Acknowledgement

Lectures 3-6: On Randomness and Percolation Theory

S. Singh (Georgia Tech), N. Pimparkar (AMD), P. Nair (Postdoc), J. Go, and B. Roy (Graduate students), T. Low (postdoc),

Prof. J. Murthy (Purdue), J. Rogers (UIUC), R. Bashir (UIUC), M. Chowwalla (Rutgers)

Lectures 7-10: On Reliability Theory

H. Kufluoglu (TI), K. Kang (Intel), A. E. Islam, D. Varghese, and M. Masuduzzaman (Graduate Students)

Prof. S. Mahapatra (IIT), Prof. Roy (Purdue), B. Weir and P. Silverman (Lucent/Agere)

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And as always …

Prof. Mark Lundstrom and Prof. S. Datta

2009 NCN@Purdue-Intel Summer School
Notes on Percolation and Reliability Theory

Lecture 1
Percolation in Electronic Devices

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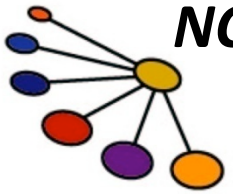

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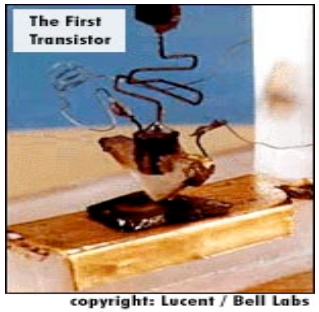
outline of lecture 1

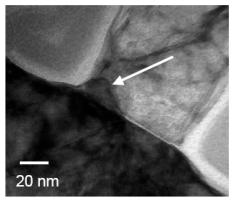
1) Reliability and Randomness in Electronics
2) Averages and Deviations
3) Nonlinear Percolation for in-plane Transport
4) Finite Fractals for out-of-plane Transport
5) Correlation in Time-dependent Degradation
6) Conclusions

reliability and randomness in electronics

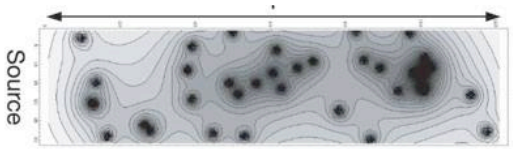
1947 ....



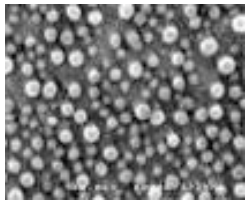
Dielectric BD

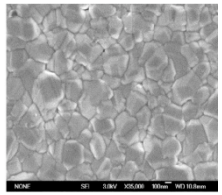


Random Dopants

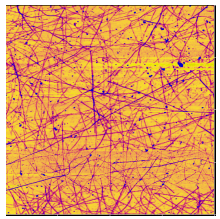


NC Flash

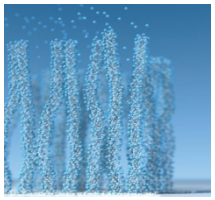




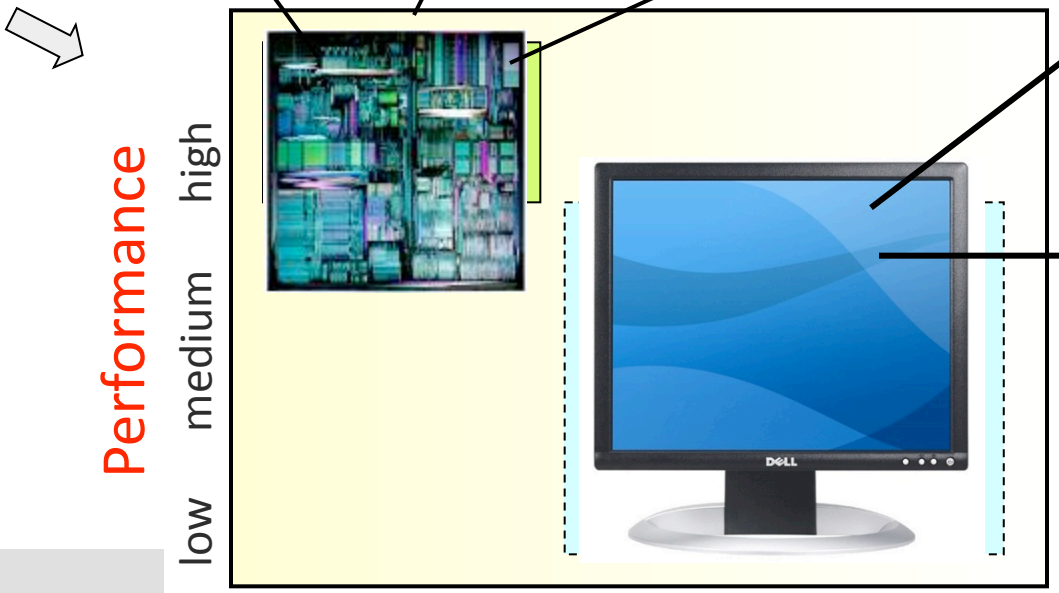
Poly-Si



NanoNet Biosensors



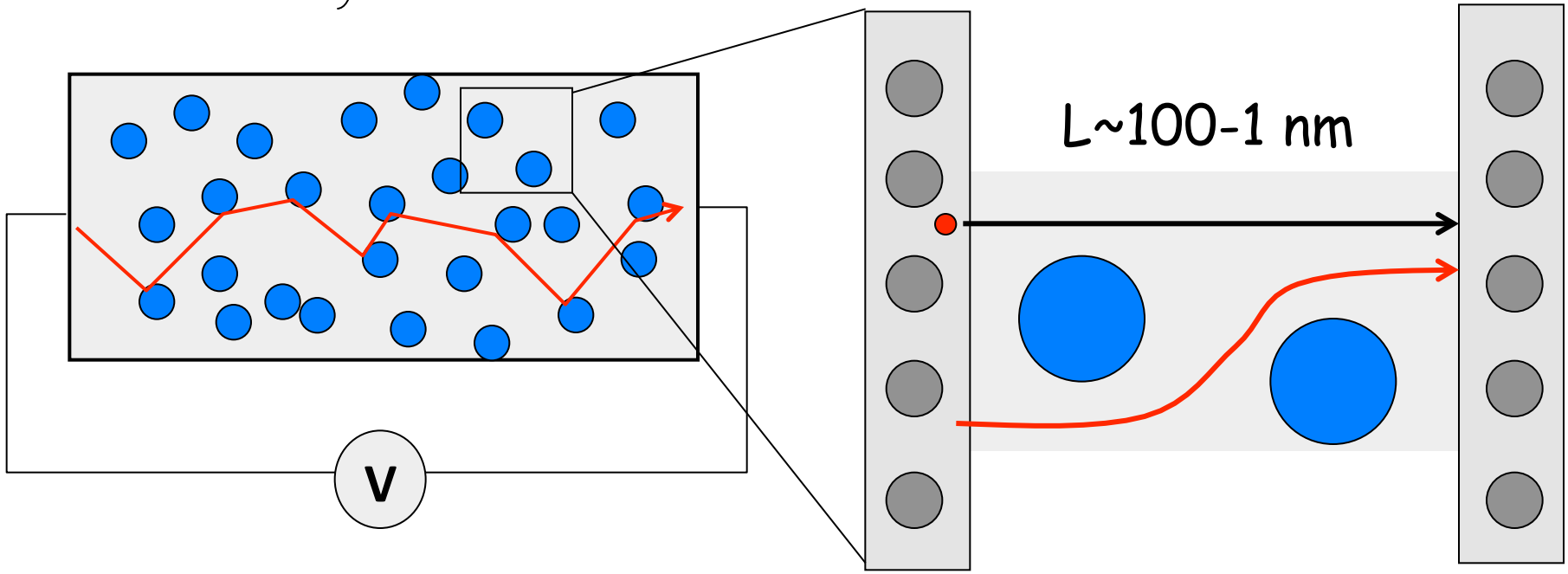
super-capacitors



Ohm's law is dead ...
And averages do not mean what they used to

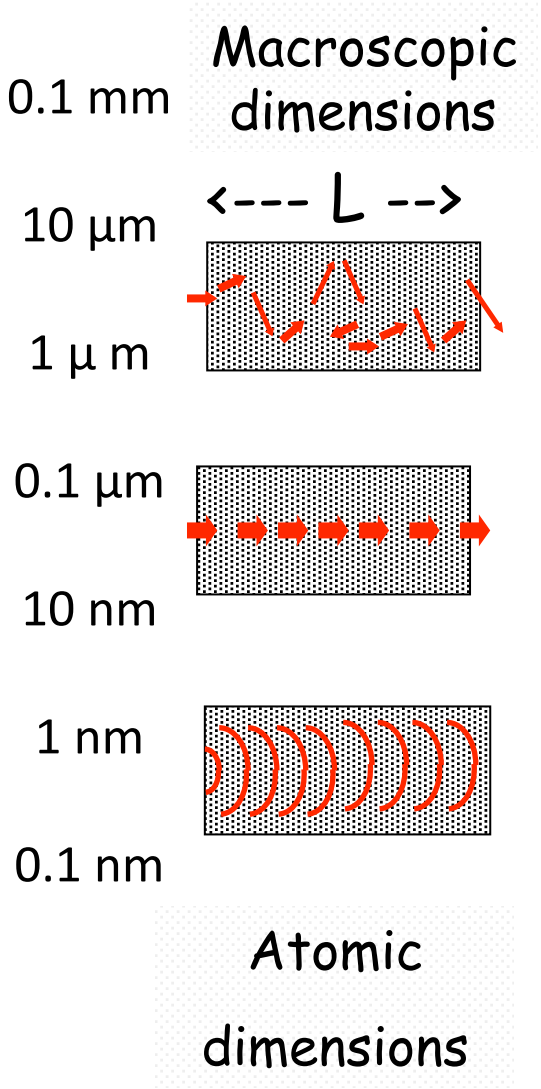
derivation of Ohm's law

$$\left.\begin{aligned} J &= \sigma E \\ J &= q n \upsilon \\ &= q n \mu E \end{aligned}\right\} \quad \sigma = q n \mu = q^2 n \frac{\tau}{m^*} \qquad G = \sigma \frac{W}{L} = q^2 n \frac{\tau}{m^*} \frac{W}{L}$$



τ, m^*, L, W do not mean what they used to ....

transport at various scales

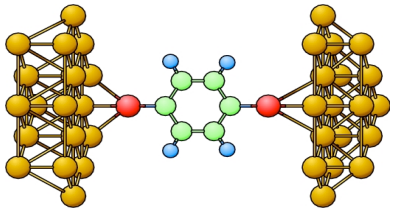


$$G = \sigma A / L$$

$$\sigma = q^2 \, n \, \tau / m^*$$

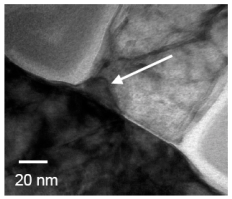
$\tau = ?$ "not well defined"

m* = ? n = ?

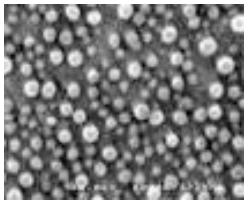


meaning of length ?!

Dielectric BD



NC Flash



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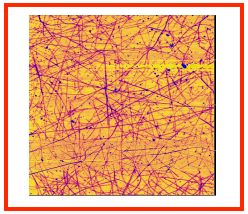
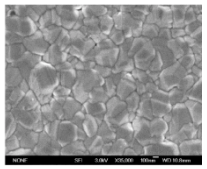
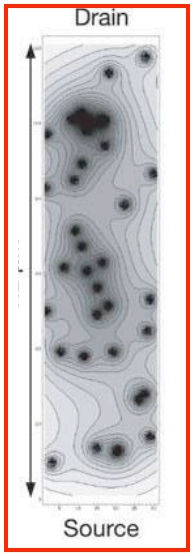


Poly-Si

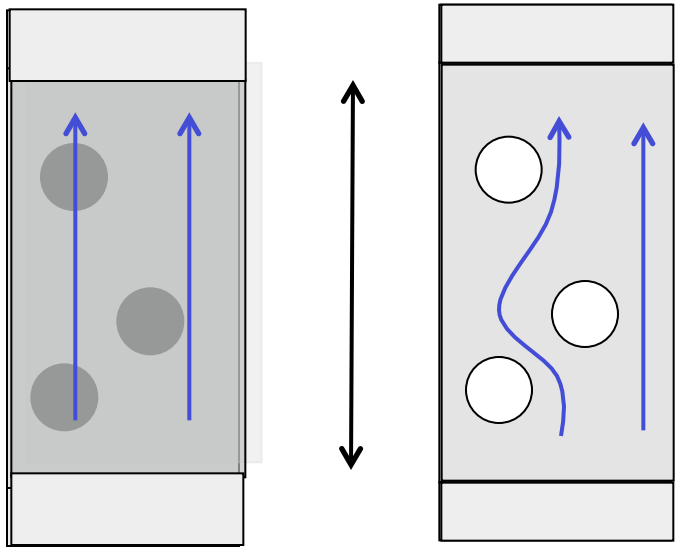


Random Dopants

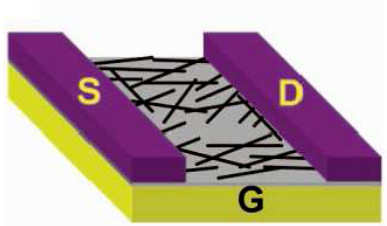


Top down

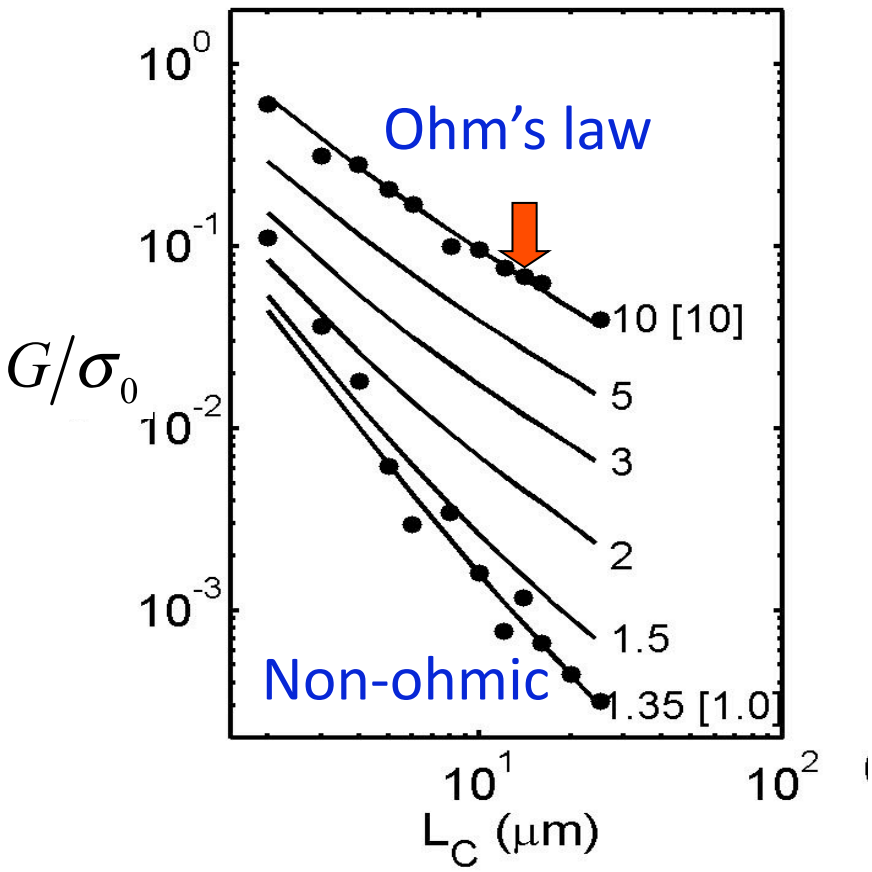
Bottom up

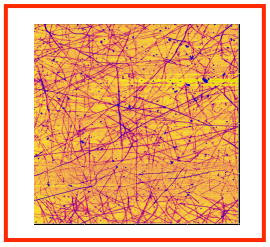


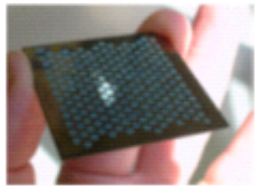
randomness & the end of Ohm's law

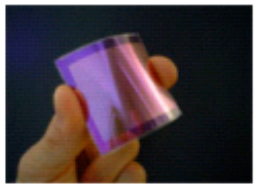


$$\frac{G}{\sigma_0} = \frac{W}{L_c}$$

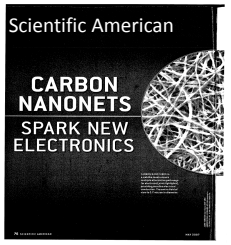





Drug Discovery Substrates


Conformal Solar Cells

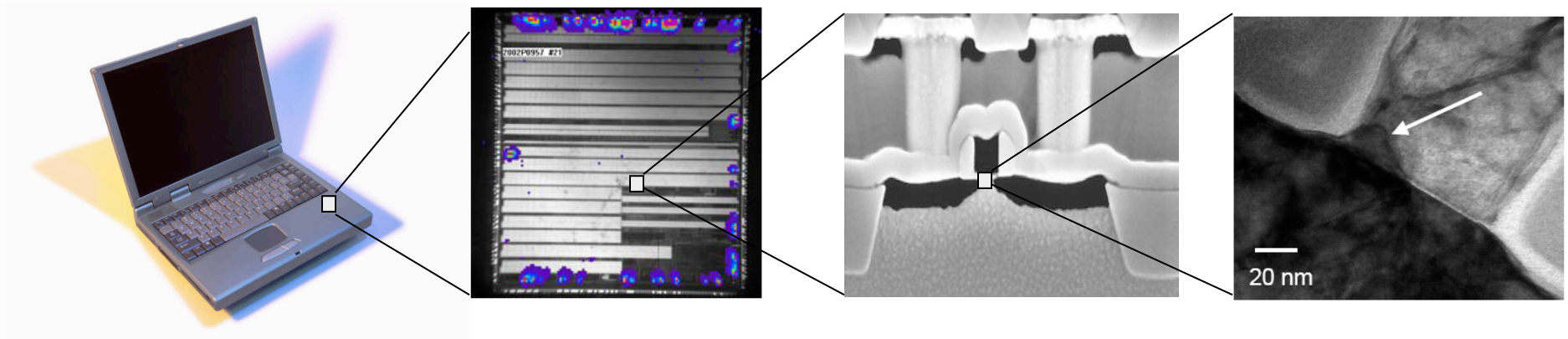

Flexible Electronics



Experimental Demonstrations

Rogers, UIUC; Lieber, Harvard; Gruner, UCLA; Seidel, Infineon; E. Snow, NRL; Nanomix Inc. Janes, Purdue; Nanosys Inc.

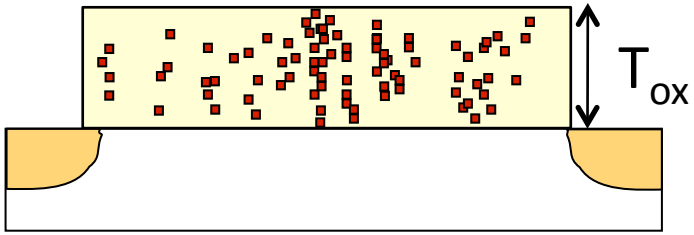
importance of reliability



ICs operate in incredibly harsh conditions and massive field-returns can put a company out of business … A very important practical problem.

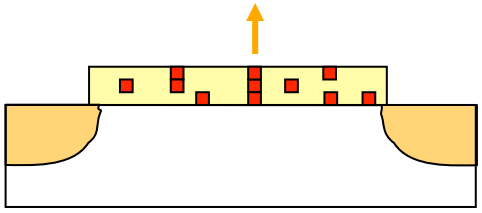
the meaning of average breakdown field

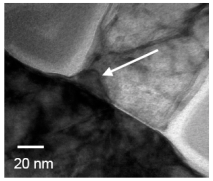
Thick Oxides (circa 1980)



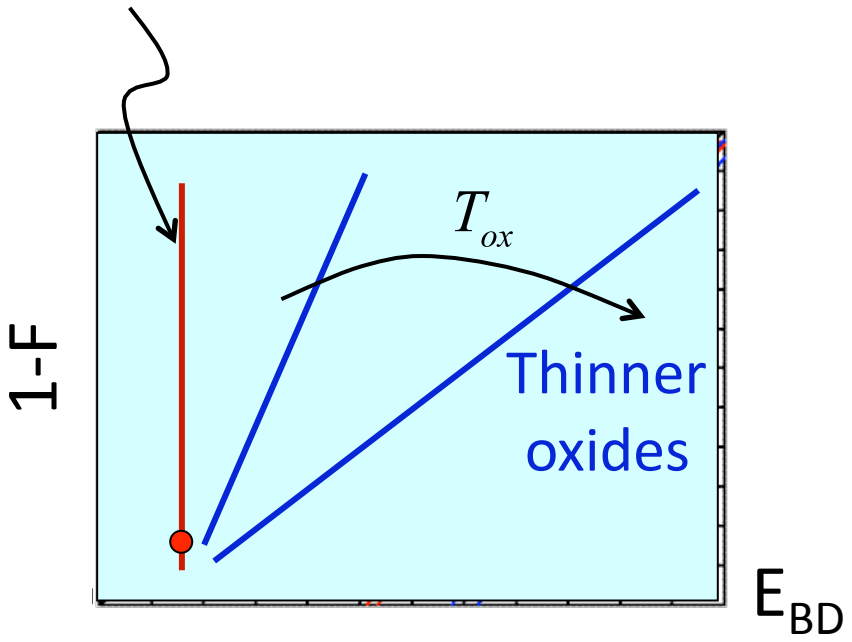
$$E_{BD} = \frac{V_{BD}}{T_{ox}}$$

Thin Oxides (late 1990s)





Thick oxide



What does Tox mean?

the "bottom-up" view of a resistance

Ballistic Transistors (Prof. Lundstrom)

$$G = \sigma \frac{W}{L} = q^2 n \frac{\tau}{m^*} \frac{W}{L}$$

Percolation theory (This Series)

Quantum transport (Prof. Datta)

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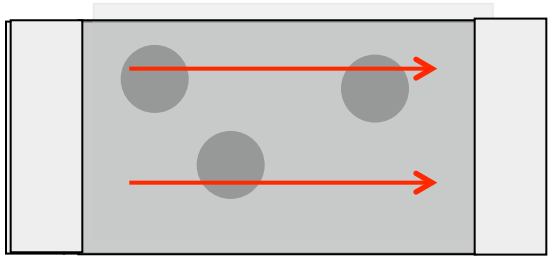
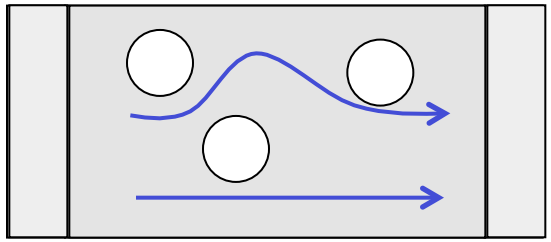
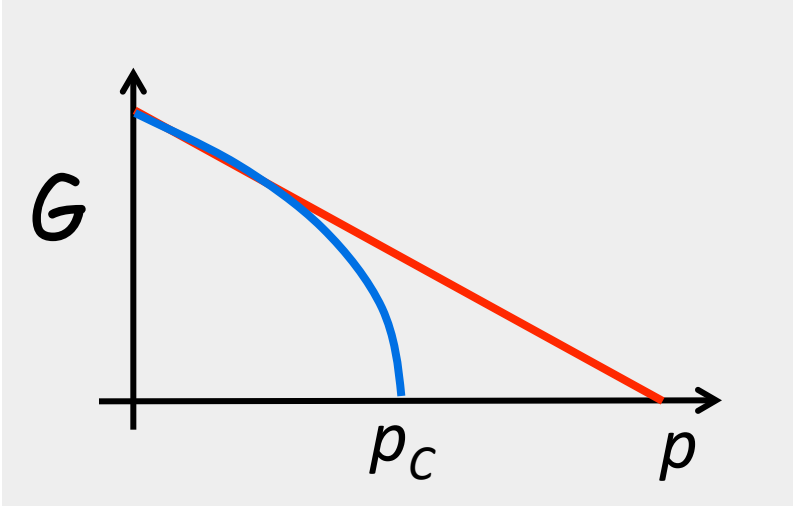
averages and deviation

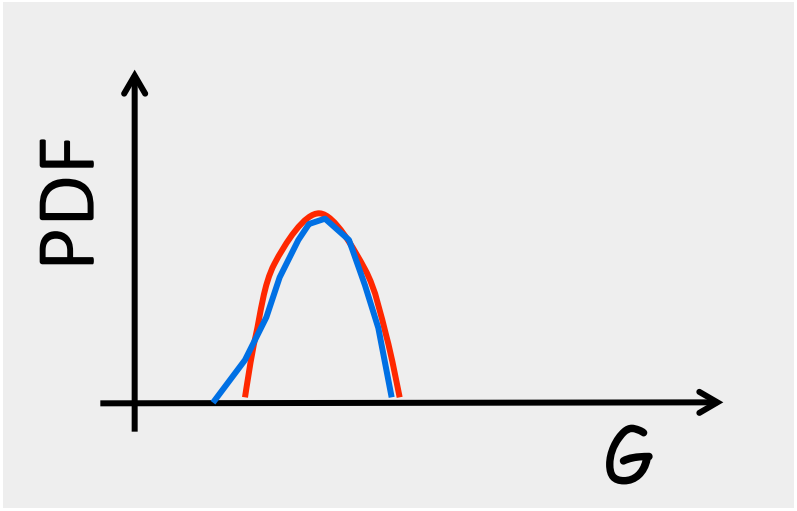
Top down



Bottom up



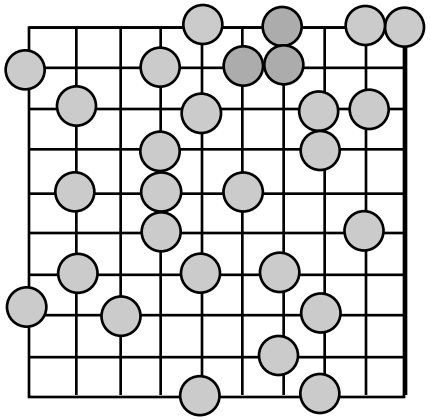




…. wrong on both counts and computer alone can not help

top down classical approach ….

p=0.3



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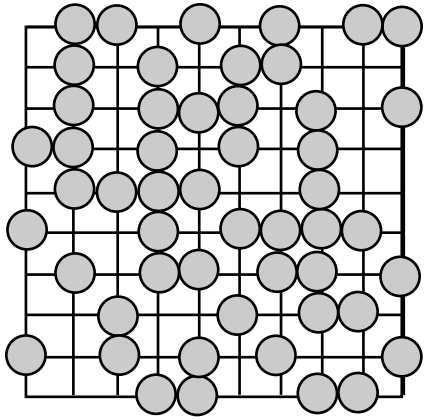

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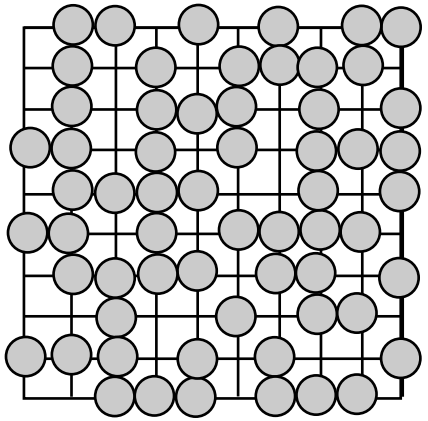
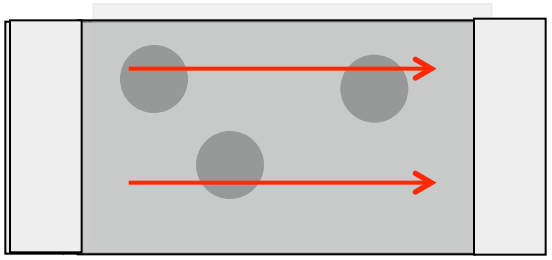
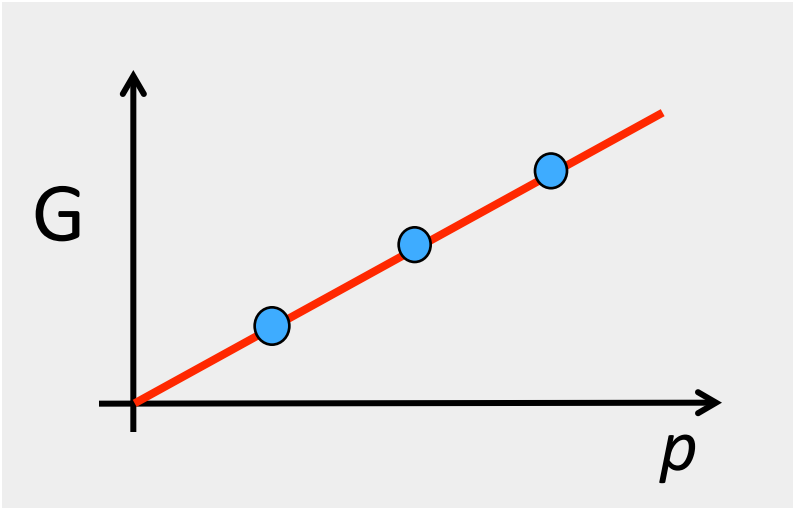


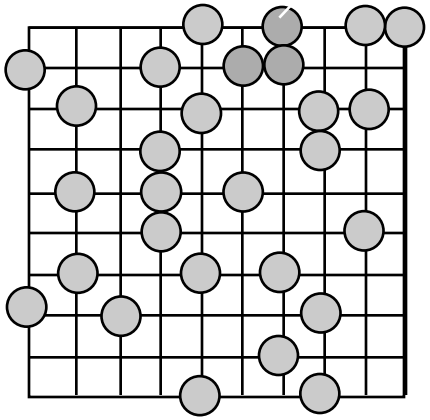




… that's what textbooks say!

basics of percolation: averaging matters

p=0.3



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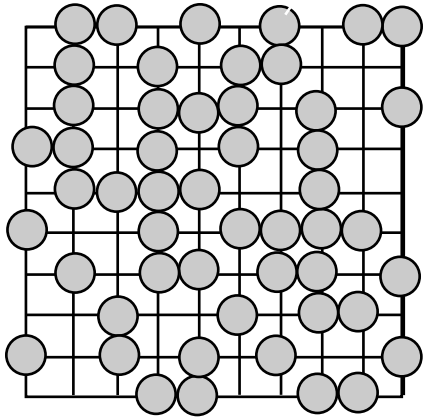

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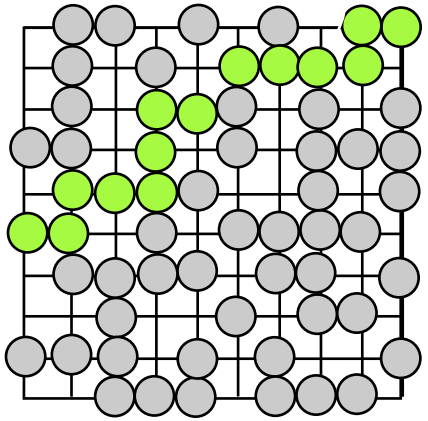
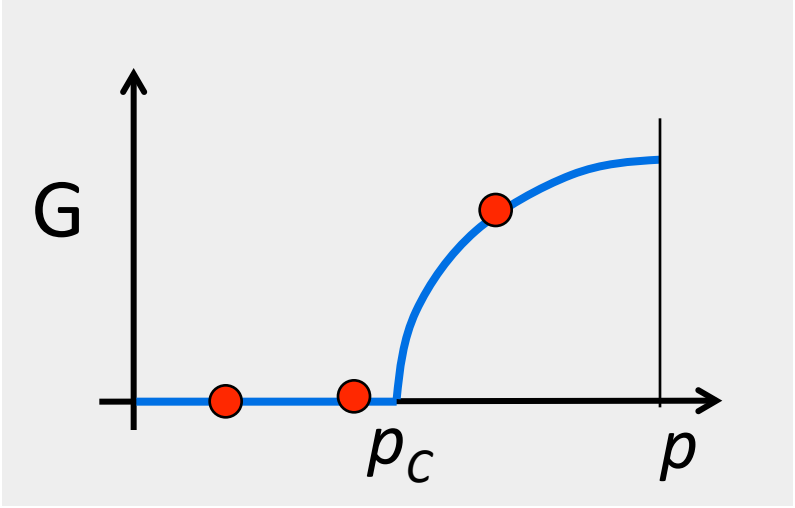
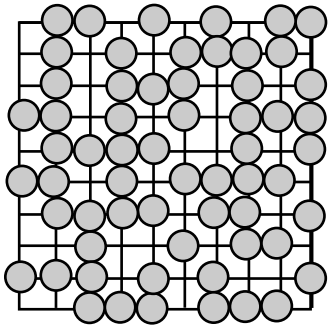




Consequences of adding a new disk depends on existing configuration ...

… and so does the fluctuation

p=0.8



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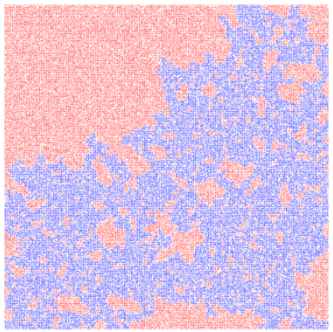

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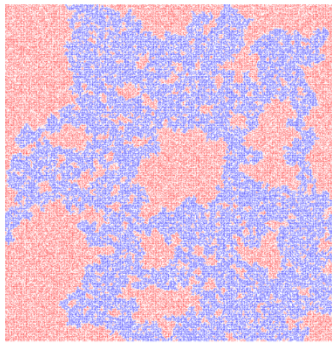
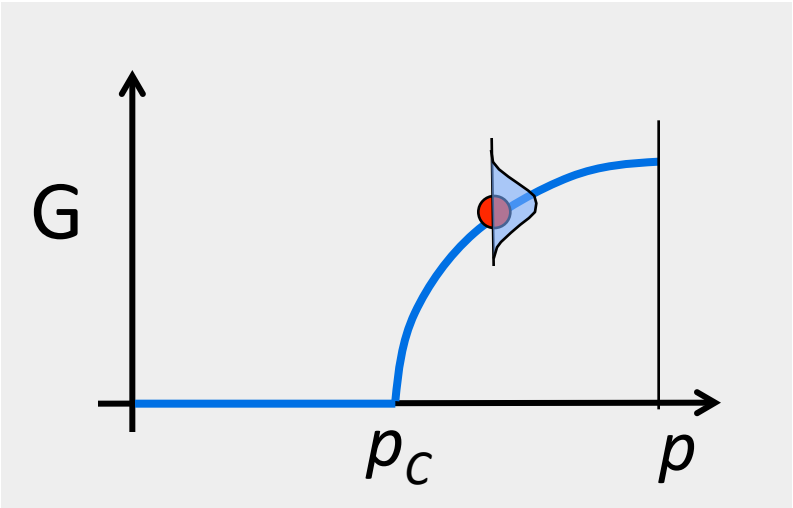
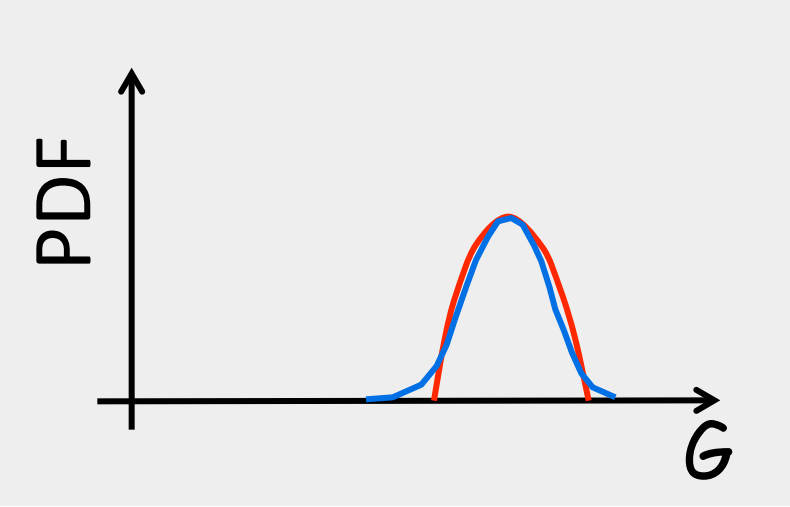
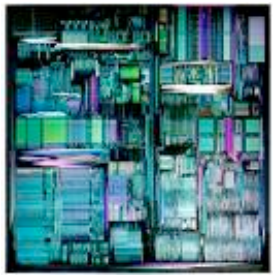


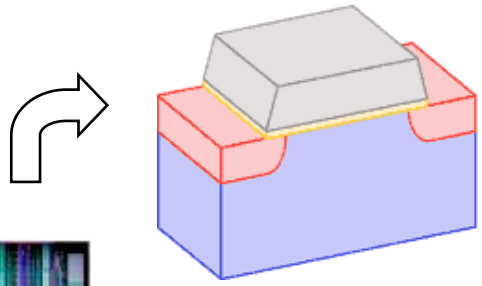


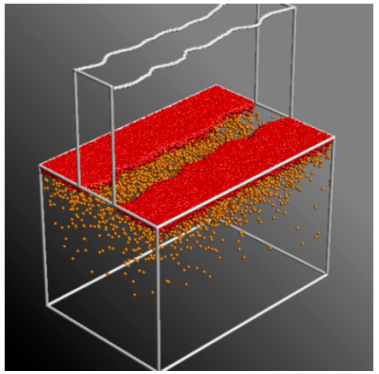


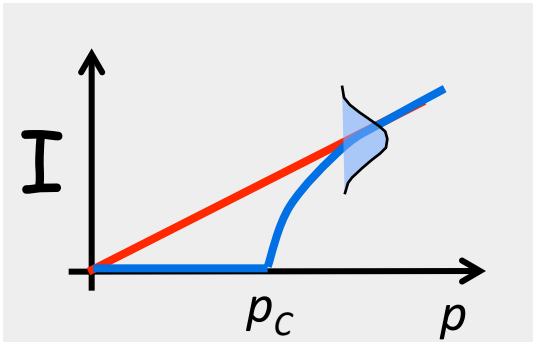
May look the same, but have very different implications

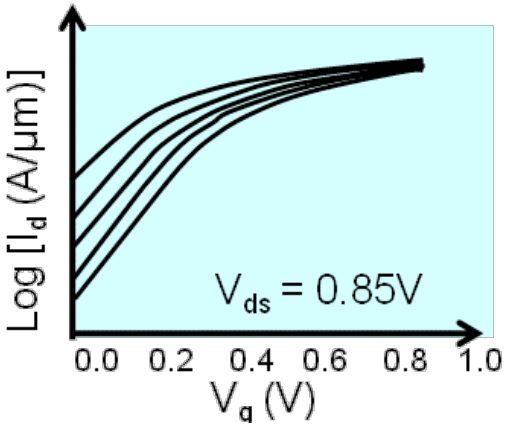
current approach: transistor design

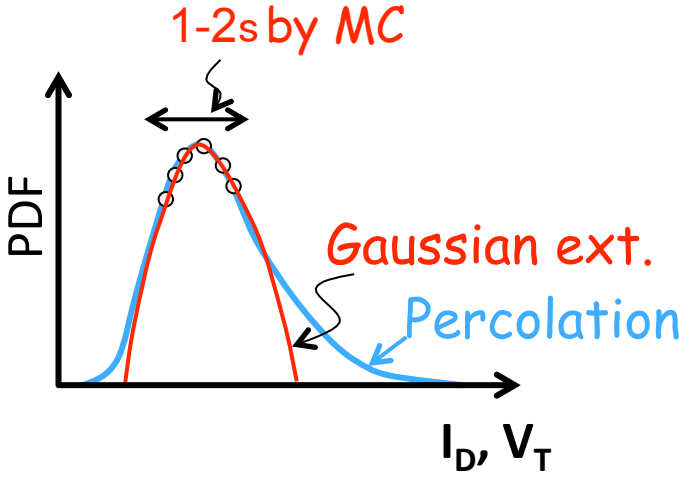






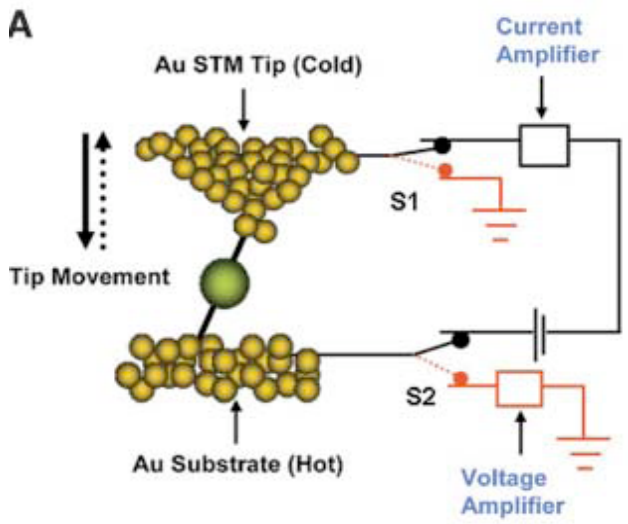


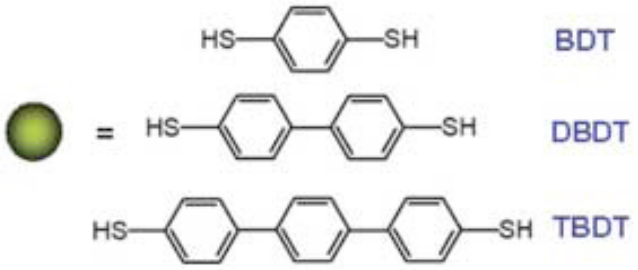


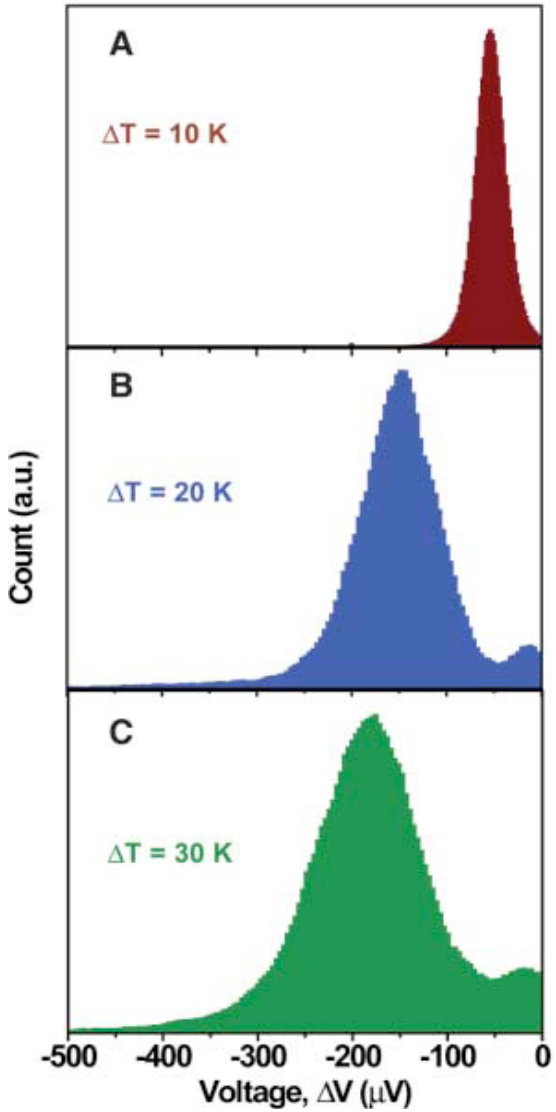


Gaussian distribution inappropriate …
Monte Carlo simulation is not enough

thermal conduction in molecules



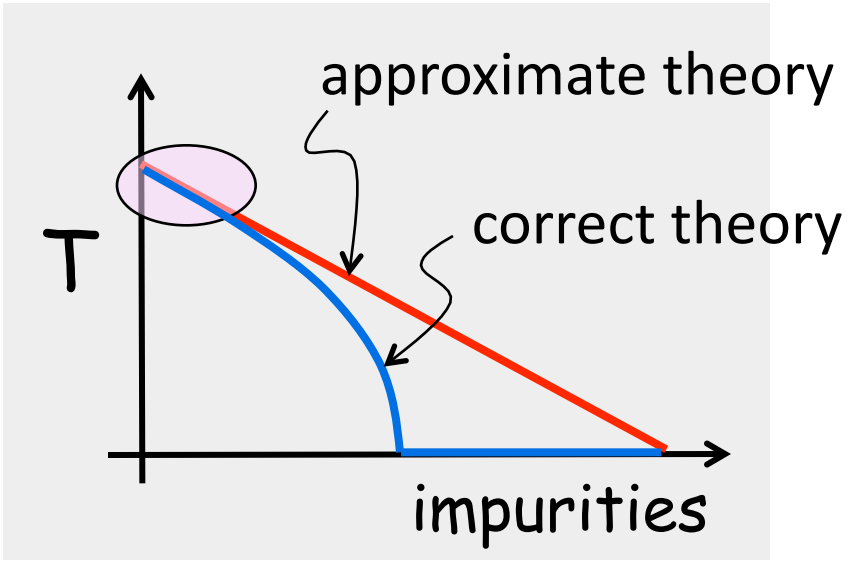




A. Majumdar, Nature, 2007

why do we not hear about percolation (1) ?

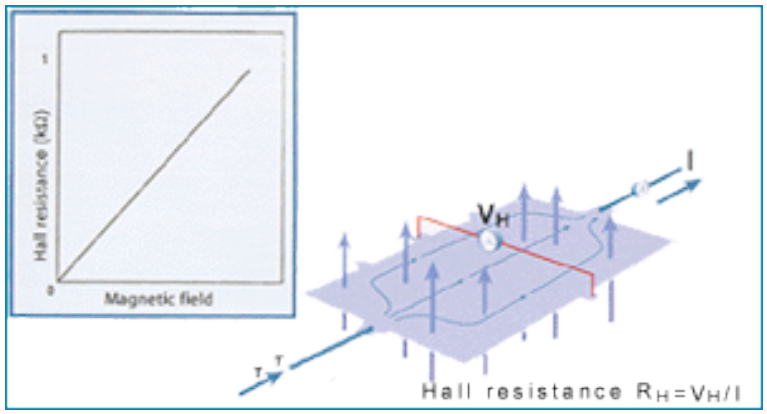
1 mm^3 ~ 10^{17} molecules

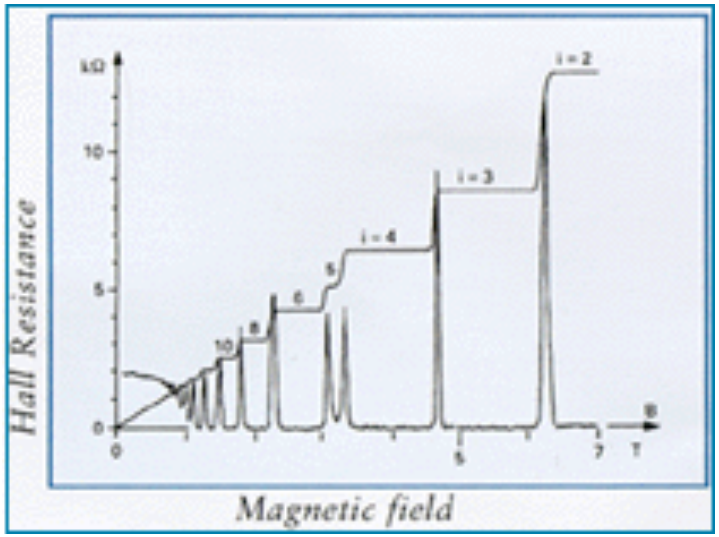


Given traces of impurity, change in property (e.g. transmission) is easily predicted.

Fluctuation in properties of large system is small and all approach Gaussian distribution at its limit.

why do we not hear about percolation (2) ?





Some small systems have unusually robust properties, (e.g., quantum Hall effect) and physicists often focus on those extra-ordinary aspects of small systems …

outline of lecture 1

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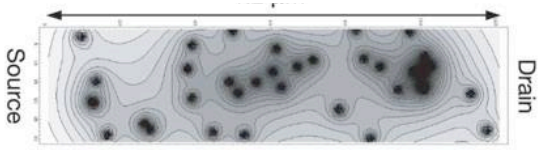
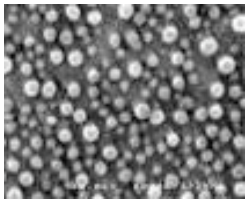
5) Correlation in Time-dependent Degradation
6) Conclusions

Mapping electronic device problems to percolation

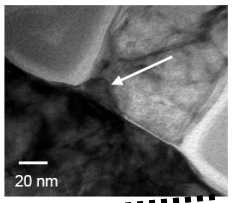
Random Dopants

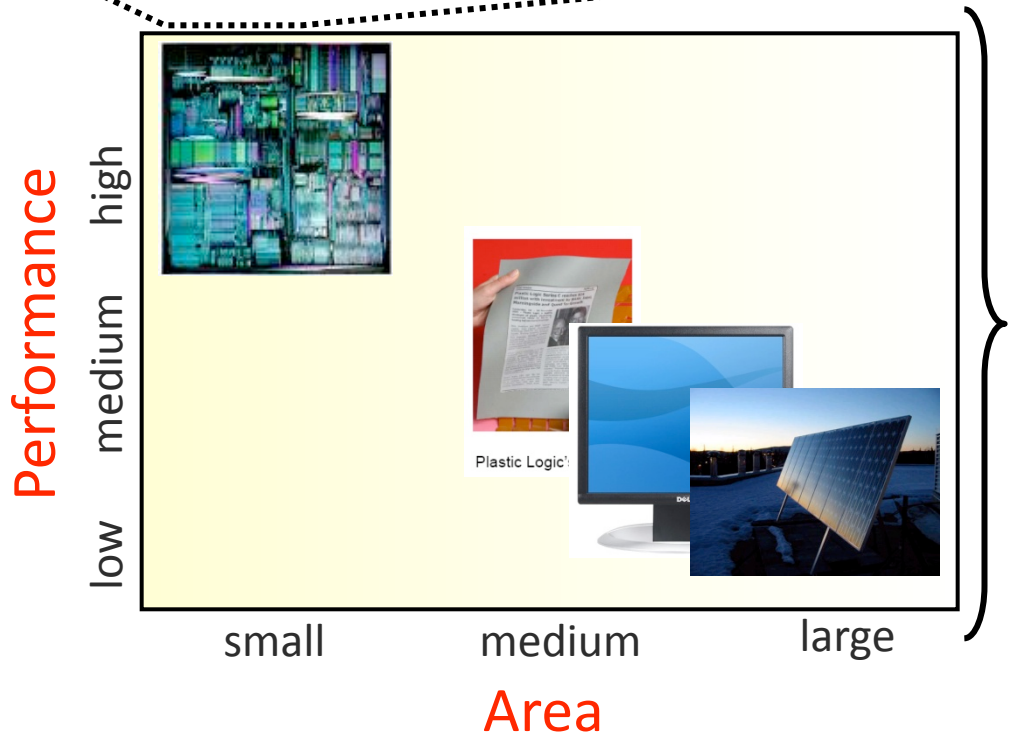


NC Flash

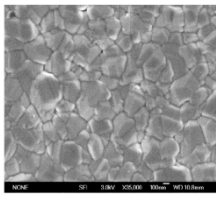


Dielectric BD

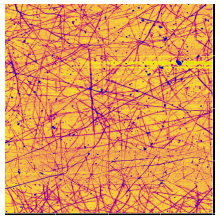




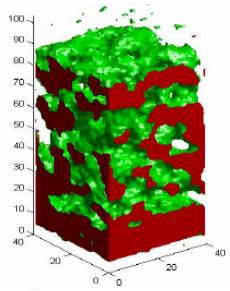
Poly-Si



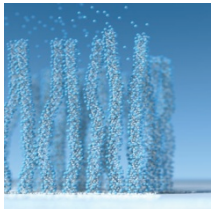
NanoNet/ Biosensors



Solar cells

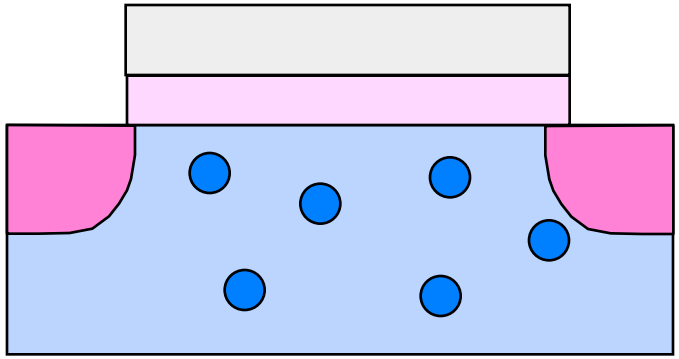


super-capacitors

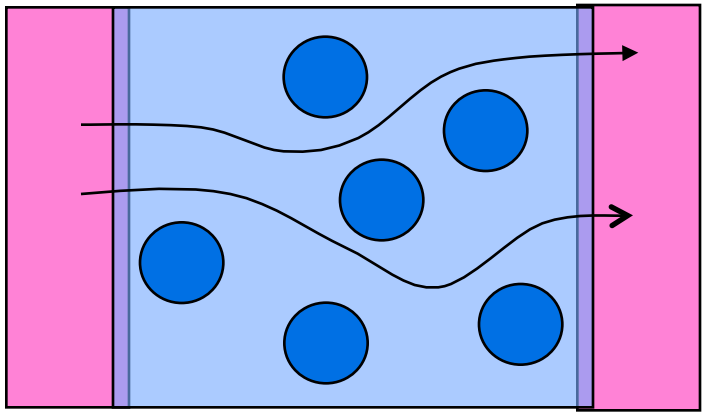


random dopant fluctuation

side view



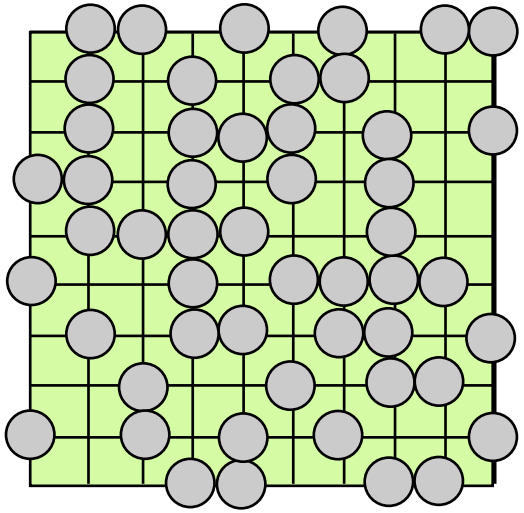
top view



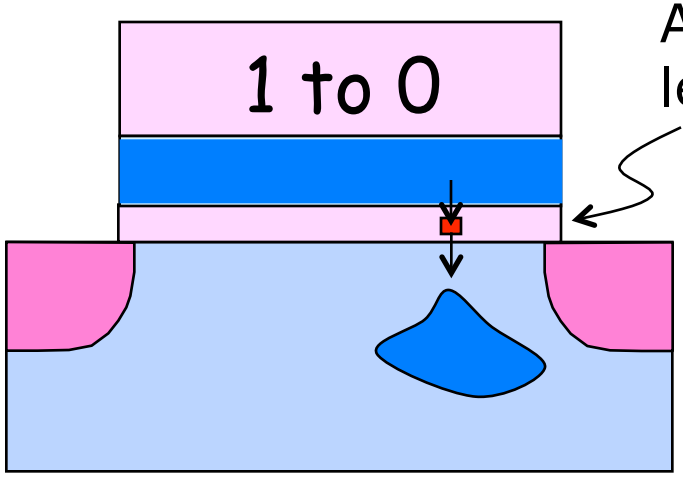
@1e18/cm^3

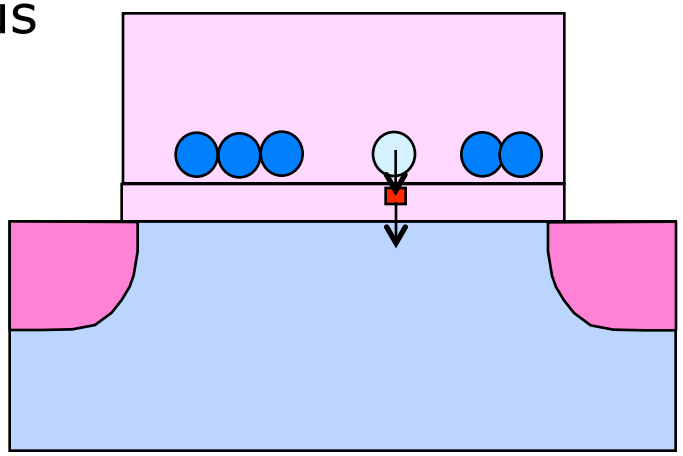
100 nm --- 1000 dopants
20 nm --- 40 dopants
10 nm --- 10 dopants

model

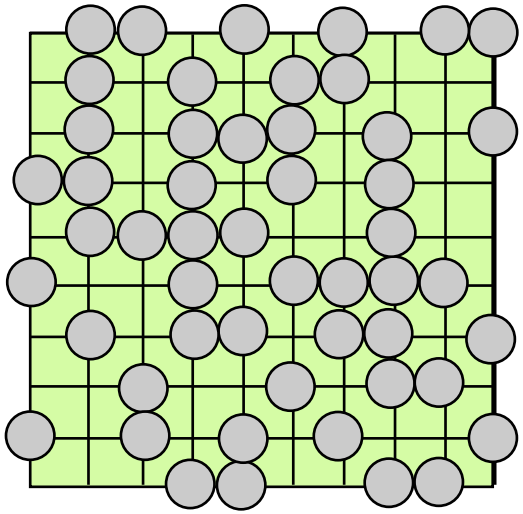


flash vs. nanocrystal flash

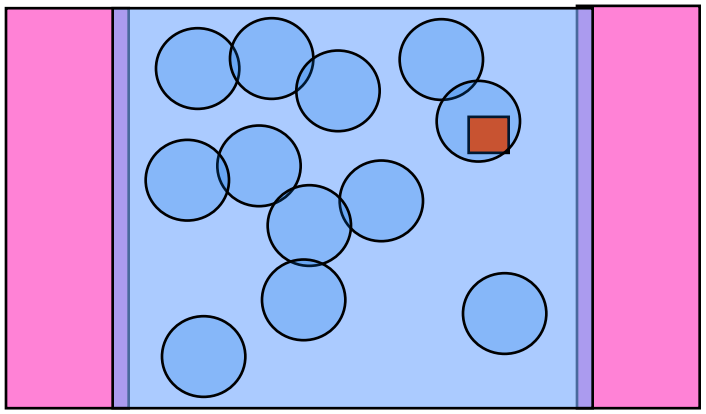




model

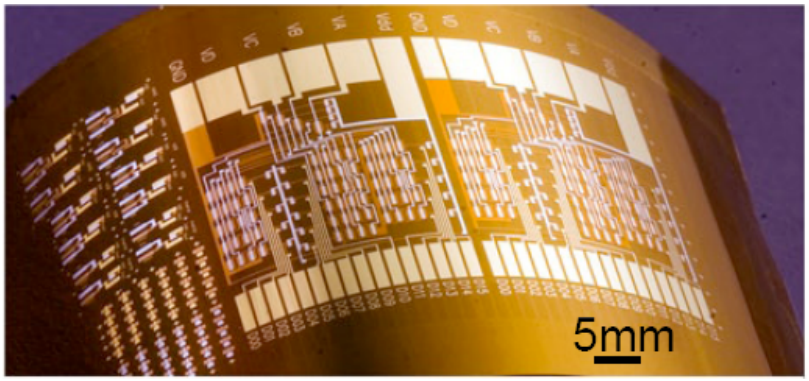


Top view

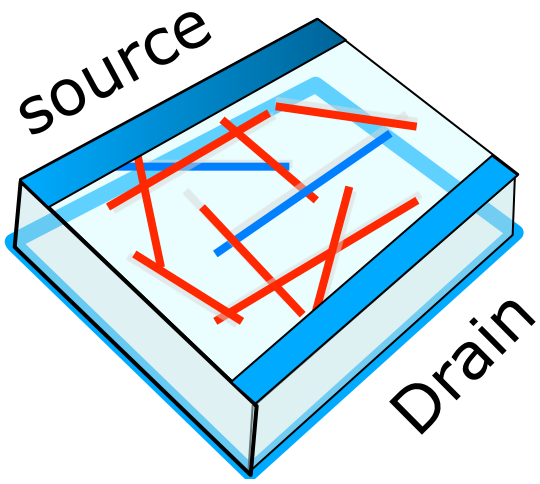


island size distribution ...

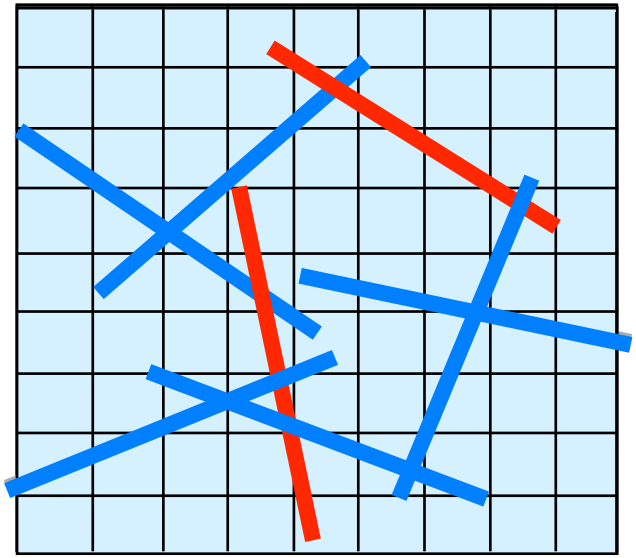
flexible nanonet transistors (lectures 3, 4)



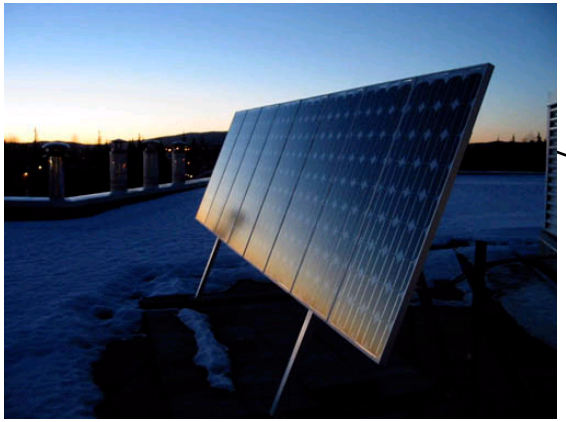
Cao, Nature, 2008

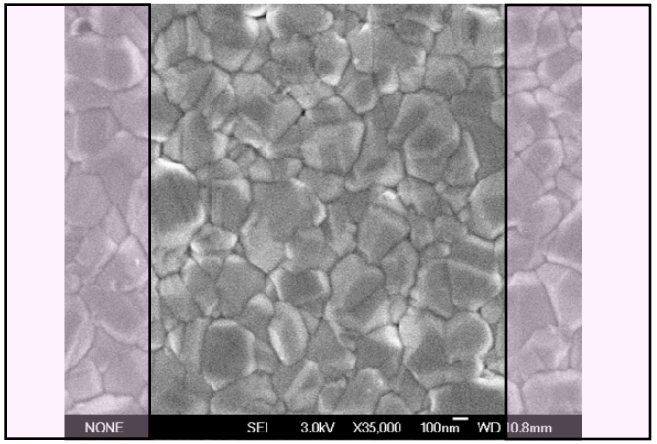


Heterogeneous percolation



solar cells and display electronics



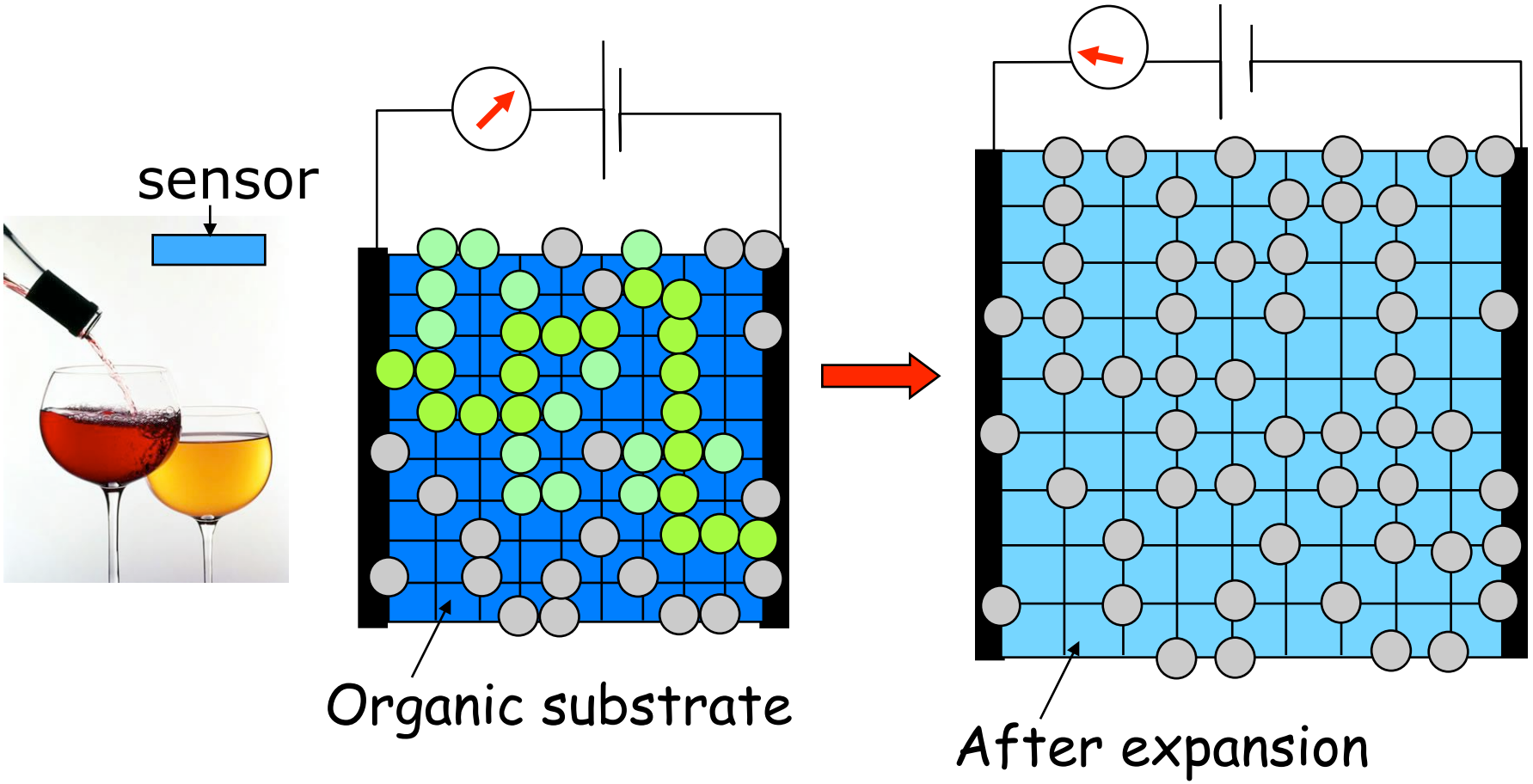


Key issues:

Transport through barriers created by grain boundaries

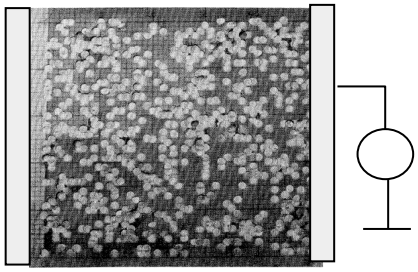
Device/device fluctuation

chemical sensors and e-nose



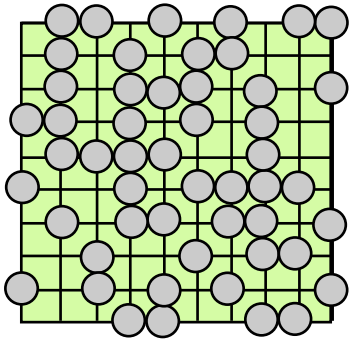
percolation threshold …

classical vs. nonlinear percolation



Dobson, PRL, 1971

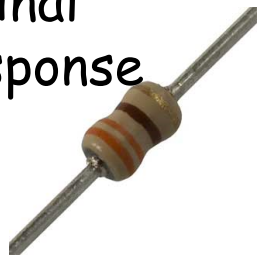
Schmelzer, PRL, 2002

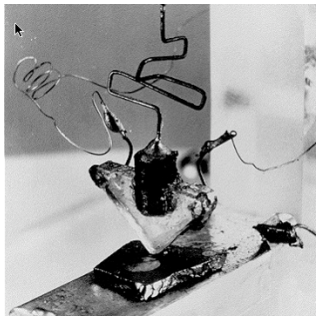


Percolation (1970s)

Theory of Nonlinear Percolation ?!

Two Terminal
Linear Response





Multiple Terminal
Nonlinear Response

Ohm's law (1827)

Transistor Theory (1947)

outline of lecture 1

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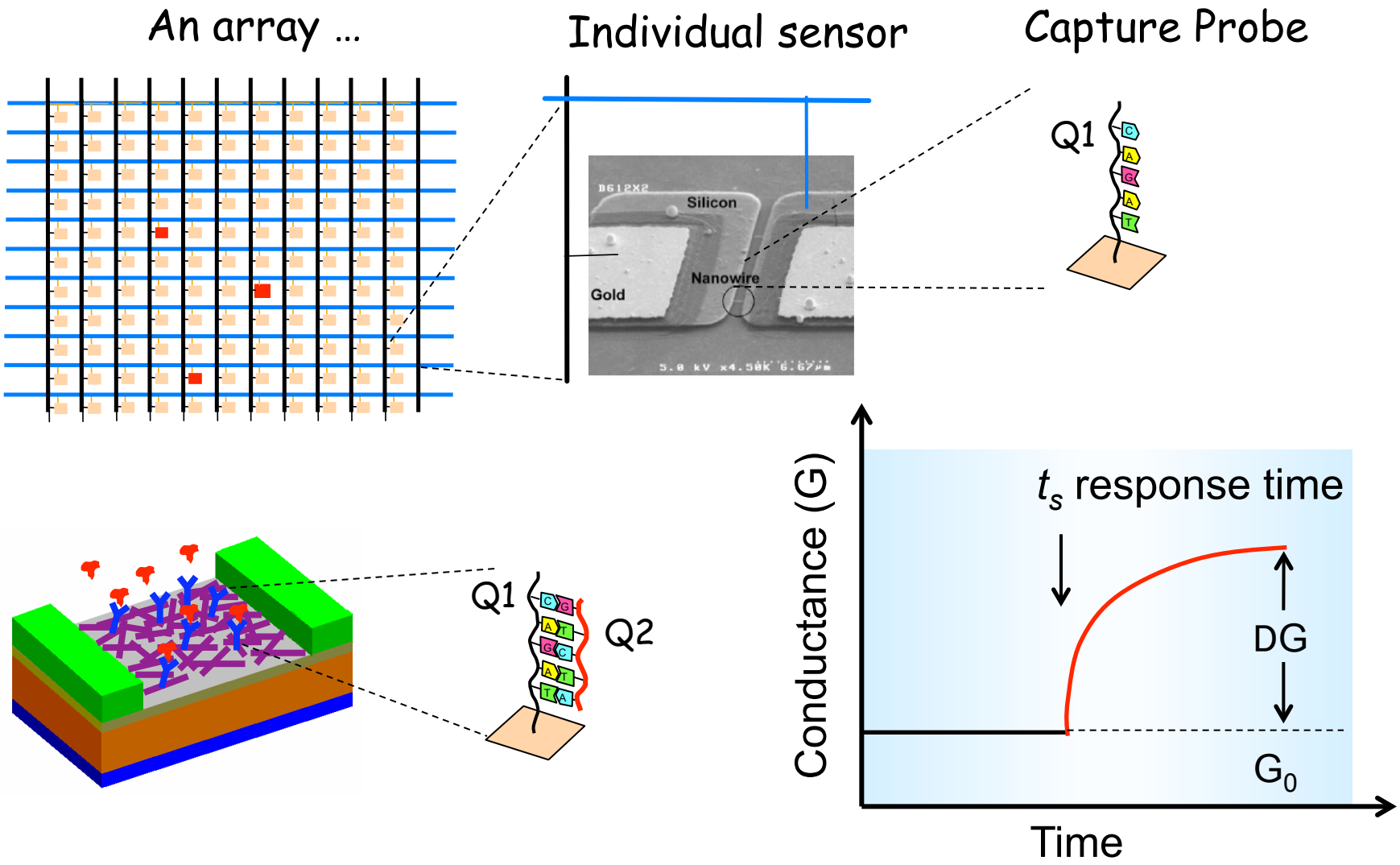
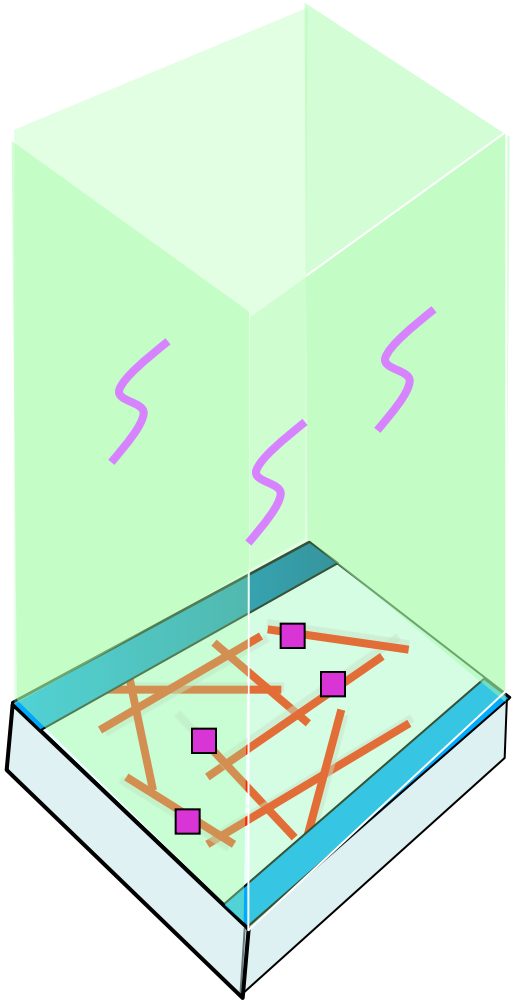
6) Conclusions

biosensors (lecture 5)

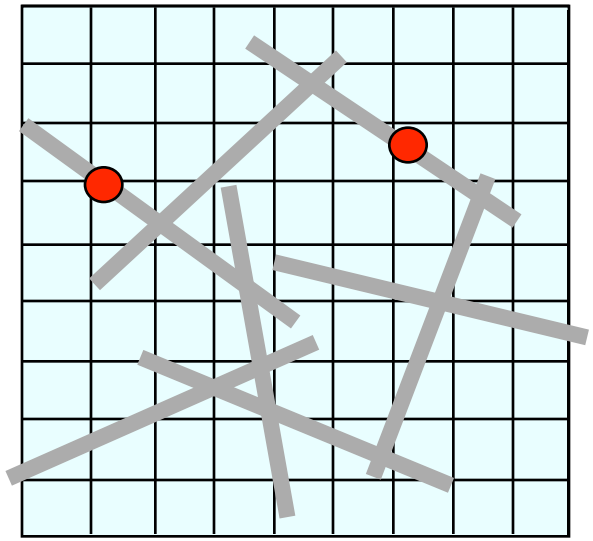


diffusion towards disordered biosensors…

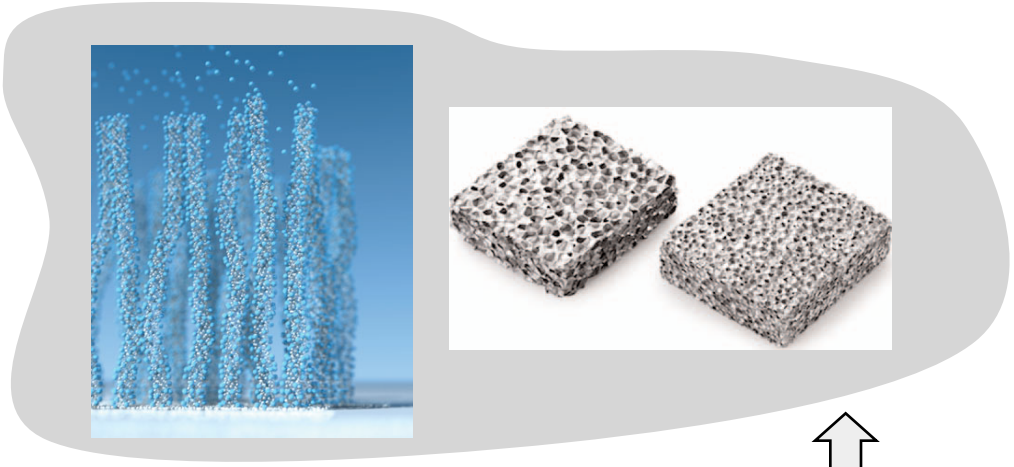


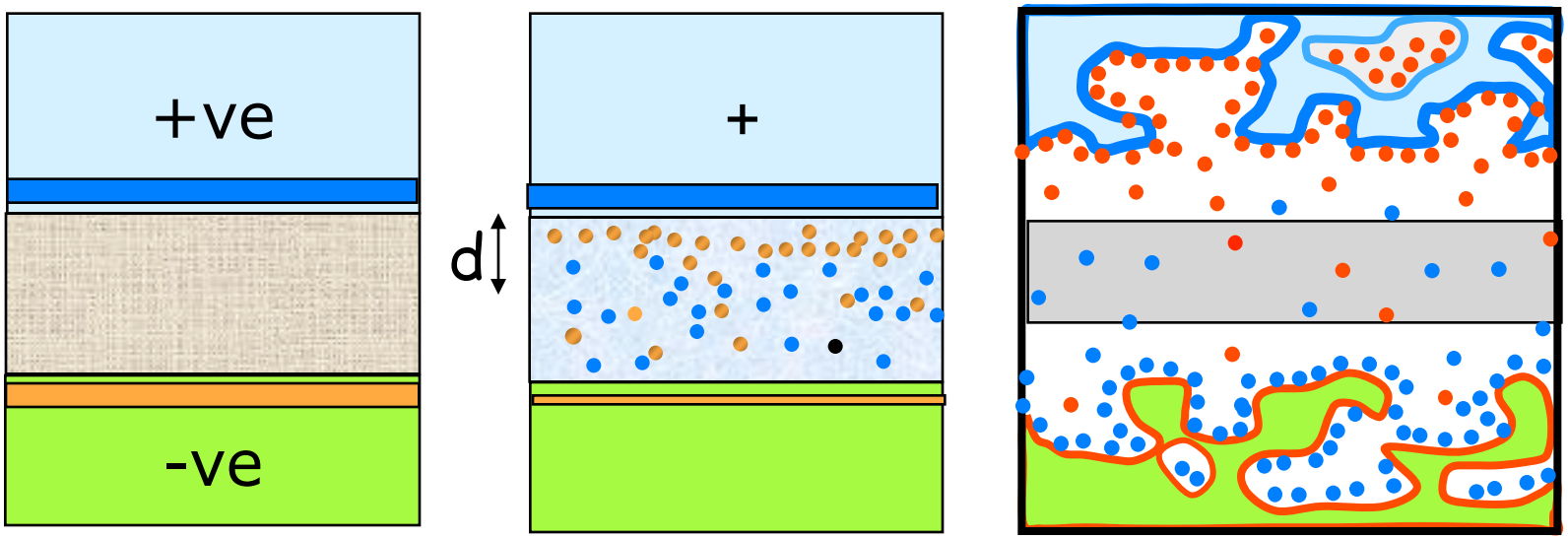
Key issues:

- density dependent response time
- conductivity, transfer resistance or substrate dependence
- Channel length scaling



super-capacitors (lecture 6)



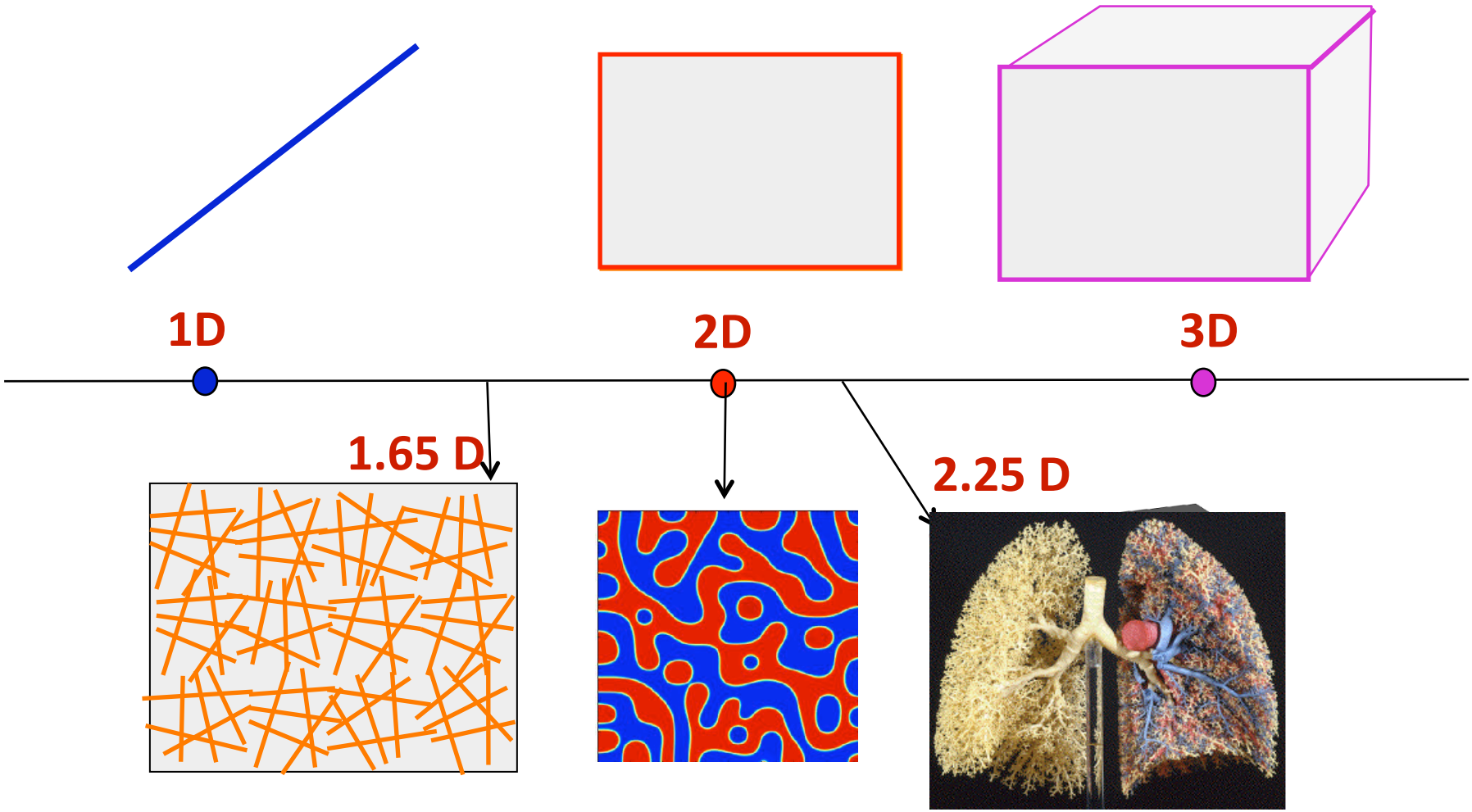


Parallel plate capacitor

Electrolyte capacitor

Super-capacitor

finite fractals …



Fractal theory is for infinite, scale-invariant systems,
Electrical devices involve finite fractals

outline of lecture 1

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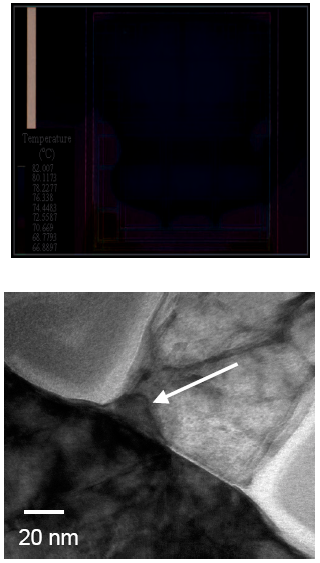
6) Conclusions

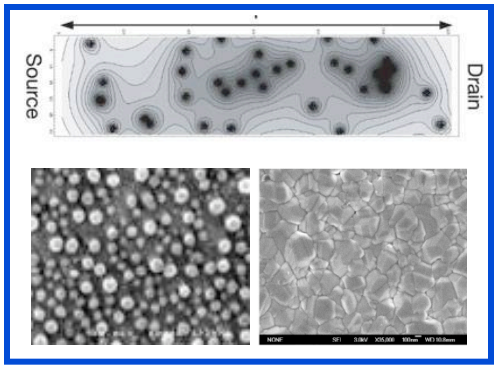
reliability and randomness (lecture 7-10)

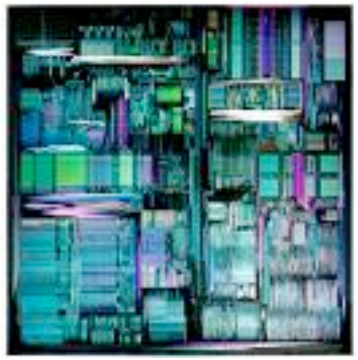
Reliability

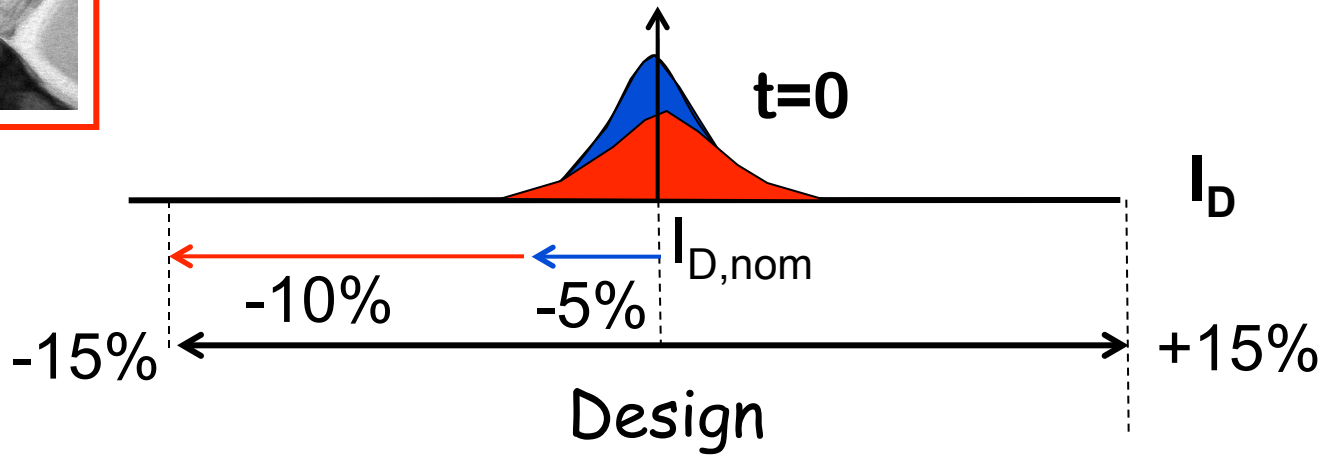


plus

Process

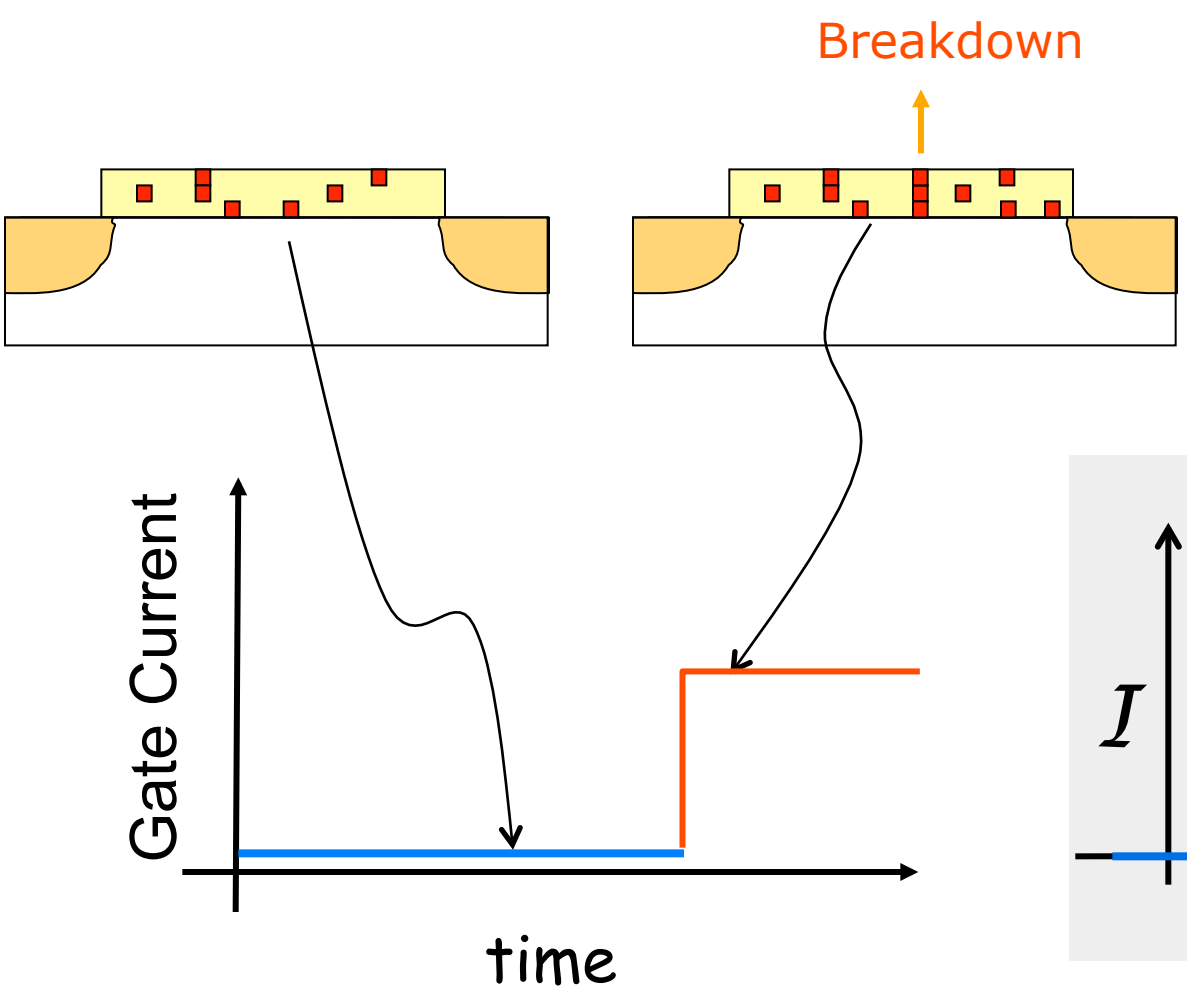


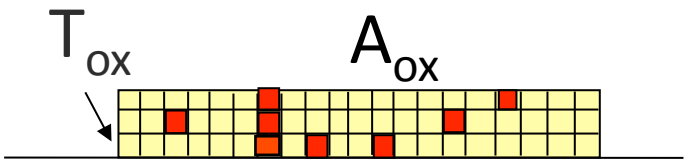




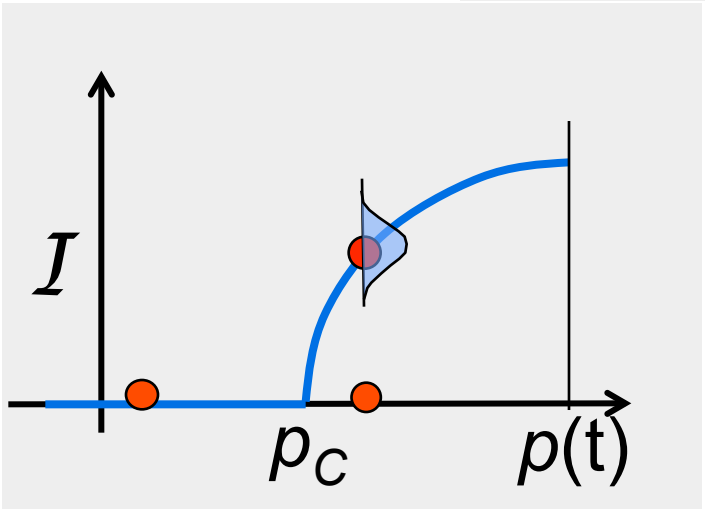
Reliability is a very important practical problem…

oxide degradation/breakdown (lectures 8,9)





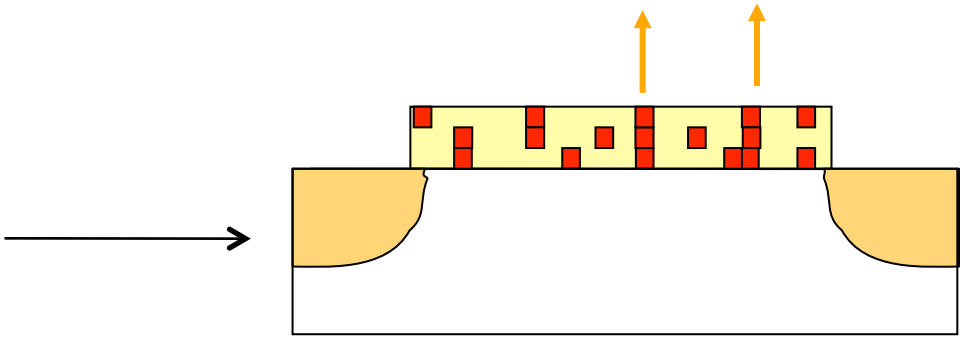
$$p = q^{M}$$
$$= (t/t_0)^{M\alpha}$$



correlation, power-laws, role of contacts

Correlated breakdown
in Thick Insulators

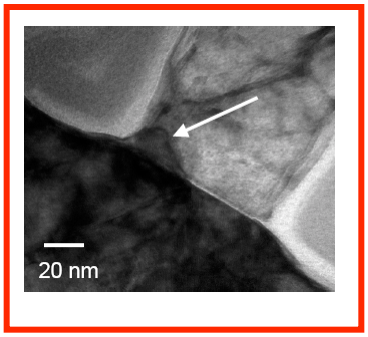
Uncorrelated Breakdown
In Thick Insulators



Theory of partially correlated breakdown
is important and contacts define everything.

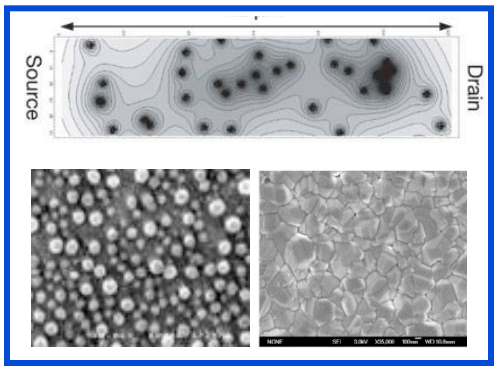
equivalence between spatial/temporal fluctuation

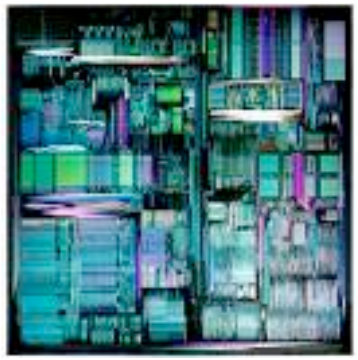
Reliability



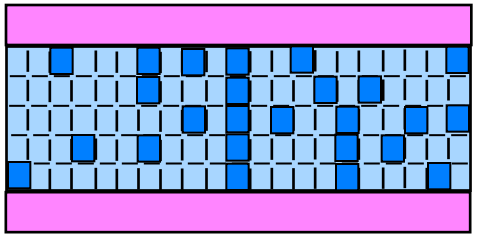
plus

Process

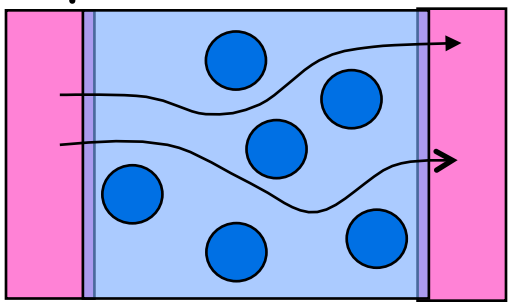




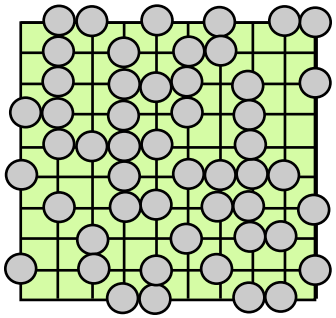
Side view (TDDB)



top view (RDF)



model

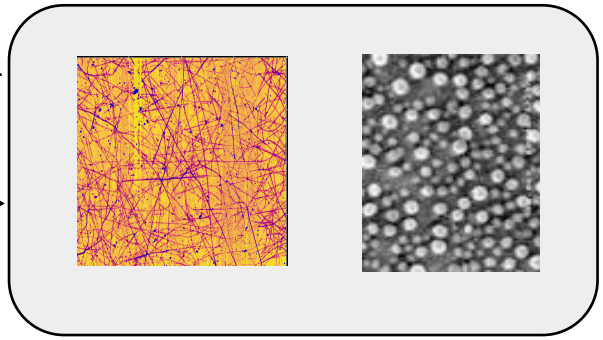


Spatial and temporal fluctuation should be considered with same framework …

theory and application: back & forth

Nonlinear

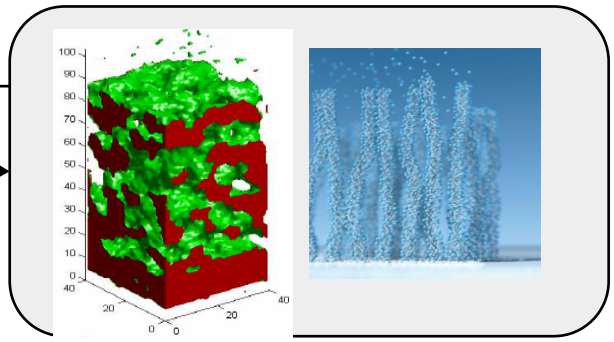
Percolation



Lectures 3,4

Finite

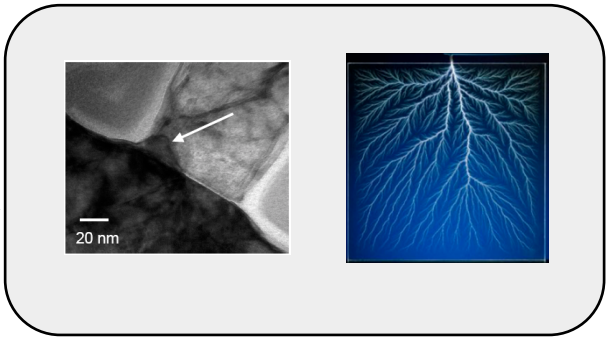
Fractals



Lectures 5,6

Correlated

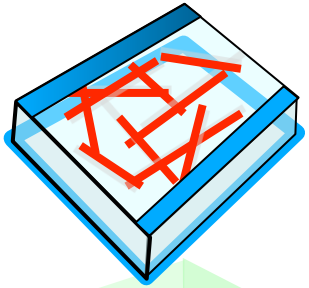
Temporal Percolation



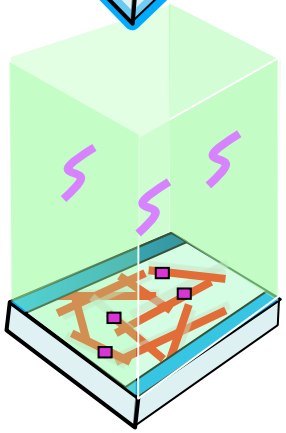
Lectures 7-10

conclusions

- Properties of small electronic devices are dictated by spatial and temporal randomness that cannot be described by classical theories.



- We will use theories of percolation and fractals to describe such systems.



- Even these theories must be generalized to nonlinear and heterogeneous percolation, finite fractals, and correlated breakdown.

- If we understand these problem, many topics beyond electronics will also become clear.

Figure references/credits

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