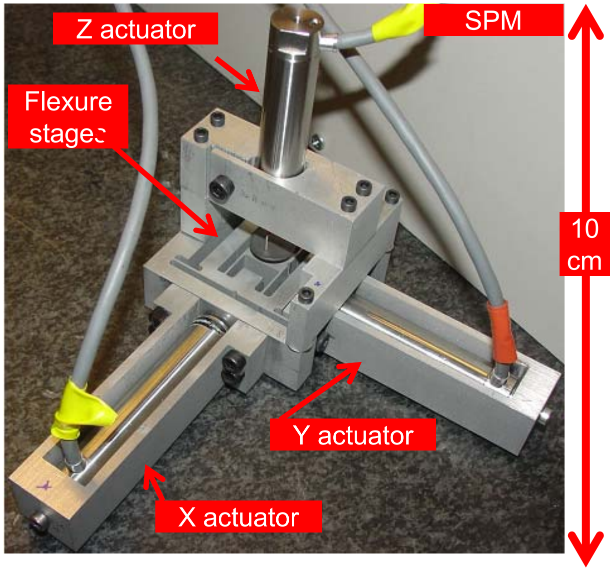
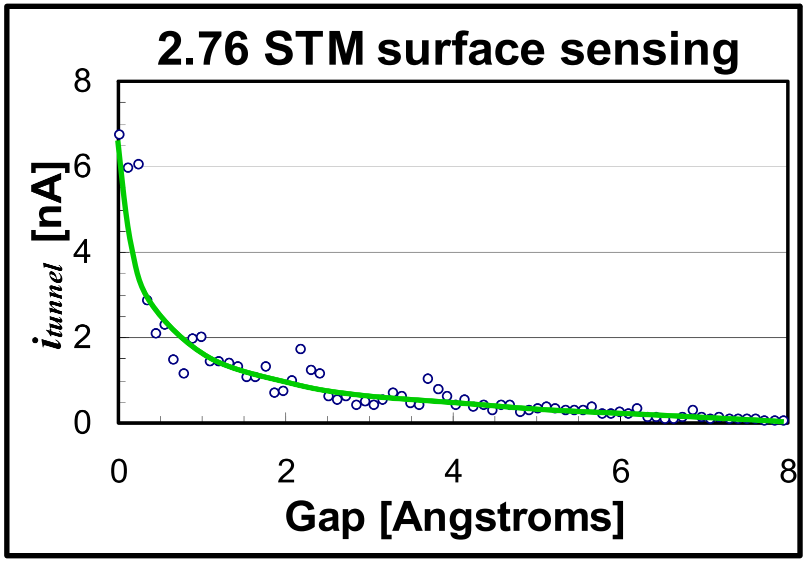
2.76 / 2.760 Lecture 6: Micro-Nano-STM

Micro-scaling

Nano-scaling

STM project





Purpose of today

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

Finish micro-scale gain factors

Nano-scale phenomena (to be cont.)

STM project start

Micro-scale systems cont.

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: Electrostatic

$$\begin{tikzcd} U_{Electric-z} = \frac{\varepsilon_o \cdot L \cdot L \cdot V^2}{2 \cdot z} \arrow[r] & F_{Electric-z} = -\frac{dU}{dz} \arrow[r] & F_{Electric-z} = \frac{\varepsilon_o \cdot L^2 \cdot V^2}{2 \cdot z^2} \arrow[dl] \\ & F_{body} = \rho \cdot V^3 \arrow[r] & \left| \frac{F_{Electric}}{F_{Body}} \right| \sim \frac{1}{L} \end{tikzcd}$$

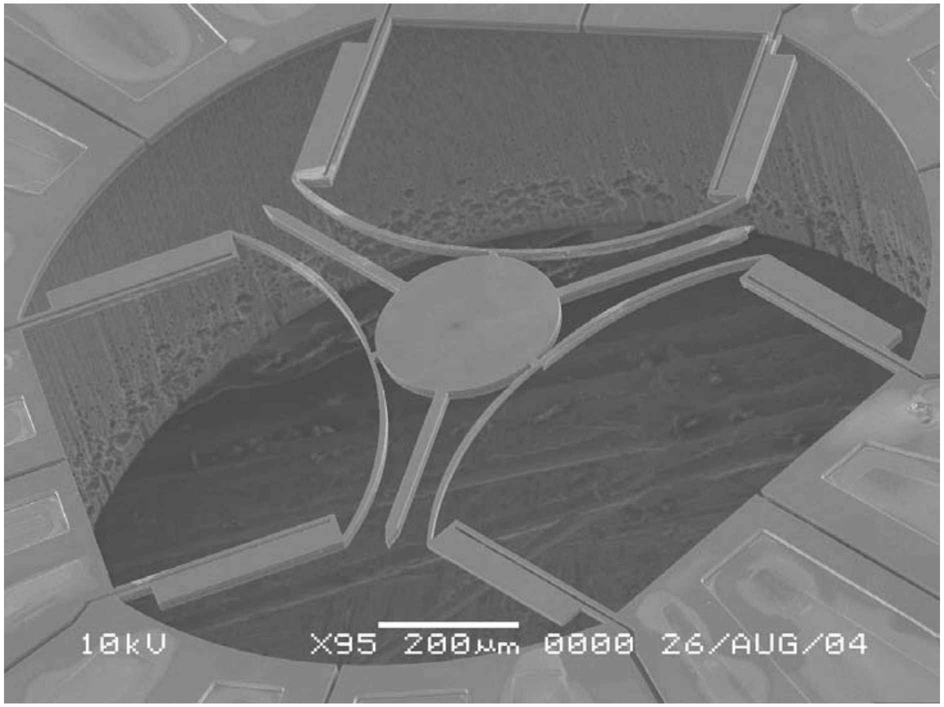
class	maximum number of particles per cubic foot of air of diameter greater than or equal to each indicated size					typical uses
	0.1 µm	**0.2 µm**	**0.3 µm**	**0.5 µm**	**5.0 µm**	
1	35	7.5	3	1	—	integrated circuits
10	350	75	30	10	—	
100	—	7502	300	100	—	miniature ball bearings; photo labs; medical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

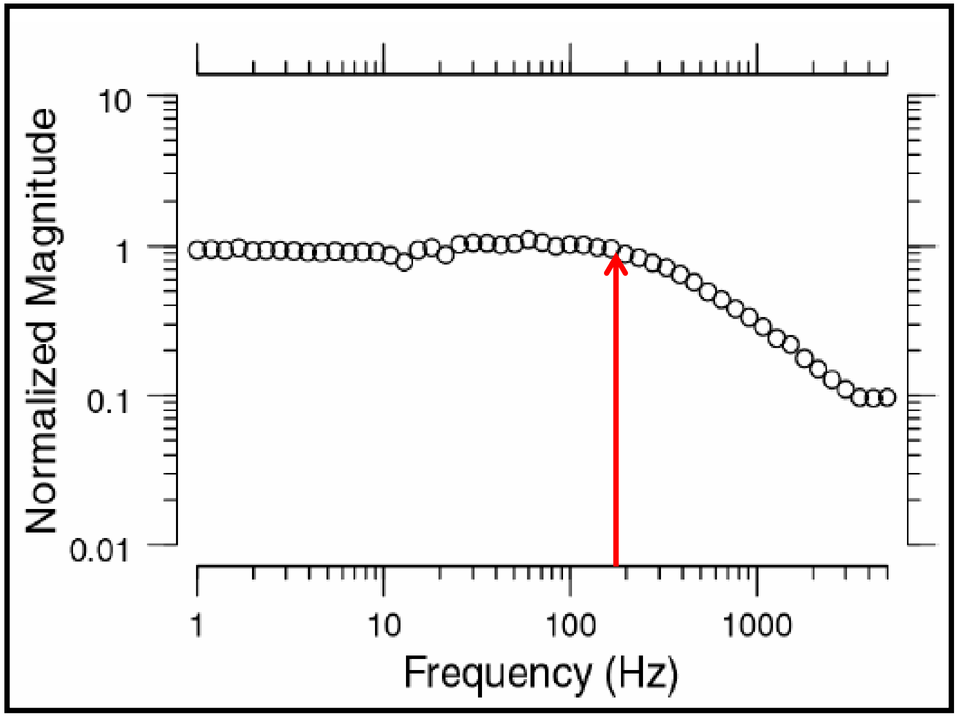
Micro-scale physics: Thermal

How does thermal physics scale (small Bi #)?

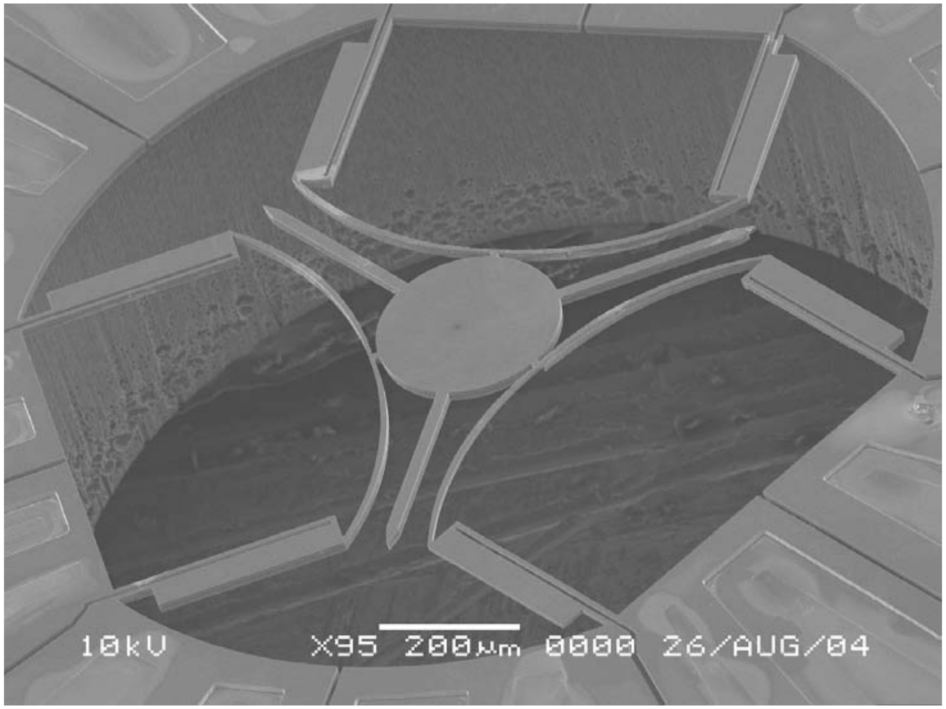
$$e^{\left[-\left(\frac{h\cdot A}{\rho\cdot \cancel{V}\cdot c}\right)\cdot t\right]} = \frac{\theta}{\theta_{\inf}} = \frac{T - T_{\inf}}{T_{initial} - T_{\inf}}$$

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





Micro-scale physics: Dynamics



$$\omega_n = \sqrt{\frac{k}{m}} \sim \sqrt{\frac{E \cdot f(\text{topology})}{\rho \cdot V}} \rightarrow \sqrt{\frac{E \cdot f\left(L^A, h^B, w^C\right)}{\rho \cdot f\left(L^D, h^E, w^F\right)}}$$

$$\alpha = A + B + C - D - E - F$$

Micro-scale physics: Dynamics

How does natural frequency scale?

$$\omega_n = \sqrt{\frac{k}{m}} \sim \sqrt{\frac{E\cdot f(\text{topology})}{\rho\cdot V}} \rightarrow \sqrt{\frac{E\cdot f\left(\overset{\sim -3}{L^A}, \overset{\sim 3}{h^B}, \overset{\sim 1}{w^C}\right)}{\rho\cdot f\left(\underset{\sim 1}{L^D}, \underset{\sim 1}{h^E}, \underset{\sim 1}{w^F}\right)}}$$

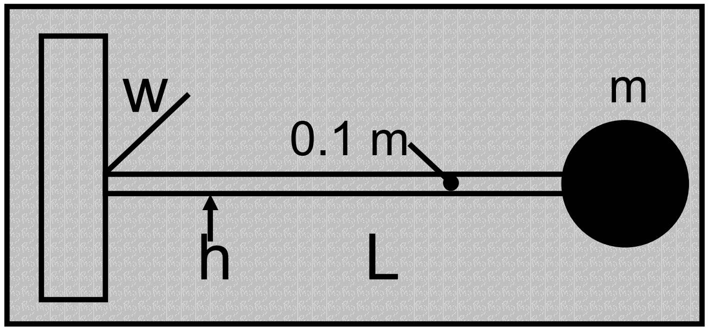
$$\delta = F\frac{L^3}{3\cdot E\cdot I} = F\frac{L^3}{3\cdot E\cdot \frac{w\cdot h^3}{12}}$$

$$k = \frac{dF}{d\delta} = \frac{E}{12}\cdot\frac{w\cdot h^3}{L^3} \sim C_1\cdot[L]$$

$$m = 10\cdot\rho\cdot L\cdot h\cdot w \sim C_2\cdot\left[L^3\right]$$

$$\omega_n = \sqrt{\frac{k}{m}} \approx C_3\cdot\sqrt{\frac{L}{L^3}} \rightarrow \left[\frac{1}{L}\right]$$

$$\alpha = -2$$

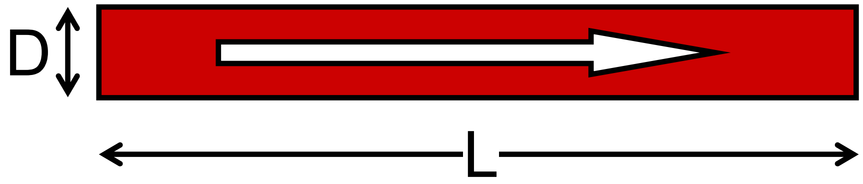


Micro-scale physics: Fluidics

How do fluid-based physical phenomena scale?

$$Q = \frac{\pi \cdot \boxed{r^4} \cdot \Delta p}{8 \cdot \mu \cdot L}$$

$$Q = U \cdot \pi \cdot r^2$$



$$\Delta p = -\frac{8 \cdot \mu \cdot U}{\boxed{r^2}} \cdot L$$

High pressure change over narrow flow paths…

Reynolds number

$$\mathrm{Re} = \frac{\rho \cdot U \cdot D}{\mu} \longrightarrow \text{Ratio of inertial forces to viscous forces}$$

D = 50 μm

U = 500 μm/s

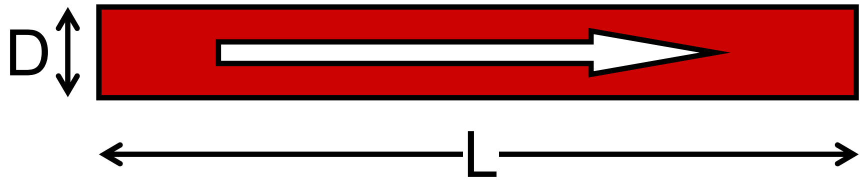
L = 1000 μm

Re_{Air} and $\mathrm{Re}_{H2O} << 1$

Heavily damped, limits response time (ms vs. μs)

Micro-scale physics: Fluidics

Reynolds number



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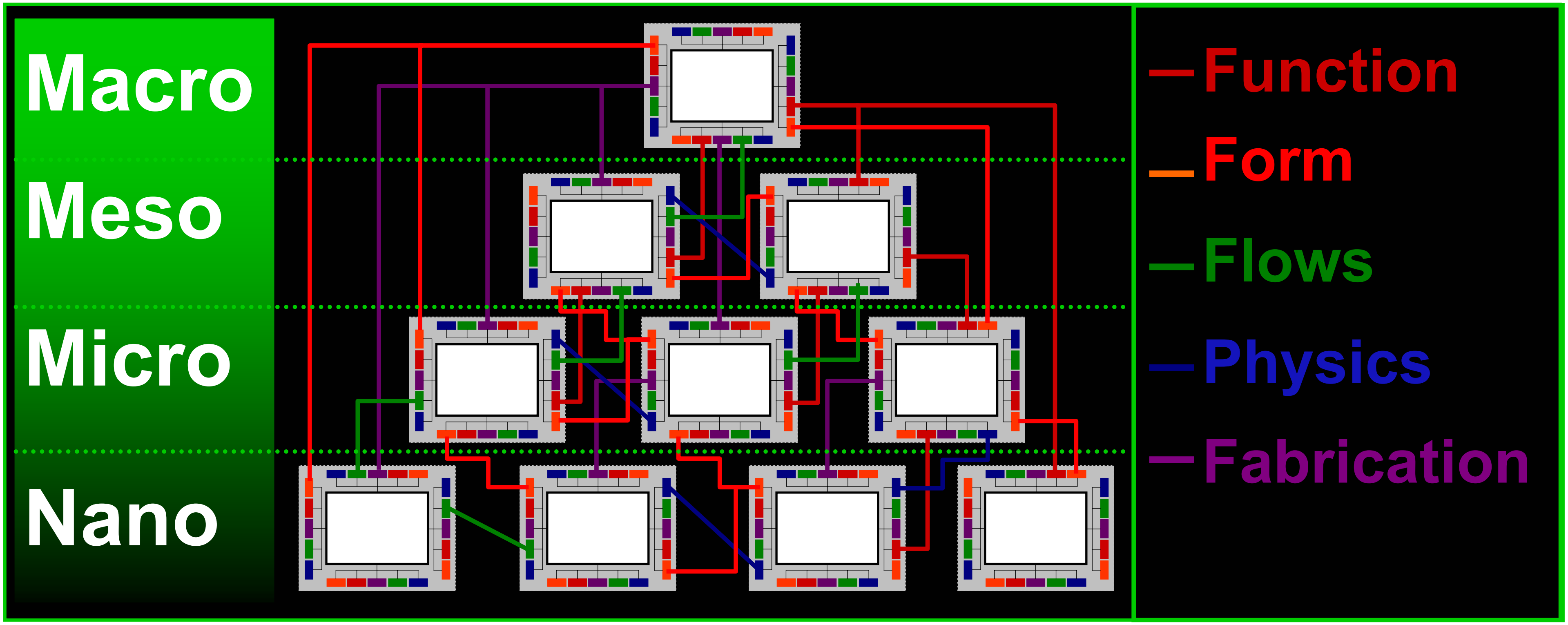
Heavily damped

Limits response time (ms vs. μs)

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…

Strategies for jumping scales

1. Functional requirements

System

Subsystem

FR-DP relationships

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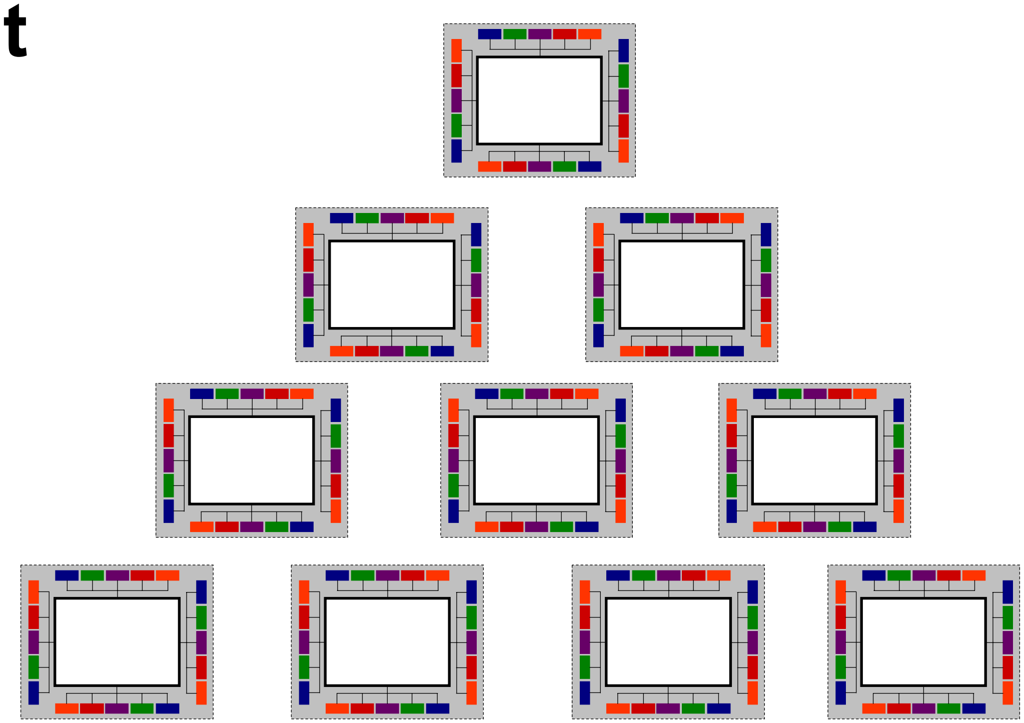
Strategies for jumping scales

2. Form & concept layout

DP/module layout



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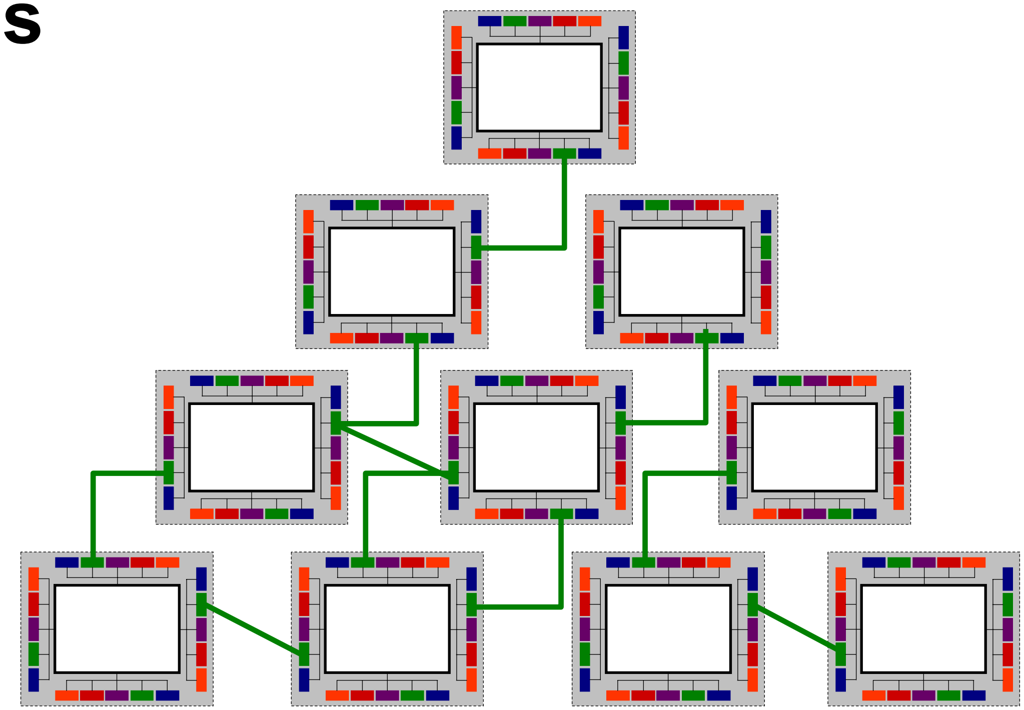
Strategies for jumping scales

3. ALL Flow/physics lines

Intra and Inter



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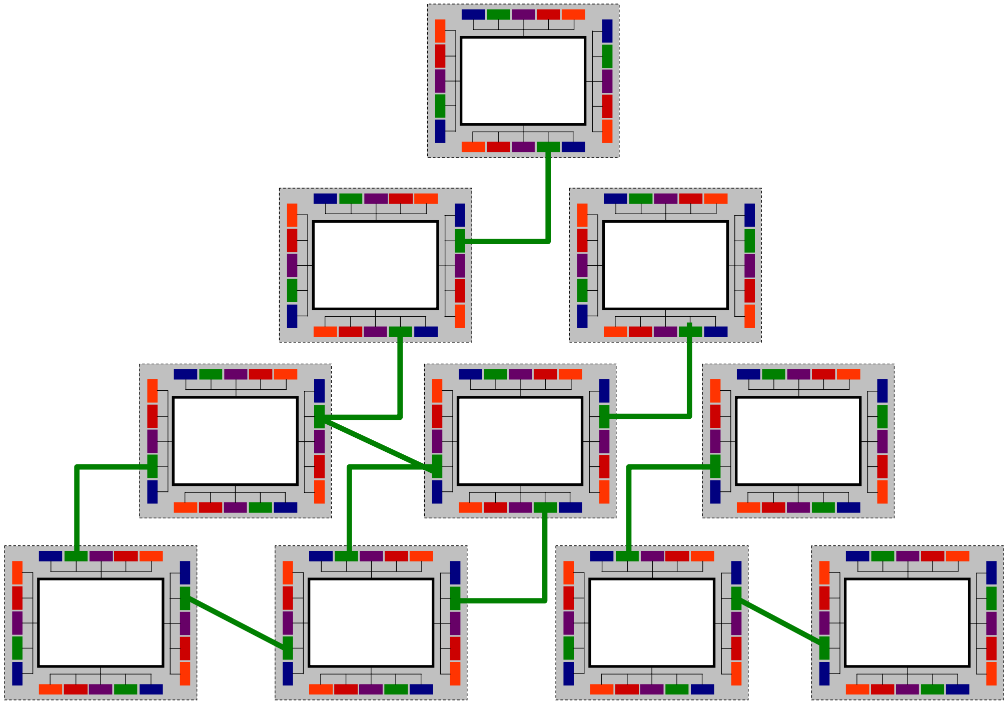
Strategies for jumping scales

4. Flow physics

List macro assmpts.

Use ratios & OOM

Select those to model



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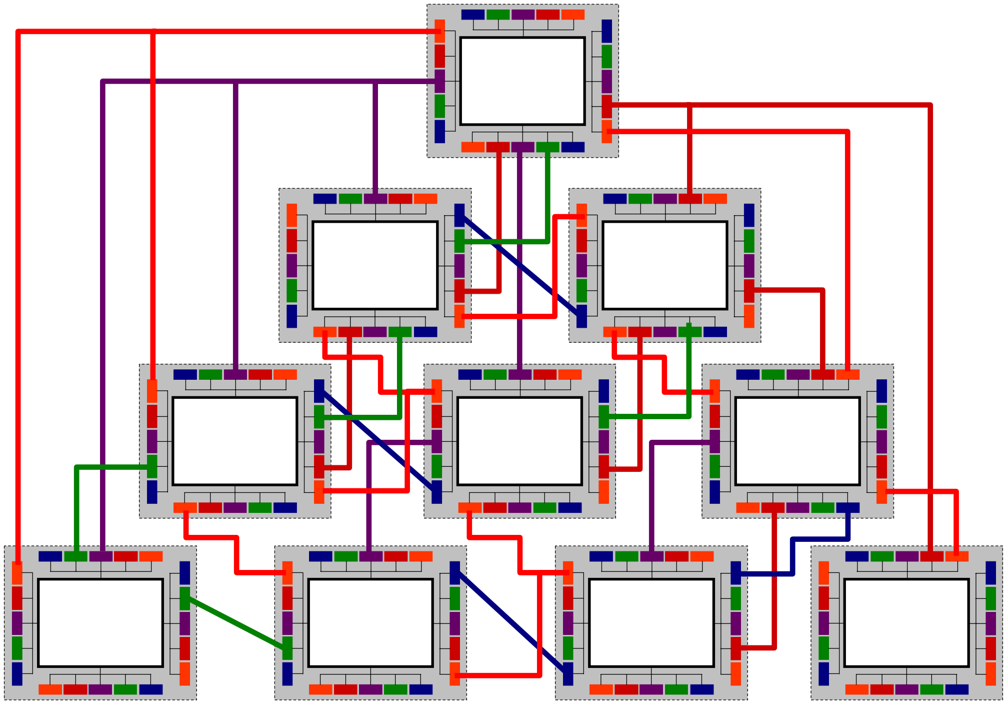
Strategies for jumping scales

5. System model

Sensitivity/gain check

Flow & fab compatibility

Un/de coupling



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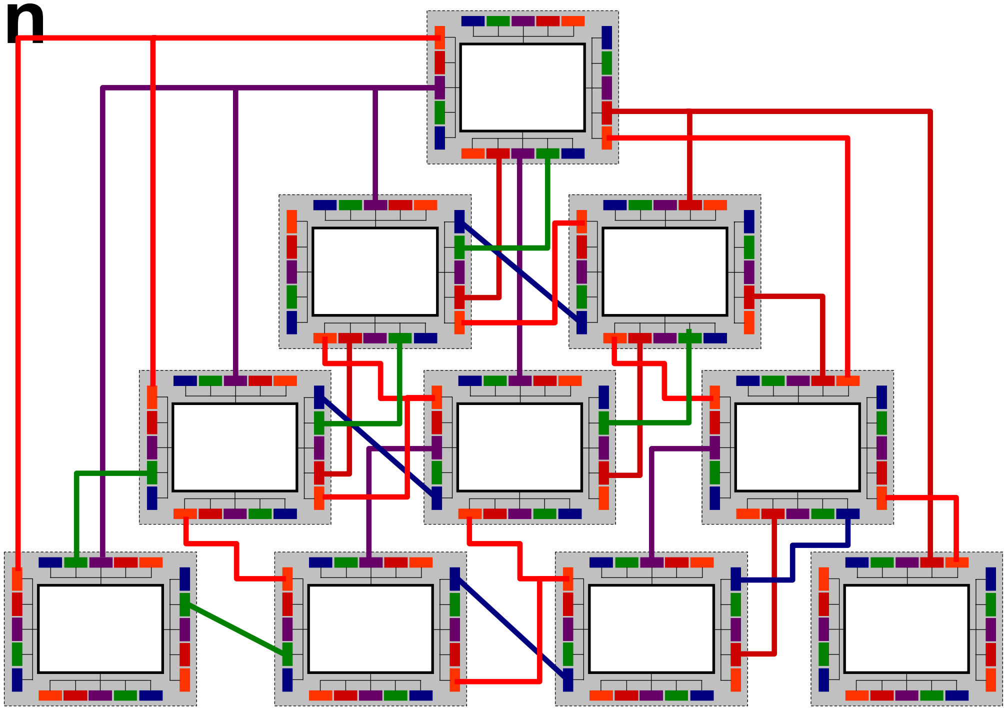
Strategies for jumping scales

6. Parametric optimization

Excel works great



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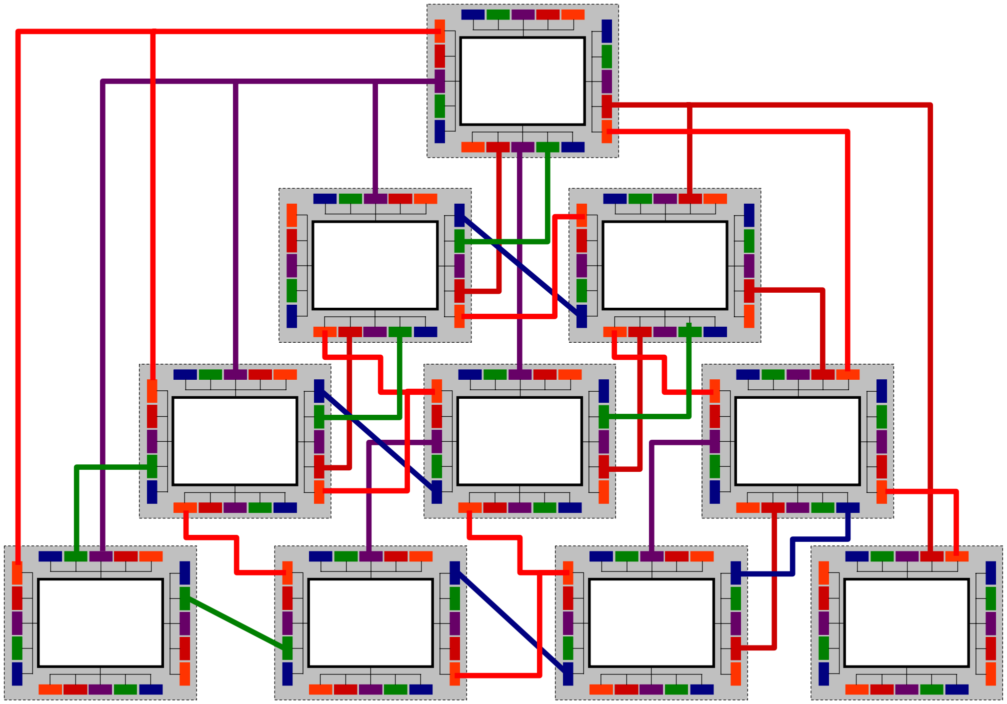
Strategies for jumping scales

7. Concept selection



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Nano-scale system components

Nano-scale for today

Driving tunneling current relationship

How this drives design

Gain and noise factors

Discussion

Group work

Gain factors to consider

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Nano-scale

Macro/meso/micro can be looked at with common Newtonian physical descriptions

For Nm-scale Quantum Mechanics dominates

Approach to teaching Nano-scale (example)

- ☐ Tunneling (Qualitative/Quantitative)
- ☐ Nano-scale structures

Today

- ☐ Governing tunneling equation
- ☐ How to apply to design
- ☐ Major design issues

Reading

Tunneling

Electrons have wave-like characteristics

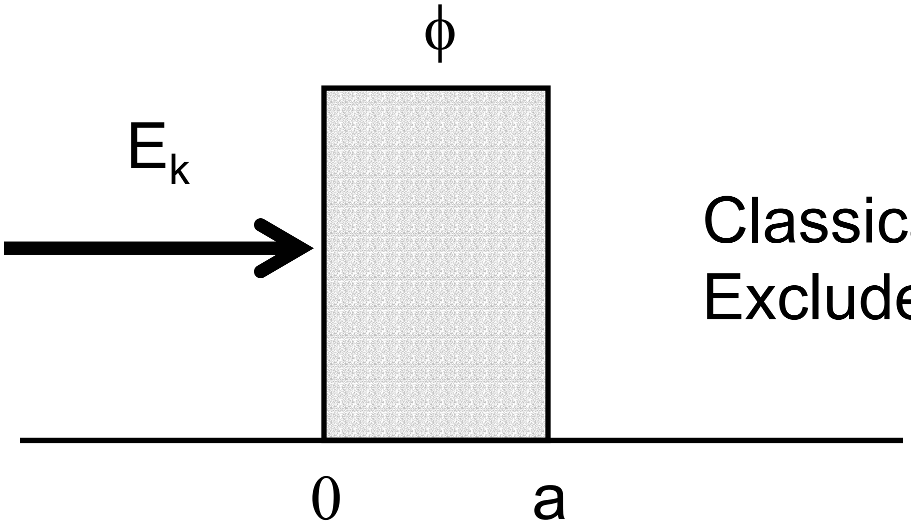
Enables them to tunnel through space when ordinarily don’t have enough kinetic energy to get through

Tunneling

Electrons have wave-like characteristics

Enables them to tunnel through space when ordinarily don't have enough kinetic energy to get through

Particle thought



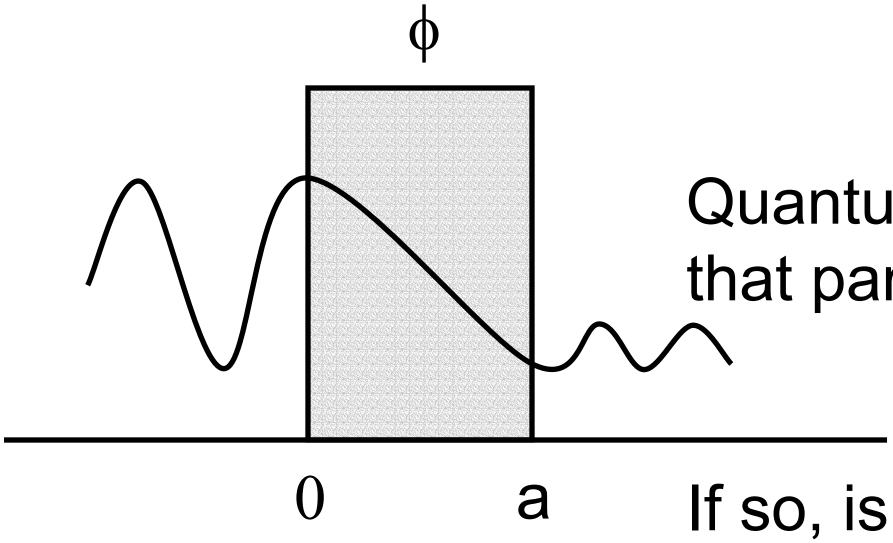
Classical theory = particle to be Excluded from x > a

Tunneling

Electrons have wave-like characteristics

Enables them to tunnel through space when ordinarily don't have enough kinetic energy to get through

Wave thought



Quantum theory = finite probability that particle can exist at x > a

If so, is said to have tunneled

Tunneling

Electrons have wave-like characteristics

Enables them to tunnel through space when ordinarily don’t have enough kinetic energy to get through

Solution to Schrodinger’s equation

$$I \propto e^{\left[-?\cdot gap\right]}$$

What should “?” depend upon?

Tunneling

Electrons have wave-like characteristics

Enables them to tunnel through space when ordinarily don’t have enough kinetic energy to get through

$$I \propto e^{\left[-2 \cdot k \cdot gap\right]}$$

m = Electron mass
= 9.11×10^{-31} kg

Local potential barrier height analogous to work (~ 5 ev)
1 eV = 1.6×10^{-19} J

$$k = \frac{\sqrt{2 \cdot m \cdot \phi}}{h}$$

h = Planks constant / 2 π
= 1.05×10^{-34} J-s

Fundamental issue for semester

Sensitivity

Assuming a barrier width of 5 Angstroms

Barrier height of 4 eV

Exponential is on the order of 10^{-5}

Current is on the order of nAmps

$$I \propto e^{\left[-2 \cdot k \cdot gap\right]} \qquad k = \frac{\sqrt{2 \cdot m \cdot \phi}}{h}$$

Assignment

Form your STM groups

List of CS and FRs for the STM

List of 5 F’s you have to model

FR-DP mapping and de/un coupling plans

Schedule meeting with Culpepper next Friday

- ☐ Discuss theory
- ☐ Design approach
- ☐ FR-DP Matching
- ☐ Gain matrices

Fundamental issue for semester

What is the sensitivity of current to gap over the range of gap you will have to design for?

Gap of few angstroms to 10 angstroms

$$I \propto e^{\left[-2 \cdot k \cdot gap\right]}$$

$$k = \frac{\sqrt{2 \cdot m \cdot \phi}}{h}$$