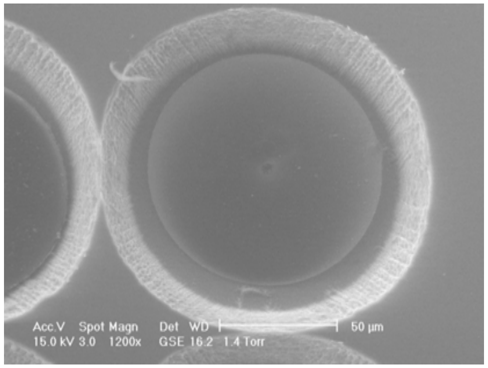
2.76 / 2.760 Lecture 5: Large/micro scale

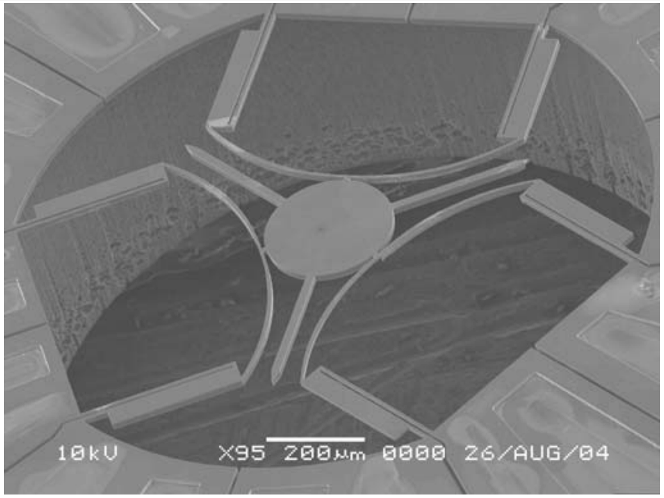
Constraints

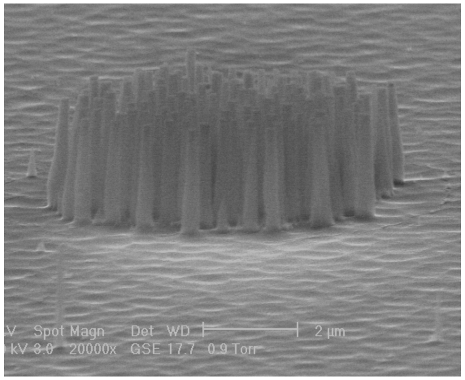
Micro-fabrication

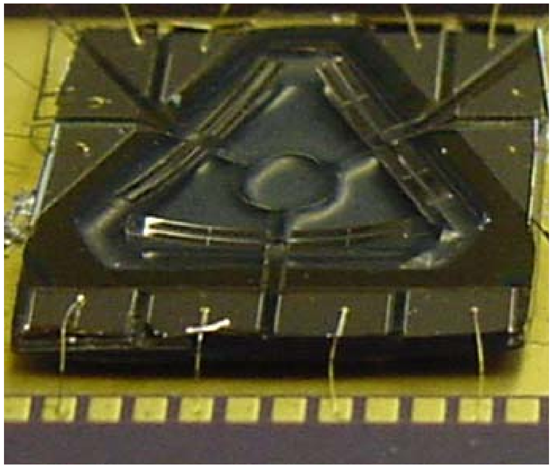
Micro-physics scaling

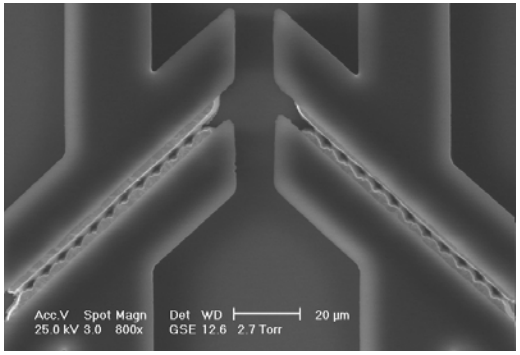
Assignment

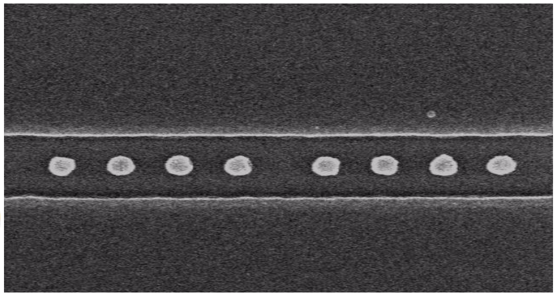












Purpose of today

$$\begin{vmatrix} O_{Macro} \\ O_{Meso} \\ O_{Micro} \\ O_{Nano} \end{vmatrix} = \begin{vmatrix} \cancel{f_{11}\left(SR_{\frac{Macro}{Macro}}\right)} & \cancel{f_{12}\left(SR_{\frac{Meso}{Macro}}\right)} & \boxed{f_{13}\left(SR_{\frac{Micro}{Macro}}\right)} & f_{14}\left(SR_{\frac{Nano}{Macro}}\right) \\ \cancel{f_{21}\left(SR_{\frac{Macro}{Meso}}\right)} & \cancel{f_{22}\left(SR_{\frac{Meso}{Meso}}\right)} & \boxed{f_{23}\left(SR_{\frac{Micro}{Meso}}\right)} & f_{24}\left(SR_{\frac{Nano}{Meso}}\right) \\ \boxed{f_{31}\left(SR_{\frac{Macro}{Micro}}\right)} & \boxed{f_{32}\left(SR_{\frac{Meso}{Micro}}\right)} & \cancel{f_{33}\left(SR_{\frac{Micro}{Micro}}\right)} & f_{34}\left(SR_{\frac{Nano}{Micro}}\right) \\ \boxed{f_{41}\left(SR_{\frac{Macro}{Nano}}\right)} & \boxed{f_{42}\left(SR_{\frac{Meso}{Nano}}\right)} & \boxed{f_{43}\left(SR_{\frac{Micro}{Nano}}\right)} & \cancel{f_{44}\left(SR_{\frac{Nano}{Nano}}\right)} \end{vmatrix} \cdot \begin{vmatrix} I_{Macro} \\ I_{Meso} \\ I_{Micro} \\ I_{Nano} \end{vmatrix}$$

Finish mechanical gain factors to make big machines work with little machines

Micro-scale flow/interface dominators

- Micro-scale fabrication
- Micro-scale surface/volume physics

Constraints

Constraint-based design

Constraint-based compliant mechanism design

STEP 1: Design requirements

Motion path, stiffness, load capacity, etc…

STEP 2: Motion path decomposition

Arcs, lines, rotation pts. sub-paths

STEP 3:Kinematic parametric concepts

Motions, constraint metric, symmetry, etc.

STEP 4:Constraint-motion addition rules

Serial, parallel, hybrid

STEP 5: Topology concept generation

Path & constraint driven

STEP 6: Concept selection phase I

Path errors & over constraint

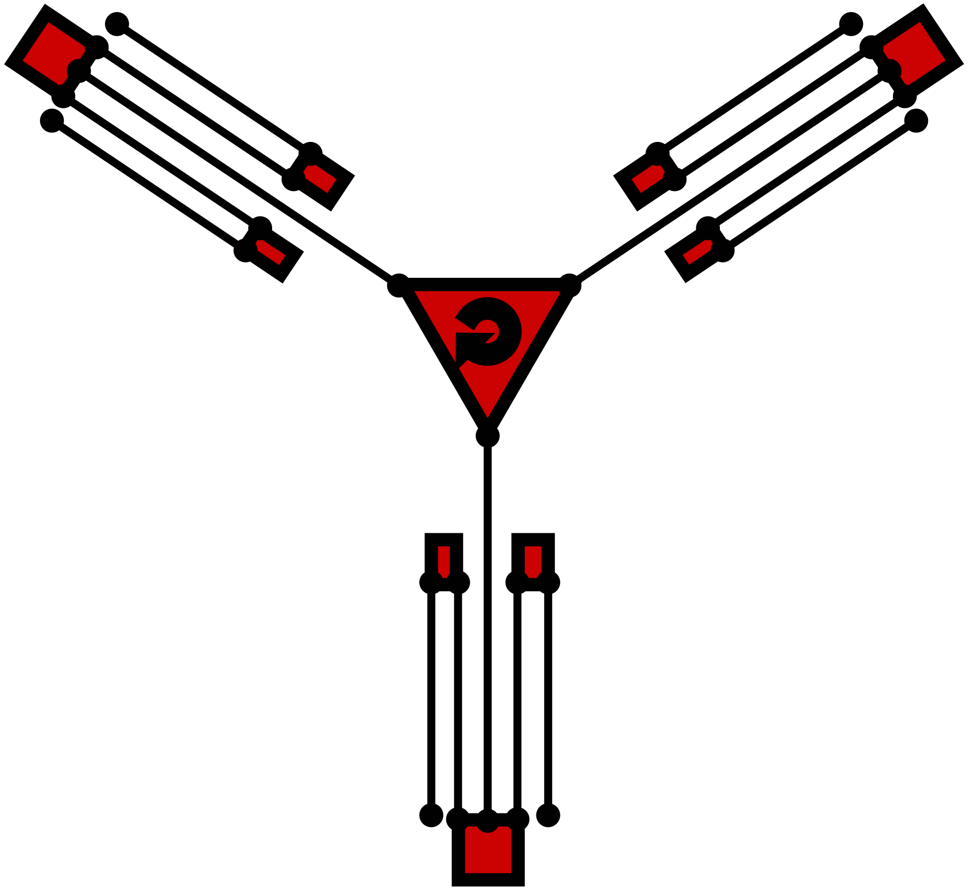
STEP 7: Size and shape optimization

Stiffness, load capacity, efficiency, etc…

STEP 8: Concept selection phase II

Direct comparison with design requirements

Photo removed for copyright reasons.
Compliant test rig for automotive
steering column.



Exact constraint

At some scale, everything is a mechanism

Exact constraint: Achieve desired motion

- ☐ By applying minimum number of constraints
- ☐ Arranging constraints in optimum topology
- ☐ Adding constraints only when necessary

Visualization is critical, this is not cookbook

For now:

- ☐ Start with ideal constraints
- ☐ Considering small motions
- ☐ Constraints = lines

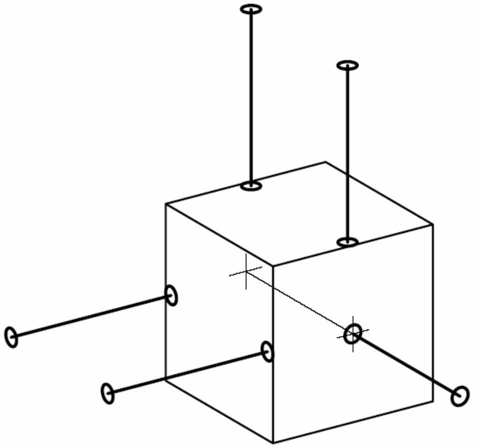


Figure: Layton Hales PhD Thesis, MIT.

Constraint fundamentals

Rigid bodies have 6 DOF

DOC = # of linearly independent constraints

DOF = 6 - DOC

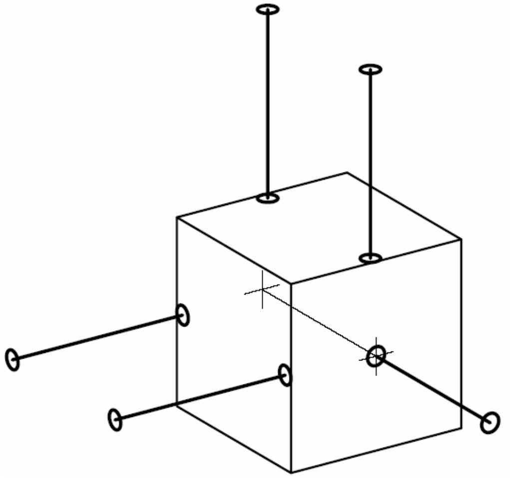


Figure: Layton Hales PhD Thesis, MIT.

A linear displacement can be visualized as a rotation about a point which is "far" away

Statements

Points on a constraint line move perpendicular to the constraint line

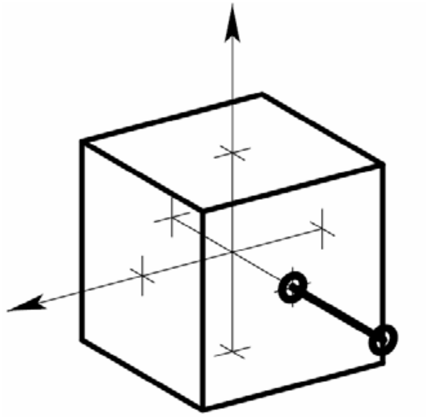
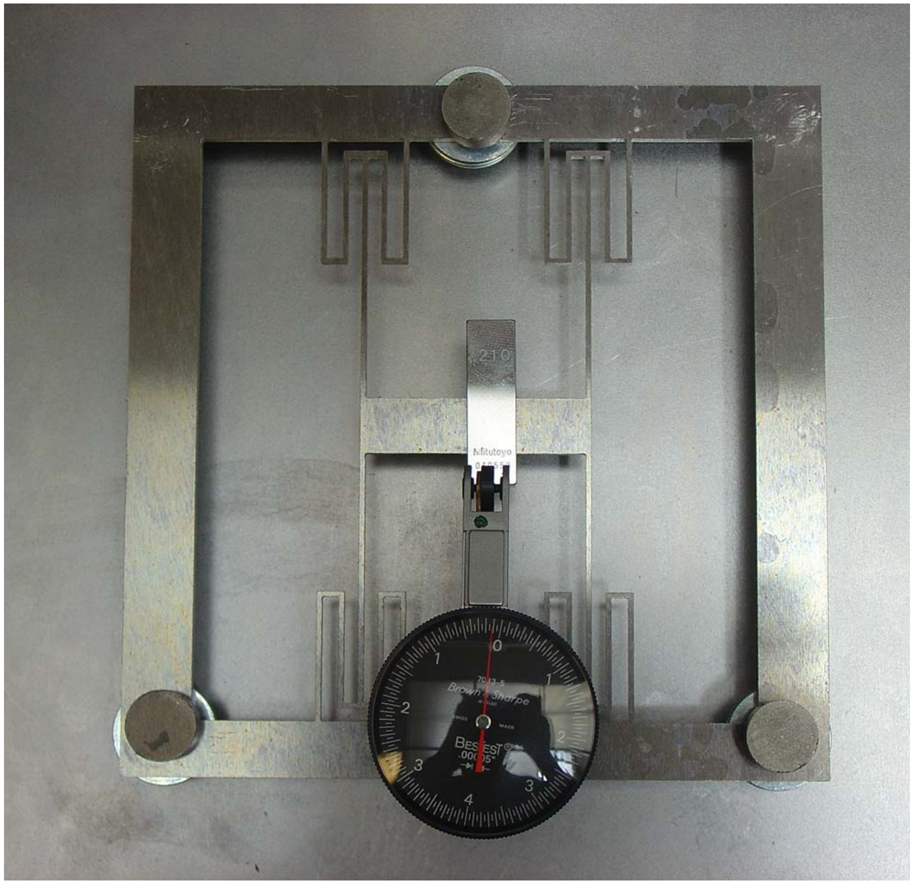


Figure: Layton Hales PhD Thesis, MIT.

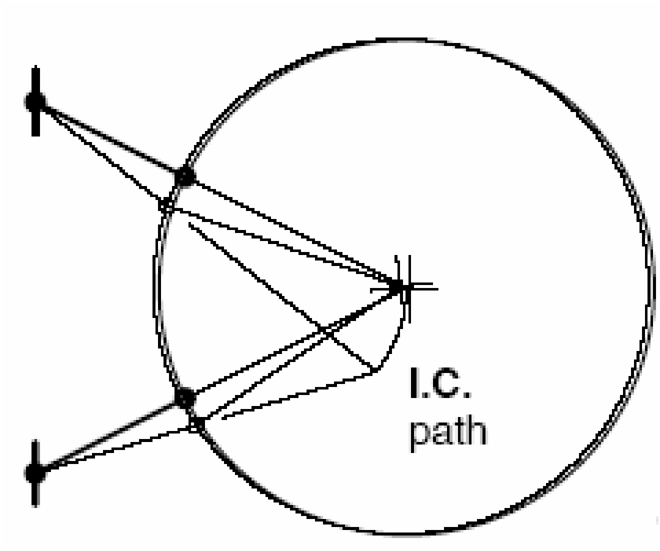


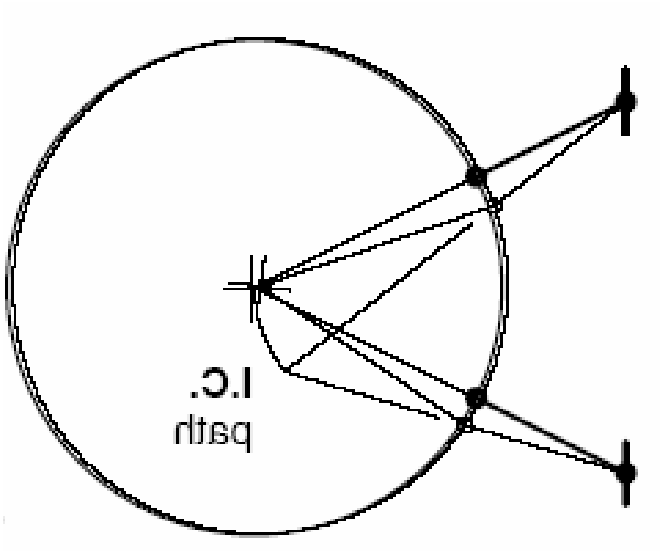
Constraints along this line are equivalent

Diagram removed for copyright reasons.
Source: Blanding, D. L. *Exact Constraint: Machine Design using Kinematic Principles*. New York: ASME Press, 1999.

Statements

- Intersecting, same-plane constraints are equivalent to other same-plane intersecting constraints

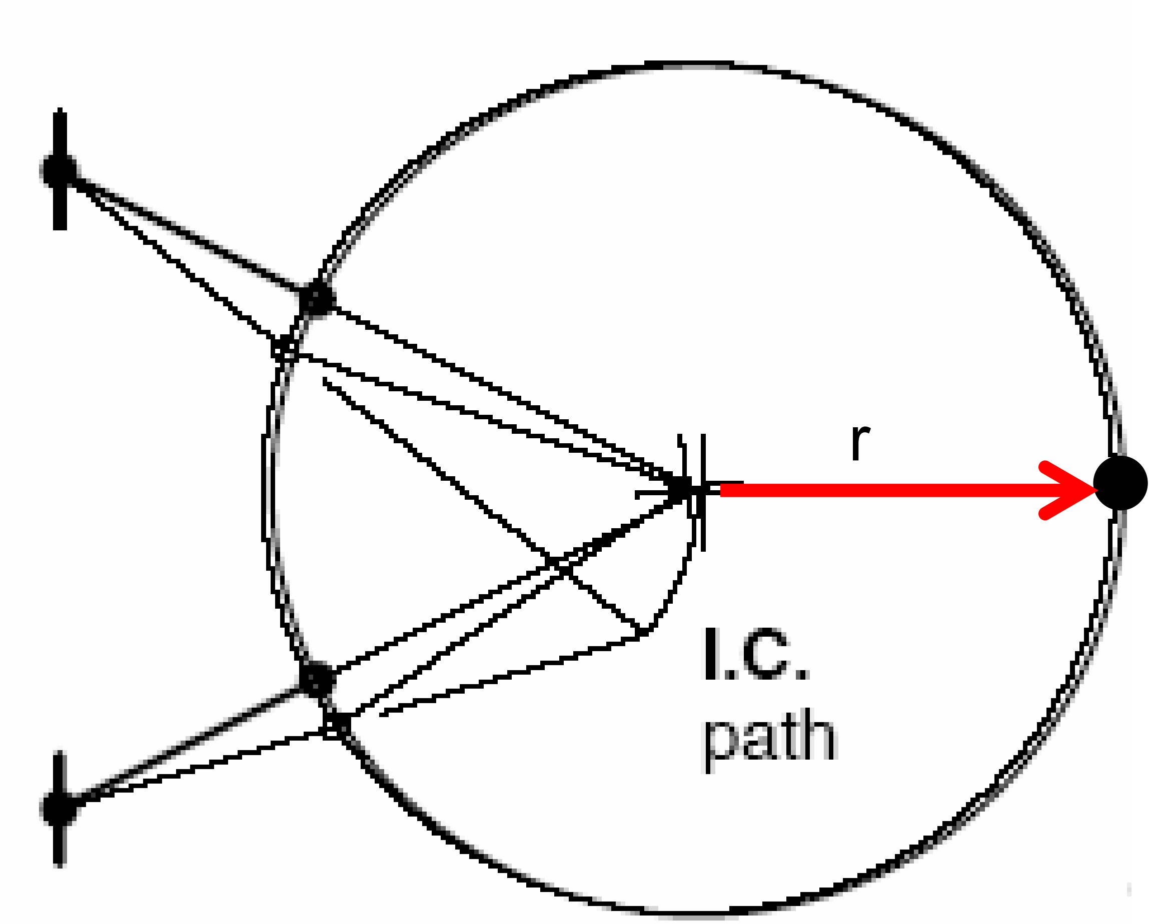




- Instant centers are powerful tool for visualization, diagnosis, & synthesis

Abbe error

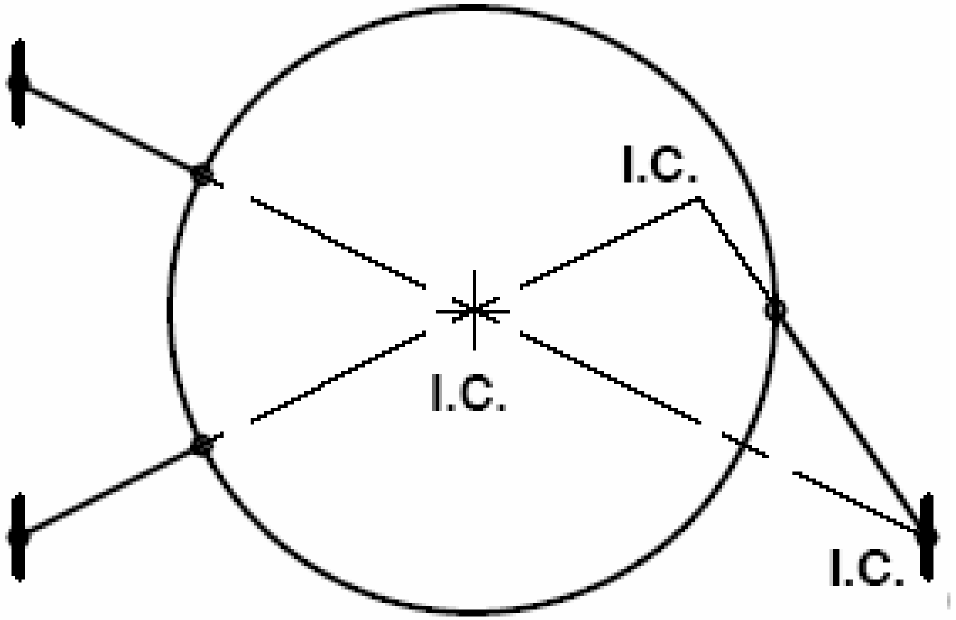
Error due to magnified moment arm



Statements

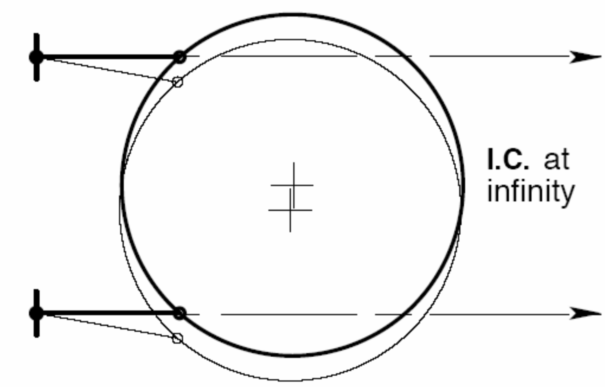
Constraints remove rotational degree of freedom

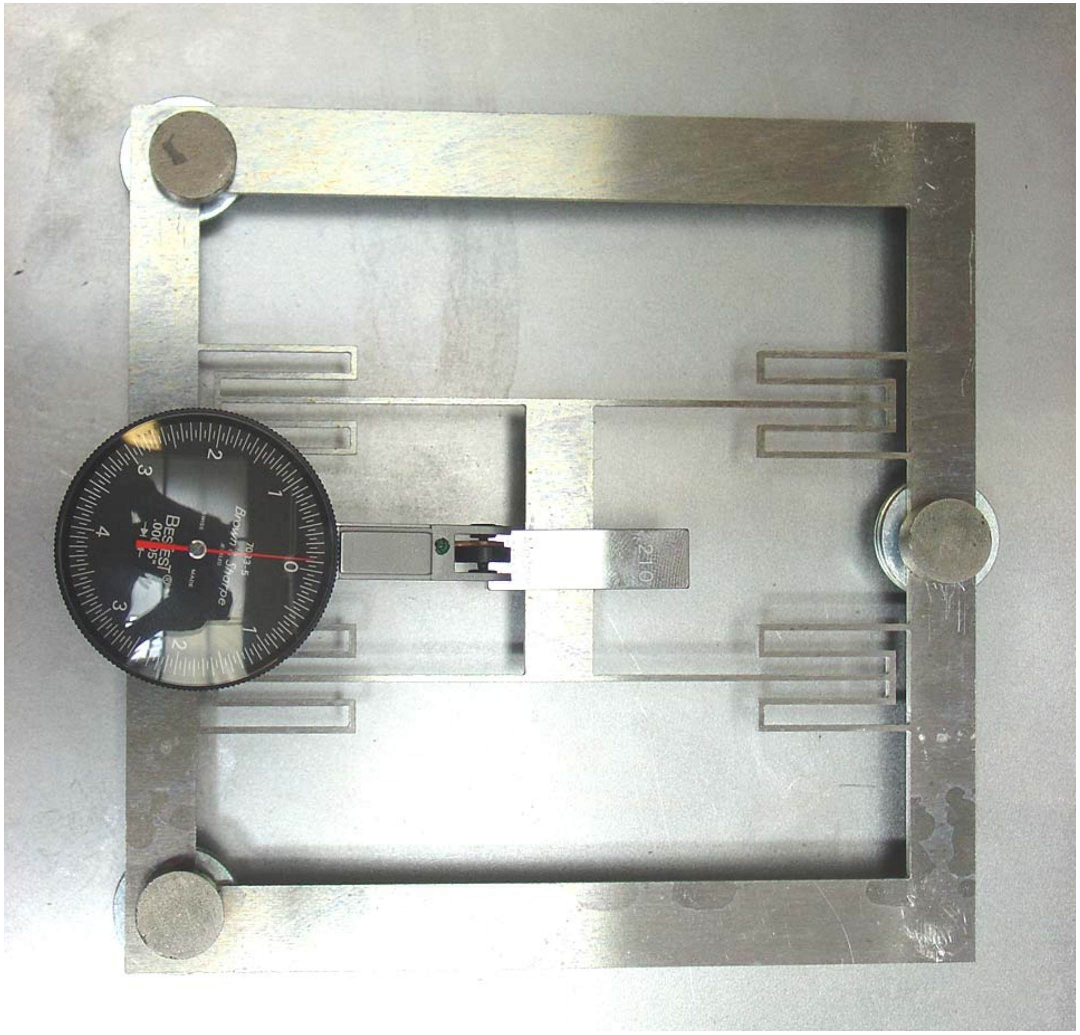
Length of moment arm determines the quality of the rotational constraint



Statements

Parallel constraints may be visualized/treated as intersecting at infinity





Basic elements

Bars

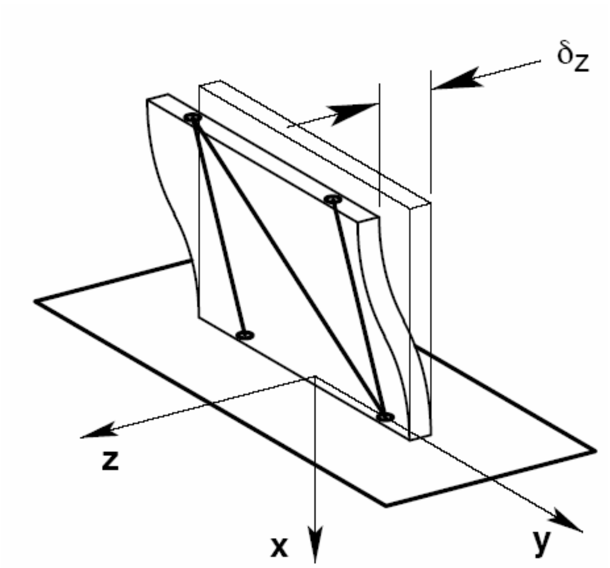
Beams

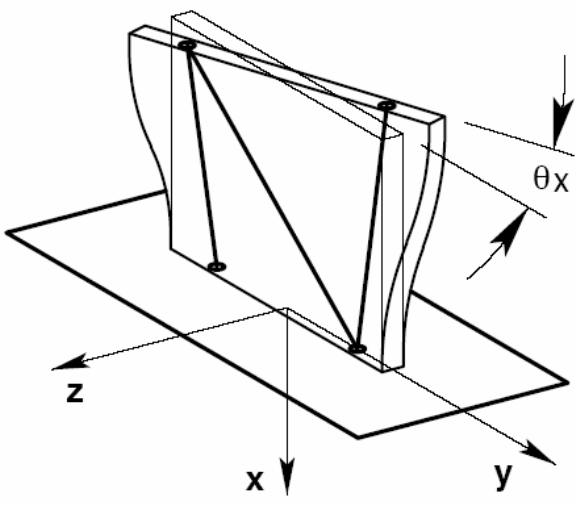
Plates

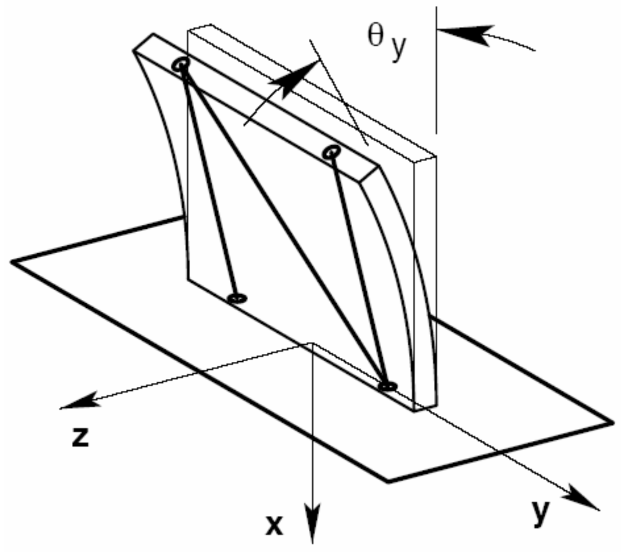
Diagrams removed for copyright reasons.
Source: Blanding, D. L. *Exact Constraint: Machine Design using Kinematic Principles*.
New York: ASME Press, 1999.

Notch Hinge

Examples







Do you really get δz?

Figures: Layton Hales PhD Thesis, MIT.

Examples

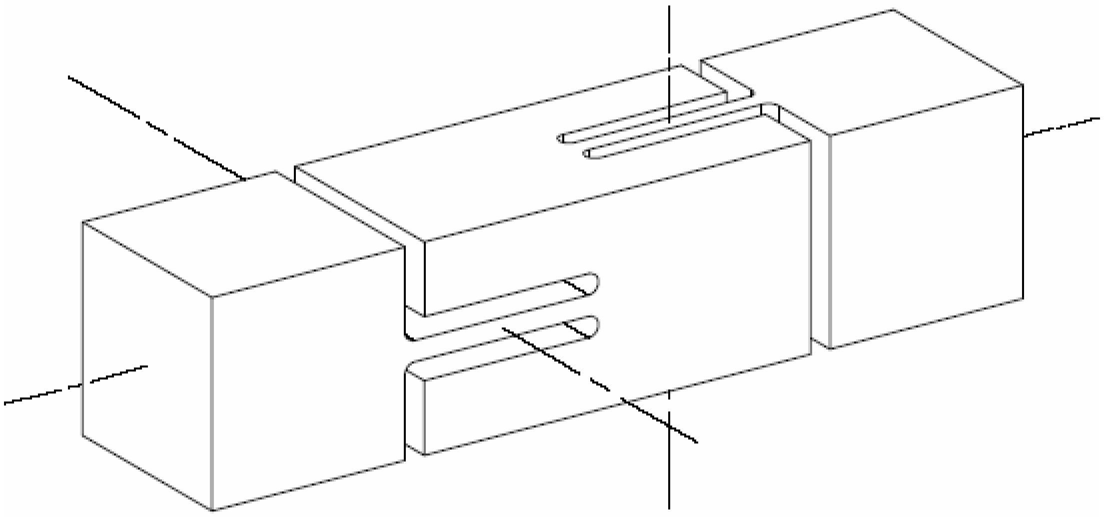


Figure: Layton Hales PhD Thesis, MIT.

Series: Add DOF

Follow the serial chain

Pick up every DOF

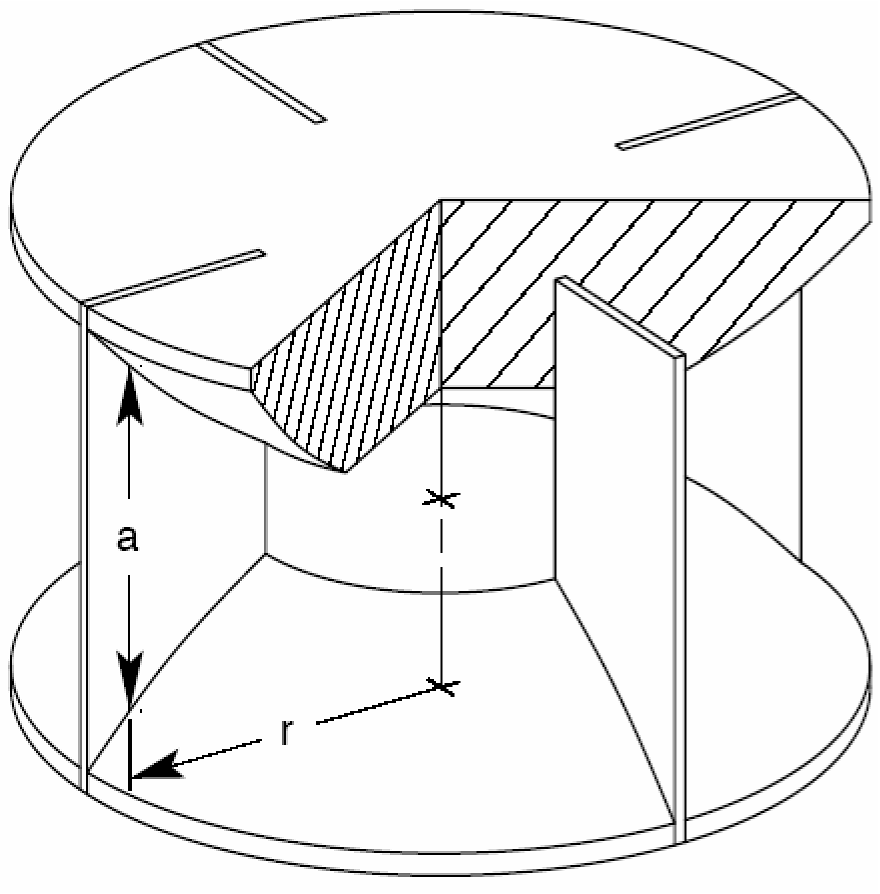
Differentiate series by Load path

Shared load path = Series

This could be 5 DOF

Depends on blade length

Examples



Parallel: Add Constraints

Where there is a common DOF, then have mechanism DOF

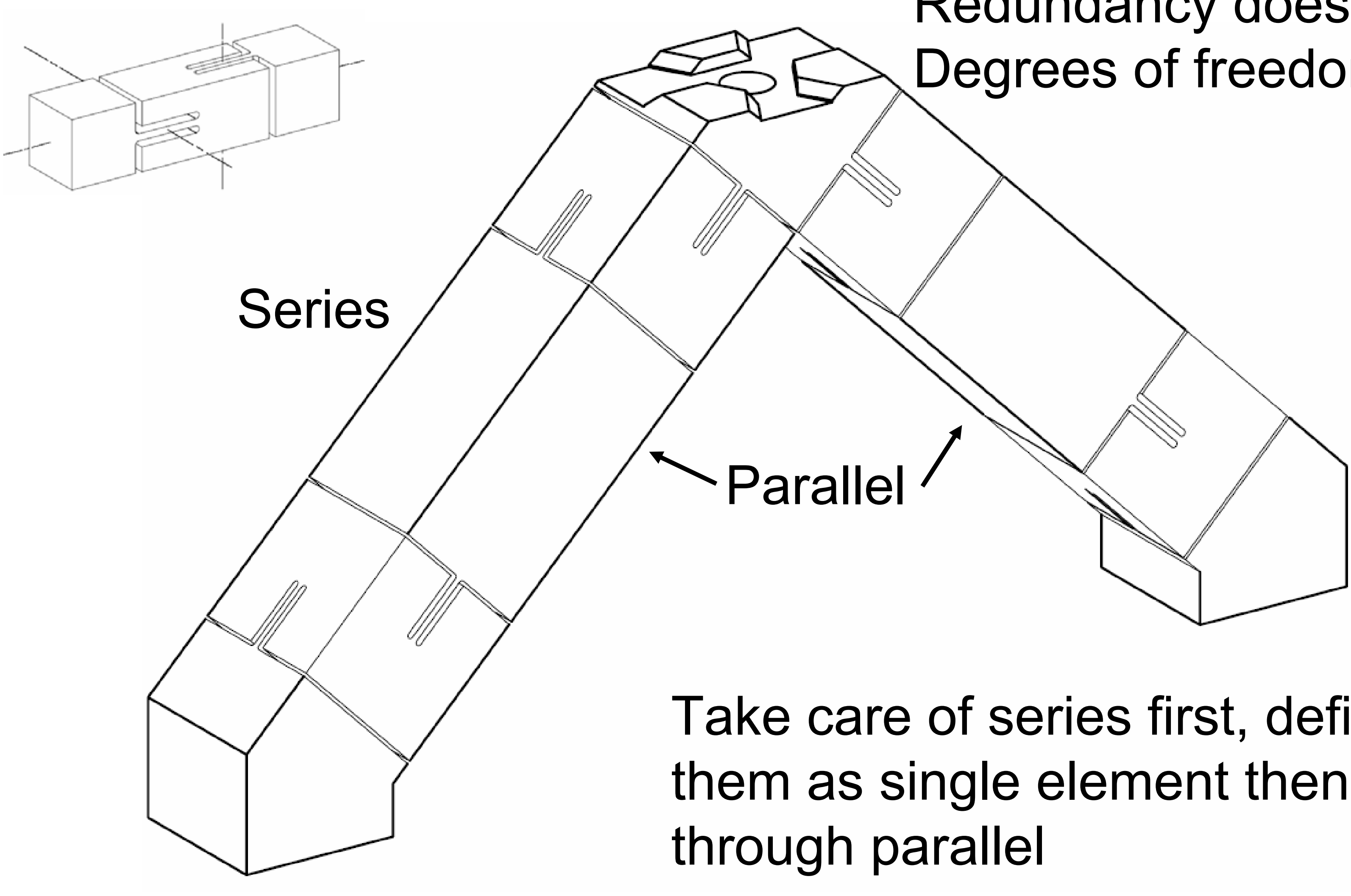
There are no conflicts in circumferential displacement To θz

Non-shared load paths = parallel

Figure: Layton Hales PhD Thesis, MIT.

Examples

Redundancy does not add Degrees of freedom



Series

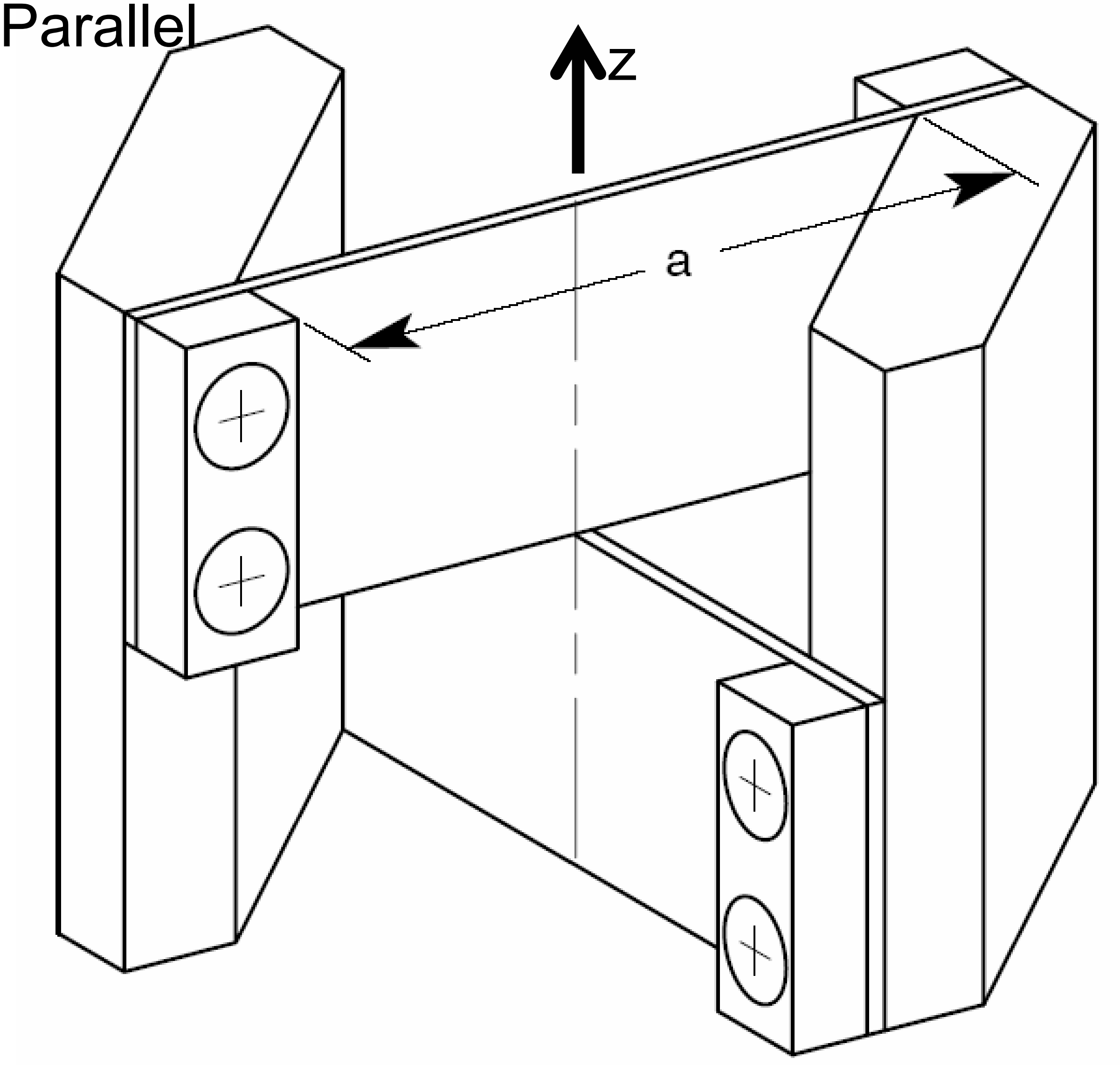
Parallel

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

Figure: Layton Hales PhD Thesis, MIT.

Examples

Parallel



Theta z is a common
Degree of freedom

All others conflict

Figure: Layton Hales PhD Thesis, MIT.

Examples

Parallel

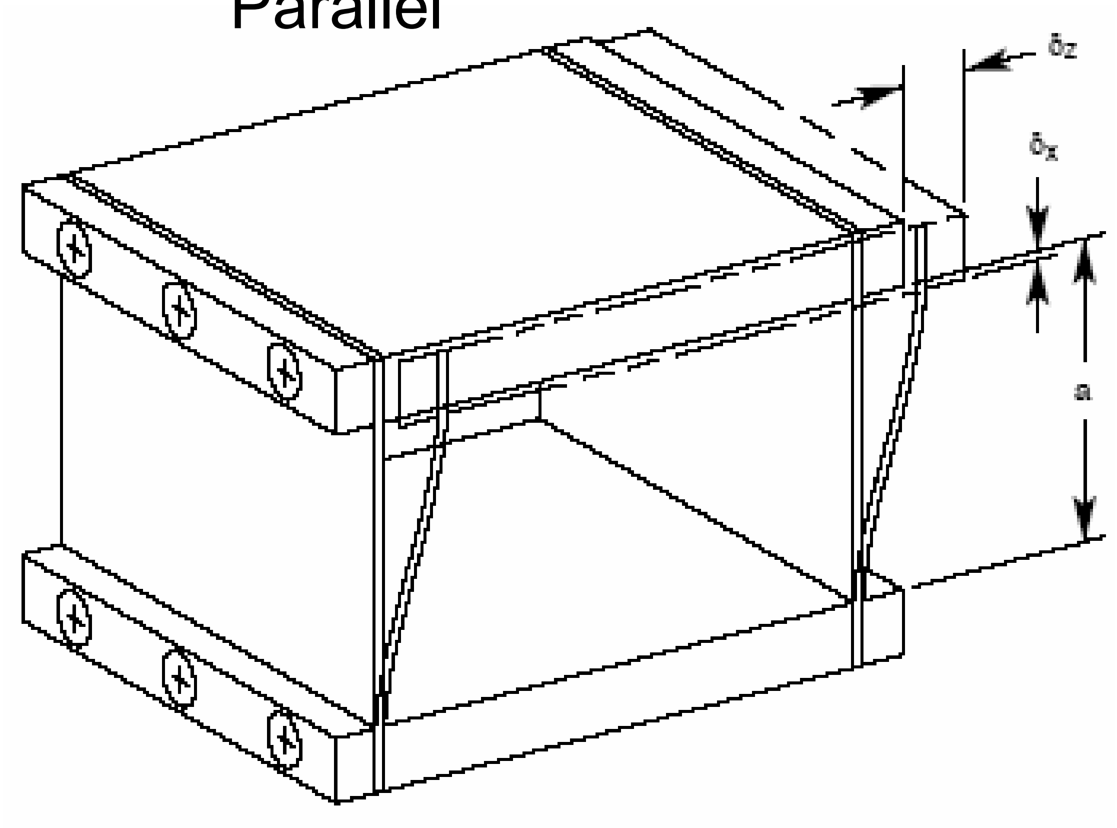


Figure: Layton Hales PhD Thesis, MIT.

δz is a common
Degree of freedom

All others conflict

Rotation arms cause
Conflict in out-of-plane
rotations

Over constraint

Flexures are often forgiving of over constraint

Over constraint = redundant constraint

Identifying over constraint

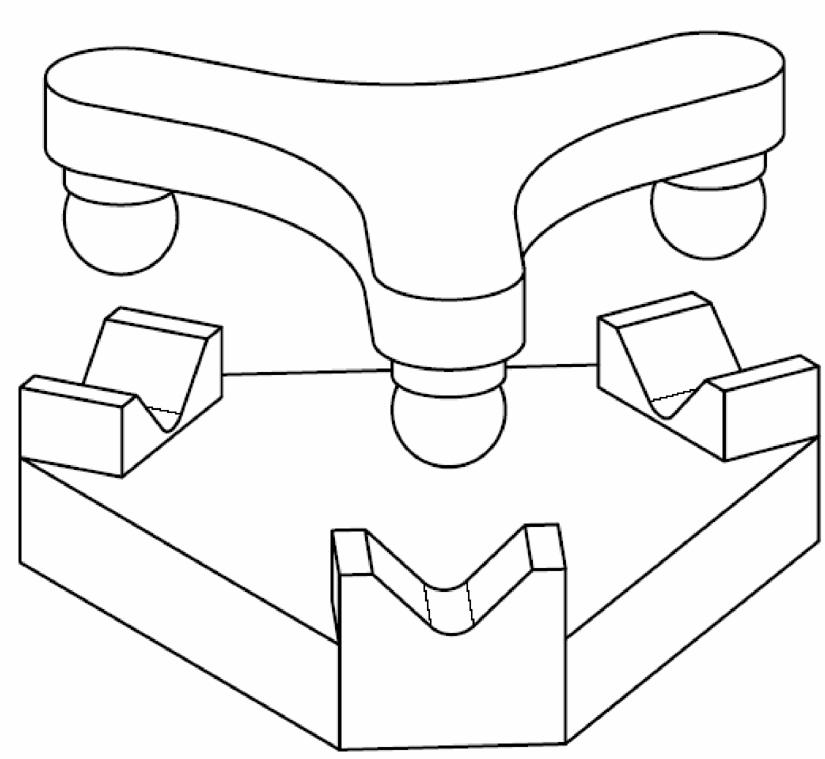
- ☐ How much energy is stored?

General metric relating constraint stiffness to motion along constraint

$$\frac{K_{\parallel}}{K_{\perp}} \cdot \frac{\delta_{\perp}}{\delta_{\parallel}} \rightarrow CM_k \cdot CM_\delta << 1$$

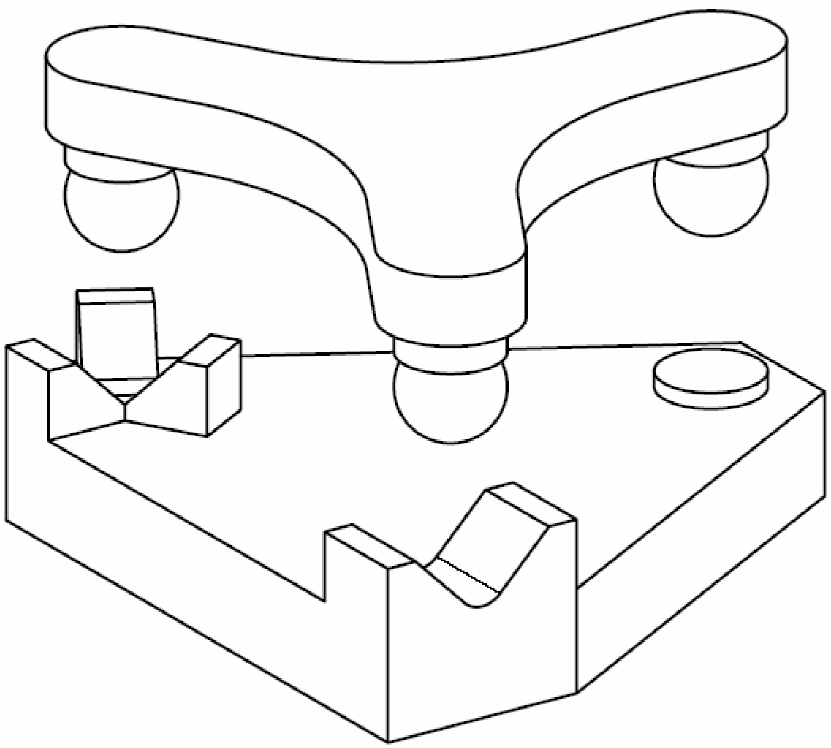
Extension: Fixtures

You will need to build a Passive fixture for your STM



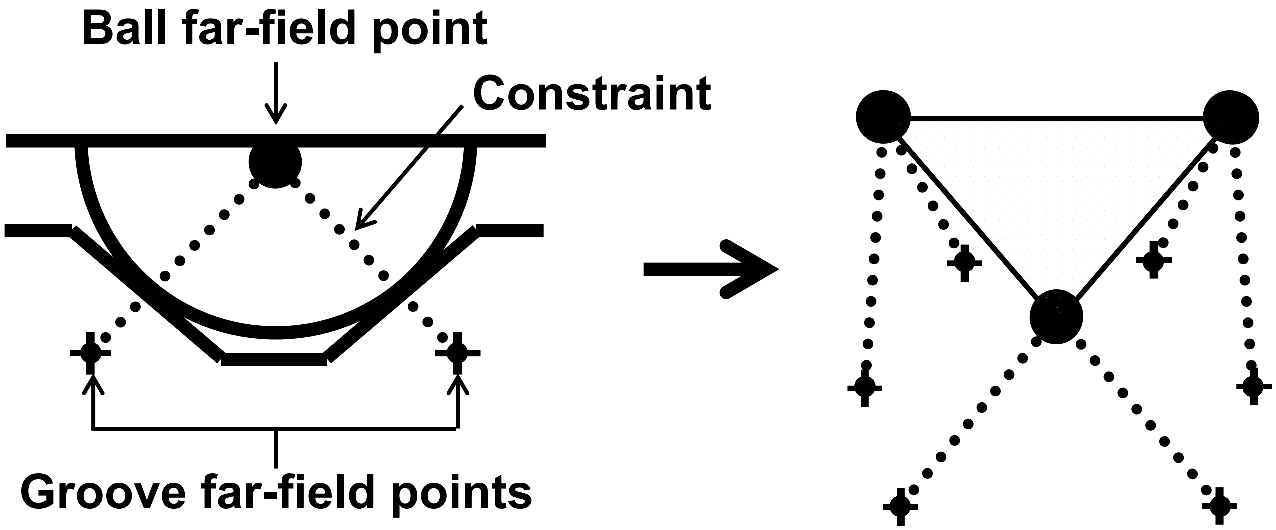
Maxwell

Kelvin



Figures: Layton Hales PhD Thesis, MIT.

Fixtures as mechanisms



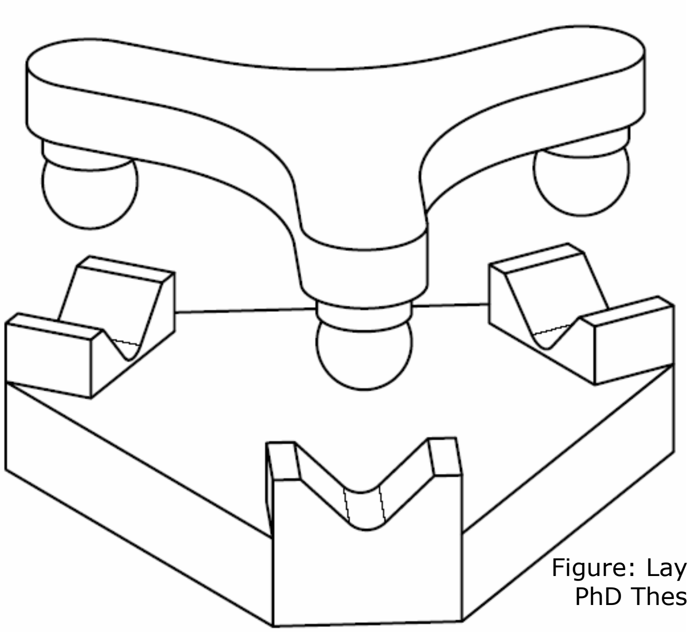


Figure: Layton Hales
PhD Thesis, MIT.

Details of QKC element geometry

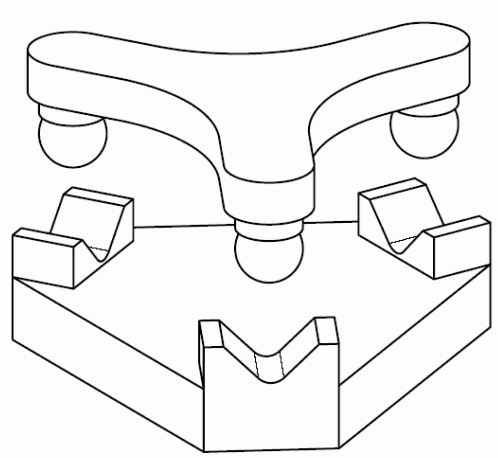
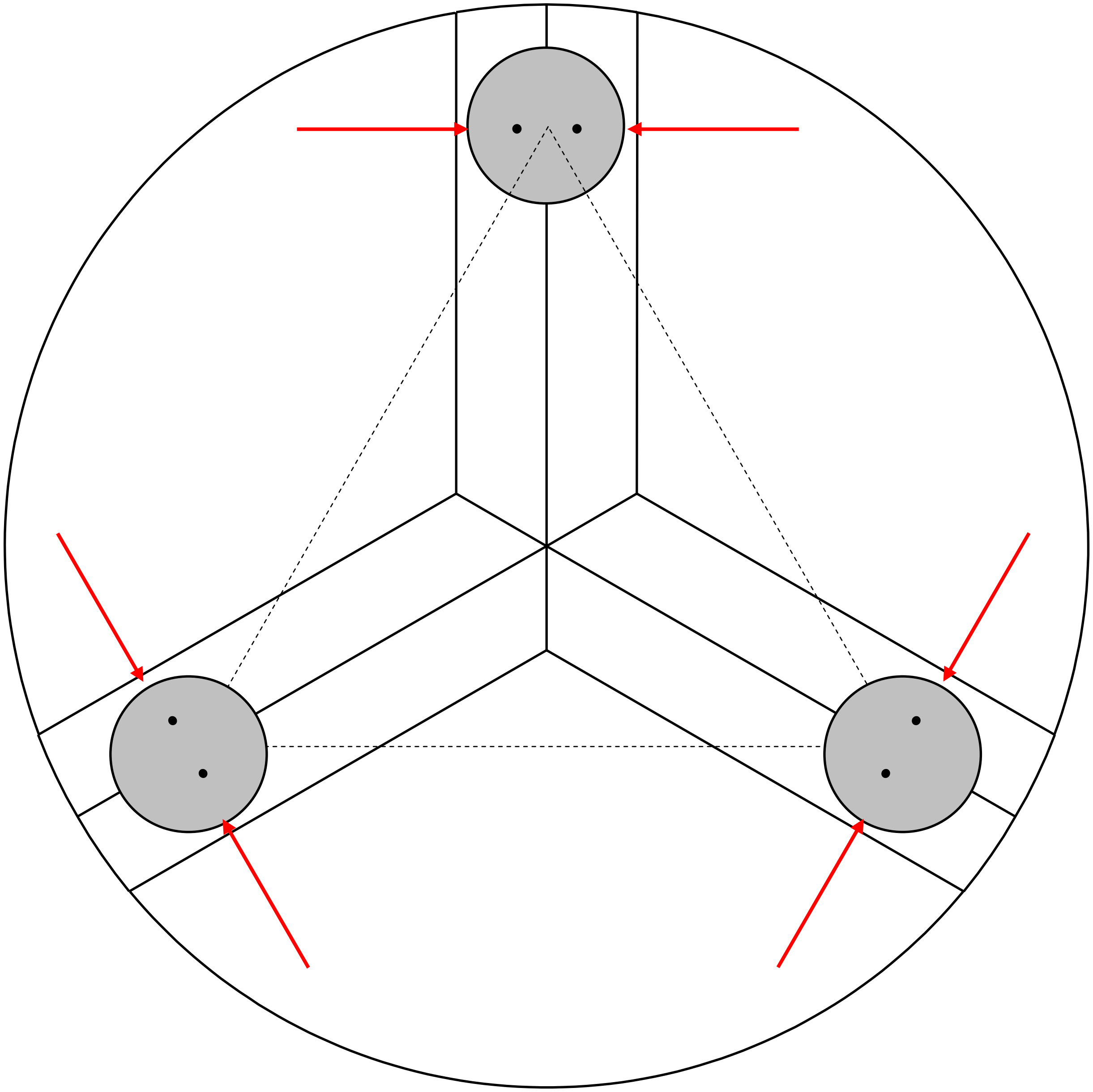
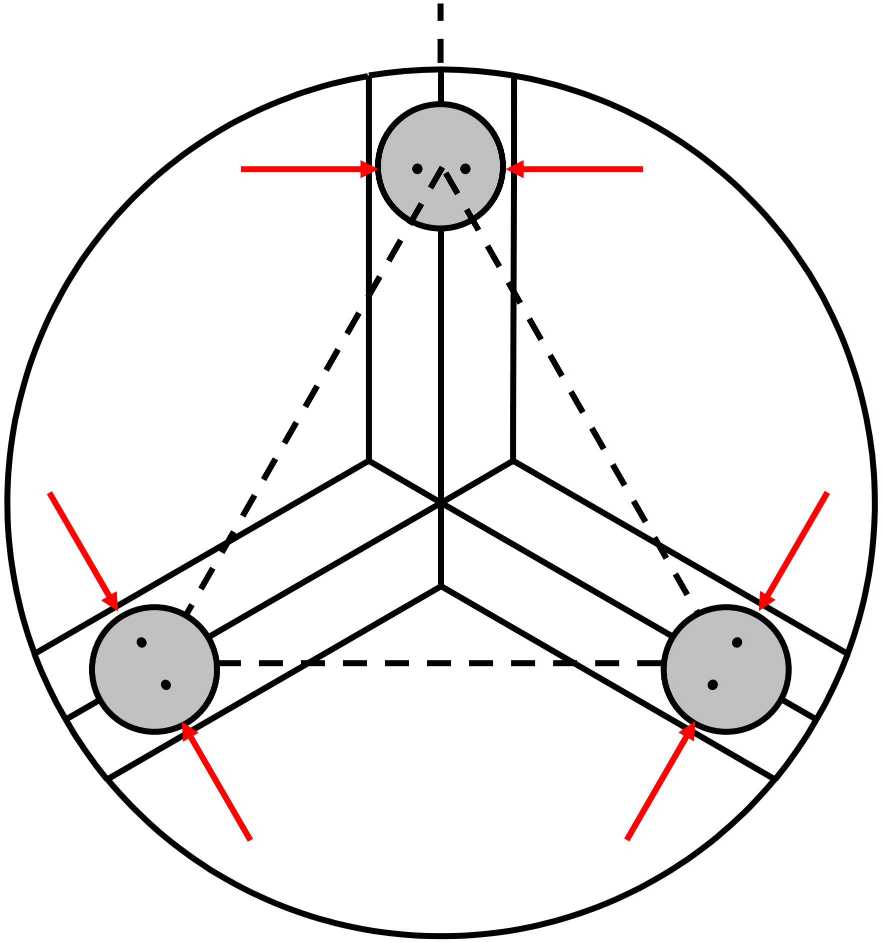


Figure: Layton Hales
PhD Thesis, MIT.

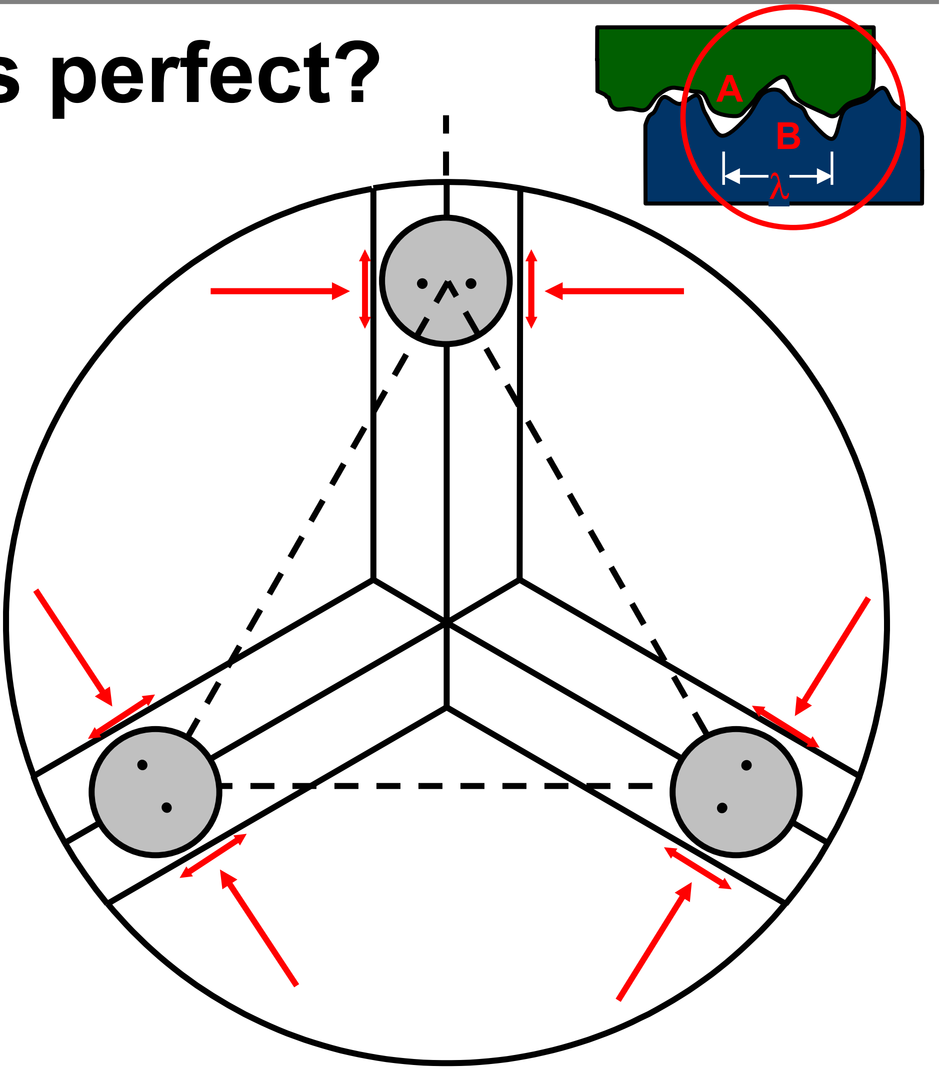


Consequences of friction

Are kinematic couplings perfect?

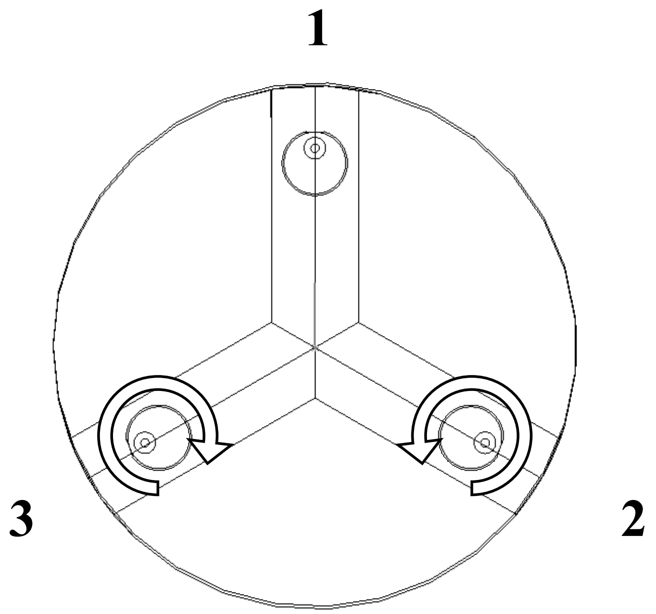


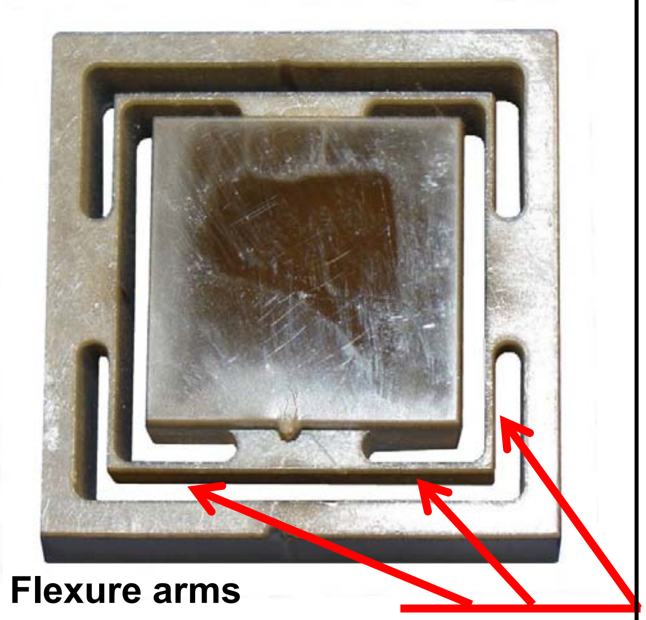
Ideal in-plane constraints

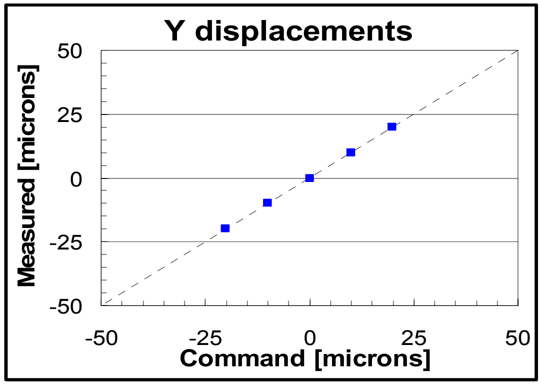


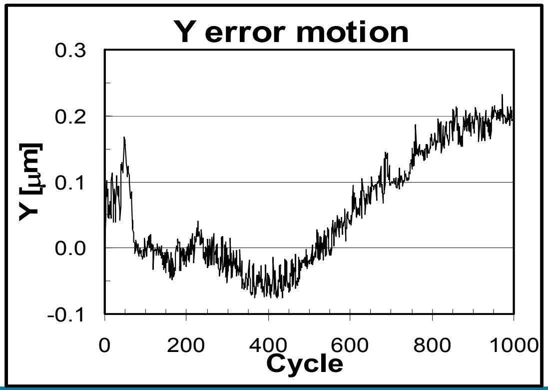
Real in-plane constraints

Flexure grooves reduce friction effect









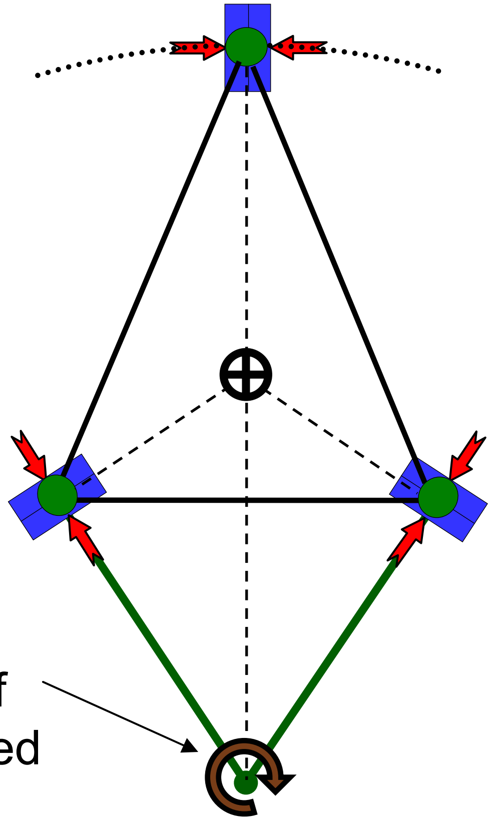
Instant center visualization example

Instant center can help you identify how to best constrain or free up a mechanism

$$\frac{K_{\parallel}}{K_{\perp}} \cdot \frac{\delta_{\perp}}{\delta_{\parallel}} \rightarrow CM_k \cdot CM_\delta << 1$$

Diagram removed for copyright reasons.
Source: Alex Slocum, *Precision Machine Design*.

Poor **Good**



Instant center if ball 1 is removed

Examples

Is it a wise idea to put three balls in three cones while the balls are rigidly attached to a rigid part?

$$\frac{K_{\parallel}}{K_{\perp}} \cdot \frac{\delta_{\perp}}{\delta_{\parallel}} \rightarrow CM_{k} \cdot CM_{\delta} << 1$$

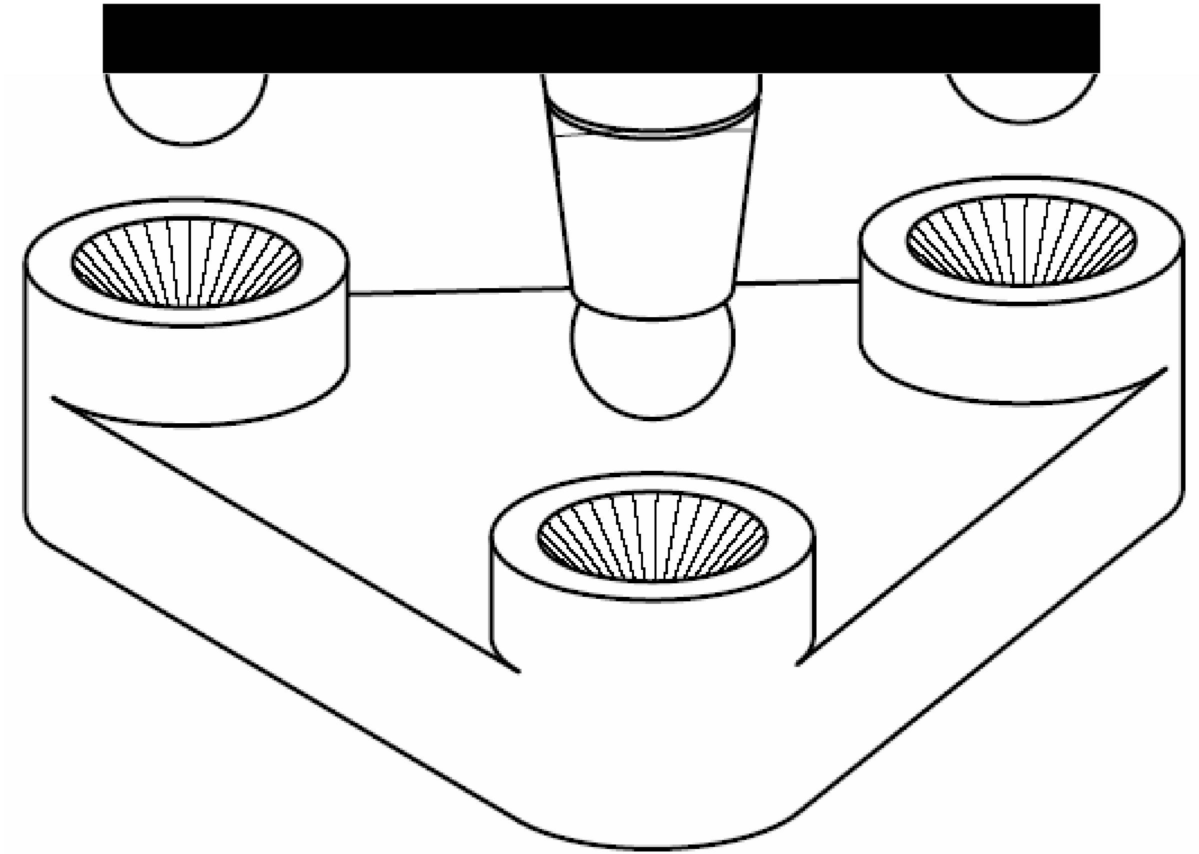
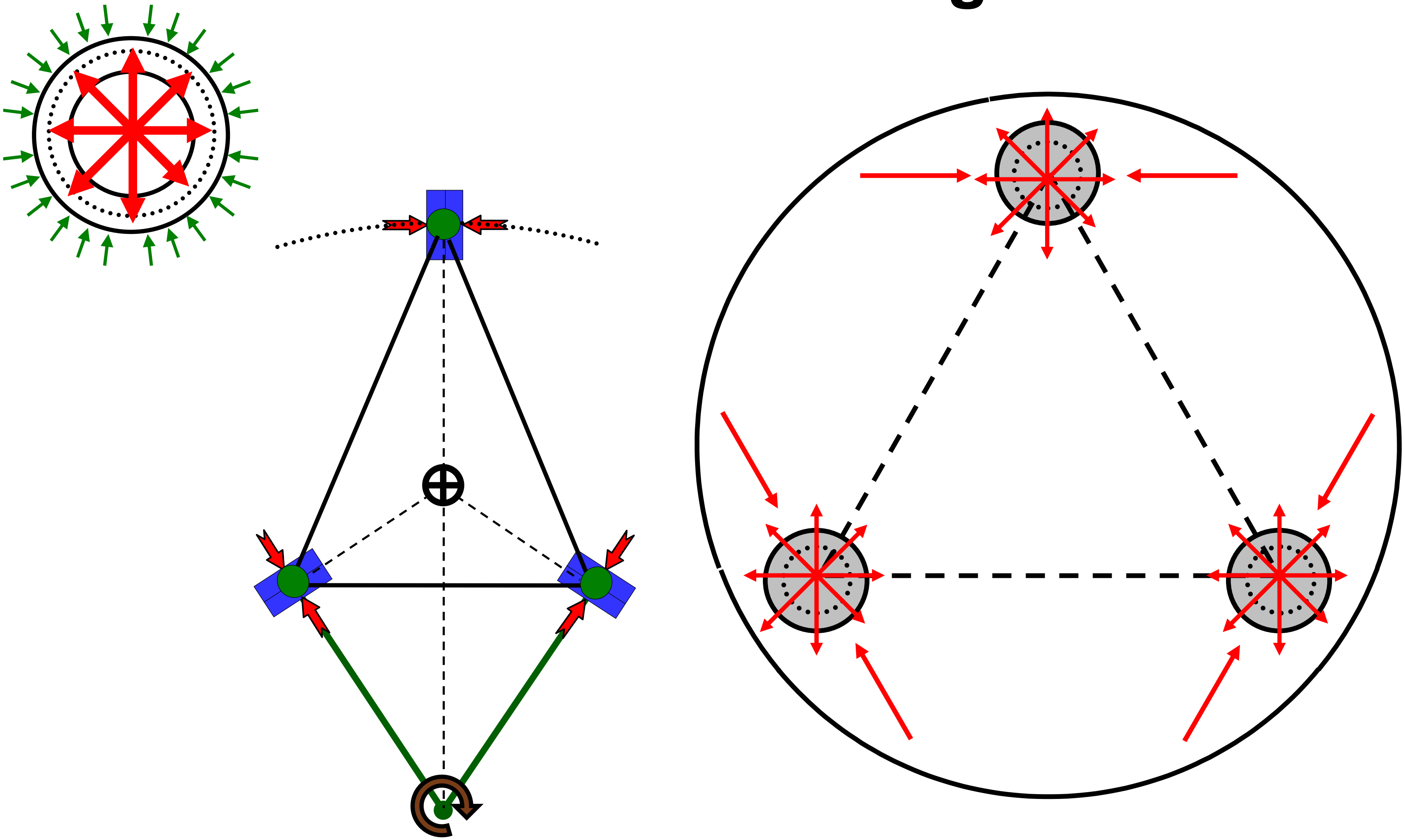


Figure: Layton Hales PhD Thesis, MIT.

In-plane use of flexures

Three balls in three cones

What does the constraint diagram look like?



Use of flexures to avoid over constraint

Flexures provide a very low CM for each joint

- Energy stored due to over constraint is minimized
- Energy is channeled through continuously variable
- Is possible to reach a true minimum

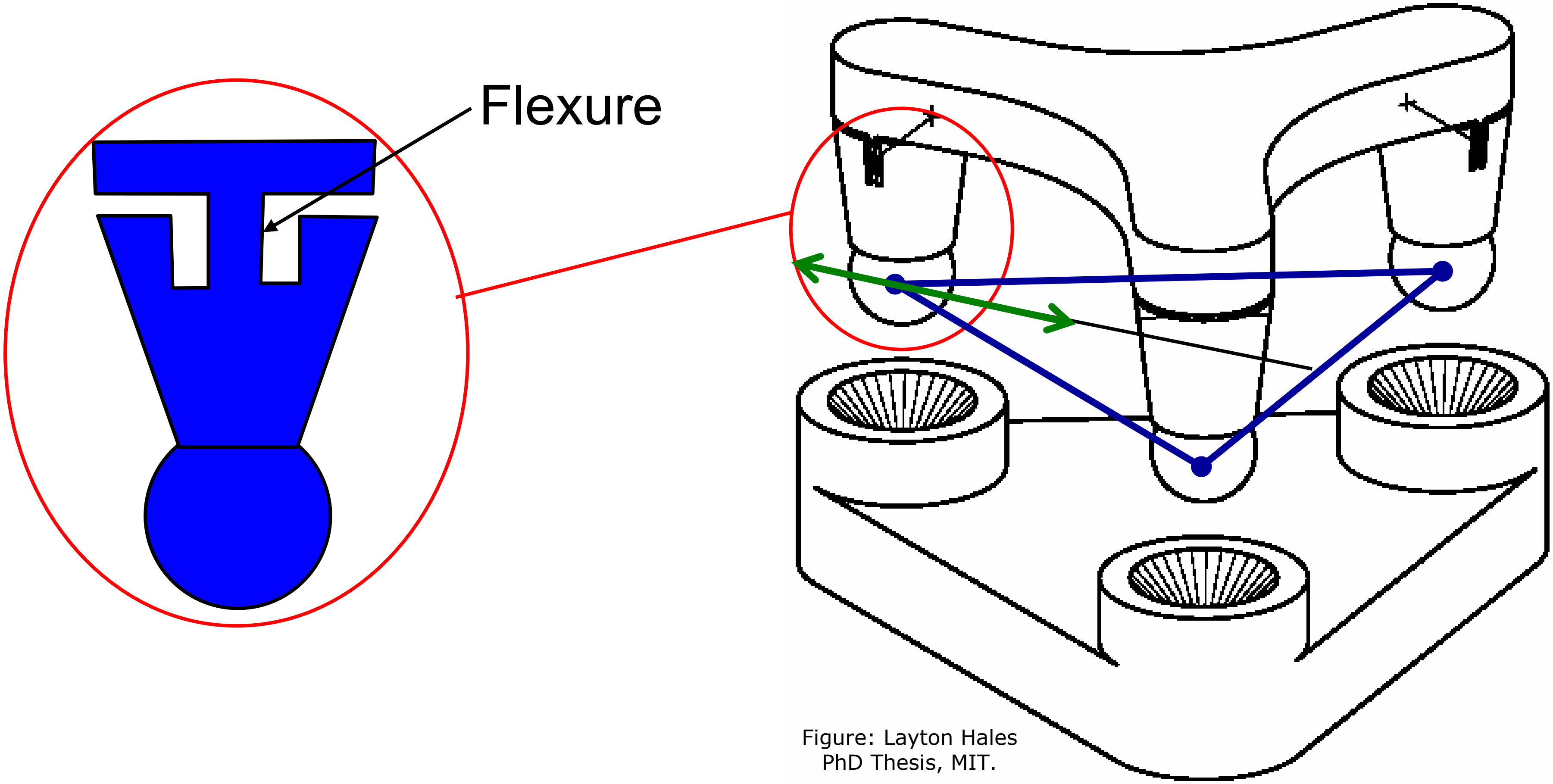
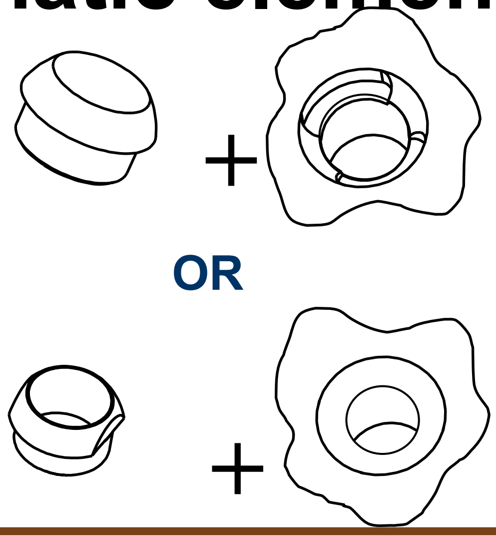


Figure: Layton Hales
PhD Thesis, MIT.

Low-cost couplings

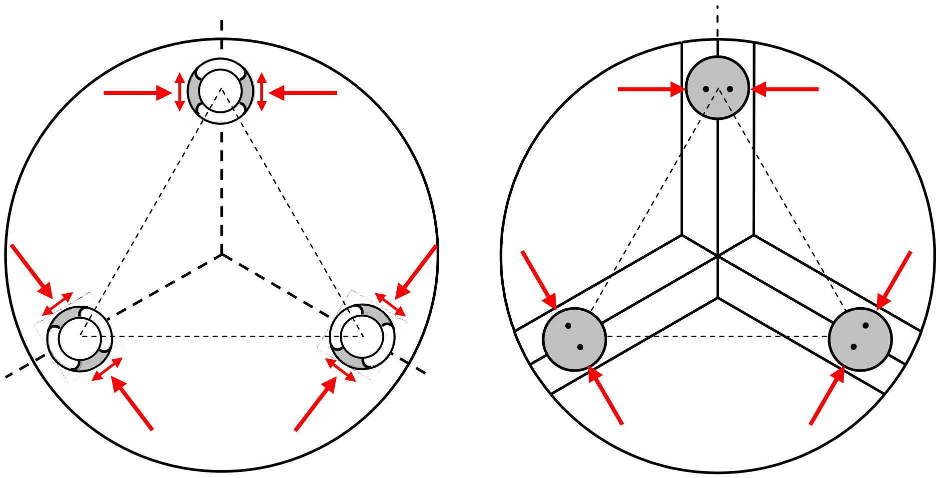
Kinematic elements



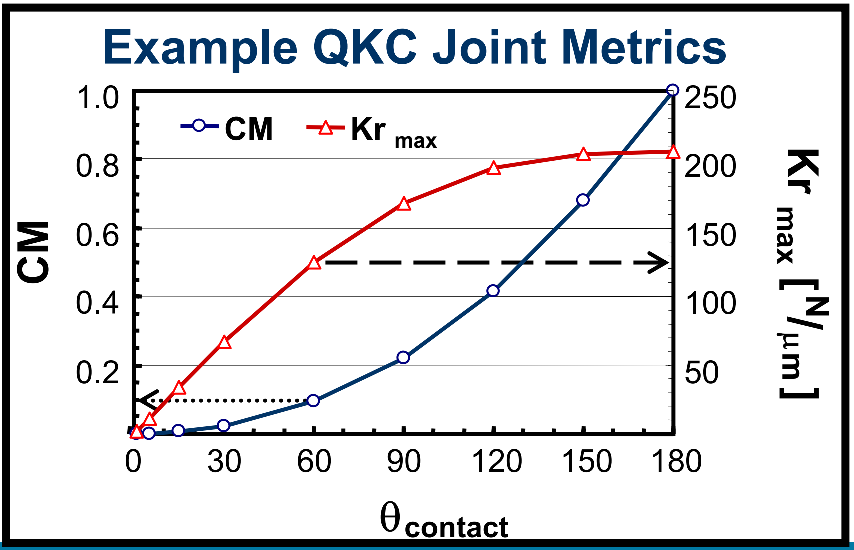
Manufacturing

Diagrams removed for copyright reasons.
“Cast + Form Tool = Finished”

Constraint diagrams



Metrics

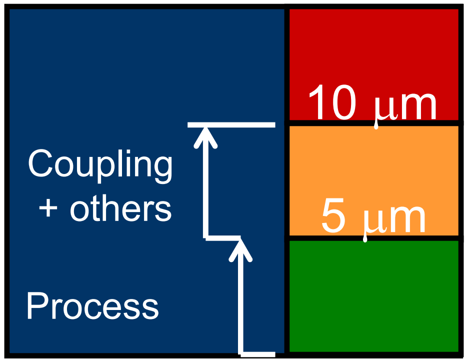


Case study: Duratec engine

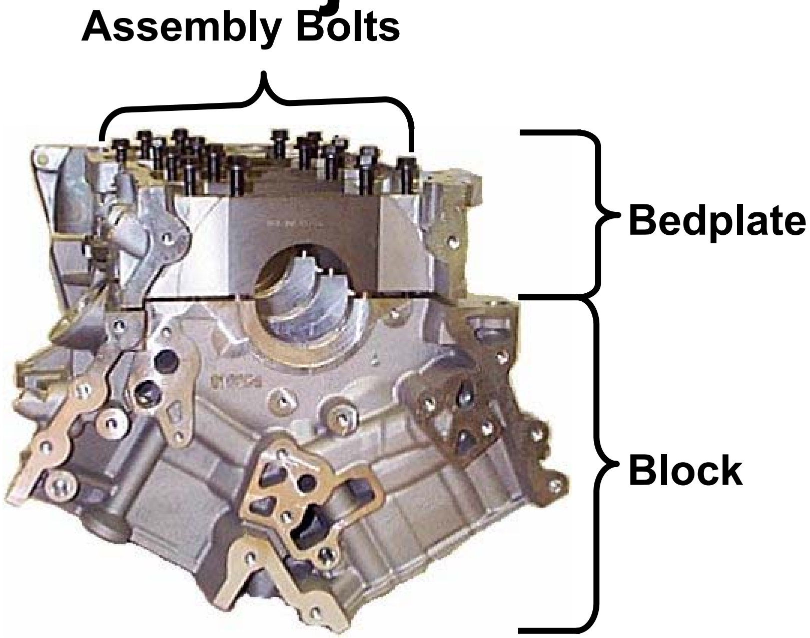
Components

Block

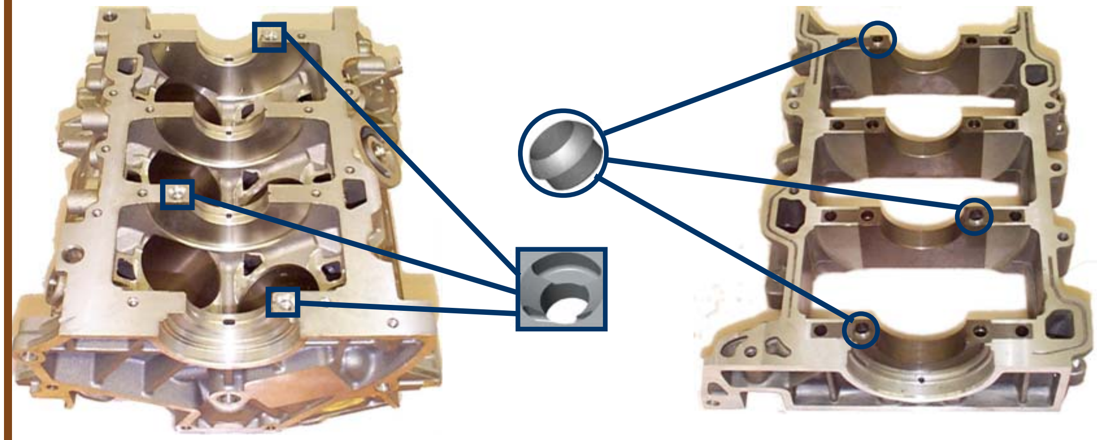
Bedplate



Pinned joint



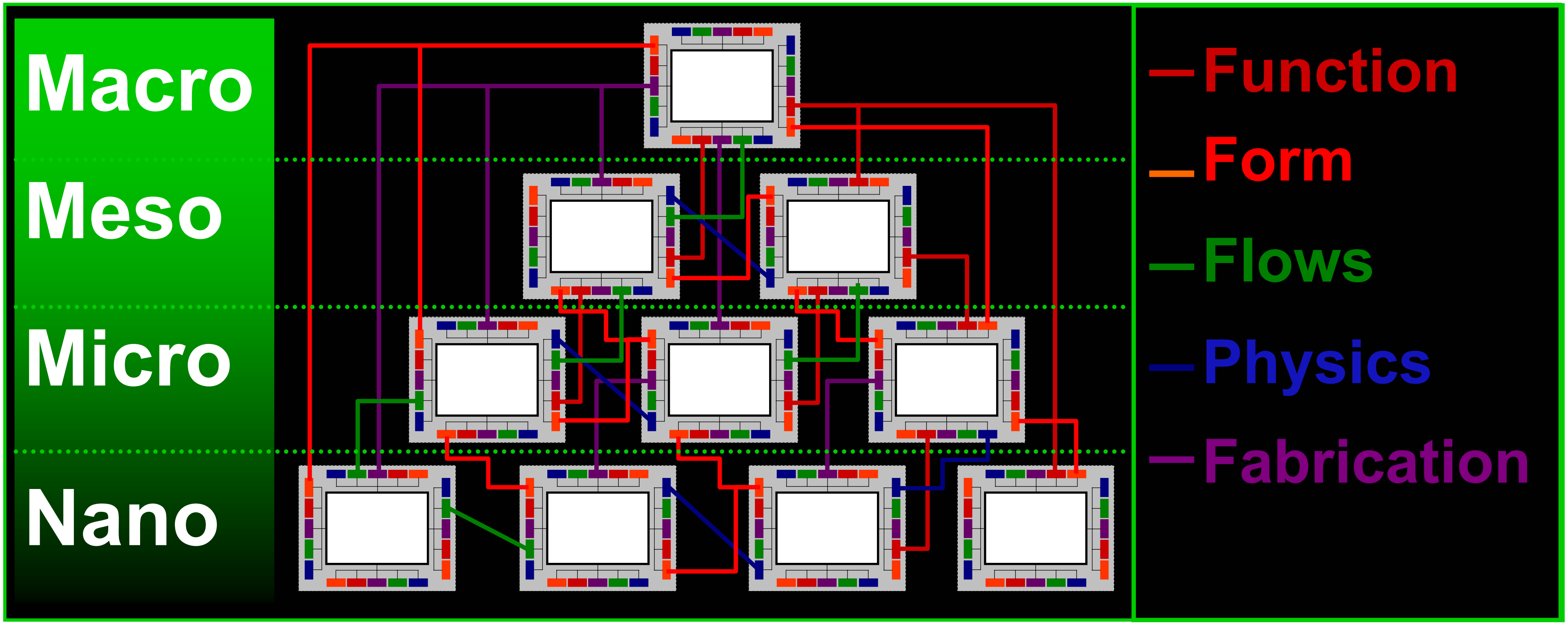
QKC



Photos by Prof. Martin Culpepper, courtesy of Ford Motor Company. Used with permission.

Micro-scale systems

Cross-scale coupling



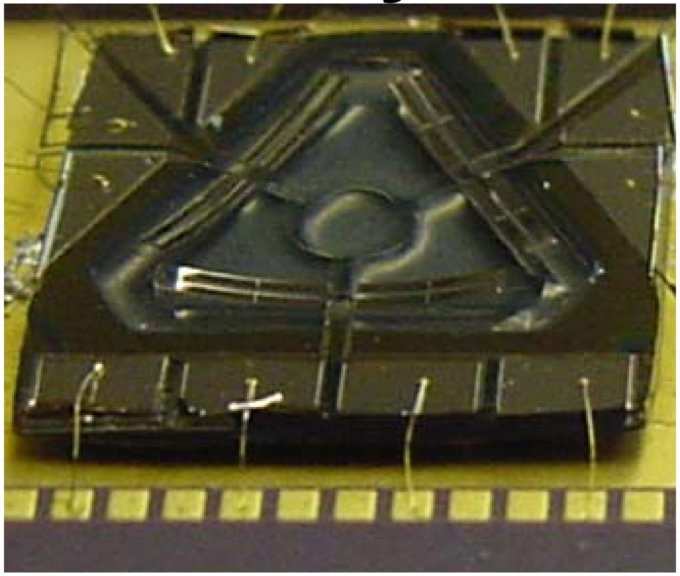
Function	Form	Flow	Physics	Fabrication
What	Geometry	Mass	Application	Compatibility
Who	Motion	Momentum	Modeling	Quality
Why	Interfaces	Energy	Limiting	Rate
Where	Constraints	Information	Dominant	Cost
Etc…	Etc…	Etc…	Etc…	Etc…

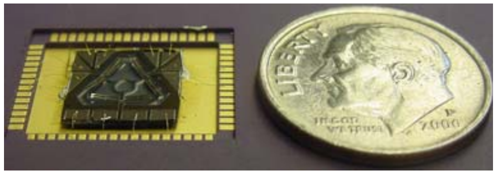
Micro-scale MuSS main challenges

Fabrication is fundamentally different

- ☐ Chemical
- ☐ Molecular
- ☐ Ballistic

- ☐ Finished geometry
- ☐ Possible geometries

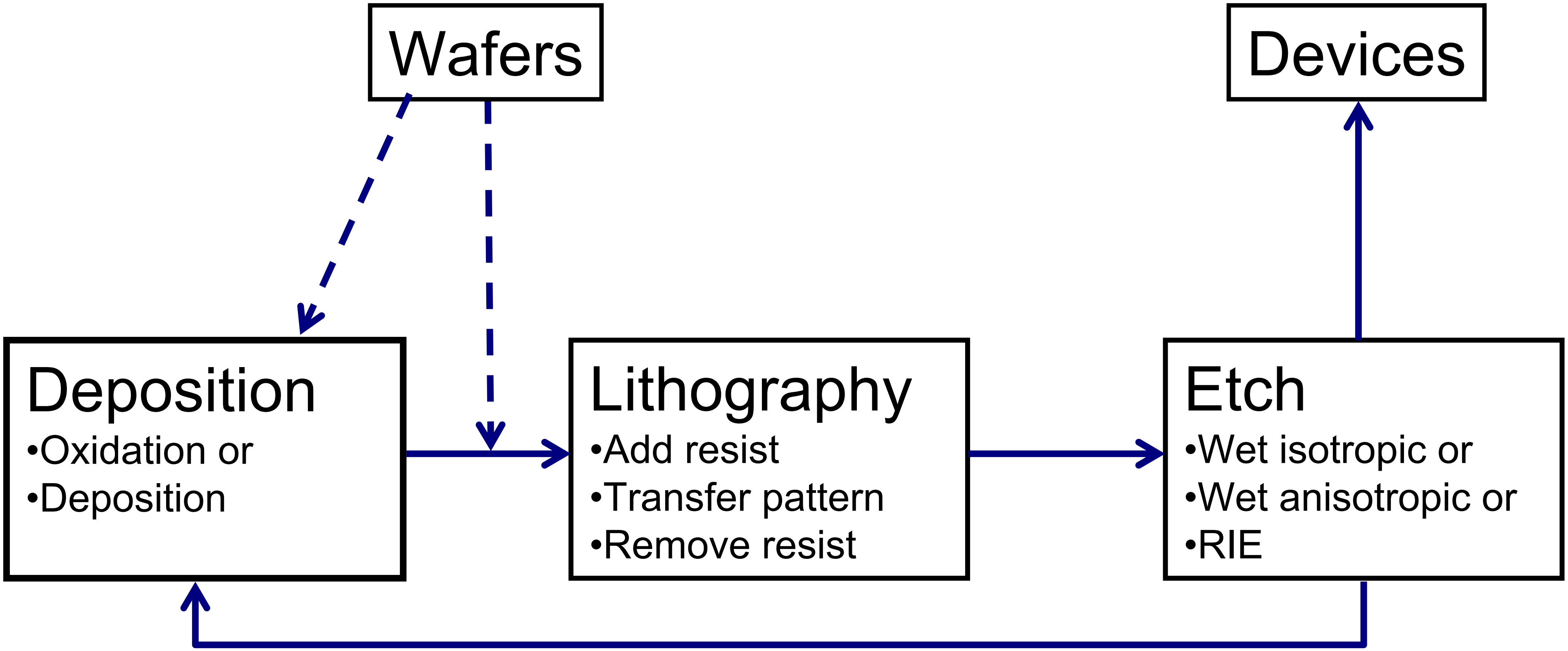




Physics "rounding" is no longer acceptable

- ☐ Surface forces
- ☐ Thermal time constants
- ☐ Strains

General process



Wafers

Devices

Deposition
- Oxidation or
- Deposition

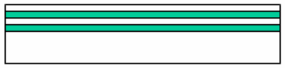
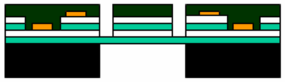
Lithography
- Add resist
- Transfer pattern
- Remove resist

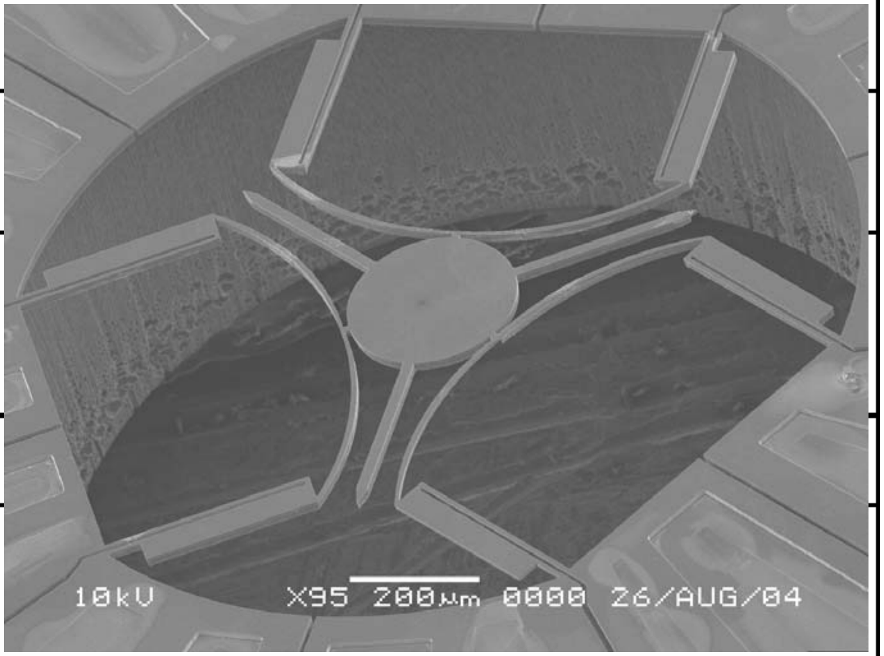
Etch
- Wet isotropic or
- Wet anisotropic or
- RIE

Bulk micromachining = Removal of the wafer

Surface micromachining = Add/remove layers

MiHx fabrication

Step	Recipe/Description
	Double deck SOIOI; Device layers @ 8 microns thickness; Oxide at 1 micron thickness
	Photoresist and pattern
	DRIE (Si) and BOE Oxide
	Pattern AL contacts at 350 nm thickness
	Photoresist and pattern
	DRIE (Si) and BOE Oxide and DRIE (Si)
	Pattern handle wafer; Mount to quartz wafer; DRIE backside etch
	Release with vapor HF
	Remove resist via plasma etch



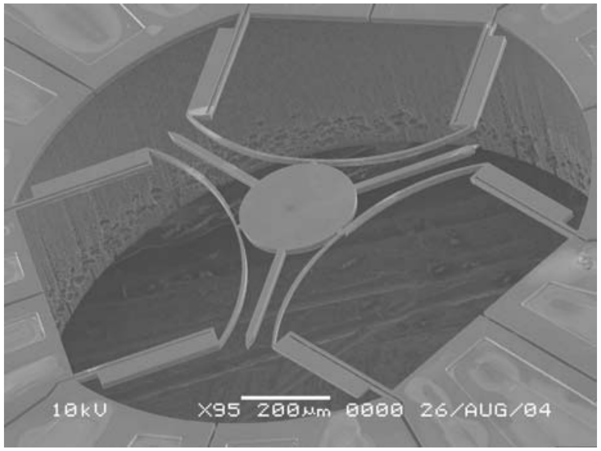
Micro-scale physics

For strong dependence on characteristic length, importance of phenomena decreases with characteristic dimension

❑ Body	L^3

For weaker dependence on characteristic length, phenomena become dominate at small scale

❑ Electrostatic	L^2
❑ Thermal	L
❑ Surface tension	L^2

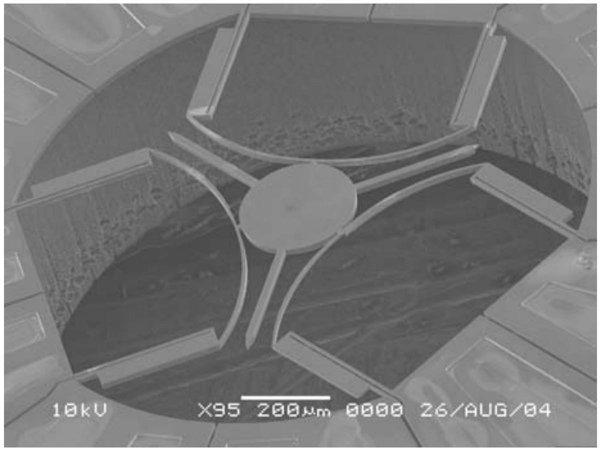


Micro-scale physics

Find the parts ALL of the flows that could exist.

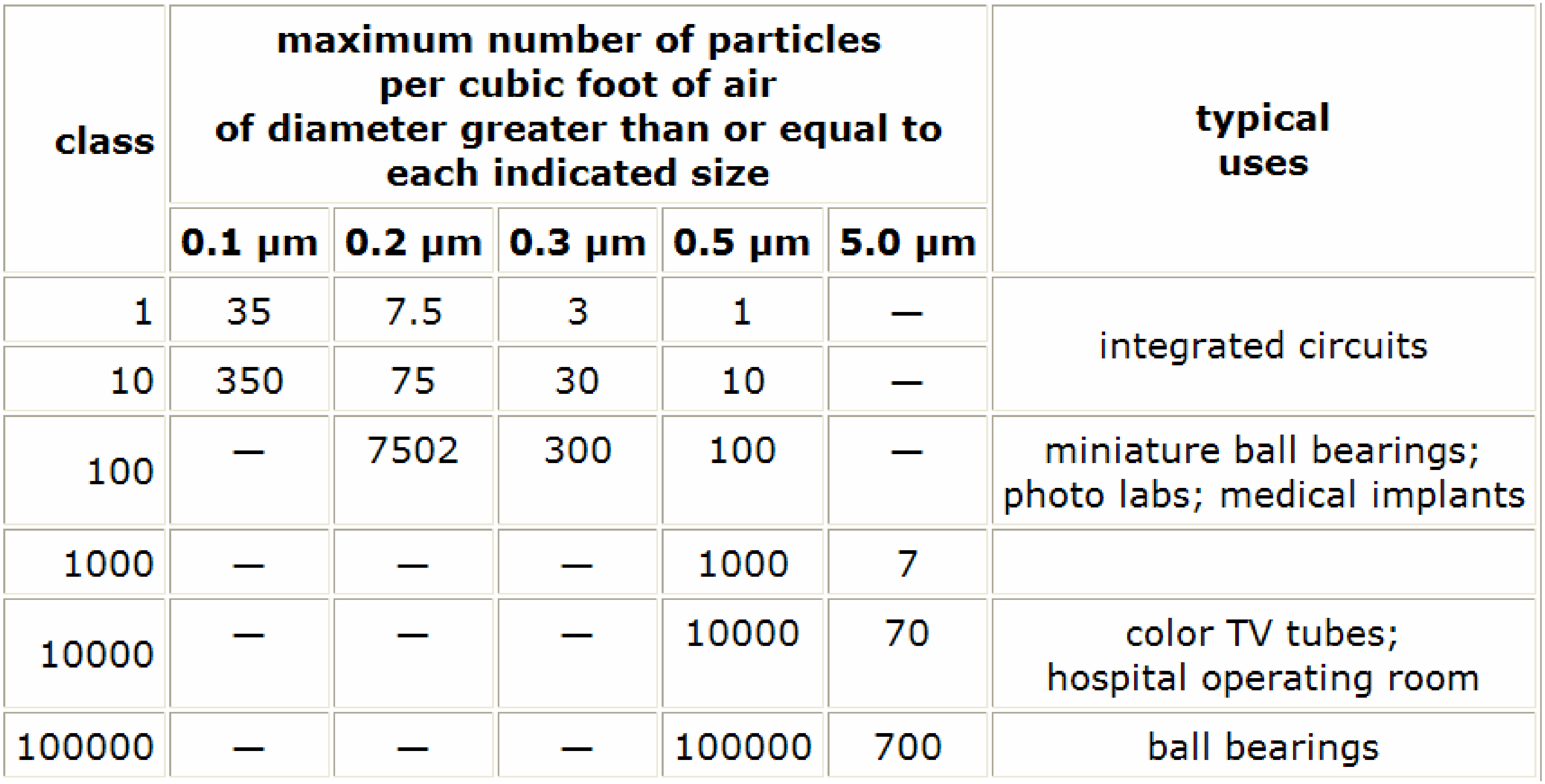
Until you gain intuition you must analyze them all with OOM and ratios…

Take ratio of important flows



Apply physics without physics “rounding”

Clean rooms and particles



class	maximum number of particles per cubic foot of air of diameter greater than or equal to each indicated size					typical uses
	0.1 µm	0.2 µm	0.3 µm	0.5 µm	5.0 µm	
1	35	7.5	3	1	—	integrated circuits
10	350	75	30	10	—	
100	—	7502	300	100	—	miniature ball bearings; photo labs; medical implants
1000	—	—	—	1000	7	
10000	—	—	—	10000	70	color TV tubes; hospital operating room
100000	—	—	—	100000	700	ball bearings

Micro-scale physics: Electrostatics

How does electrostatic physics scale?

$$U_E = \frac{\varepsilon_o \cdot L \cdot L \cdot V^2}{2 \cdot z}$$

How does ratio of $F_{Electric}$ scale to F_{Body}?

$$\left| \frac{F_{Electric}}{F_{Body}} \right| \sim \frac{1}{L}$$

What does this mean for MuSS interaction?

- ☐ What happens if you downsize each by factor of 10?

What does this mean for the STM project?

Micro-scale physics: Thermal

How does thermal physics scale?

$$\boxed{Bi = \frac{h \cdot L}{k}}$$

$$-h \cdot A \cdot (T - T_{\inf}) = \rho \cdot c \cdot \cancel{V} \cdot \frac{dT}{dt}$$

$$e^{\left[-\left(\frac{h \cdot A}{\rho \cdot \cancel{V} \cdot c}\right) \cdot t\right]} = \frac{\theta}{\theta_{\inf}} = \frac{T - T_{\inf}}{T_{initial} - T_{\inf}}$$

$$\tau \sim \frac{\rho \cdot \cancel{V} \cdot c}{h \cdot A} \rightarrow L$$

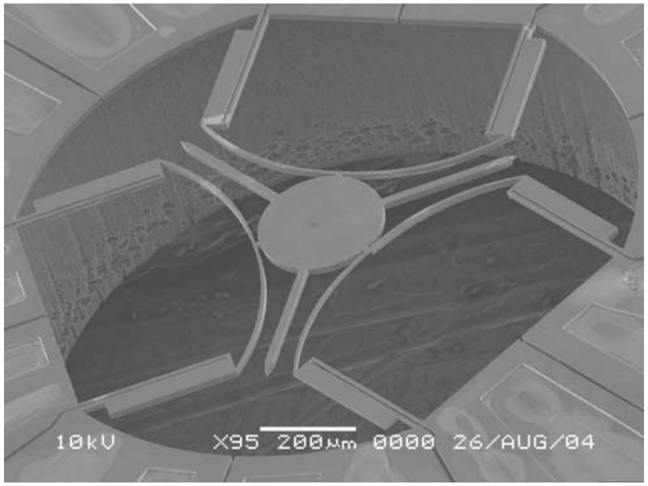
Is this a good or a bad thing for MEMS actuators?

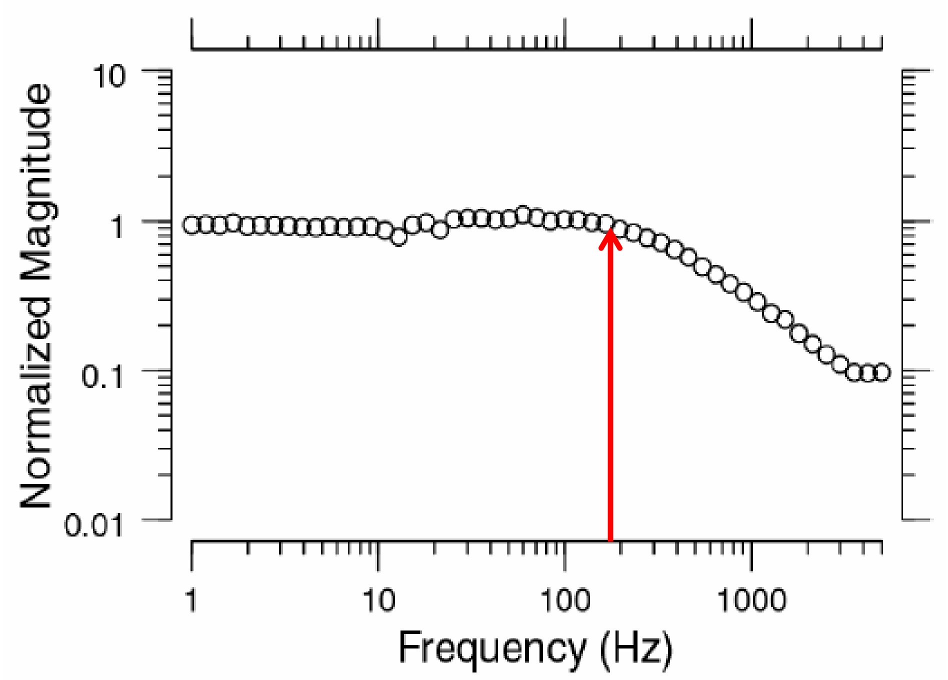
For the STM?

Micro-scale physics: Thermal

Cooling…

Heating…





Assignment

What are the implications for rinsing suspended MEMS devices clean of acids in distilled water? For example you might model a cantilever which of course has a finite stiffness…

Comment on humidity and MEMS devices

1 page maximum!!!

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Email to course secretary by Wednesday 5pm.