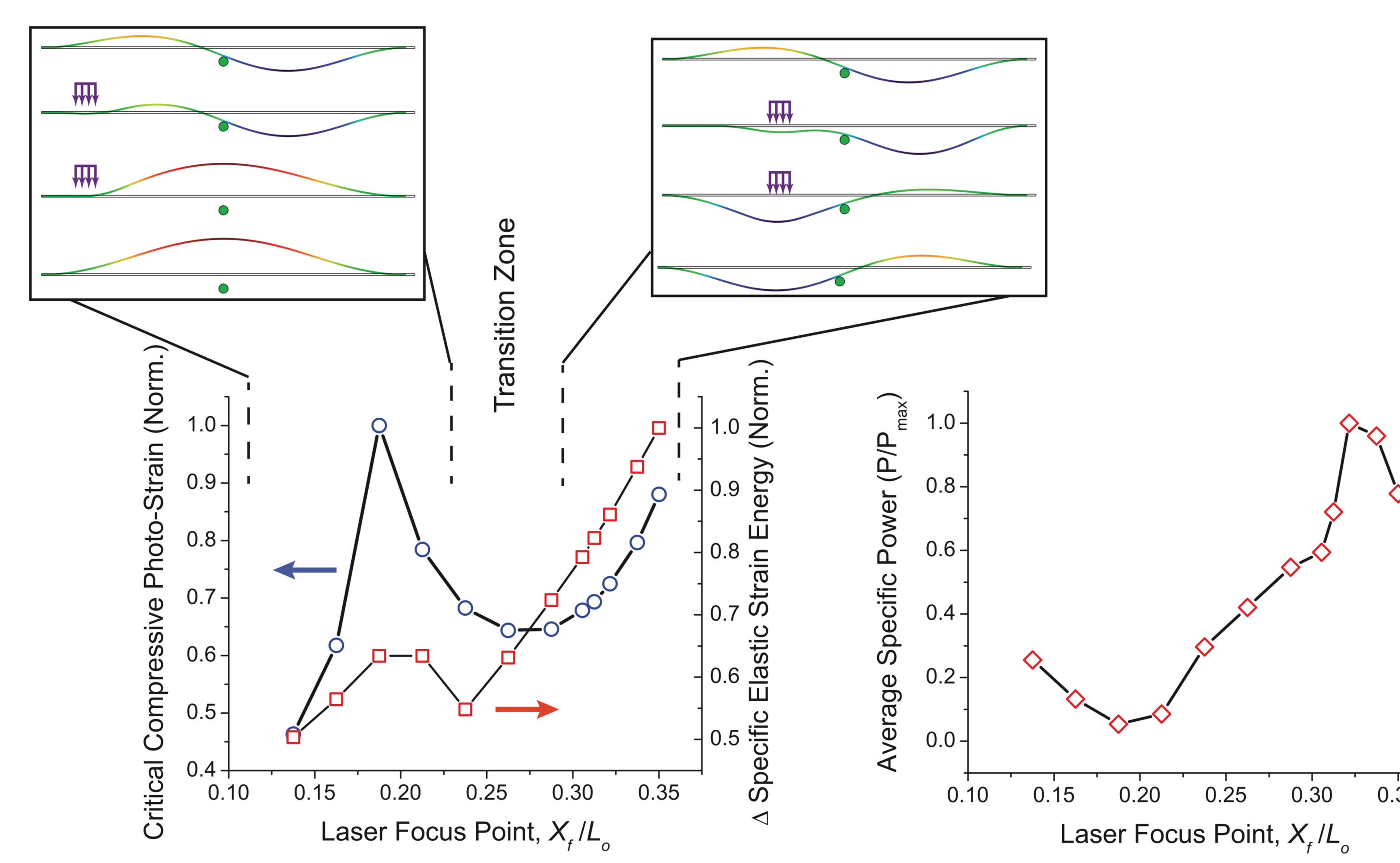
- Critical displacement of the right end leads to pin contact, and rapid snap-through upward
- This data establishes a baseline linear trend for limits on end displacements suitable for photo-induced snap

Critical Photo-Strain vs. Pin Position



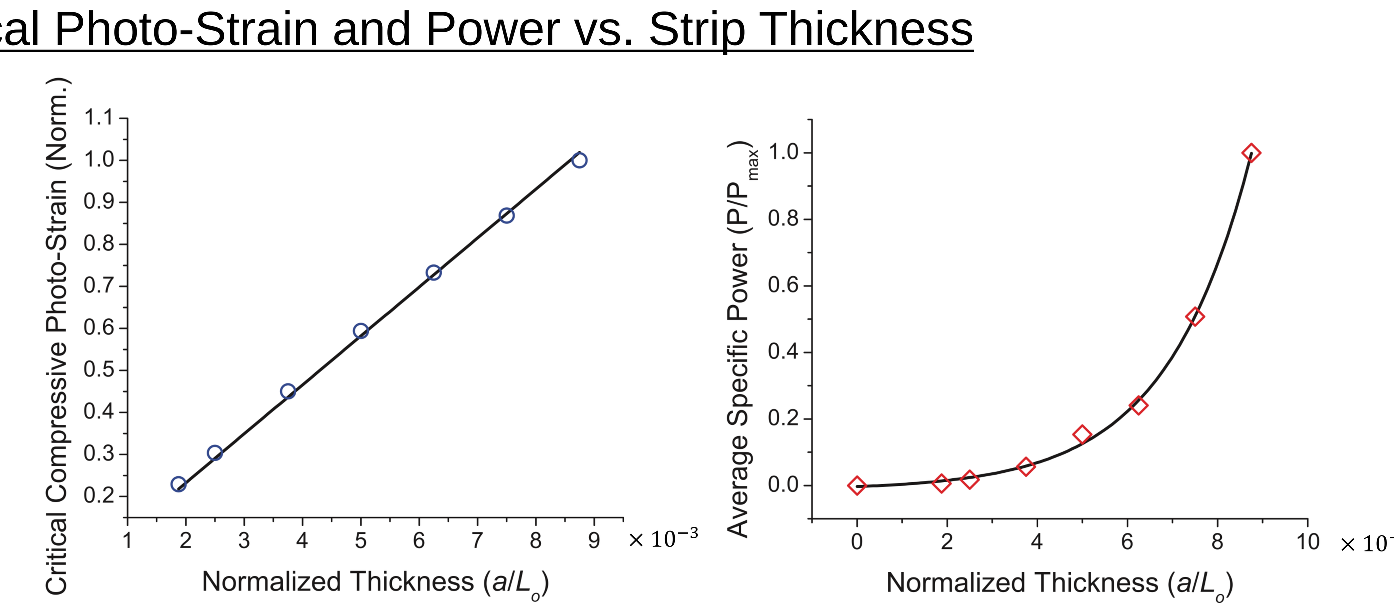
- For fixed u_o, simulations qualitatively match experiments, showing left-right snap buckling
- Critical induced photo-strain decreases as the pin is lowered, but by less than 10%

Critical Photo-Strain vs. Laser Focus Point



- Changes in the focus point of the laser reveals two response regimes, producing a discrete 3 position actuator: left, right, and up
- This result indicates that an additional pin could be placed opposite the current pin to potentially produce a discrete 4 position actuator
- Predicted powers were on the order of that produced by flight muscles in birds. Further study is required to confirm the validity of these quantitative results

Critical Photo-Strain and Power vs. Strip Thickness



Conclusions

- Simulations predict a possible route to 3 and 4 position discrete actuators driven by light
- The storage and rapid release or elastic energy results in potentially high power output actuators
- Preliminary qualitative trends in actuator behavior for variations in several design parameters were explored in order to hone future investigations

References:

1. Van Oosten, C. L., Harris, K. D. et al., Glassy photomechanical liquid-crystal network actuators for microscale devices, Eur. Phys. J. E, 23, 329-336, (2007)
2. Shankar, R. M., Smith, M. L., et al., Contactless, photoinitiated snap-through in azobenzene-functionalized polymers, PNAS, 110, 18792-18797 (2013)

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