2.72 Elements of Mechanical Design
Spring 2009

2.72

Elements of Mechanical Design

Lecture 08: Flexures

Schedule and reading assignment

Quiz

- Today: Bearing layouts (mid-class)
- Thursday: Hale 6.1
- Soon: Bolted joint qualifying quiz

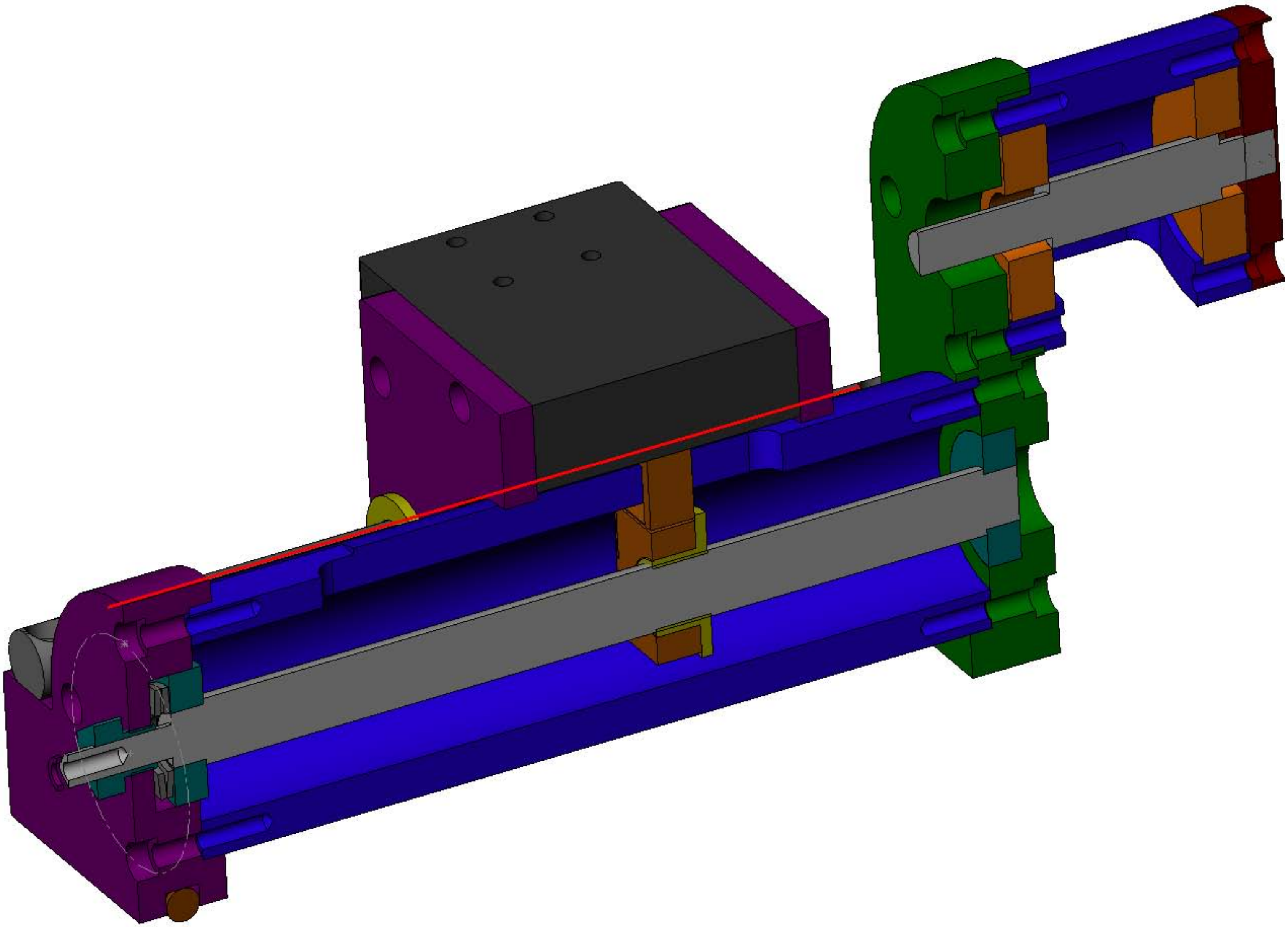
Topics

- Flexure constraints and bearings… Degrees of Freedom

Reading assignment

- Thursday:
  - *Layton Hale's thesis – Read 2.6, 2.7, 6.1, skim rest of Chapter 6*
  - *Chapter 7 is cool to look at*
- Tuesday:
  - *Read: 8.1, 8.3 – 8.5, 8.7, 8.9 – 8.11*
  - *Skim: 8.6, 8.8, 8.12*

Examples drawn from your lathe



Mechanisms: Compliant vs. rigid

Rigid mechanisms

- Sliding joints

Images removed due to copyright restrictions. Please see

http://www.physikinstrumente.com/en/primages/pi_m850_tip_i4c_o_eps.jpg

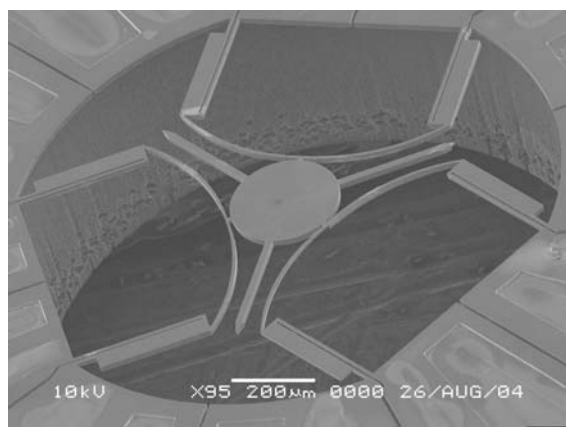
http://www.hexapods.net/images/M850Ani160-1-slow.gif

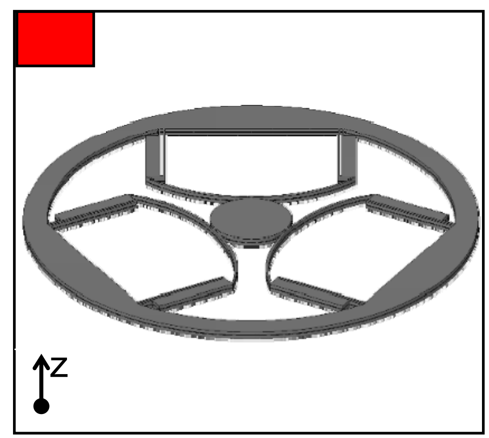
- 100s of nm resolution
- Large range
- kg load capacity

Compliant mechanisms

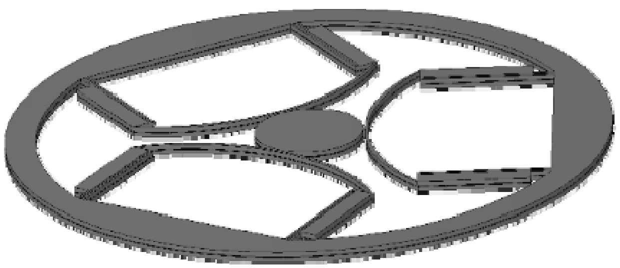
- Motion from member compliance

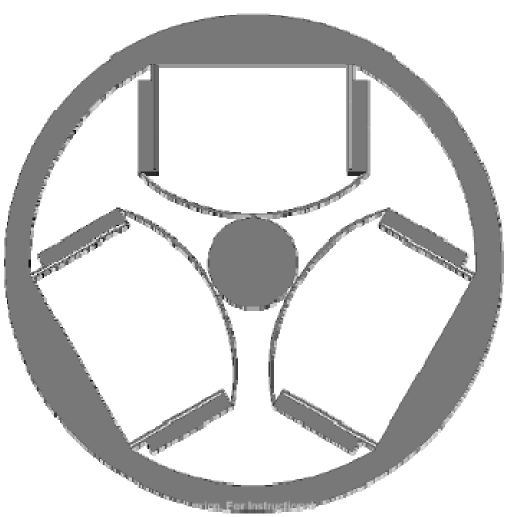
- Angstrom resolution
- Limited range
- Limited load capacity

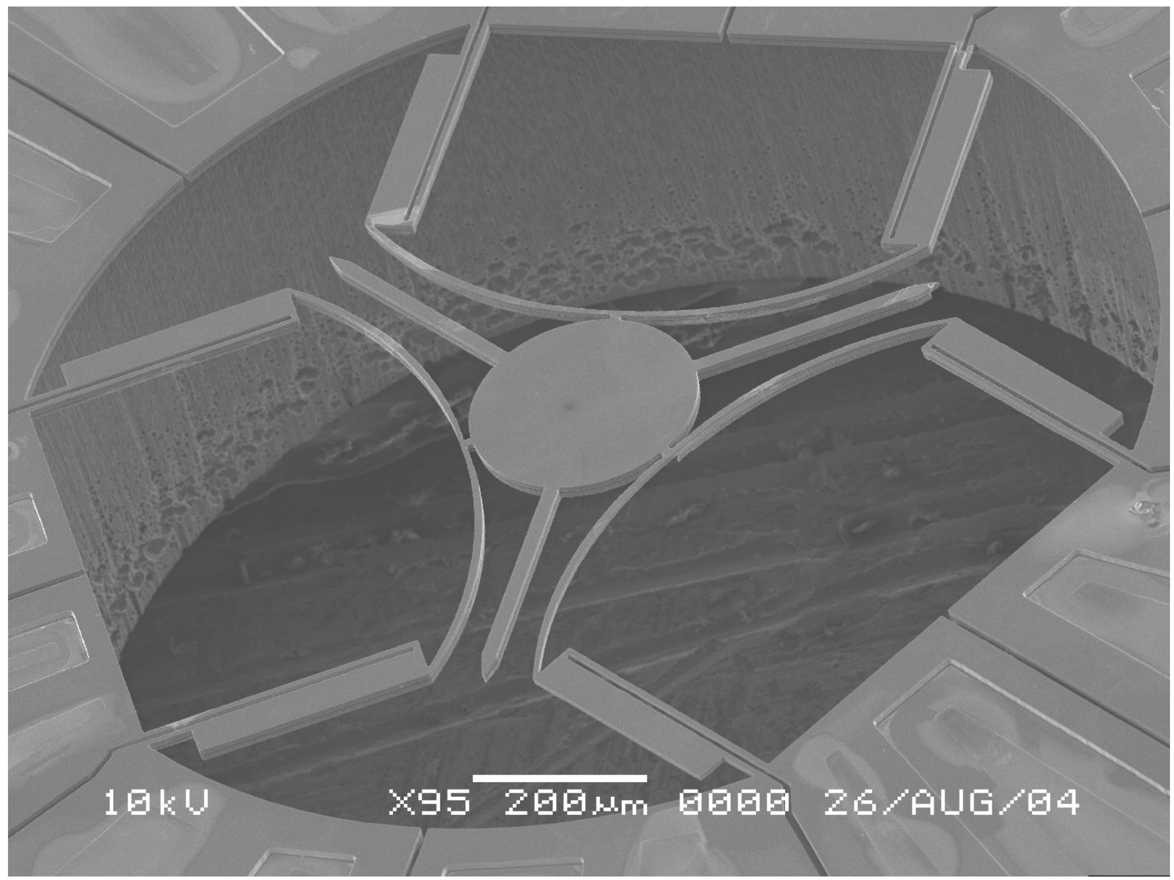




Micro-scale precision machines

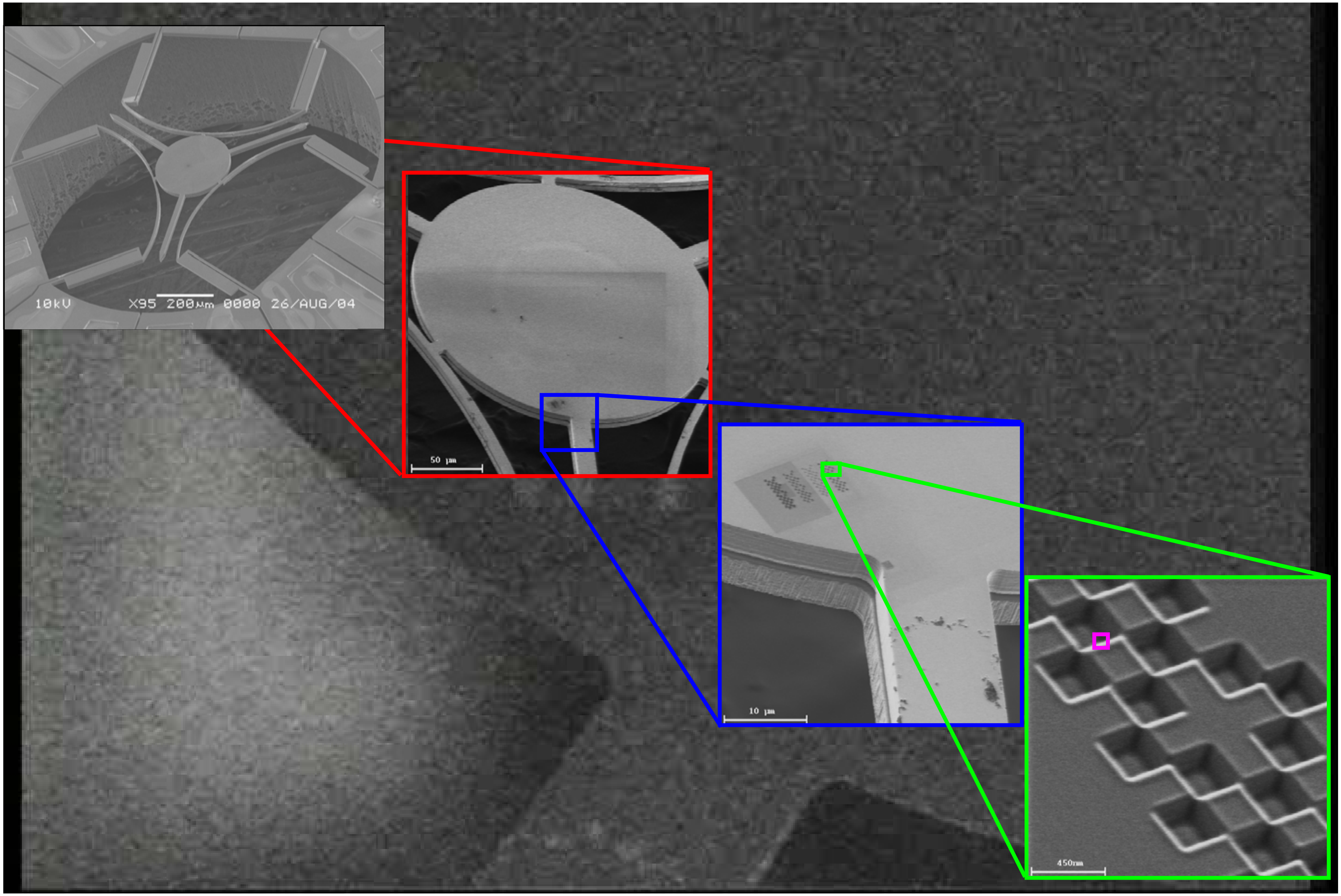






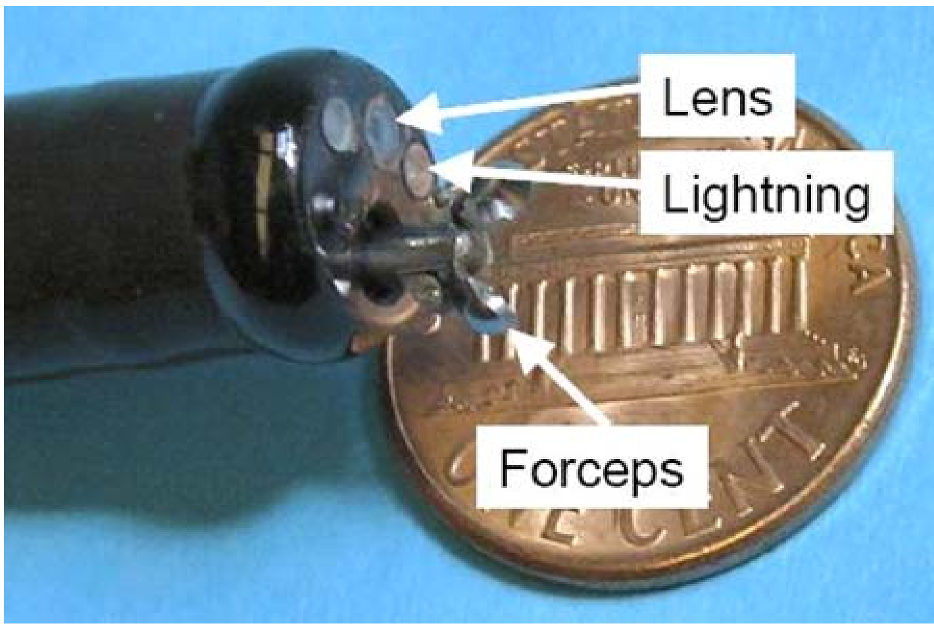
Static

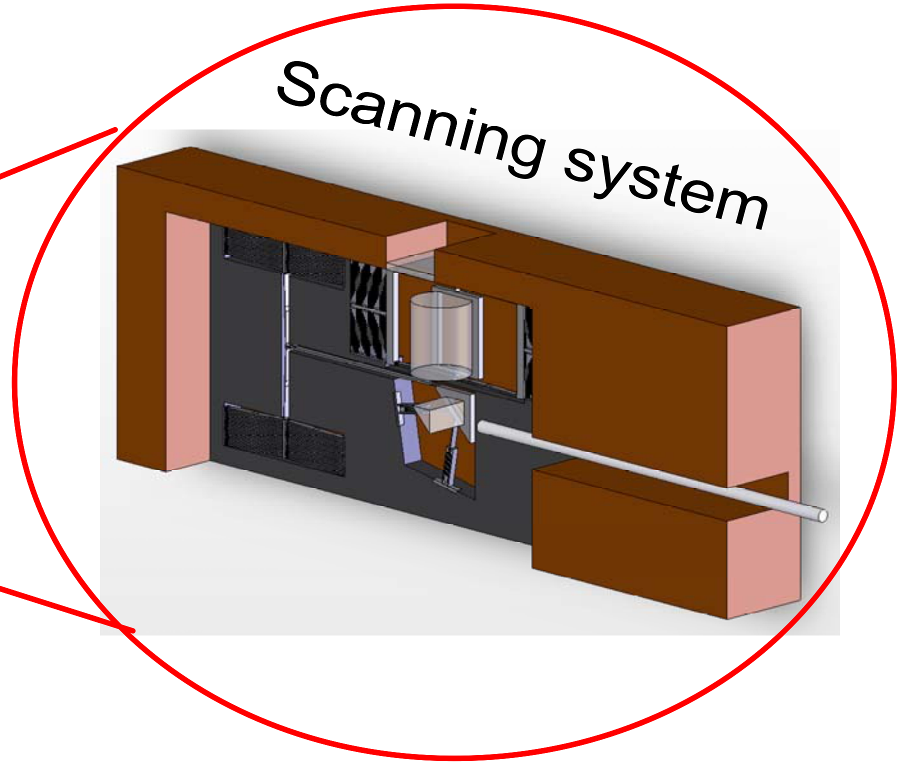
SEM: Drs. Andras Vladar & Jason Gorman (NIST)
FIB: Dr. Konrad Jarush (Hitachi)



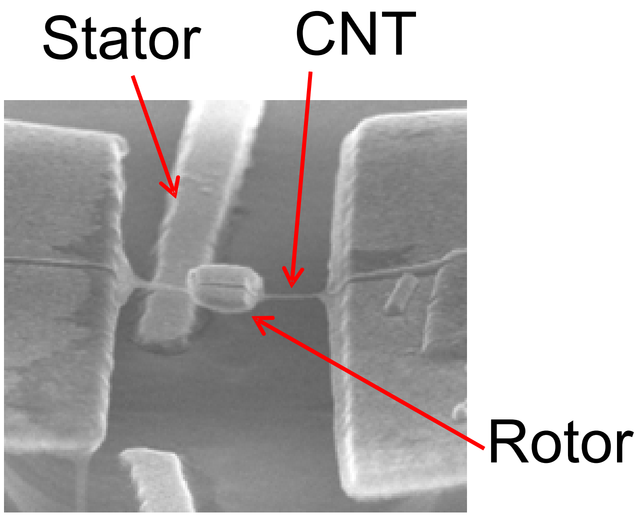
Meso-scale devices: Biomedical

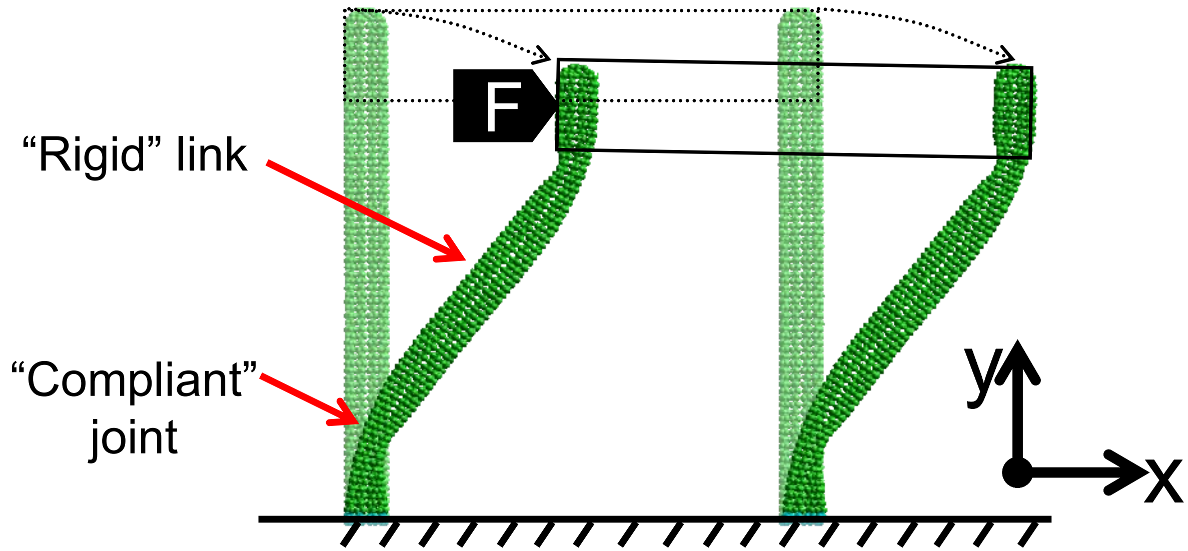
Two -photon endomicroscope

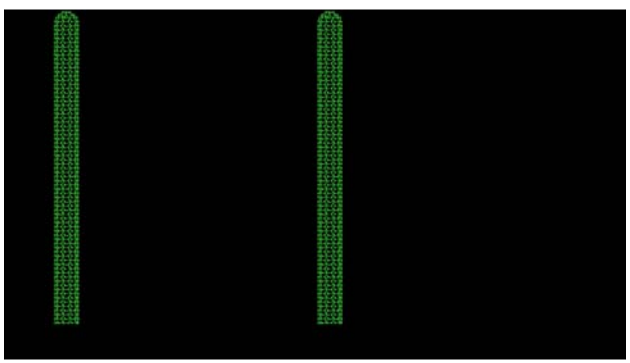


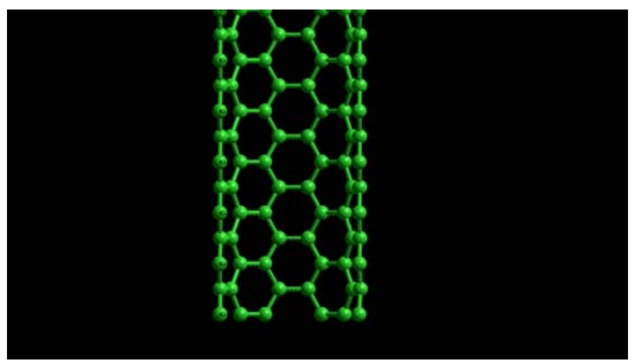


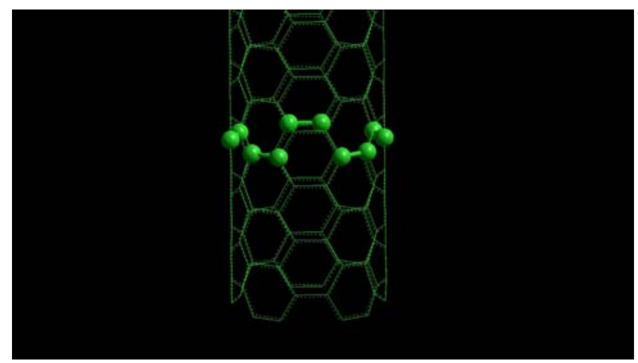
Nano-scale devices



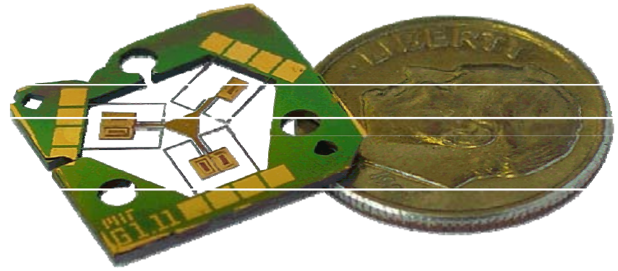


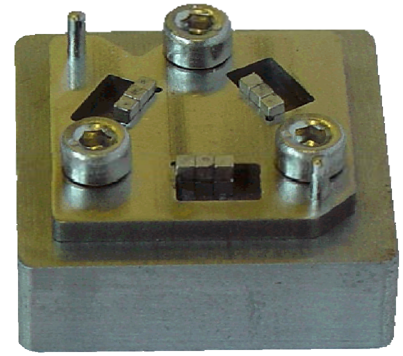


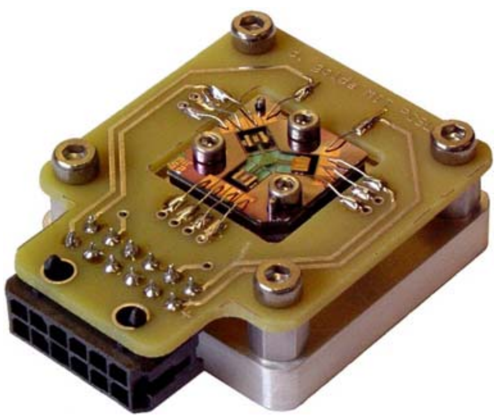


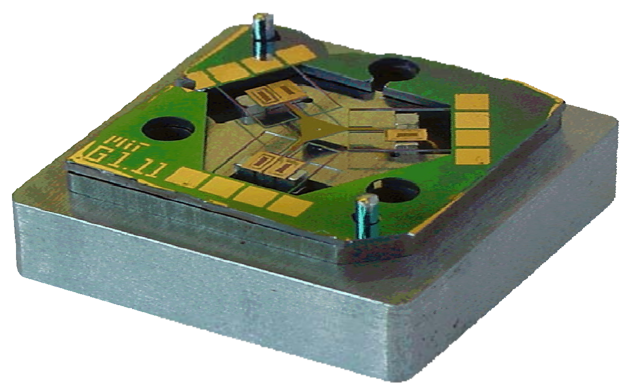


Meso-scale precision machines

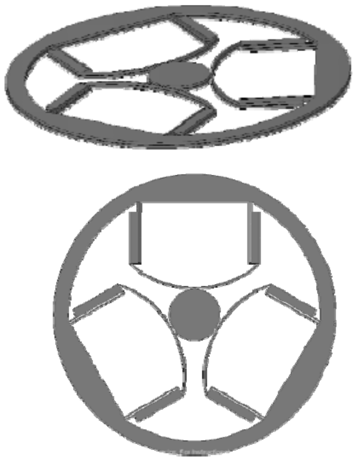


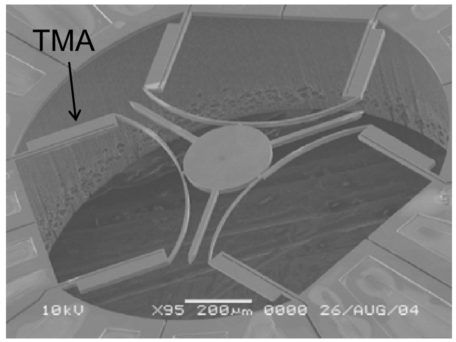


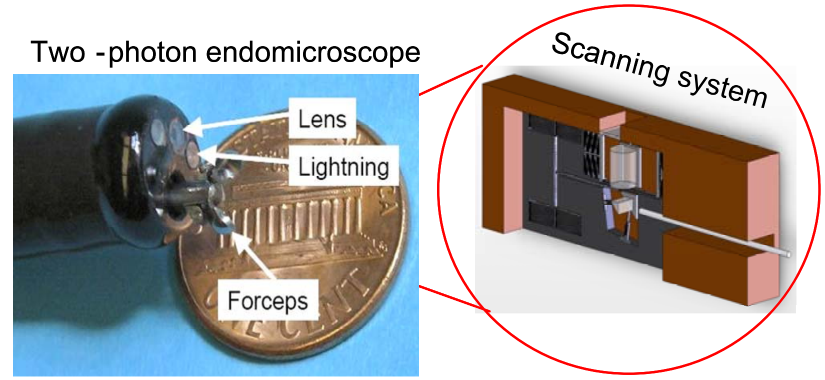


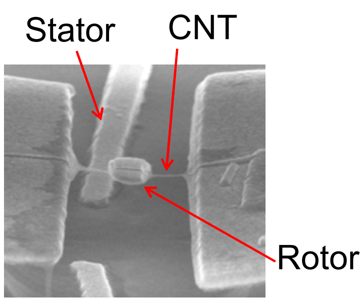


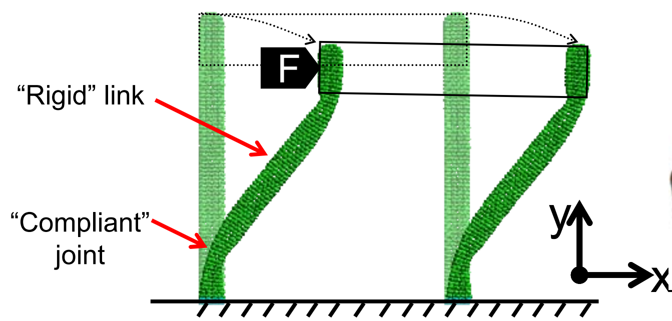
Nano-scale devices

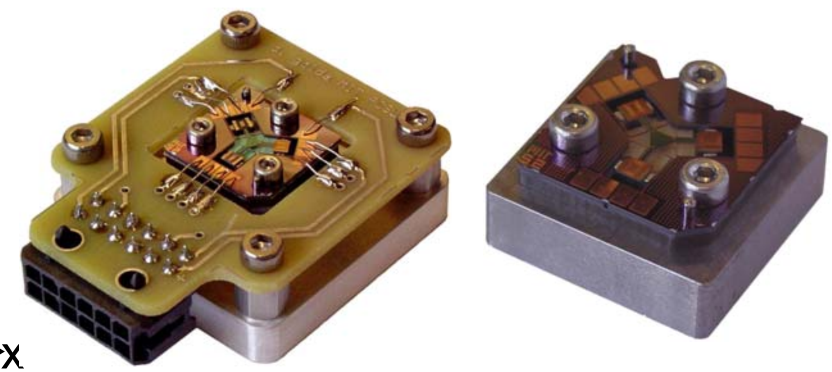


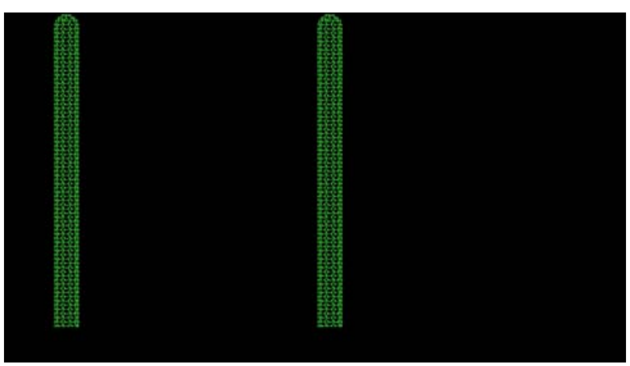


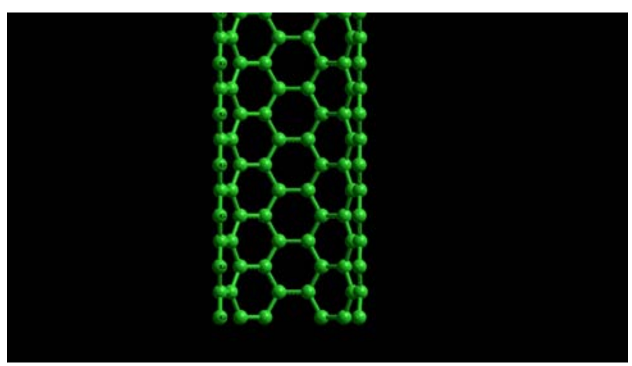


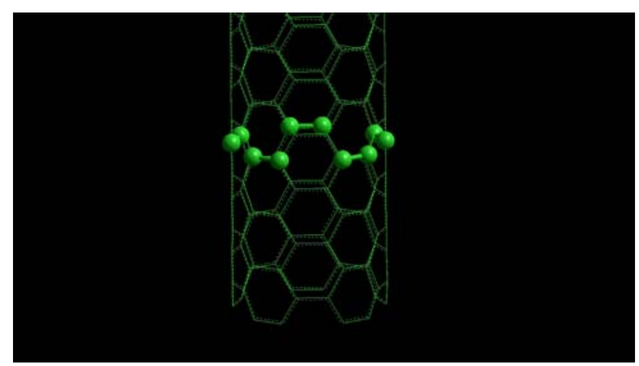












Dip pen nanolithography on DNA arrays

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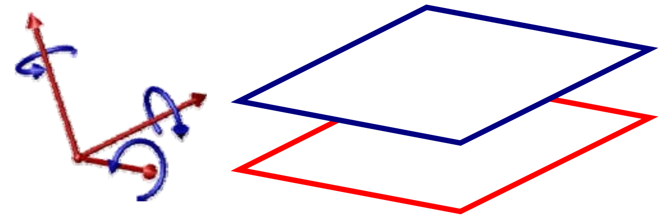
http://mcf.tamu.edu/images/DPN_process.png

http://www.nanoink.net/d/Nano%20-%20Part%201_Sm_Lo-Res_240x180.wmv

http://images.iop.org/objects/nano/news/4/12/10/diagnal.jpg

What is fundamentally different?

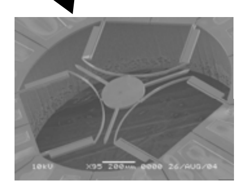
- Size → Physics → Fabrication
- Raw materials
- Surfaces vs. points or lines



250 mm

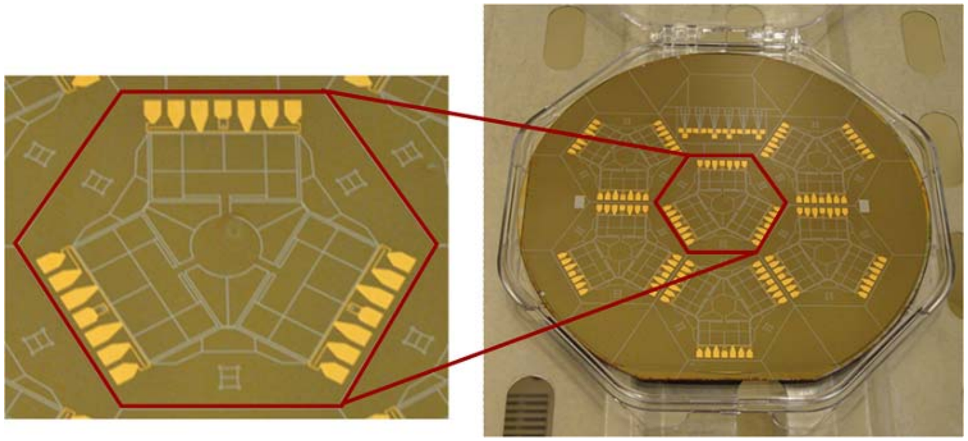
Courtesy PI

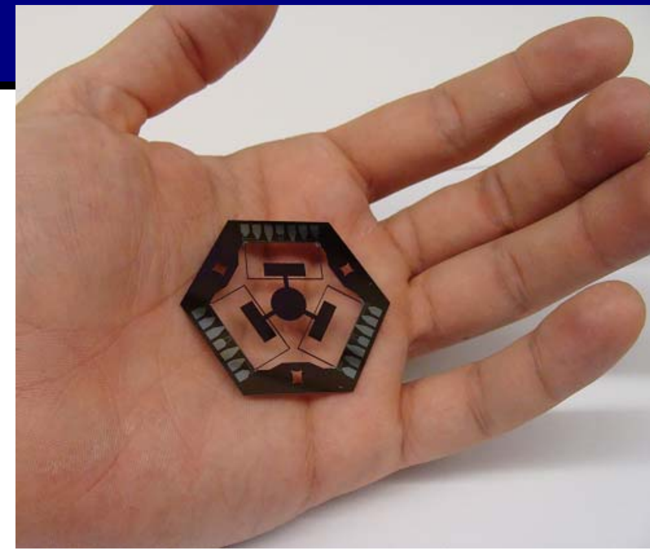
~20 mm

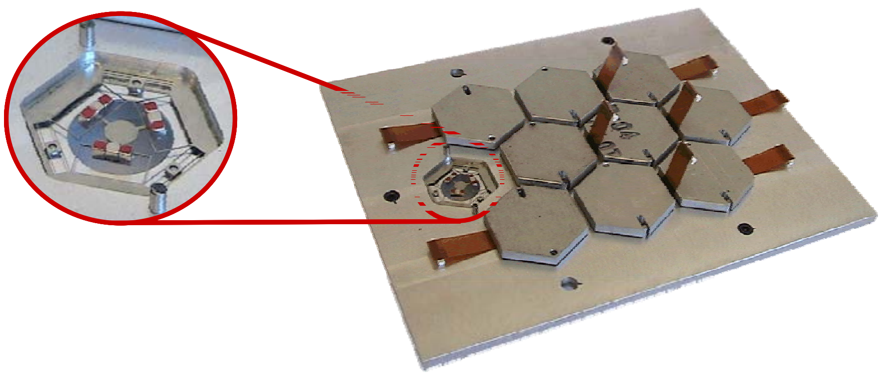


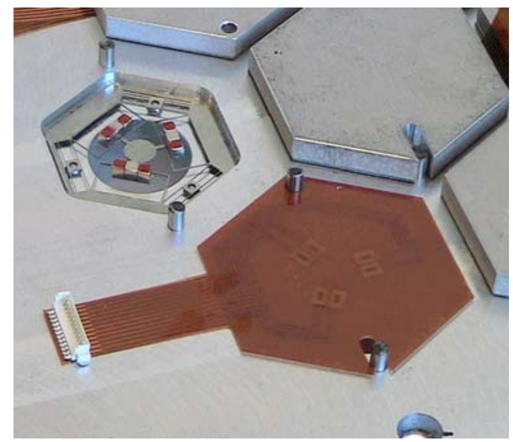
~1 mm

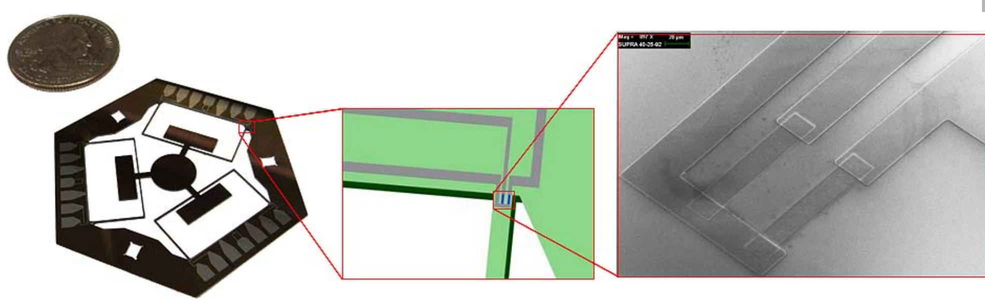
Nanomanufacturing







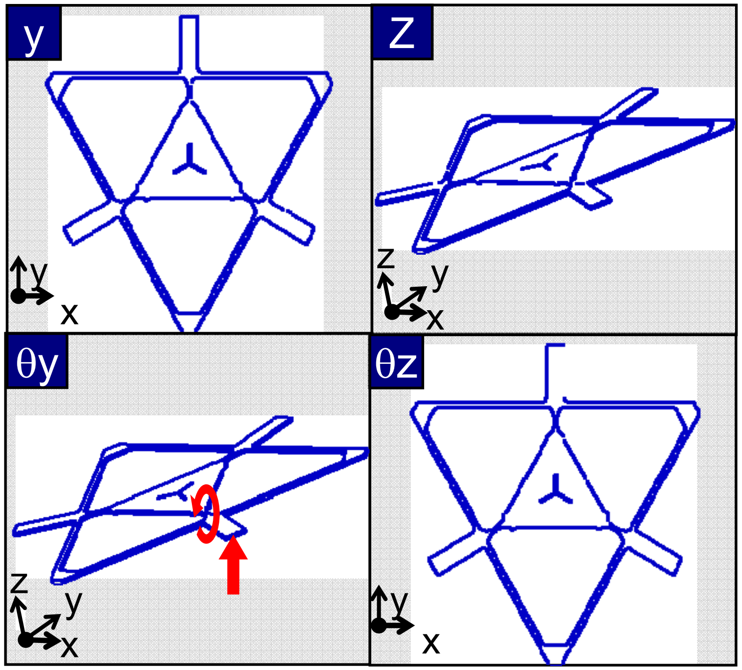




Advantages of flexures

Advantages

- Smooth, fine motion
- Linear/elastic operation in absence
- Failure modes are well understood
- Monolithic or assembled
- 2D nature lends to 2½D mfg.
- Miniaturization



Disadvantages

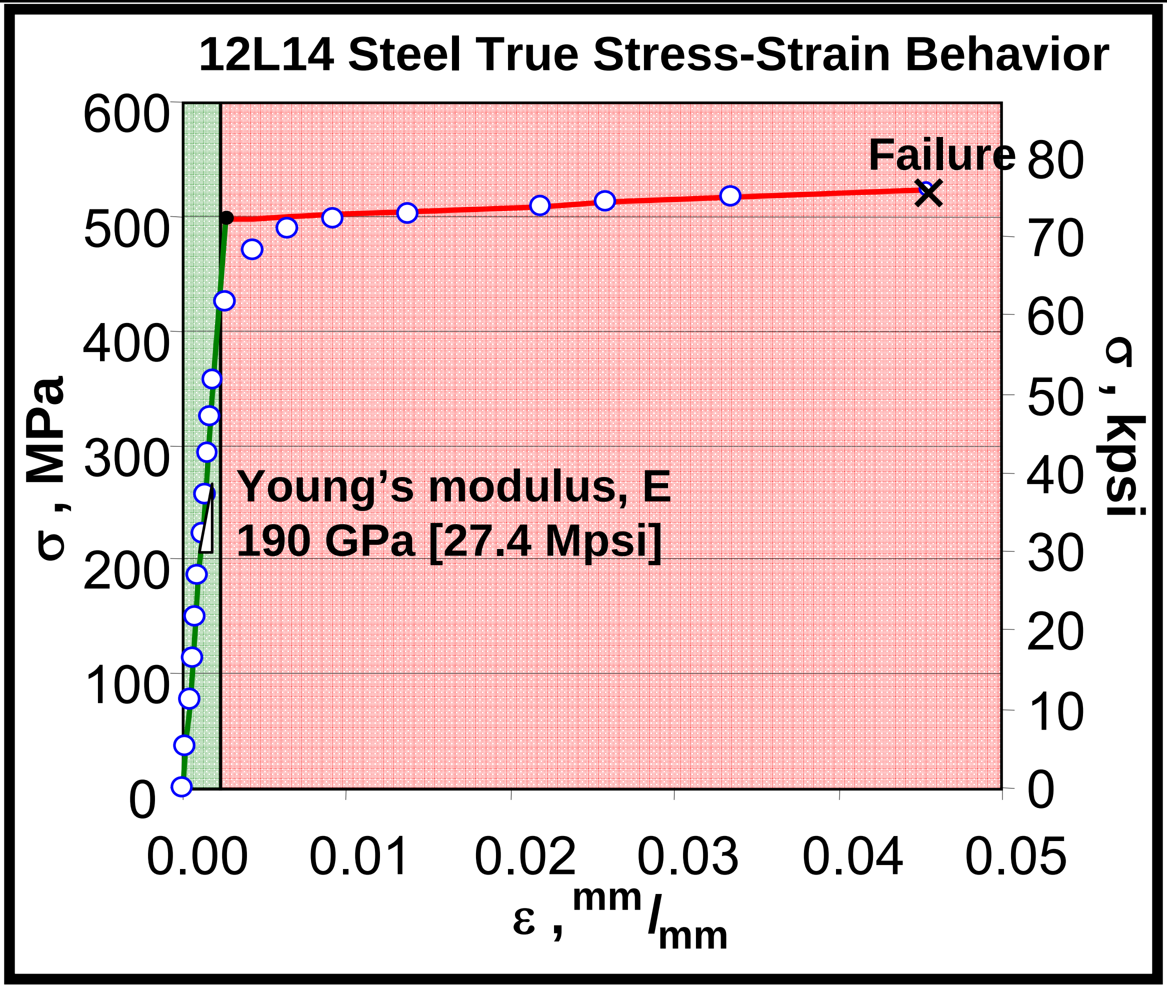
- Accuracy and repeatability sensitive to several variables
- Limited motion/stroke (usually a few to 10s % of device size)
- Instabilities such as axial or transverse buckling
- Dynamics
- Sensitivity to tolerance

Elastomechanics (σ & ε) relationship

Elastic

$$\sigma = \varepsilon \cdot E$$

Plastic



Material	σy/E
Titanium V	**1.00**
Aluminum 7075	0.70
Stainless 316	0.09
Invar - Annealed	0.19

Important material properties

Nominal values

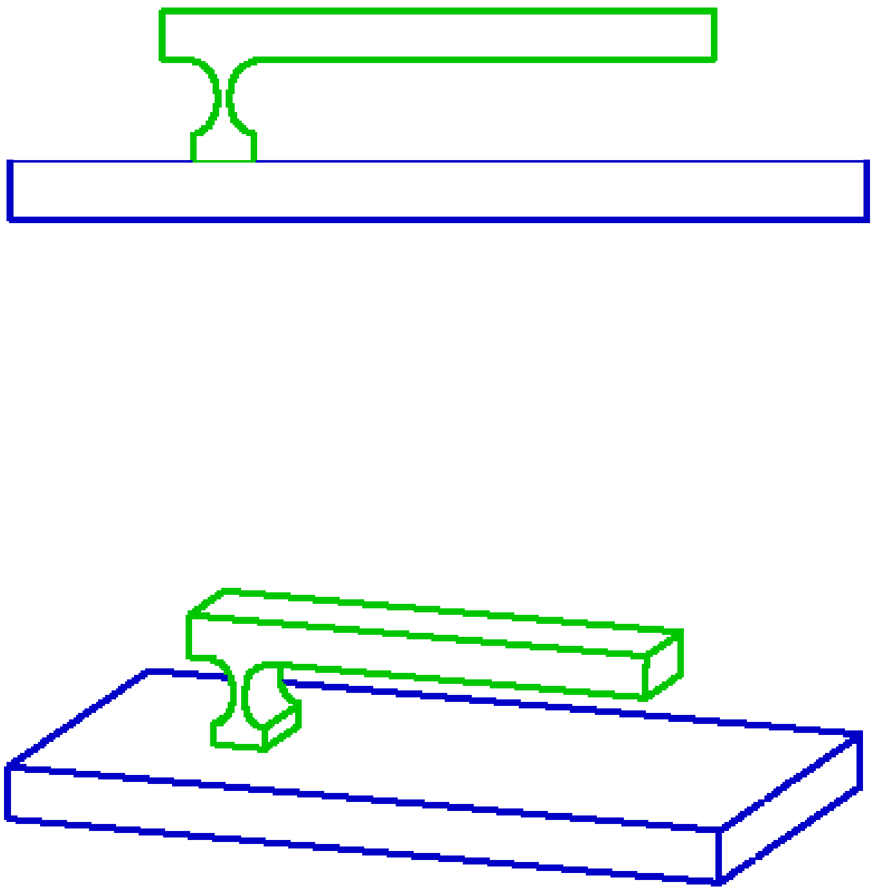
- Modulus
- Yield stress
- Coefficient of thermal expansion
- Thermal diffusivity
- Density

Material property ratios

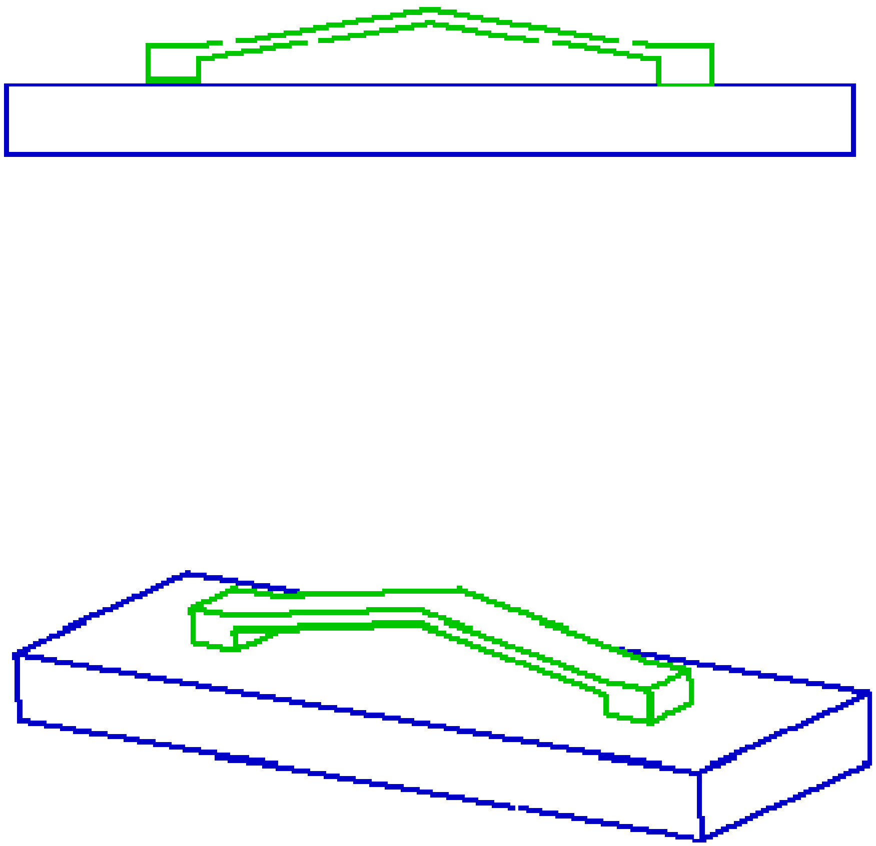
	Normalized Values			
Material	**$\sigma y/E$**	**$\alpha_{diff}/\alpha_{CTE}$**	**E/ρ**	**Cost**
Titanium V	**1.00**	0.14	0.92	3.77
Aluminum 7075	0.70	**1.00**	**1.00**	**1.00**
Stainless 316	0.09	0.13	0.94	3.50
Invar - Annealed	0.19	0.87	0.70	5.21

Modules

Lever

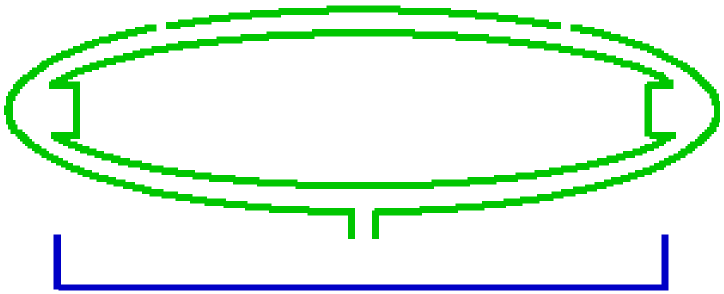


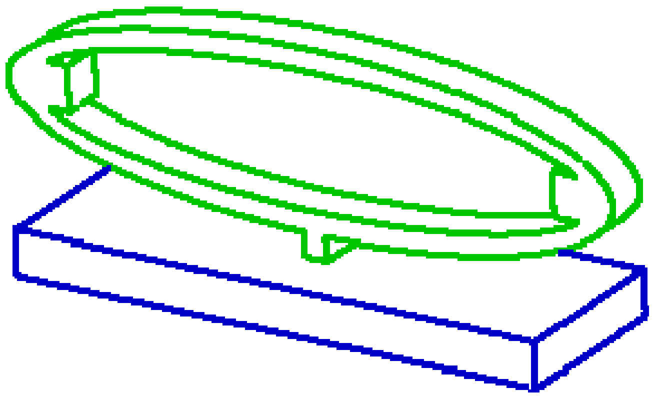
Chevron



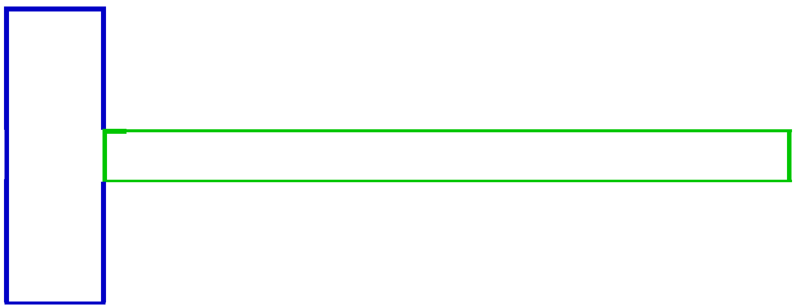
Modules cont.

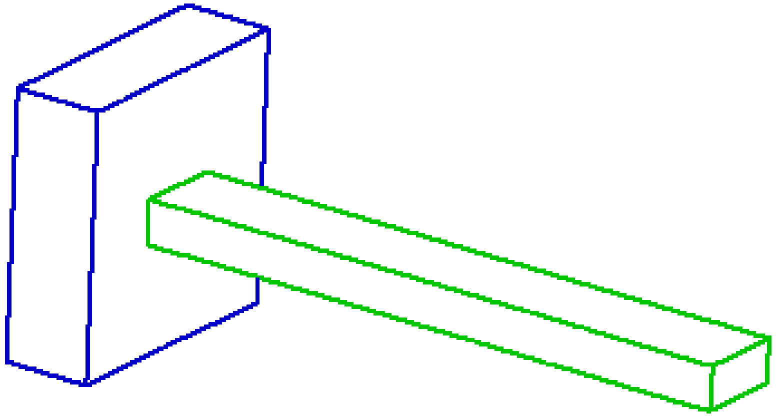
Ellipse





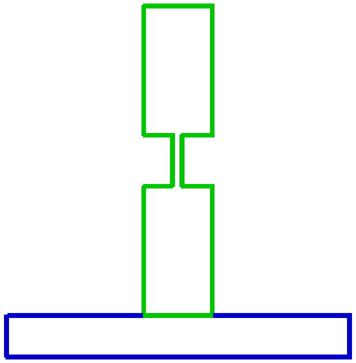
Cantilever/flexure blade



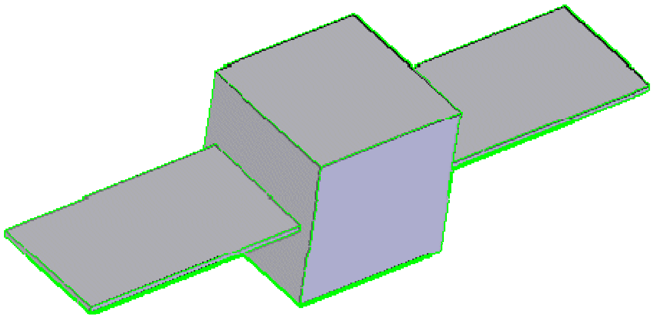


Modules cont.

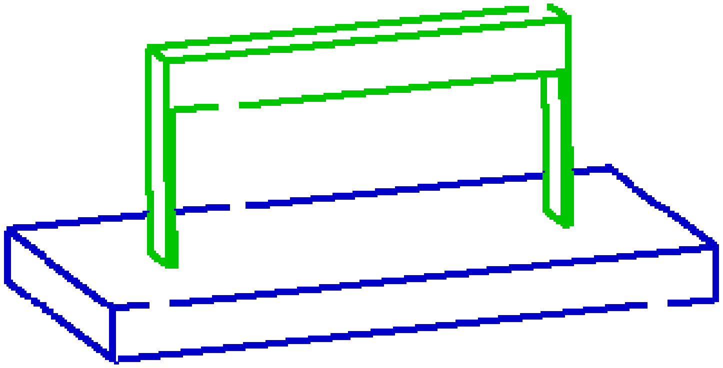
Flexure hinge



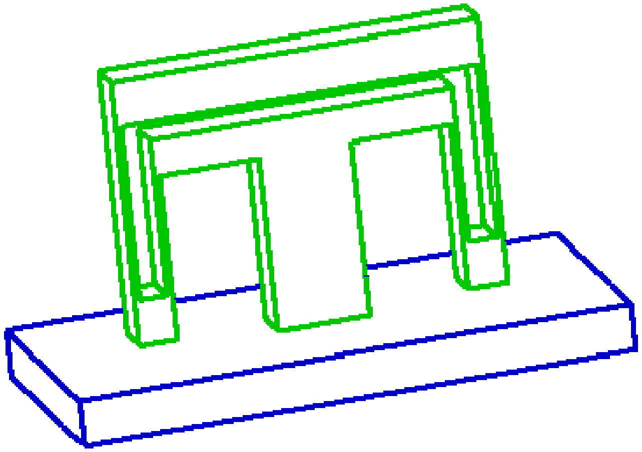
Torsion



Parallel four bar

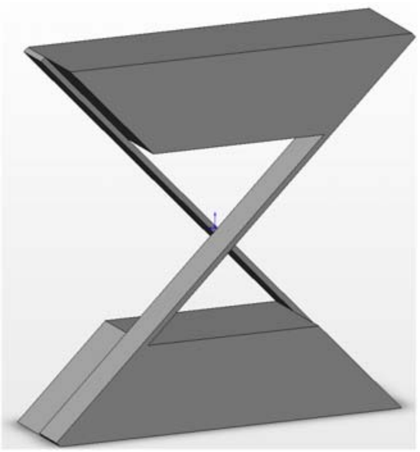


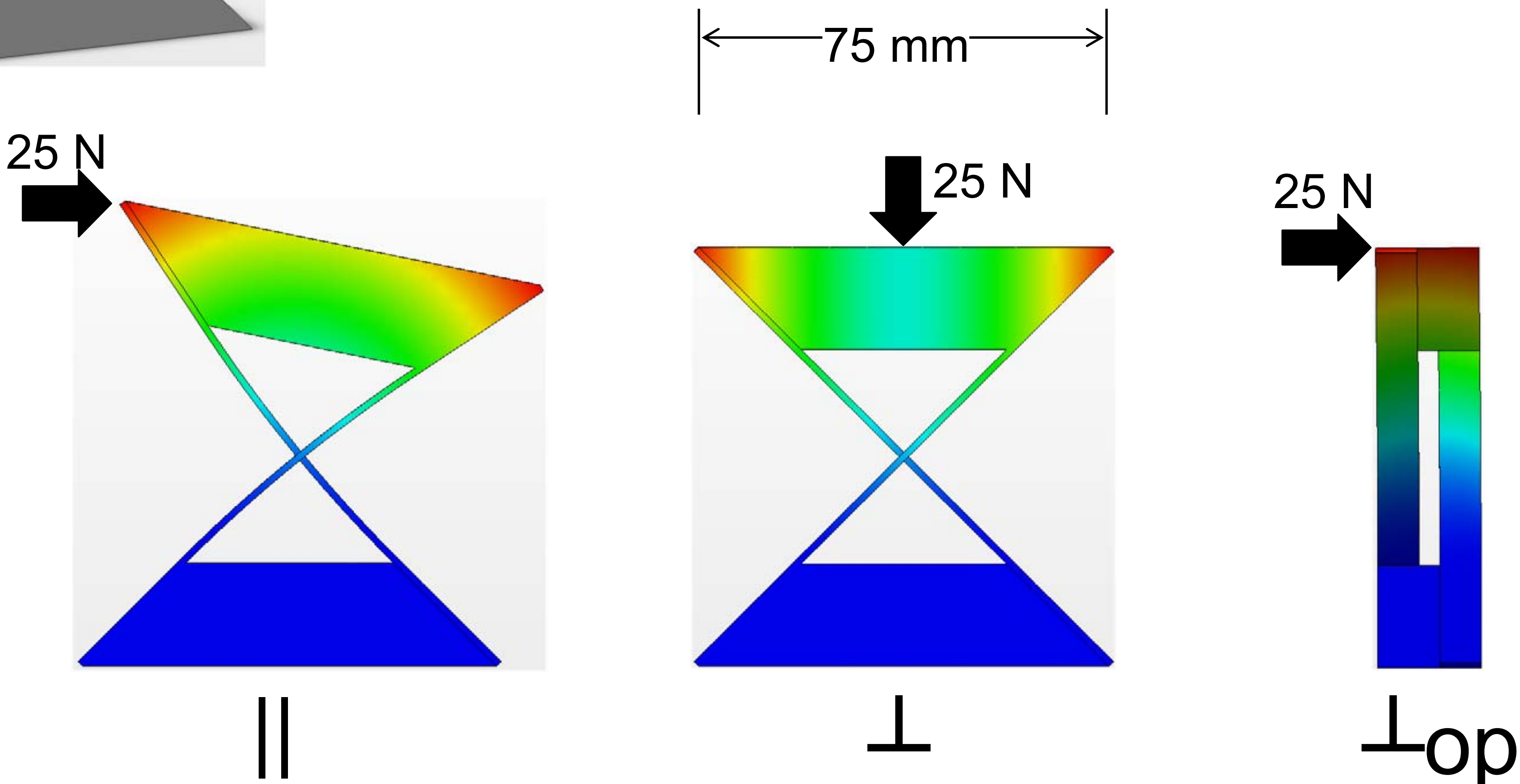
Double parallel four bar



Module cont.: Cross flexure pivot

Deformation scale 1 : 1

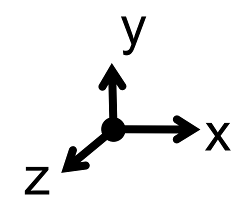


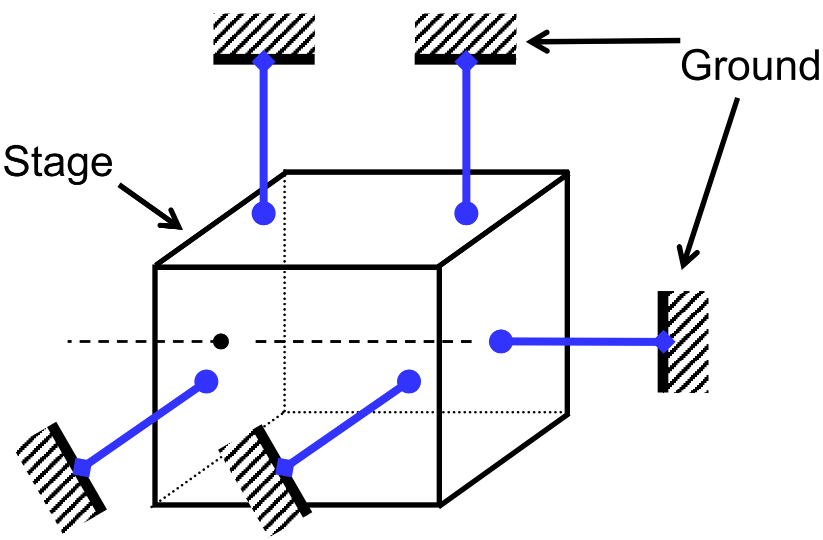


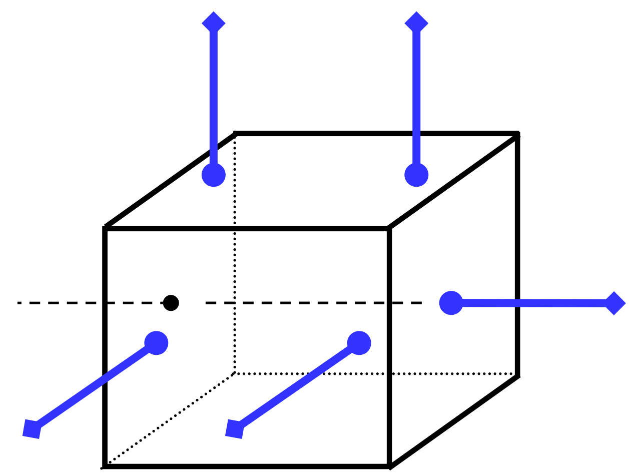
Review of constraint fundamentals

Rigid bodies have 6 DOF

- Constraints have lines of action
- C = # of linearly independent constraints
- DOF = 6 – C → F = 6 – C

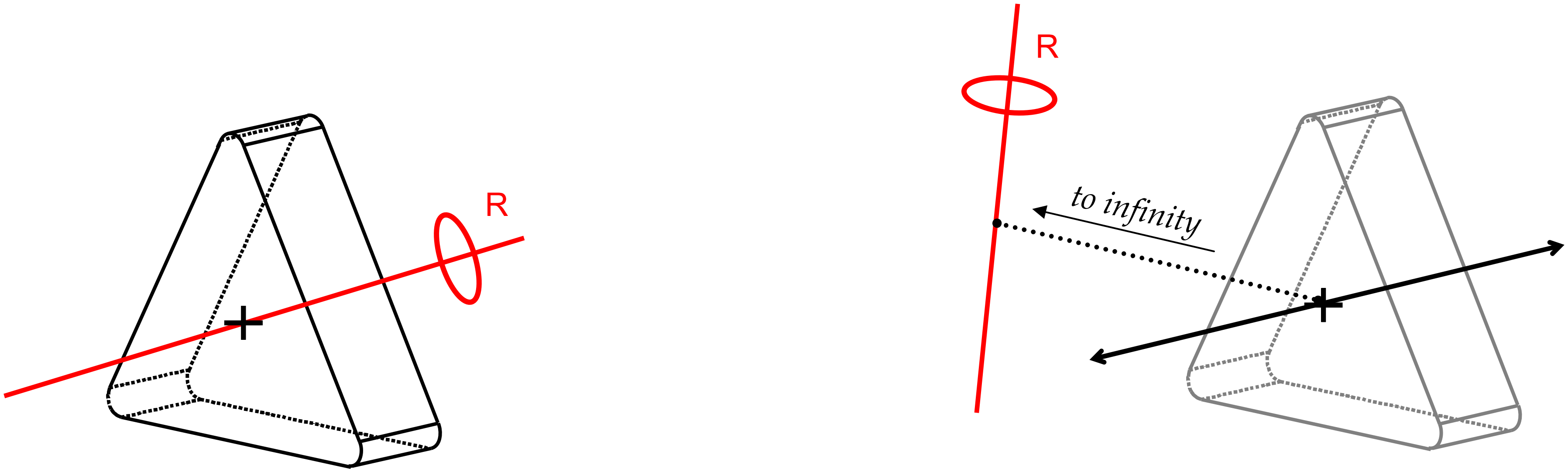






DOF in constraint-based design

A linear displacement may be visualized as a rotation about a point which is “far” away

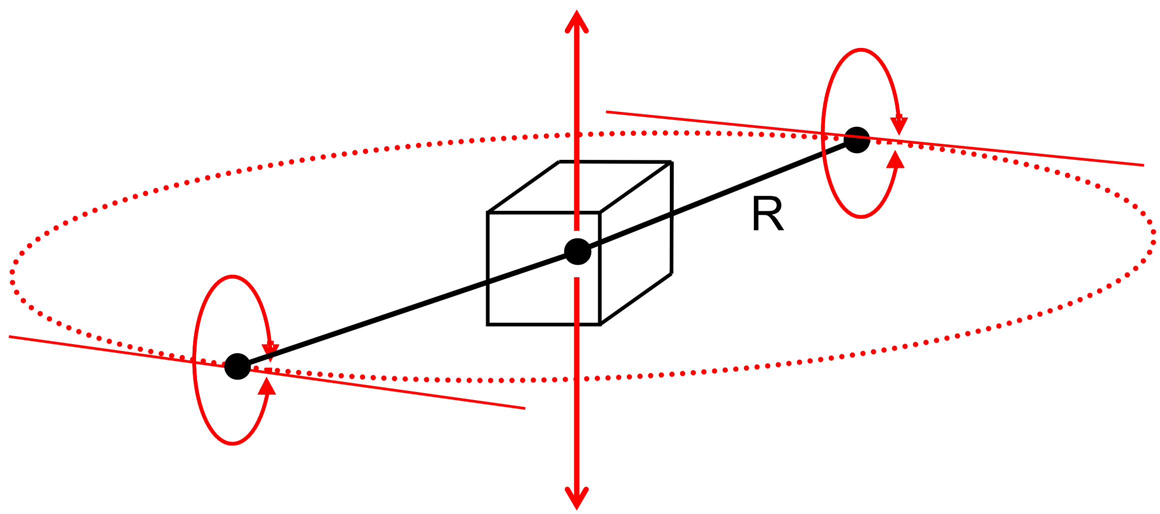


Two principles of projective geometry

Projective geometry comes in useful here

- Parallel lines intersect at infinity
- Translation represented by a rotation line at a hope of “infinite radius”

Image courtesy of John Hopkins
MIT MS Thesis



Constraint fundamentals

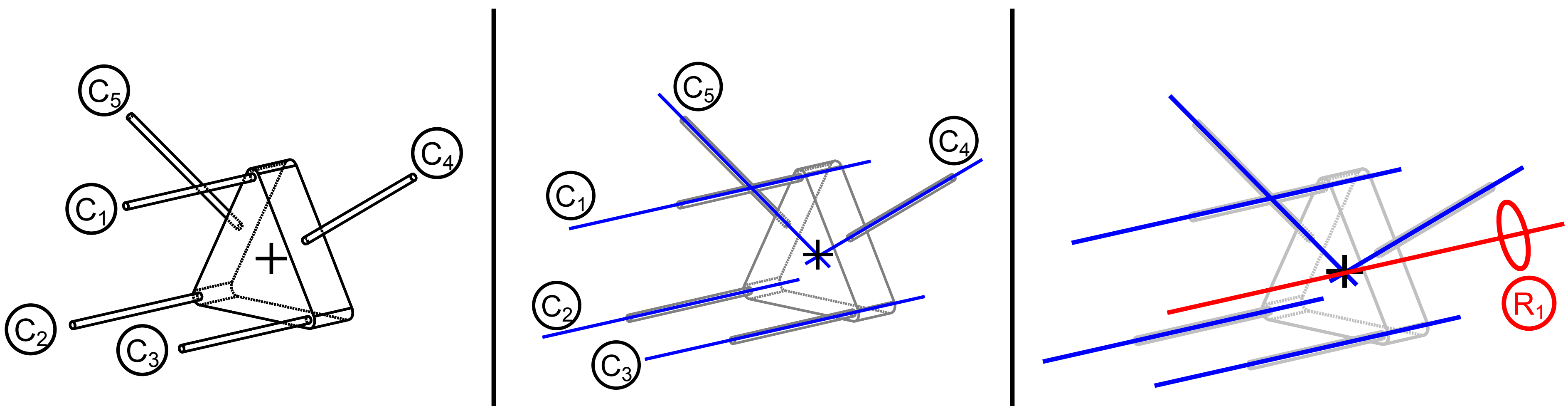
Blanding’s RULE OF COMPLIMENTARY PATTERNS

- Each permissible Freedom (F) is a rotation about a line and each permissible freedom rotation line must intersect each Constraint (C)

Remember these principles of projective geometry

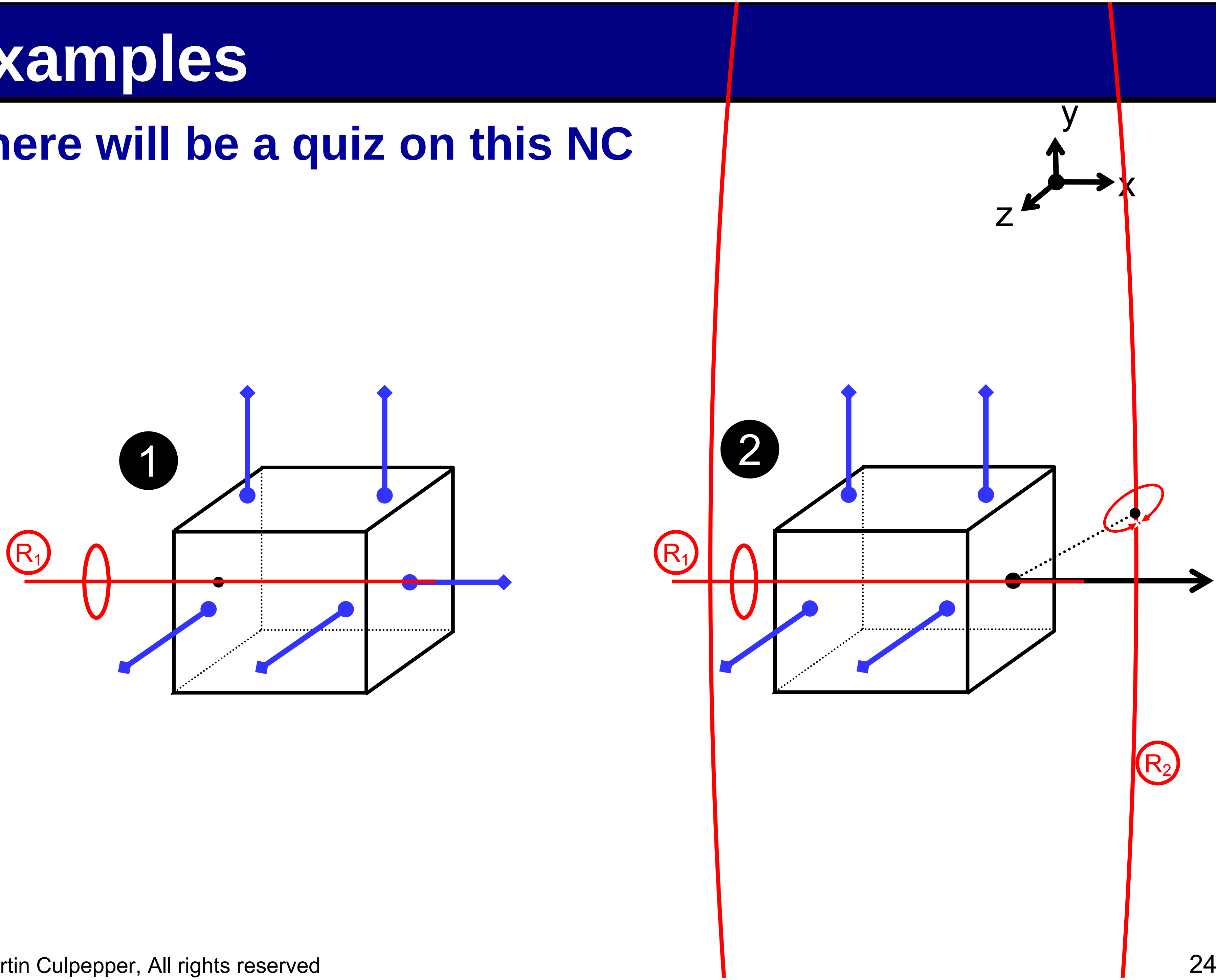
- Parallel lines intersect at infinity
- Translation represented by a rotation line at a hope of “infinite radius

R = 6 – C = 6 – 5 = 1…   so where is it?



Examples

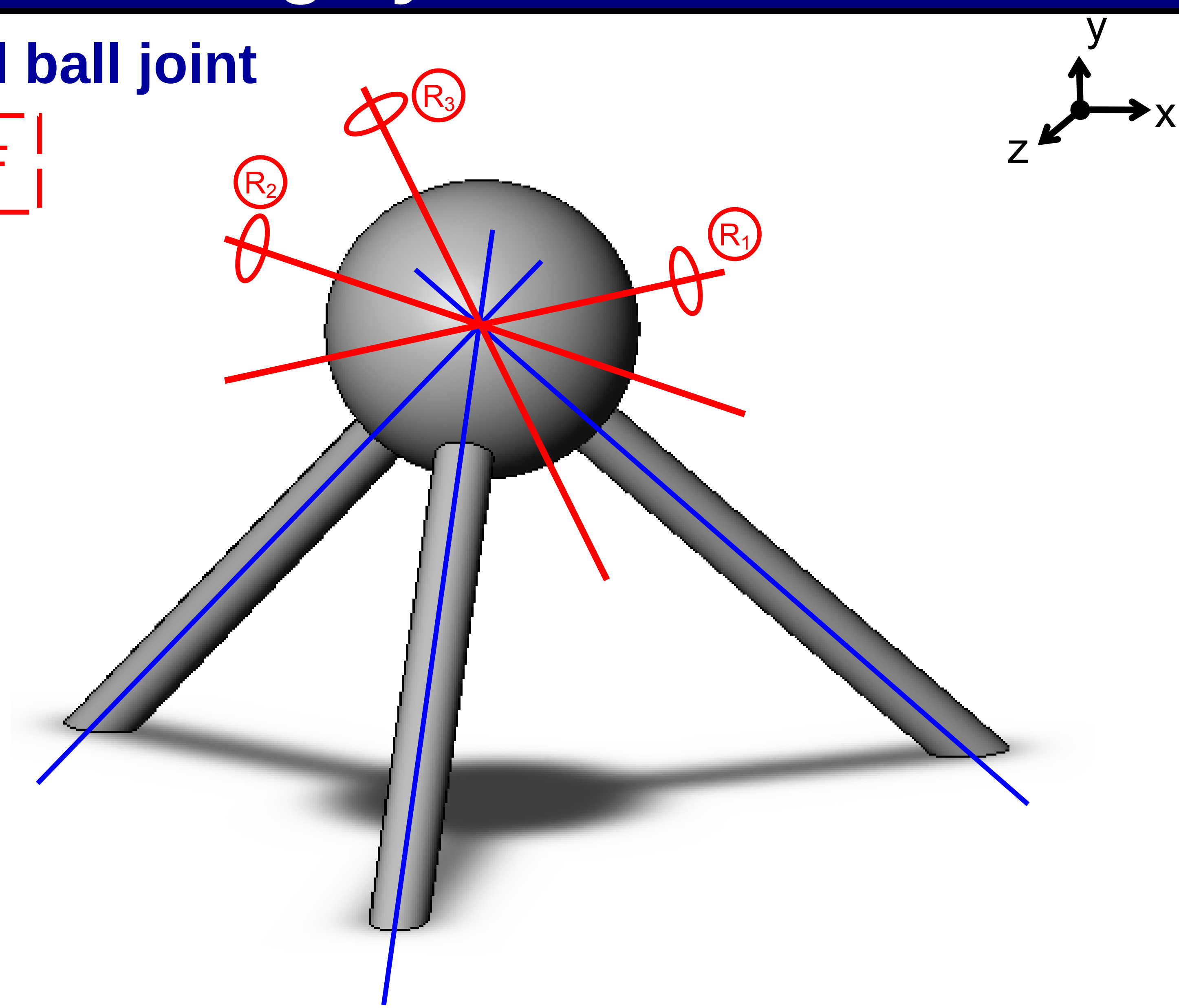
There will be a quiz on this NC



Flexure bearing systems

Spherical ball joint

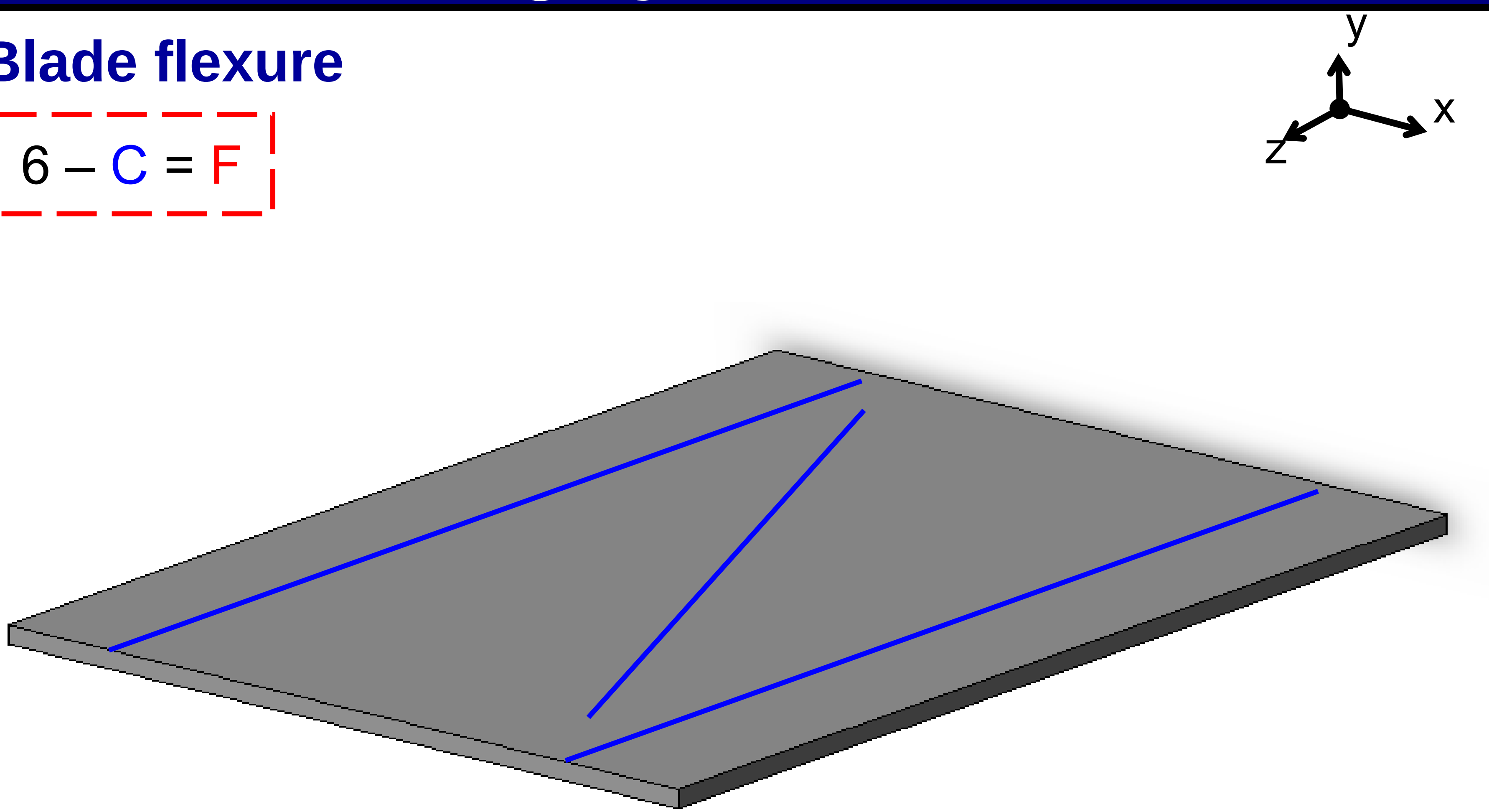
$6 - C = F$



Flexure bearing systems

Blade flexure

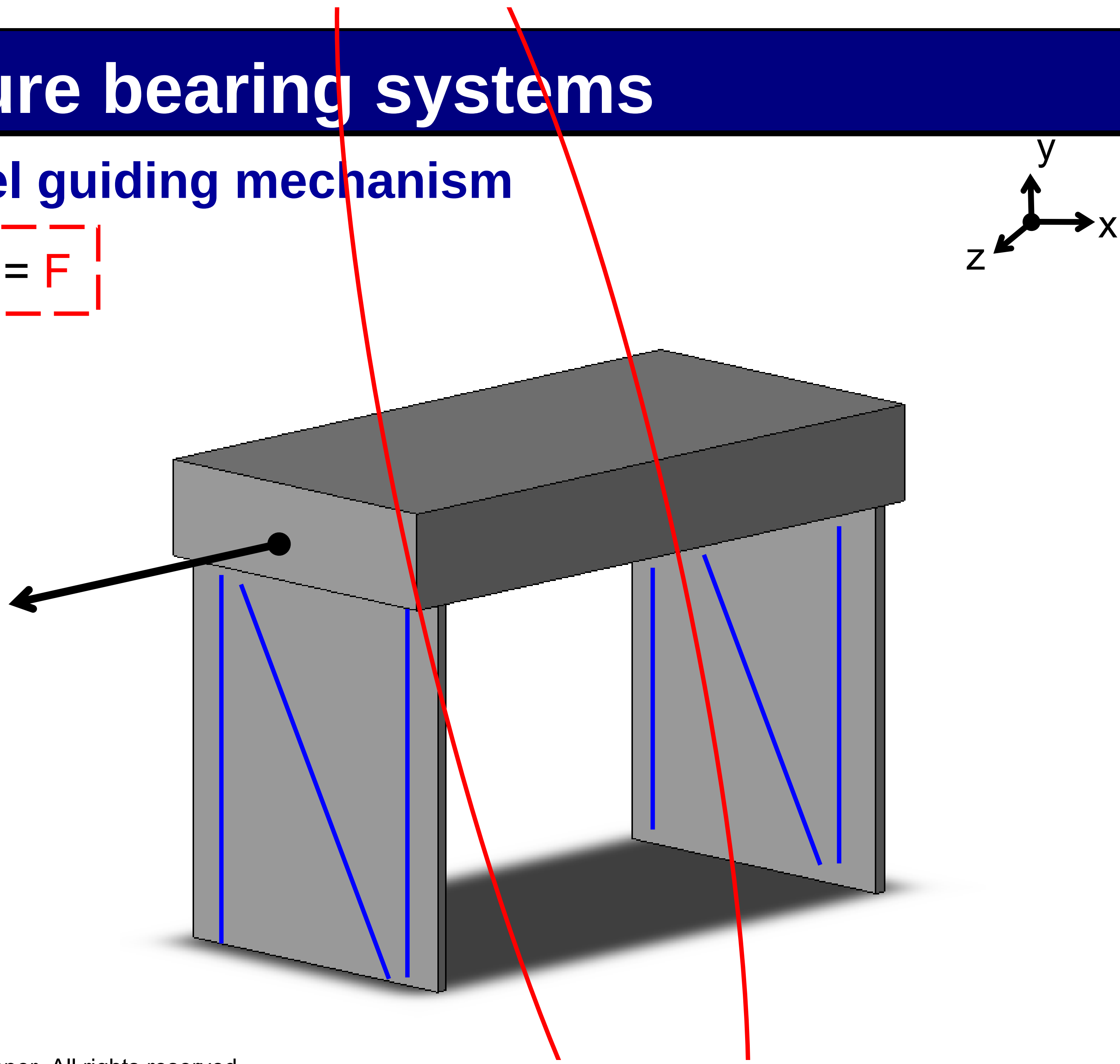
6 – C = F



Flexure bearing systems

Parallel guiding mechanism

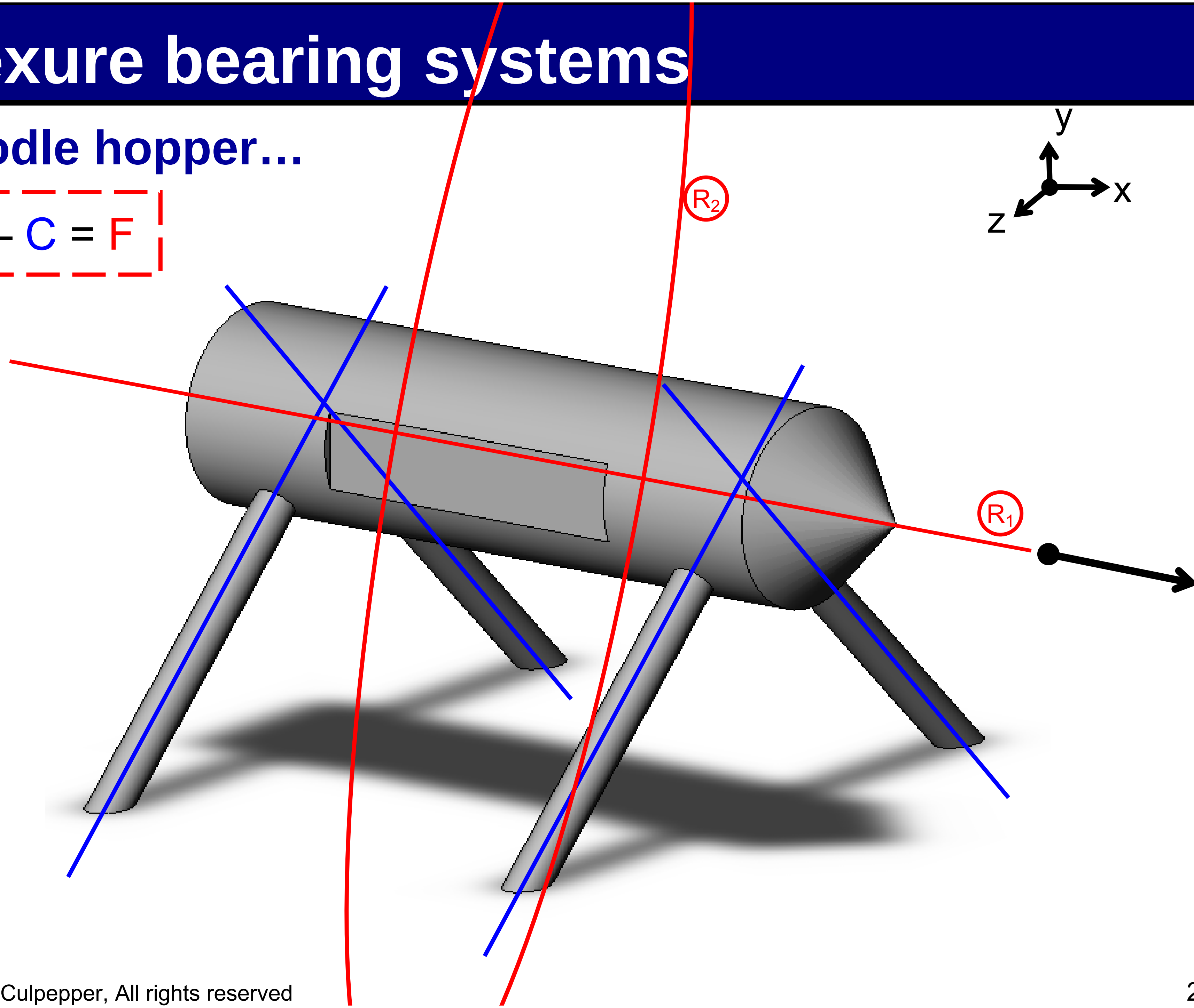
6 – C = F



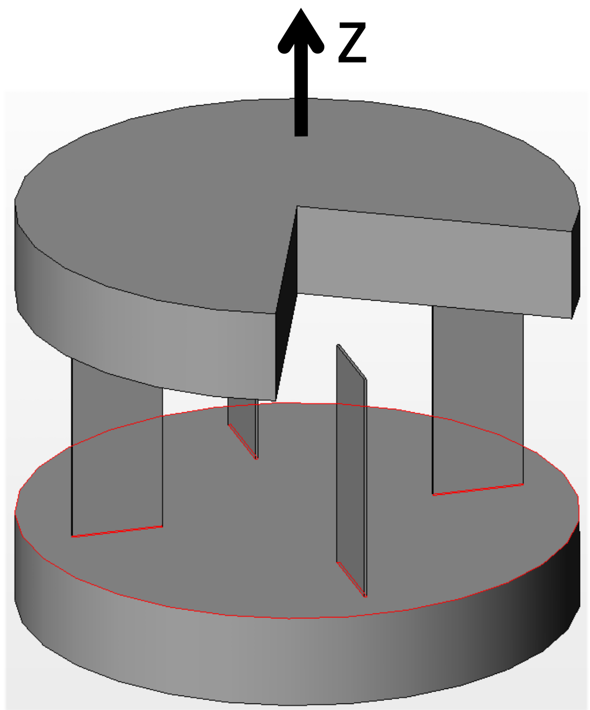
Flexure bearing systems

Doodle hopper…

$6 - C = F$



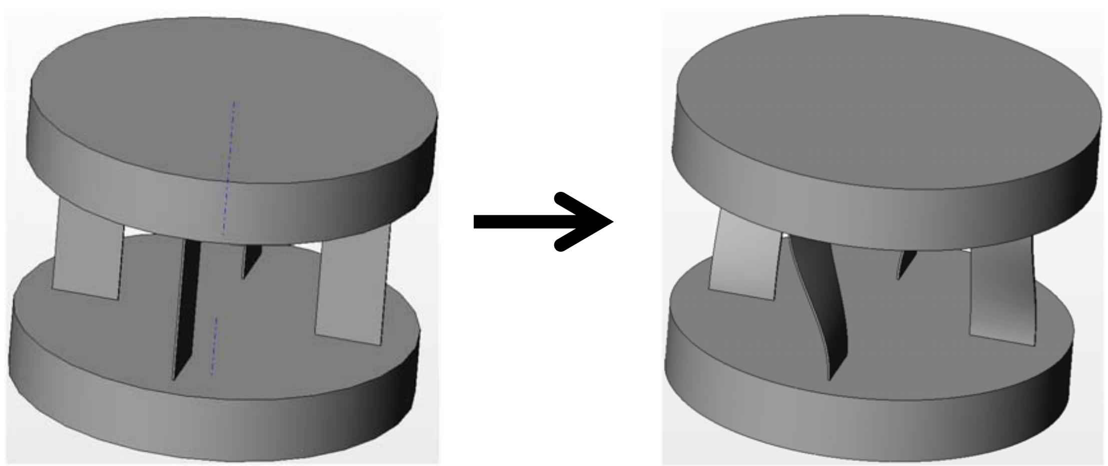
Parallel addition rules



What is parallel ? Elements are not in the same load path. Loads are split between the elements

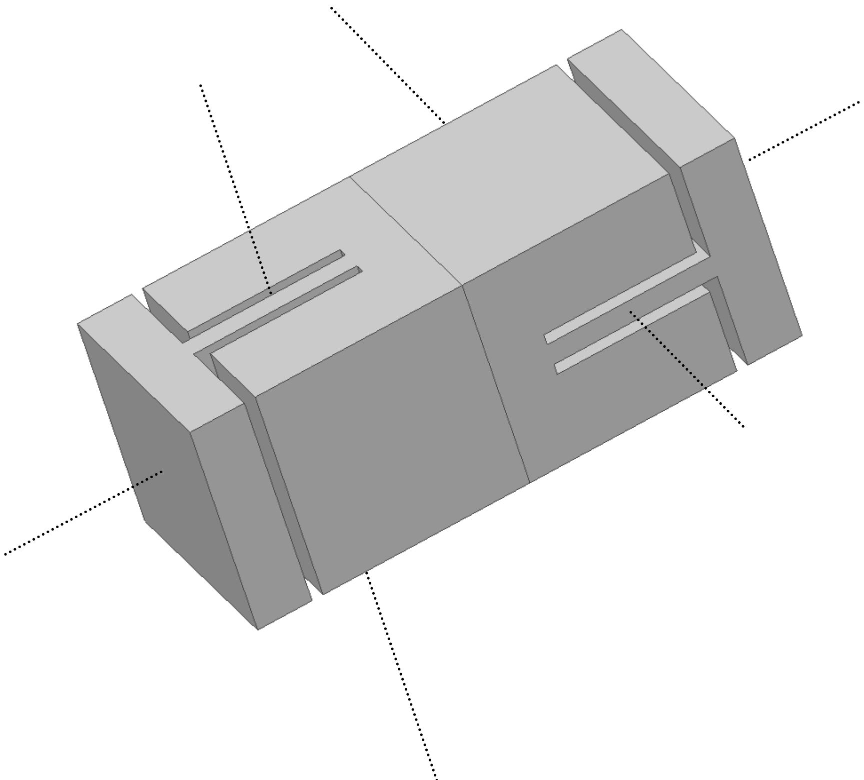
Add constraints so where there is a common DOF, then have mechanism DOF

Example: For instance, there are no conflicts in displacement to θz



Adapted from Layton Hale's Ph.D. Thesis (MIT)

Series addition rules



What is series?

-Differentiate series by load path

-Shared load path = series

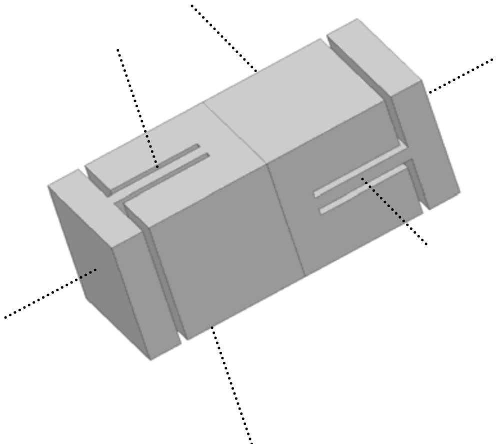
Series: Add DOF

Find common constraints

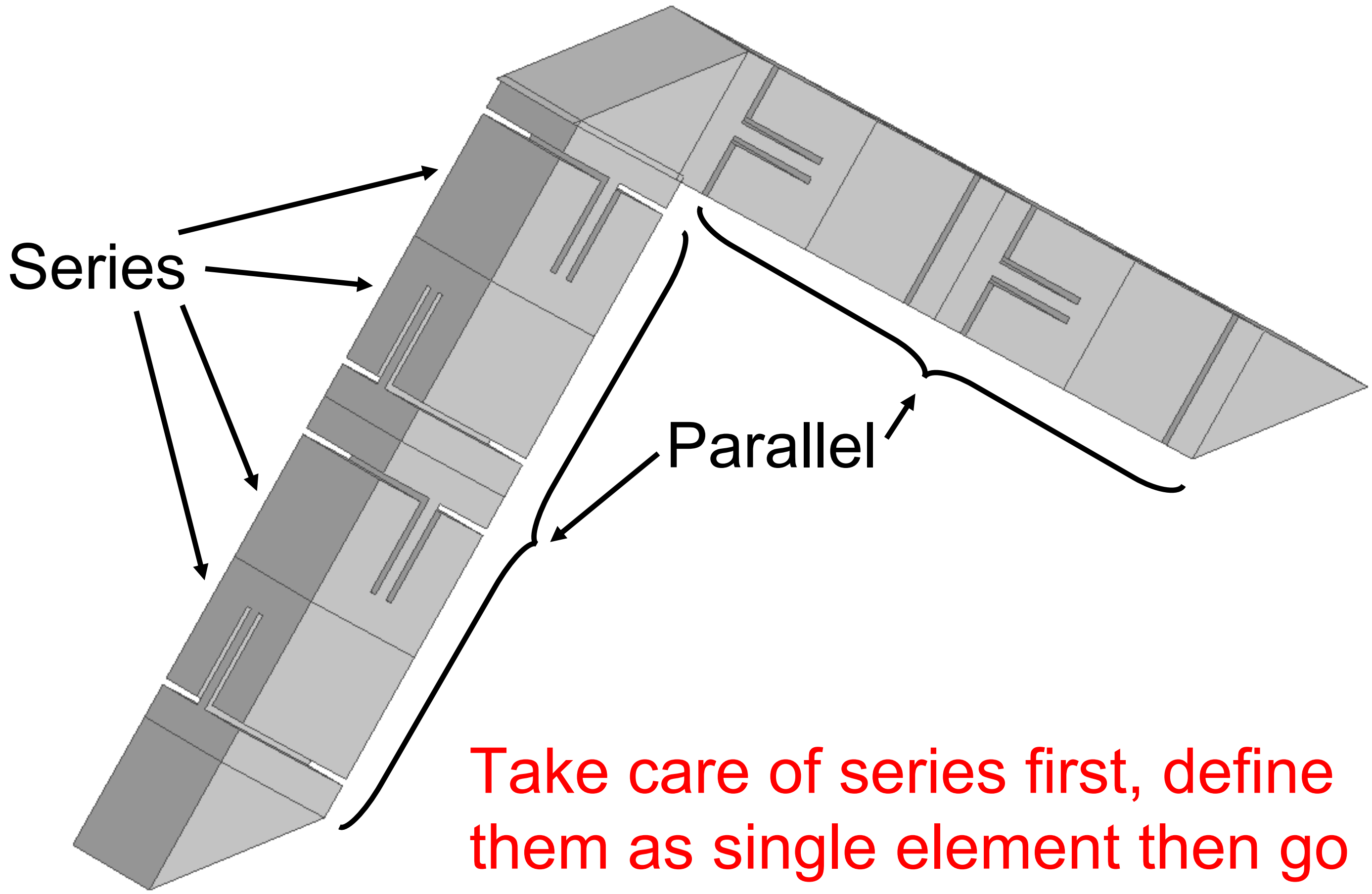
Follow the serial chain

Adapted from: Layton Hale's Ph.D. Thesis (MIT)

Parallel and series systems



Redundancy does not add Degrees of freedom



Take care of series first, define them as single element then go through parallel

Adapted from Layton Hale's Ph.D. Thesis (MIT)

Accuracy

The accuracy of most flexures is sensitive to:

- 1. Small variations in dimensions, e.g. $\delta_{thickness}$

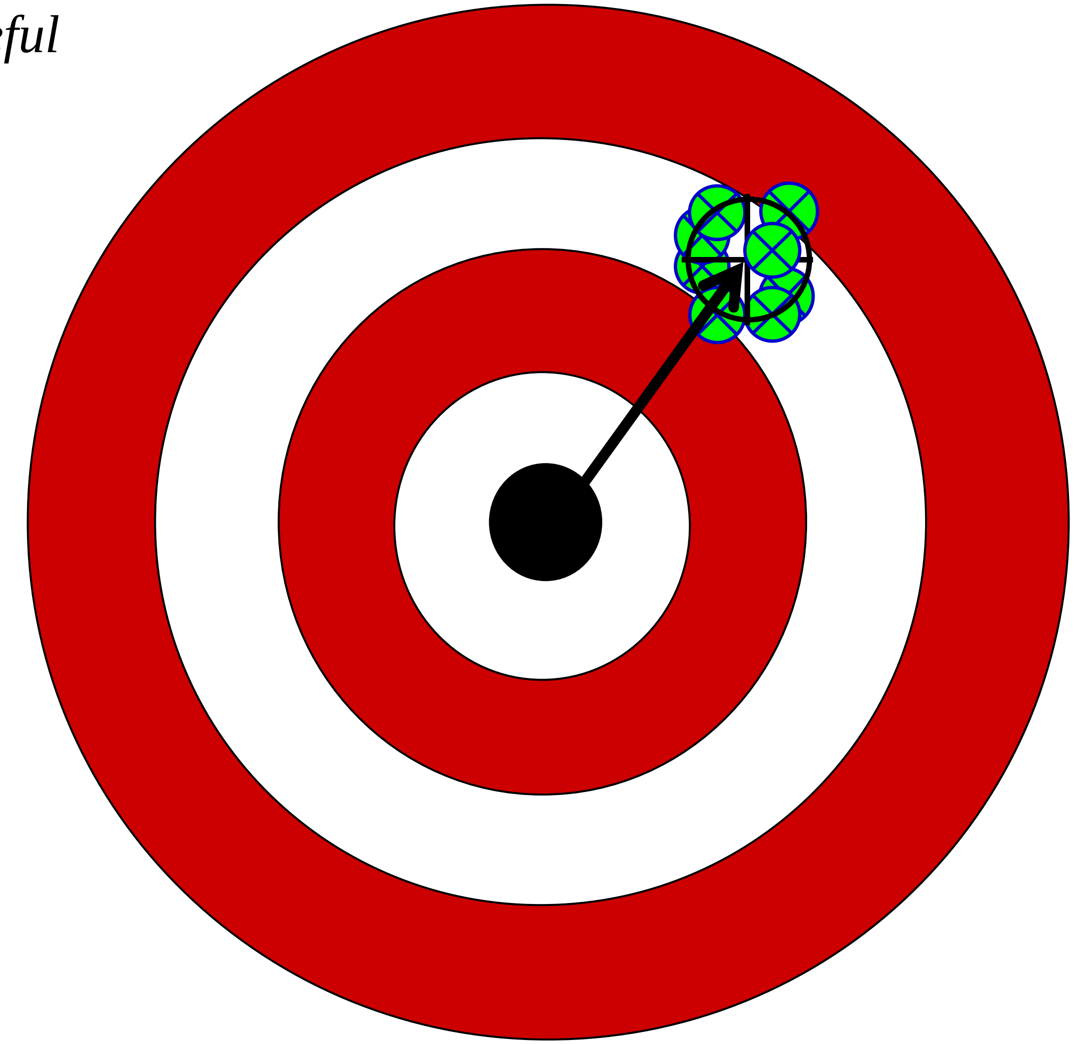
- 2. Young's Modulus (E)

- 3. Time variable errors
  - *Creep*
  - *Stress relaxation*
  - *Thermal*
  - *Dynamic/vibration*

Repeatability

Flexures can exhibit Angstrom-level repeatability if:

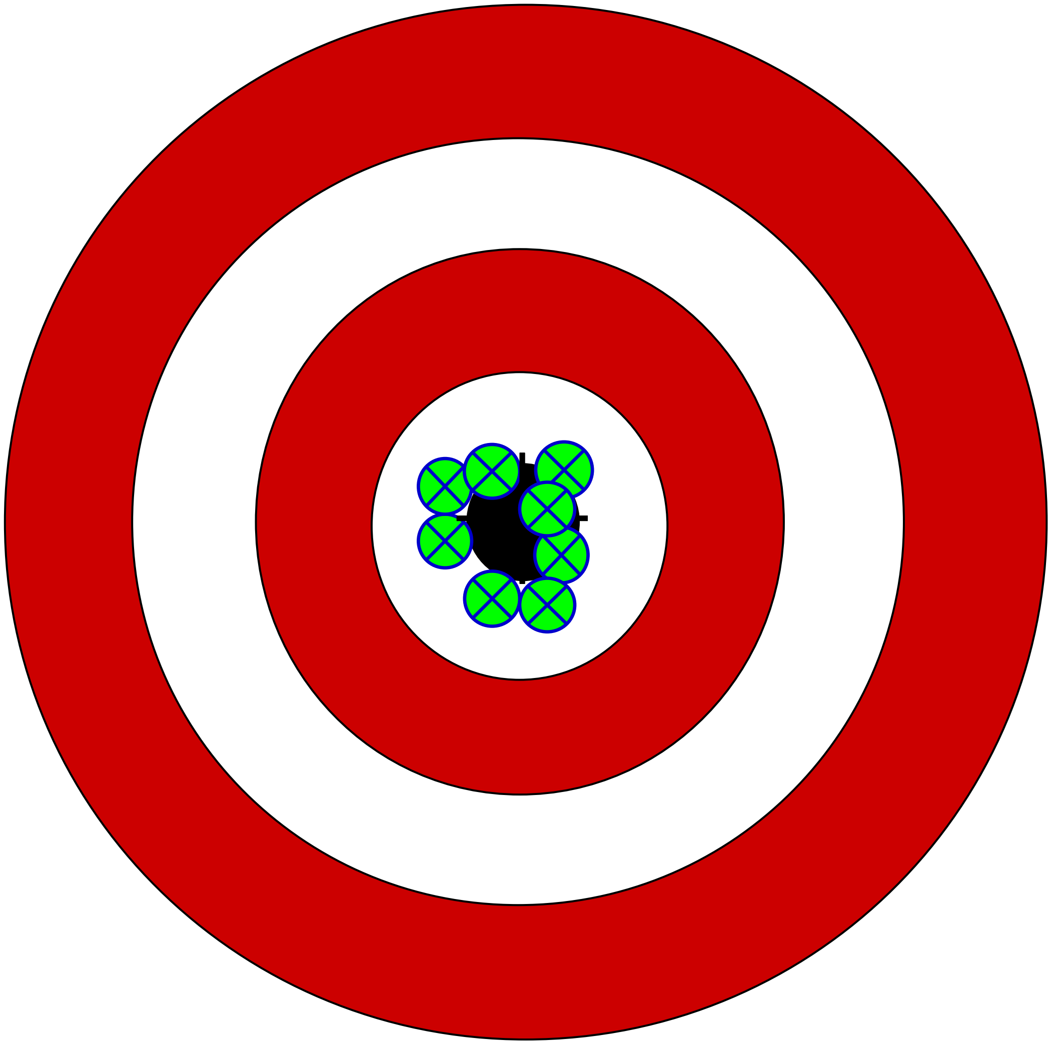
- Low material hysteresis
  - *Single crystal materials useful*
- No dislocation motion
  - $\sigma << \sigma_{yield}$
- Load is repeatable
  - *Magnitude*
  - *Direction*
- Assembly is correct
  - *No micro-slip*
  - *No friction in assembly*
  - *No yield during assembly*



Accuracy and repeatability

Difficult to obtain without calibration or adjustment

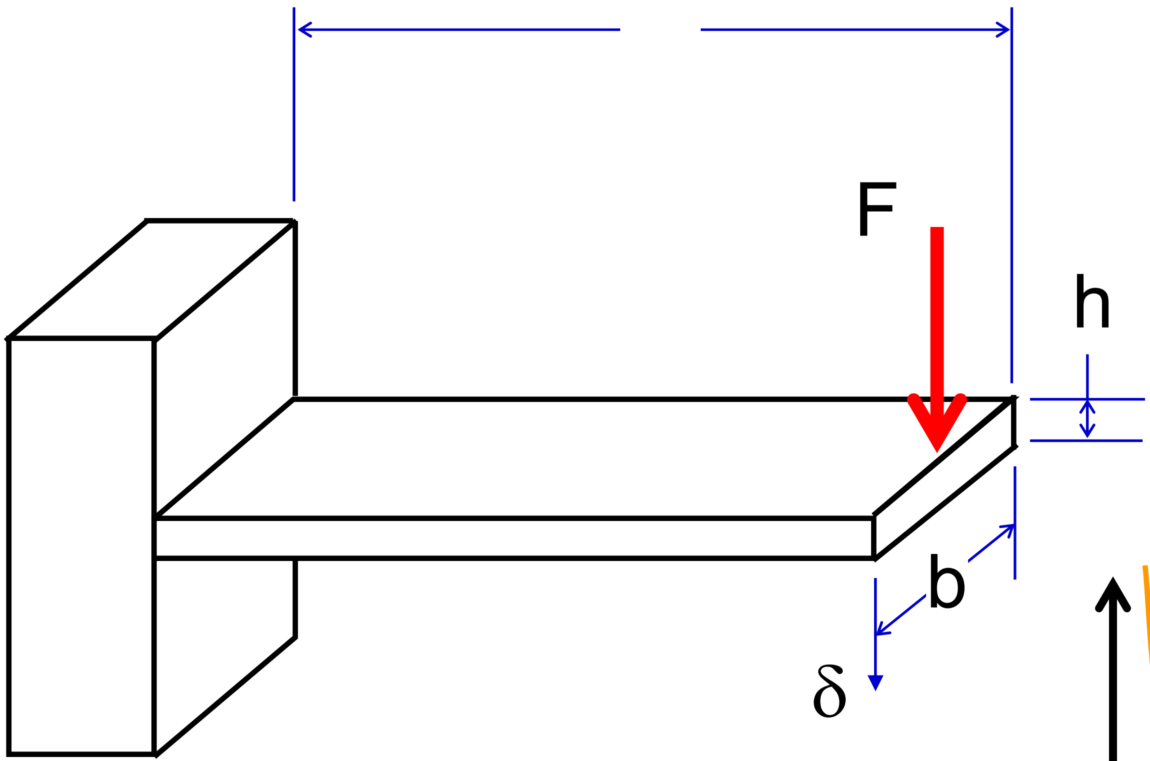
- Geometry
- Materials
- Loading
- Assembly/integration
- Environmental



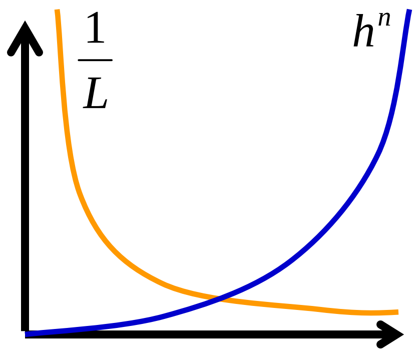
Links between kinematics and elasticity

Cantilever

$$\delta = \frac{F \cdot L^3}{3 \cdot E \cdot I}$$



$$I = \frac{1}{12} \cdot b \cdot h^3$$



$$F = \left(\frac{E \cdot b}{4} \cdot \left[\frac{h}{L} \right]^3 \right) \cdot \delta$$

$$k = \frac{dF}{d\delta} = \frac{d}{d\delta} \left\{ \frac{E \cdot b}{4} \cdot \left[\frac{h}{L} \right]^3 \cdot \delta \right\} \rightarrow \frac{E \cdot b}{4} \cdot \left[\frac{h}{L} \right]^3$$

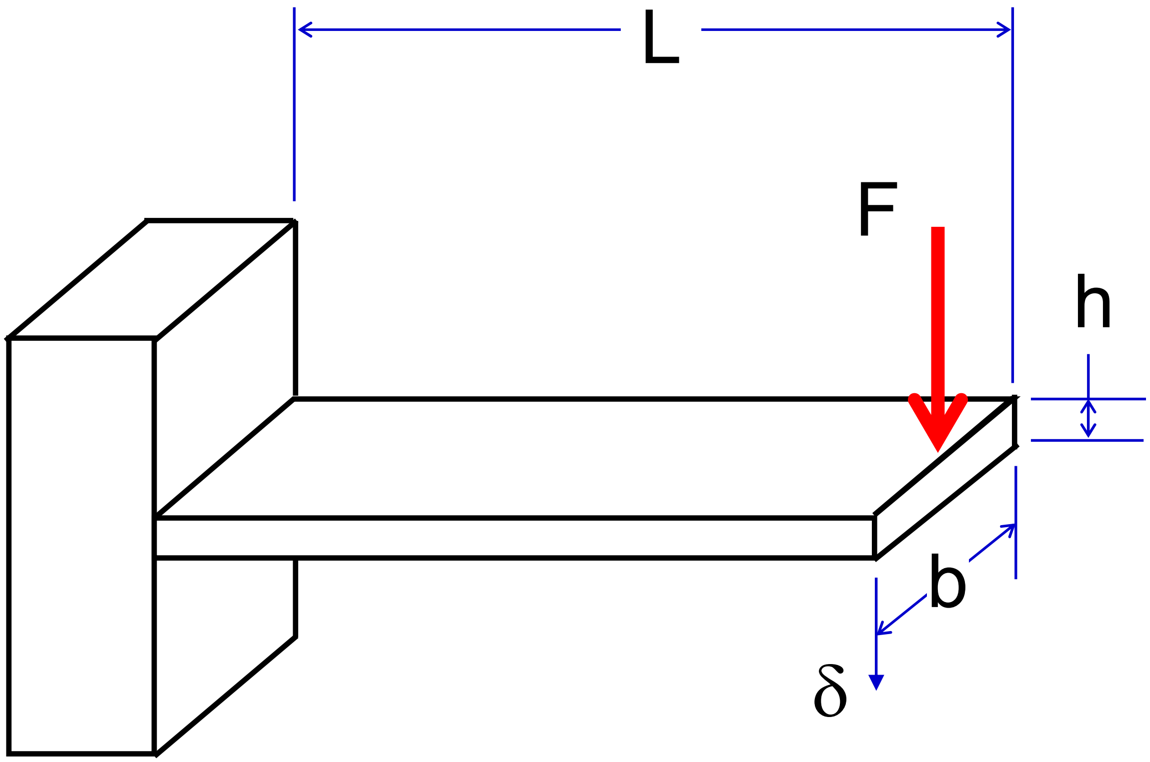
Links between kinematics and elasticity

Cantilever

$$\Delta L = 0.05 \cdot L$$

$$\Delta h = 0.05 \cdot h$$

$$\Delta b = 0.05 \cdot b$$



$$k + \Delta k = \frac{E \cdot (b + \Delta b)}{4} \cdot \left[\frac{h + \Delta h}{L - \Delta L}\right]^3 \rightarrow \frac{E \cdot b}{4} \cdot \left[\frac{h}{L}\right]^3 \cdot \left(1.05 \cdot \left[\frac{1.05}{0.95}\right]^3 - 1\right) = k \cdot (1 + 0.42)$$

$$\Delta k = 0.42 \cdot k$$

Fabrication processes: EDM

EDM positives

- Accuracy (micrometers)
- 3D
- Surface finish (sub-micrometers)

Image removed due to copyright restrictions. Please see

http://www.physikinstrumente.com/en/about/images/pi_WIREEDMC_i4c_K50_eps.jpg

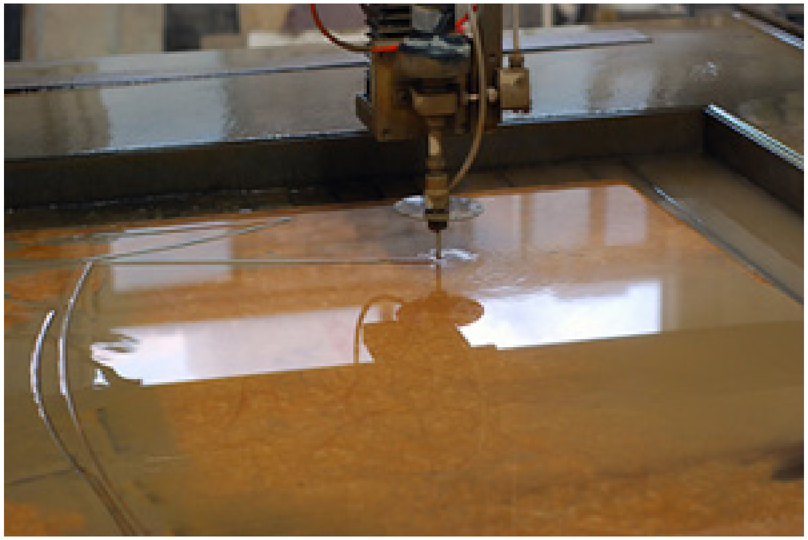
EDM drawbacks

- Time (mm/minute)
- Cost

Fabrication processes: Waterjet

Waterjet positives

- Low force
- Many materials including brittle materials and heat sensitive materials
- Rapid (inches/min)



Images courtesy of xiaming on Flickr.

Waterjet drawbacks

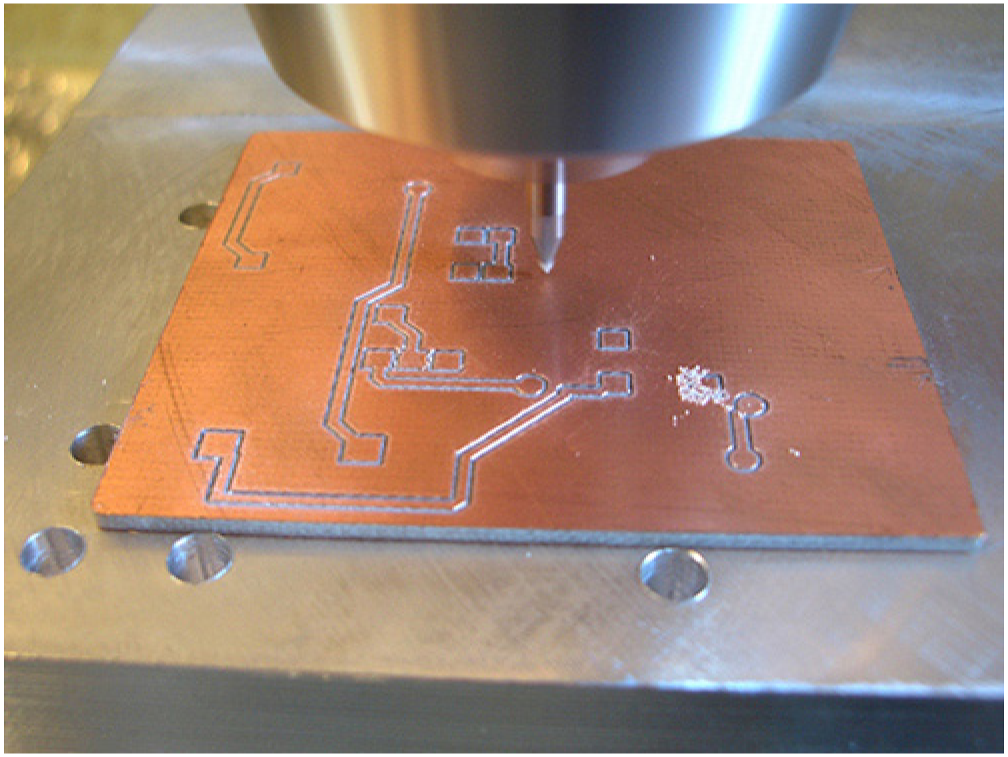
- Thickness limitations
- Kerf limitations
- Draft limitations
- Accuracy ~ 125 micrometers

Images courtesy of lansoper on Flickr.

Fabrication processes: Milling/cutting

Milling/cutting positives

- ❑ Flexibility
- ❑ Any material
- ❑ Nearly any shape



Milling/cutting drawbacks

- ❑ Fixturing
- ❑ Compliance of parts
- ❑ Work hardening
- ❑ Surface damage

Image courtesy of jiskar on Flickr.

Please see any other image of milling, such as

http://students.washington.edu/dennyt/fsae/cnc/wc_fixtplate.jpg

Fabrication processes: Etching

Etching positives

- 2½ D topologies/shapes
- Monolithic
- Micron-level features

Etching drawbacks

- Dimensional control
- Scallops

Images removed due to copyright restrictions. Please see:

http://www.ee.ucla.edu/~dejan/ee115c/ucla-graphics/IBM_metal_stack.jpg

http://www.stsystems.com/uploaded_files/1101/images/scallops.jpg

Milanovic, Veljko, et al. "Deep Reactive Ion Etching for Lateral Field Emission Devices." IEEE Electronic Device Letters 21 (June 2000): 271-273.

Milanovic, Veljko, et al. "Micromachining Technology for Lateral Field Emission Devices." IEEE Transactions on Electron Devices 48 (January 2001): 166-173.

Please see 371762. "How Microprocessor Work." February 14, 2009. YouTube. Accessed October 28, 2009. http://www.youtube.com/watch?v=loMz_l_Fpx4

Assembly

Stress and energy

- Proper thickness of clamps and clamping load distribution
- Spring washer provide force source

Fusing

- Clamps members should “yield” before flexure
- Spring washer provide force source

Surface conformity

- Micro-slip is a major cause of hysteresis
- Deburring and potting/bonding

Misalignment = systematic errors

Images removed due to copyright restrictions.
Please see Fig. 8.5 and 8.6 in Smith, Stuart.
Flexures: Elements of Elastic Mechanisms.
Amsterdam, Holland: Gordon & Breach, 2000.