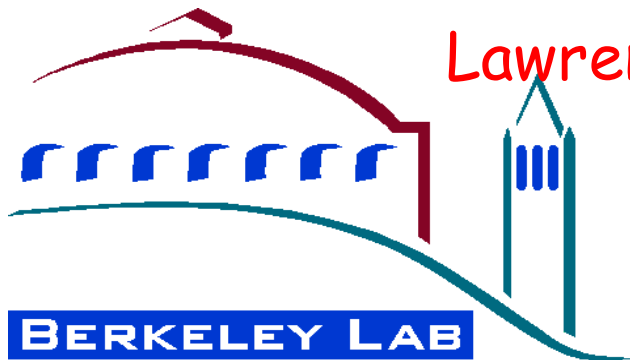


# SPM Tip-Sample Interactions: Approach, Feedback and Scanning

Frank Ogletree  
Molecular Foundry

Lawrence Berkeley National Lab

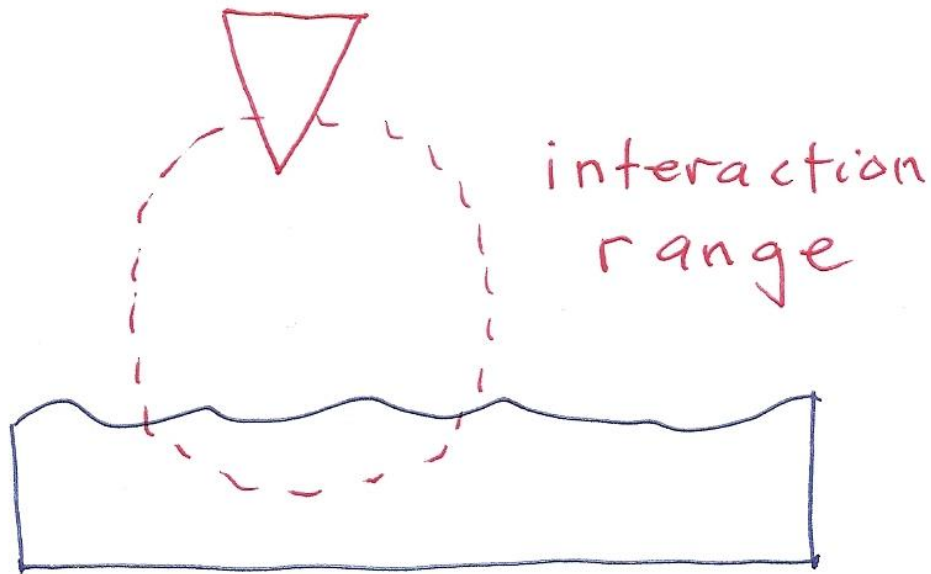


# Tip-Sample interactions

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- ◆ **Determines what can be done with SPM**
  - Spatial resolution
  - Physical properties of sample investigated
  
- ◆ **Defines instrument performance**
  - Conditions for tip crash/damage
  - Sensitivity to noise
  - Type and speed of approach
  - Speed and stability of feedback
  - Scanning/imaging performance

# Tip-Sample Interaction



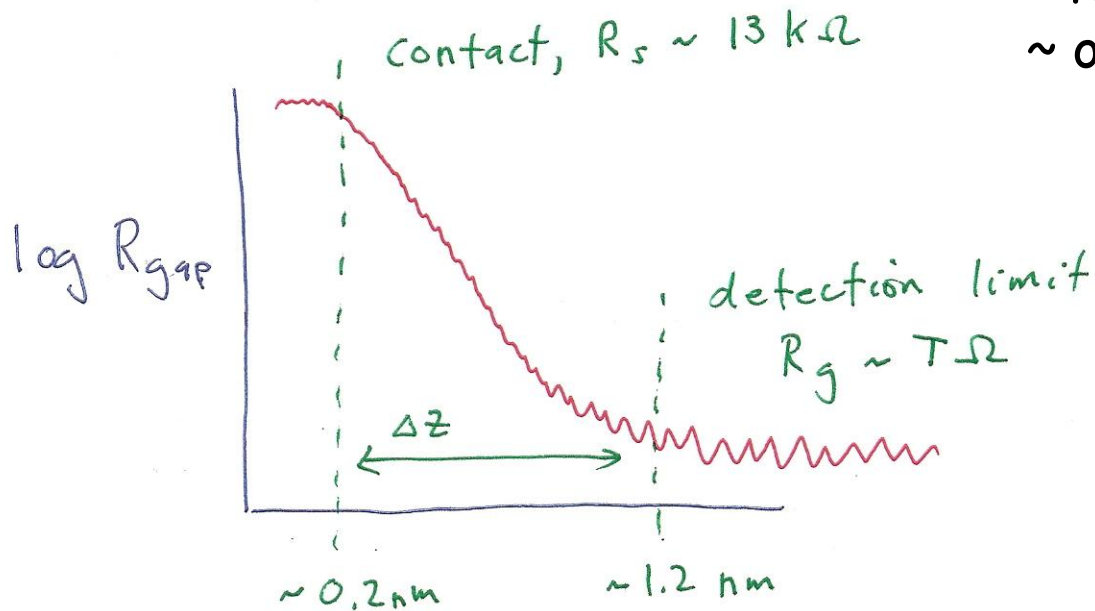
SPM based on local interactions

Range of interaction determines resolution, also approach and imaging strategy

Interaction must be ~ monotonic for stable feedback in most cases

# STM Case

$I \sim V_{\text{tip}}/R_{\text{gap}}$  for metals  
 $R_{\text{gap}}$  exponential in  $Z$   
 $\sim$  order of magnitude/ $\text{\AA}$



$\Delta Z \sim 10 \text{\AA} = 1 \text{ nm}$   
 detect - damage

Contact  $\sim 2 \text{\AA}$   
 $R_{\text{gap}} \sim 13 \text{ k}\Omega$   
 Detect  $\sim 10 \text{\AA}$   
 $R_{\text{gap}} \sim T\Omega$  (1 pA/V)  
 $\Delta z \sim 0.8 \text{ nm}$



# STM approach

sample detection range  $\sim 0.8 \text{ nm}$

feedback response  $\sim 5 \text{ ms}$  (2-3 time constants)

approach velocity  $v_{\text{approach}} \sim 0.8 \text{ nm}/5 \text{ ms} = 160 \text{ nm/s}$

for 1 mm,  $\sim 1.7 \text{ hours}$

for 10  $\mu\text{m}$ ,  $\sim 1 \text{ minute}$



# Approach Strategies

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## ◆ "Feedback detect"

- move tip toward surface at constant rate
- wait for feedback loop to respond
- approach stops at desired interaction strength
  
- default approach mode for Asylum AFM and ND-MDT AFM
- rate controlled by hand-wheel

motion must be smooth at interaction range level (angstroms) or STM will always crash

## ◆ “Tip retract”

- retract tip full piezo range
- move tip toward surface by  $\sim \frac{1}{4}$  to  $\frac{1}{2}$  Z range with coarse motor
  - » stepper, piezo, stick-slip, etc
- (let tip/preamp stabilize, DFM PLL for example)
- let feedback loop look for surface
- repeat until feedback stops at desired interaction strength

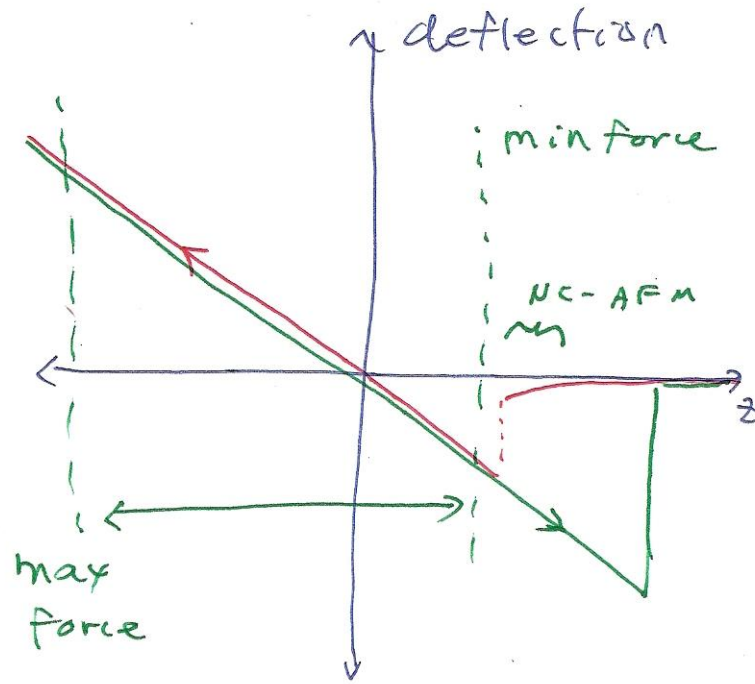
only safe means to completely avoid tip crash

usually required for STM, Atomic resolution DFM, delicate MFM or KFM...

- ◆ “Tip retract-modified/open loop”
  - retract tip full piezo range
  - move tip toward surface by  $\sim \frac{1}{4}$  to  $\frac{1}{2}$  Z range with coarse motor
    - » stepper, piezo, stick-slip, etc
  - (let tip/preamp stabilize, DFM PLL for example)
  - ramp toward surface while measuring interaction
  - repeat until interaction detected
  - yank tip back as fast as possible if interaction detected, then let feedback loop approach
- can be much faster if detection time ( $\sim 100$  us)  $\ll$  than loop response time ( $\sim 5$  ms) and control system is deterministic (fast reflexes)
- could be  $> 10x$  faster, 10 min instead of 2 hours...
- can also use for non-tip-retract approach



# Contact/Tapping AFM Case



AFM Contact/Tapping

$$\Delta z \sim 10-100 \times > \Delta z_{STM}$$

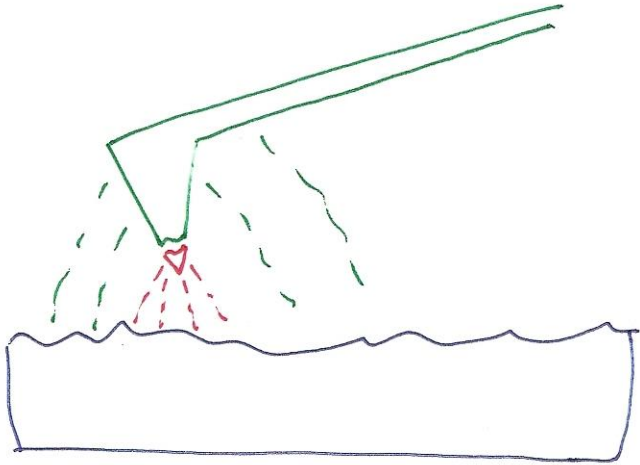
approach  $\sim 10-100 \times$  faster

Interaction range  
10-100x > STM  
Approach much faster

Incidental "crash" during approach may not matter, tip hits surface anyway...

Feedback or interaction-detect approach is fine

# Complications



Tip Apex - Sample

Cantilever,  
tip body - Sample

mixed  
interactions

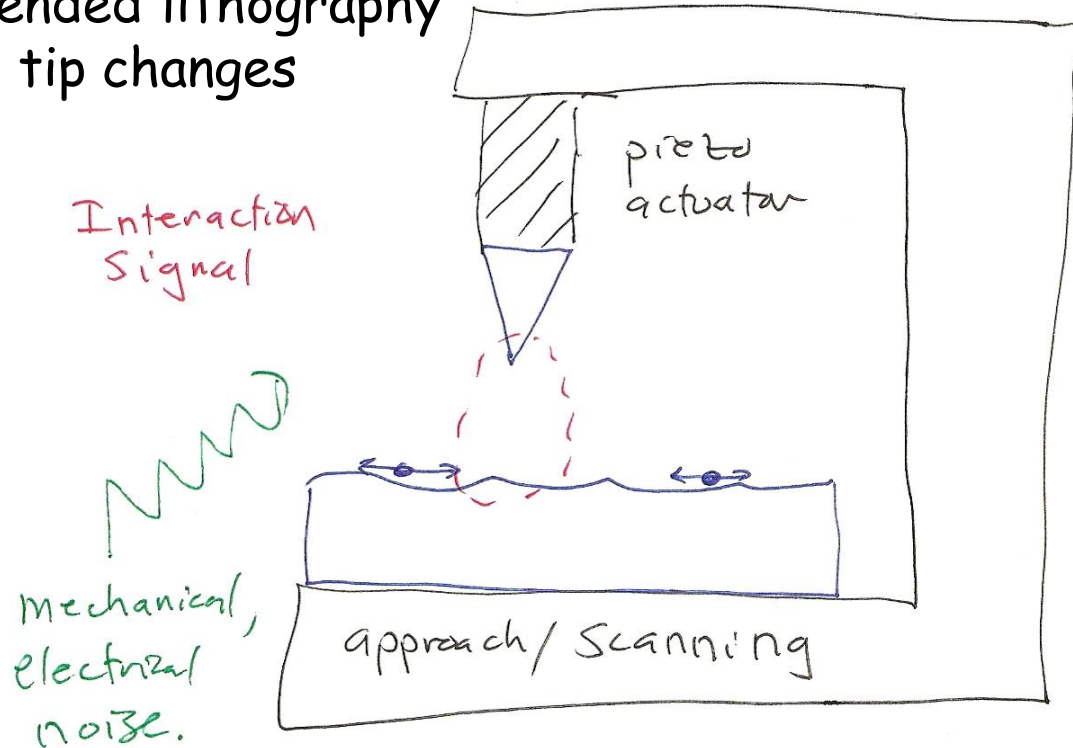
dynamical systems  
oscillating tips +  
non-linear tip-sample interactions

Tapping mode, DFM-FFM/PLL, "Shear force"

# "Real" SPM

## Tip-Sample Stability

atomic diffusion  
unintended lithography  
tip changes

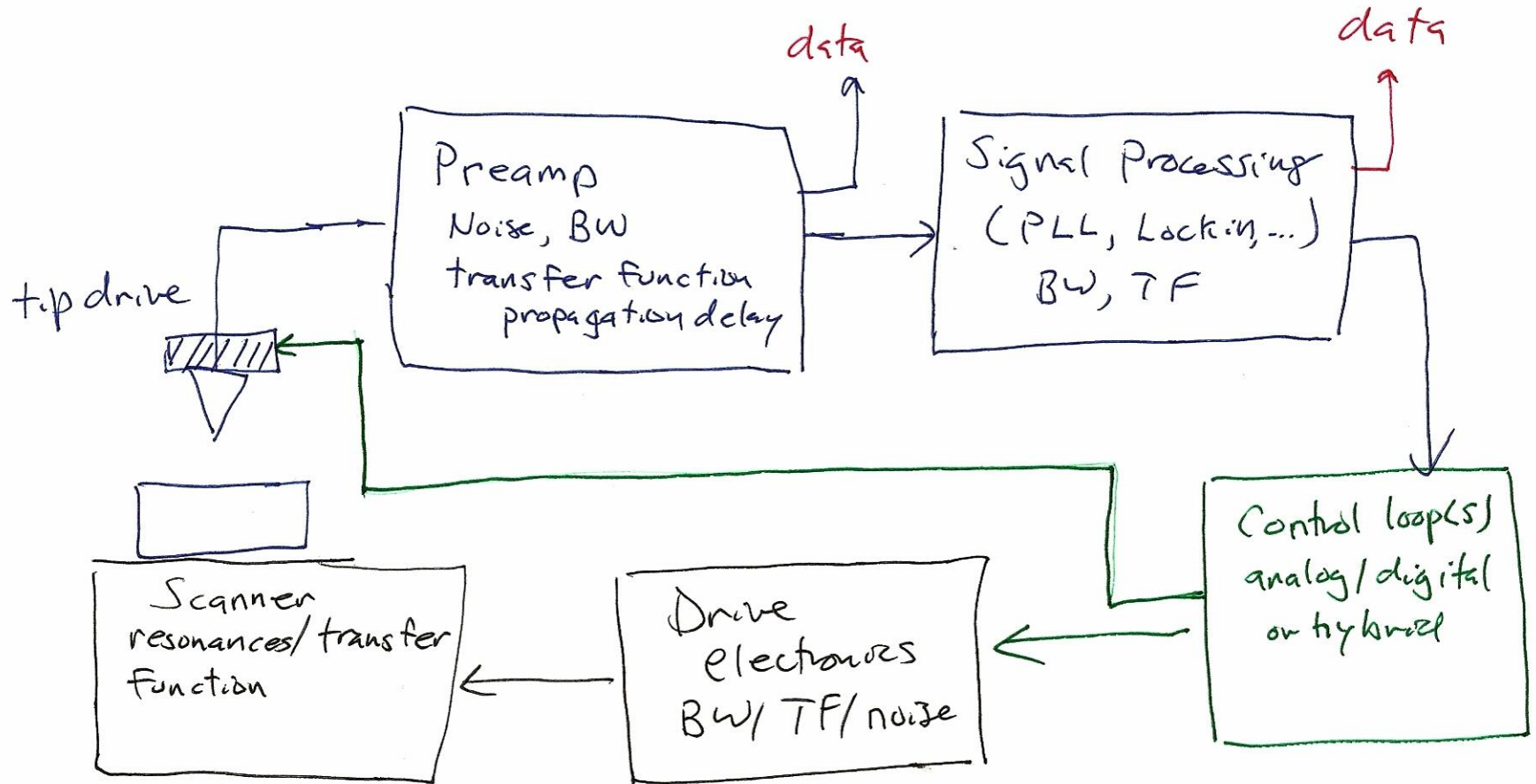


External noise  
mechanical (floor)  
acoustic (air)  
electrical  
(optical)

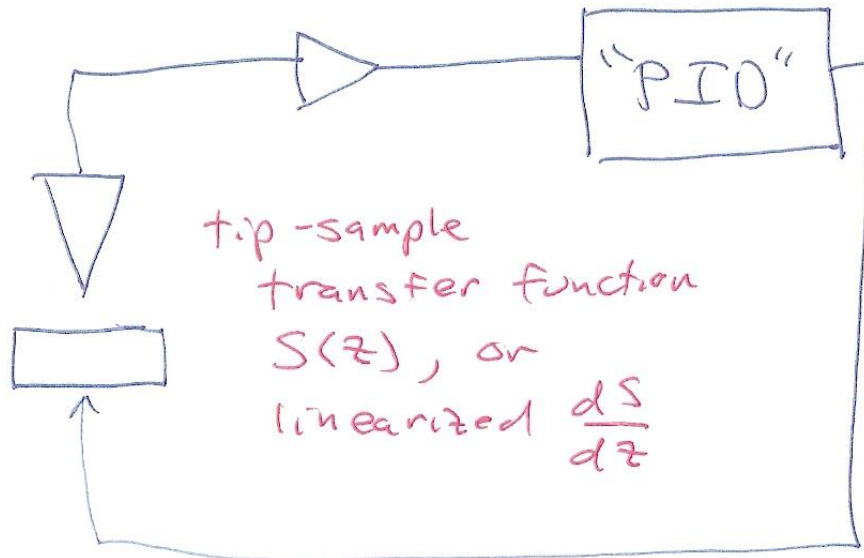
## Scanner

finite bandwidth & resonances  
(transfer function)  
thermal drift, hysteresis, creep...

# SPM Control Problem



# "Simple" Feedback



**PID**

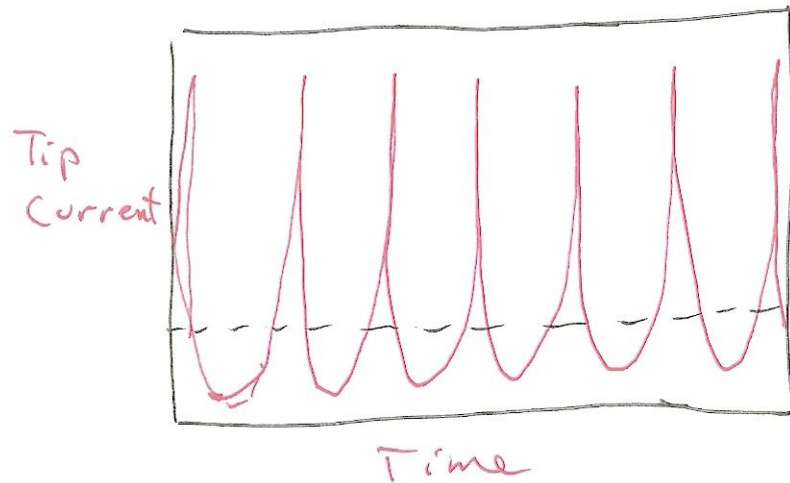
One size (kinda)  
fits all

Good for well-behaved  
"plant"

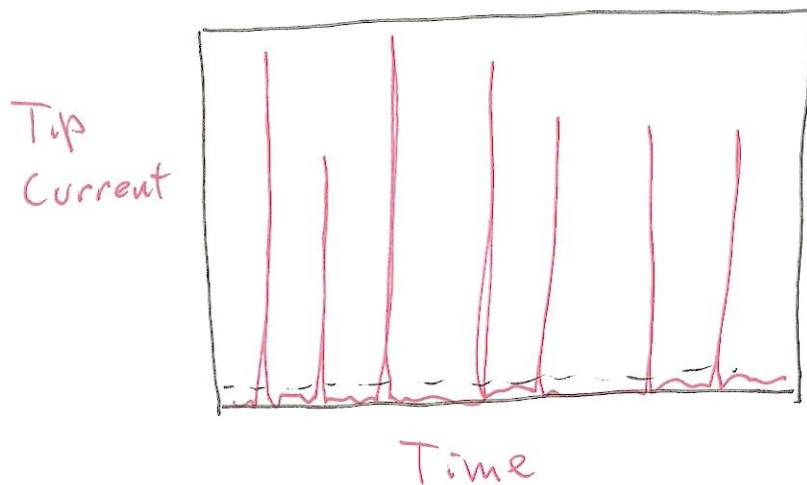
**SPM is usually not...**  
scanner resonance  
non-linear signal

...

# STM feedback issues



exponential response



pathological  
exponential response  
insulating films

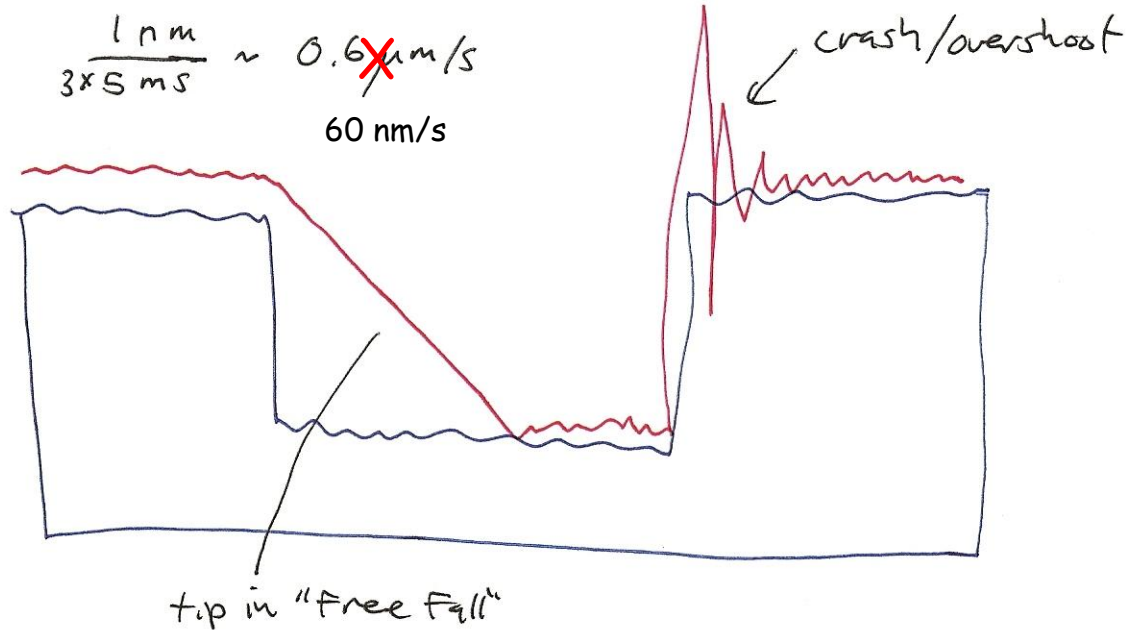
...

# Scanning Issues

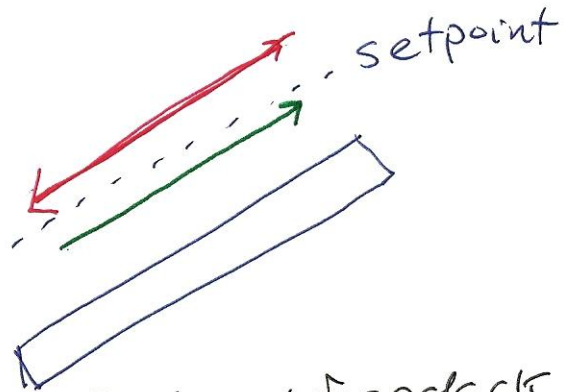
$$\text{Scan rate} < \frac{\text{feature size}}{3 \times \text{loop response}}$$

$$\frac{1 \text{ nm}}{3 \times 5 \text{ ms}} \sim 0.6 \mu\text{m/s}$$

60 nm/s



# Scanning Issues



Integral feedback  
= slope error  
P can fix...  
or "feed forward"