Reflections on the Past, Present, and Future of Device Research

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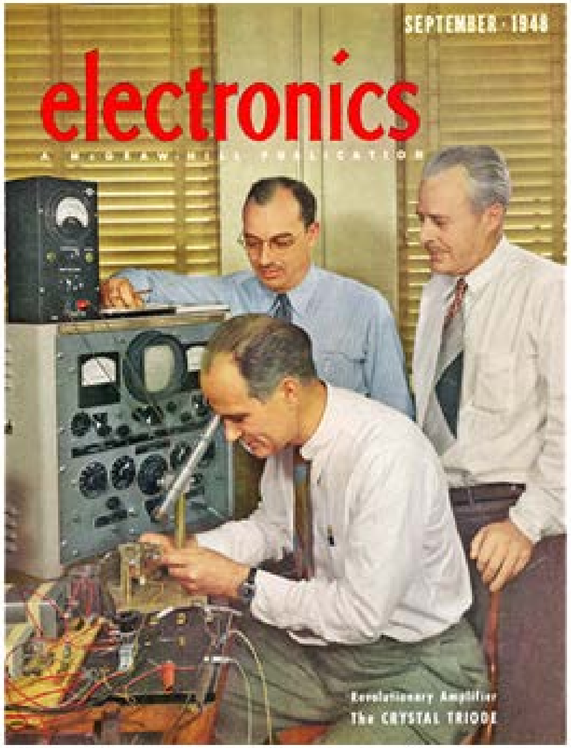
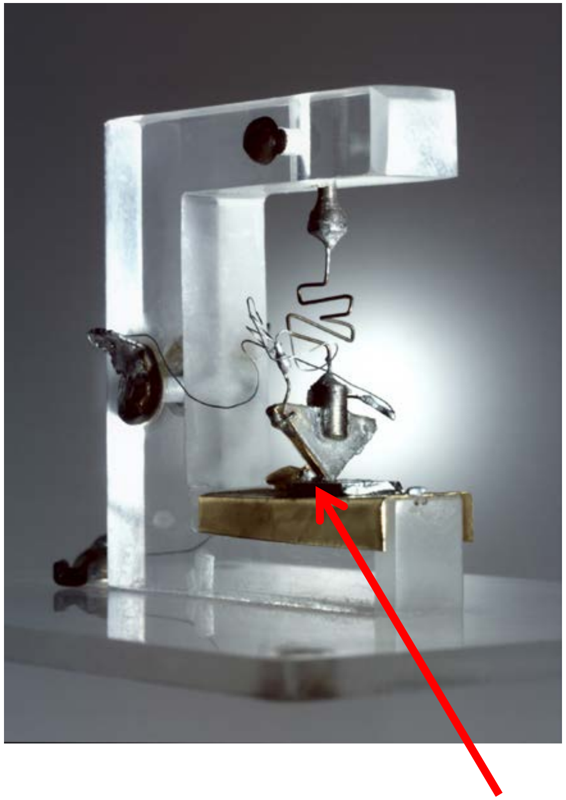
It began with the transistor



Bardeen, Brattain, Shockley, 1947



Semiconductor Science

1941: WWII: Semiconductor diode rectifiers

http://www.computerhistory.org

"Karl Lark-Horovitz is best known for turning the physics department of Purdue University, then a backwater school, into a research powerhouse."

http://www.pbs.org/transistor/album1/addlbios/lark.html

Semiconductor Device Research: Stage 1

1947: Point contact transistor
1948: Thermoelectric generator
1948: Bipolar junction transistor
1954: Modern solar cell
1956: PNPN diode
1959: Integrated circuits
1960: MOSFETs
1962: LED's and semiconductor lasers
1964: Gunn diode
1965: IMPATT diode
1967: DRAM cell
1968: Resonant gate transistor (MEMS)
1969: CCD

The value of practical knowledge

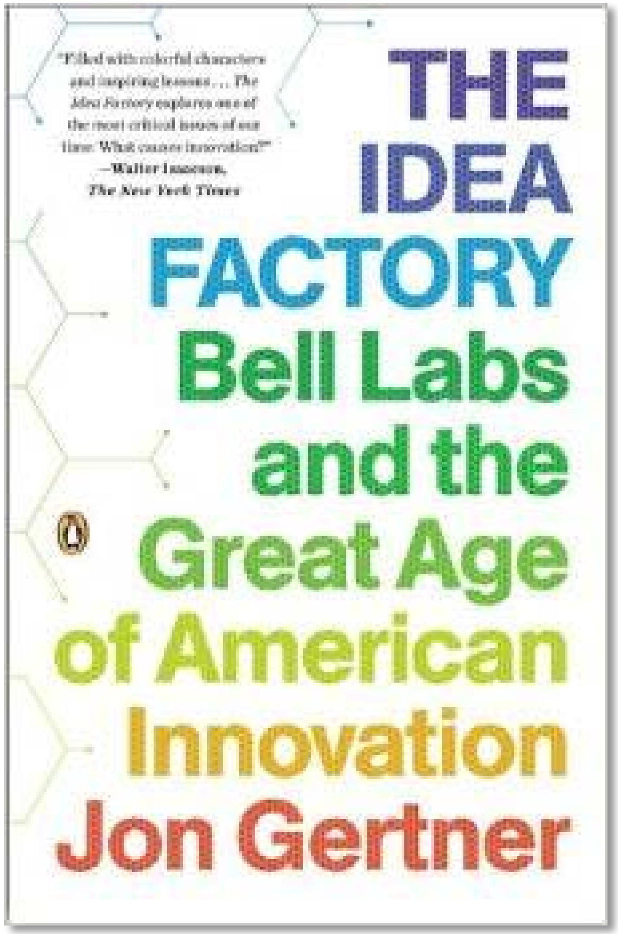
“Upon my arrival I was assigned by Dr. M. J. Kelly to an **indoctrination program** in vacuum tubes.”

Insofar as my contribution to transistor electronics has hastened the day of a fully electronic telephone exchange, it was strongly stimulated by the experiences given me during my early years at the Laboratories.”

Shockley’s 1956 Nobel Lecture nobelprize.org

The magic of Bell Labs

The great industrial research labs of yesterday



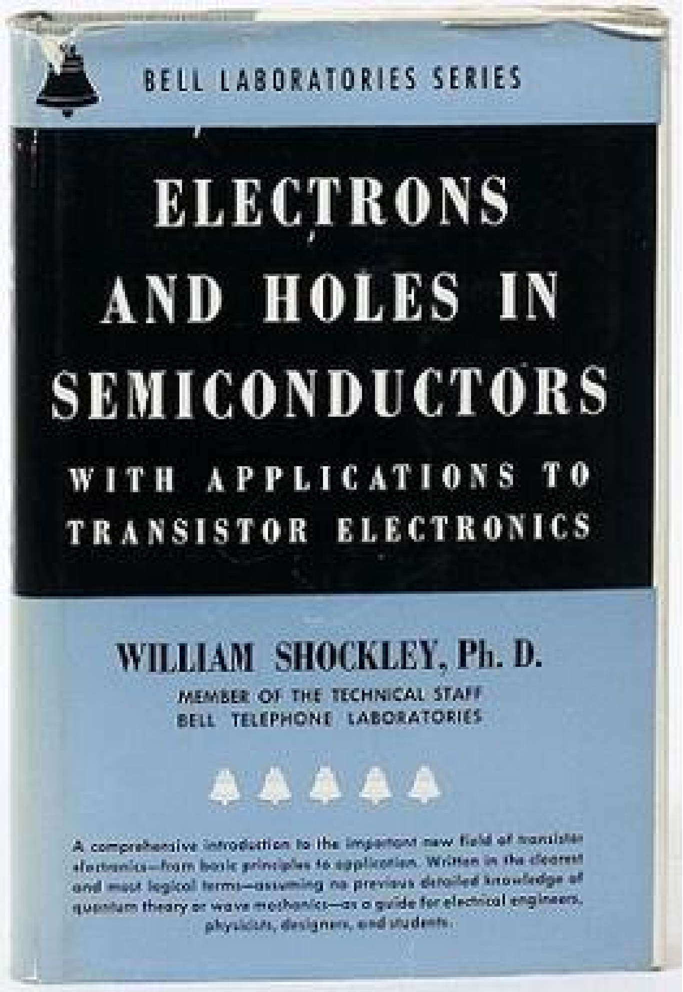
"Filled with colorful characters and inspiring lessons . . . *The Idea Factory* explores one of the most critical issues of our time: What causes innovation?"
—Walter Isaacson,
The New York Times

THE IDEA FACTORY
Bell Labs and the Great Age of American Innovation
Jon Gertner

"…Mervin Kelly, the president of Bell Labs, let many members of his research department **roam free**, sometimes **without concrete goals**, for years on end."

"Bell Labs … had **the advantage of necessity**. In Kelly's view, the members of the technical staff had the great advantage of working to improve a telephone system where there were always problems, always needs."

The science of semiconductor devices



BELL LABORATORIES SERIES

ELECTRONS
AND HOLES IN
SEMICONDUCTORS

WITH APPLICATIONS TO
TRANSISTOR ELECTRONICS

WILLIAM SHOCKLEY, Ph. D.
MEMBER OF THE TECHNICAL STAFF
BELL TELEPHONE LABORATORIES

A comprehensive introduction to the important new field of transistor electronics—from basic principles to application. Written in the clearest and most logical terms—assuming no previous detailed knowledge of quantum theory or wave mechanics—as a guide for electrical engineers, physicists, designers, and students.

Advice from Shockley

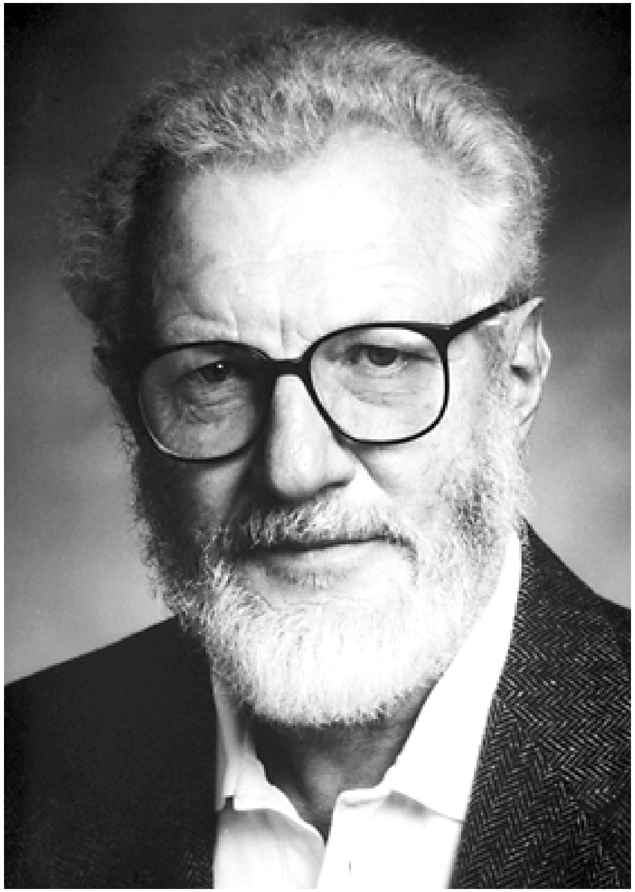
"Frequently, I have been asked if an experiment I have planned is **pure or applied research**; to me it is more important to know if the experiment will yield new and probably **enduring knowledge** about nature."

Shockley's 1956 Nobel Lecture nobelprize.org

Device Research: Stage 2

1970: ISFET
1976: Modern quantum well laser
1977: IGBT
1977: LDMOS
1979: HEMT
1980: Flash memory
1982: Modern HBTs
1987: OLED
1992: CMOS imagers
1994: Quantum cascade laser
1998: Modern FinFETs
2008: STT-MRAM
2013: Quantum dot displays

The golden age of device research



nobelprize.org

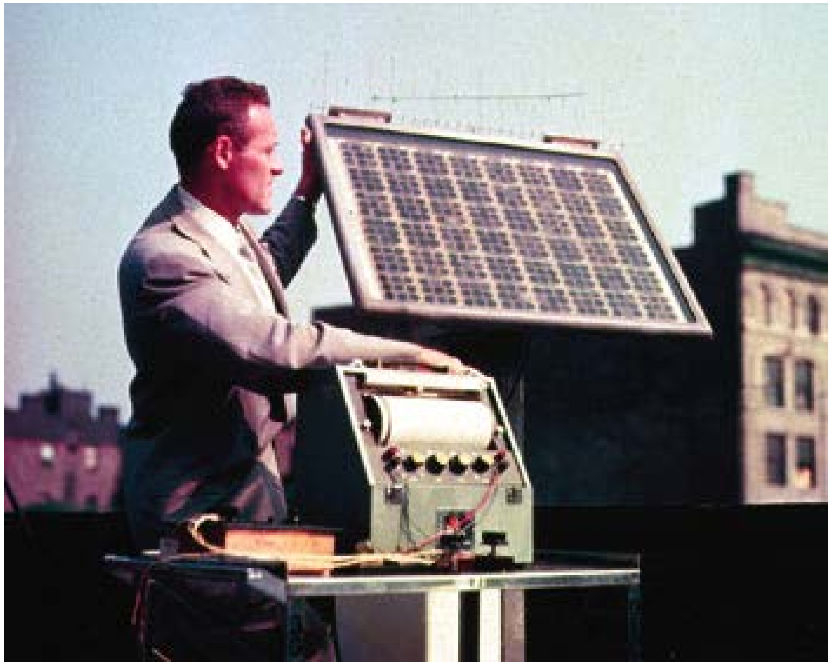
“The principal applications of any sufficiently new and innovative technology always have been – and will continue to be – applications ***created*** by that technology.”

“..a **search for applications** should be considered a part of the research.”

Outline

1) The past
2) **The present**
3) The future

The modern solar cell

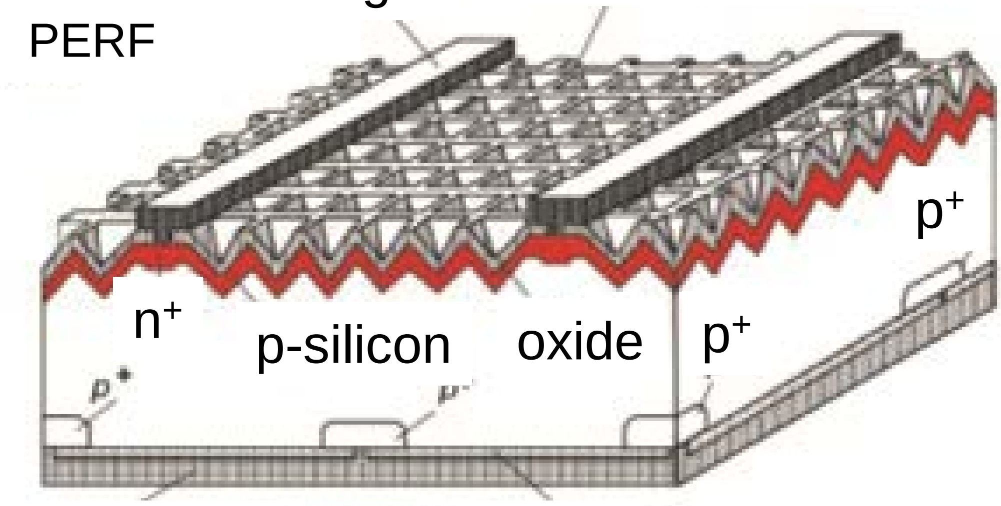


Chapin, Pearson, and Fuller, Bell Labs, 1954

http://www.bell-labs.com/org/physicalsciences/timeline/span10.html#

High-efficiency Si Solar Cells

PERD
PERL
PERT
PERF



finger

inverted
pyramids

p^+

n^+

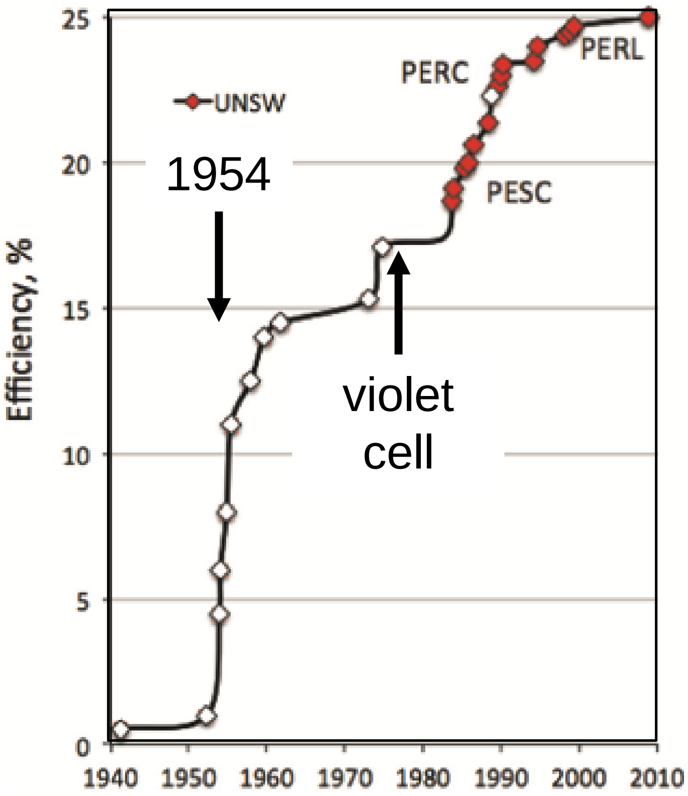
p-silicon

oxide

p^+

rear contact

oxide

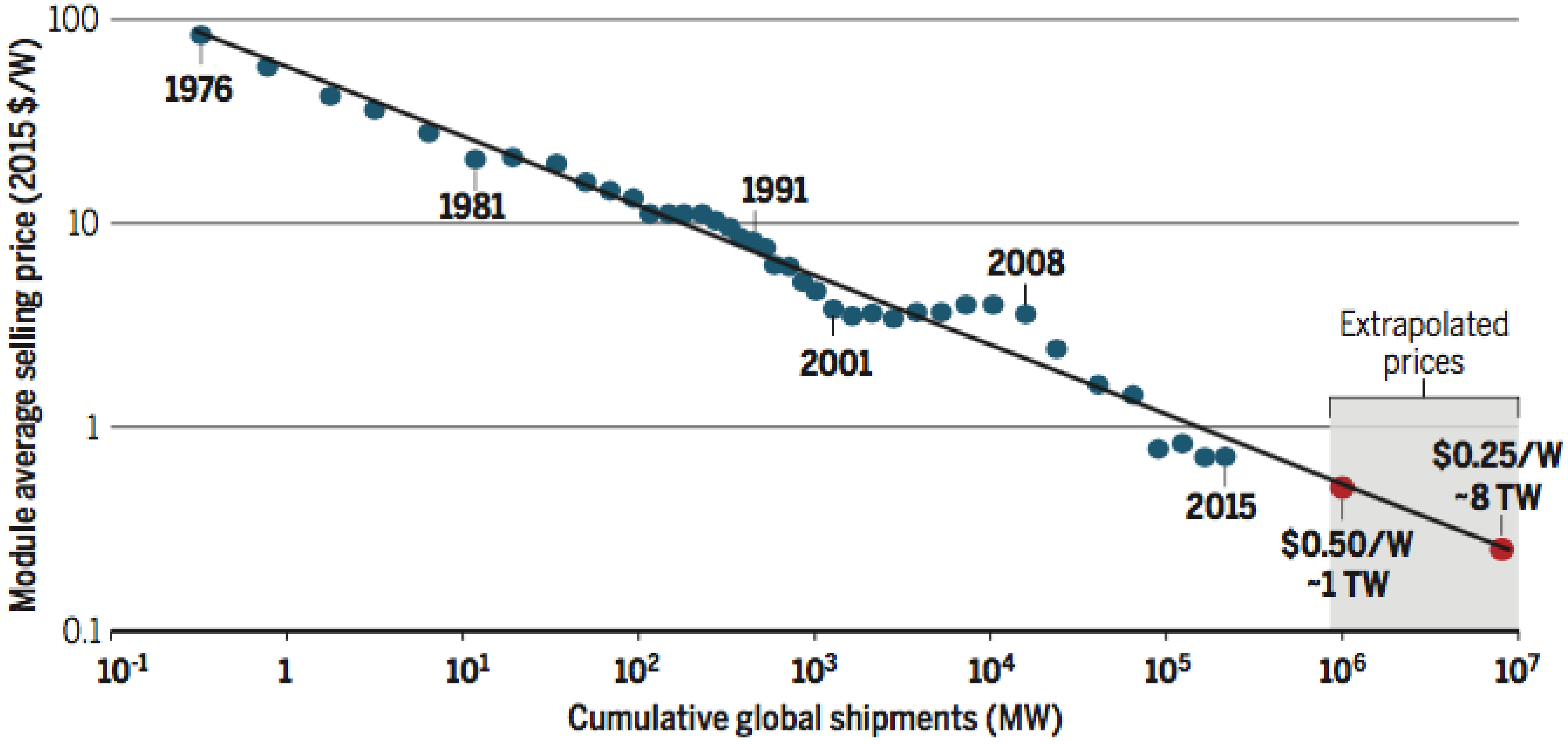


1954

violet
cell

M.A. Green, “The Passivated Emitter and Rear Cell: From Conception to Mass Production,” *Solar Energy Materials and Solar Cells*, **143**, 190-197, 2015.

PV learning curve



Nancy M. Haegel, et al., “Terawatt-scale photovoltaics, Science, **356**, 141-1143, 2017.

Device research today

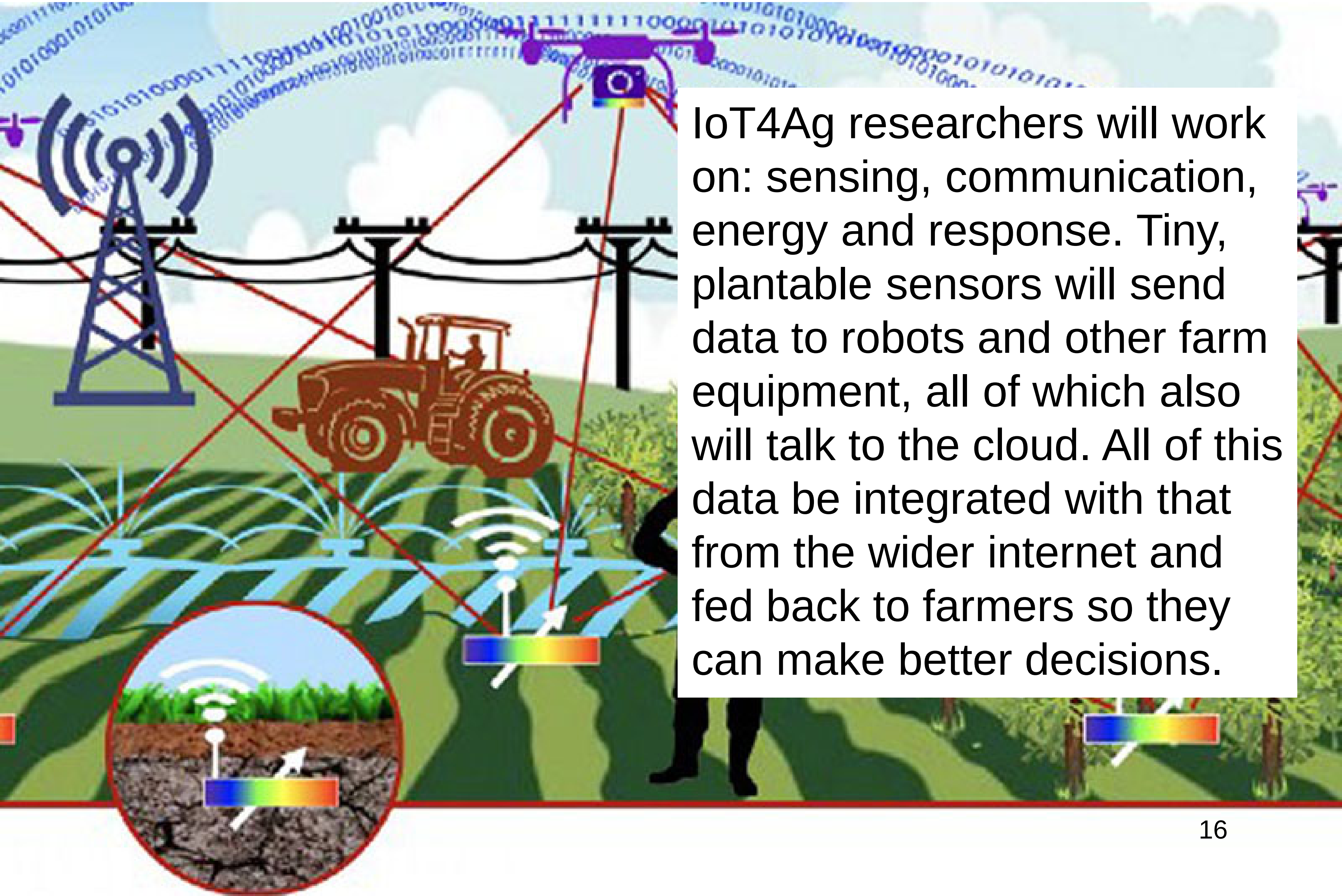
Cherie R. Kagan
Univ. Pennsylvania

"Electronic Energy Transfer in CdSe Quantum Dot Solids"

C. R. Kagan, C. B. Murray, M. Nirmal, and M. G. Bawendi
Phys. Rev. Lett., **76,** 1517, 1996.

https://en.wikipedia.org/wiki/Cherie_Kagan

IoT4Ag Engineering Research Center



IoT4Ag researchers will work on: sensing, communication, energy and response. Tiny, plantable sensors will send data to robots and other farm equipment, all of which also will talk to the cloud. All of this data be integrated with that from the wider internet and fed back to farmers so they can make better decisions.

Outline

1) The past
2) The present
3) **The future**

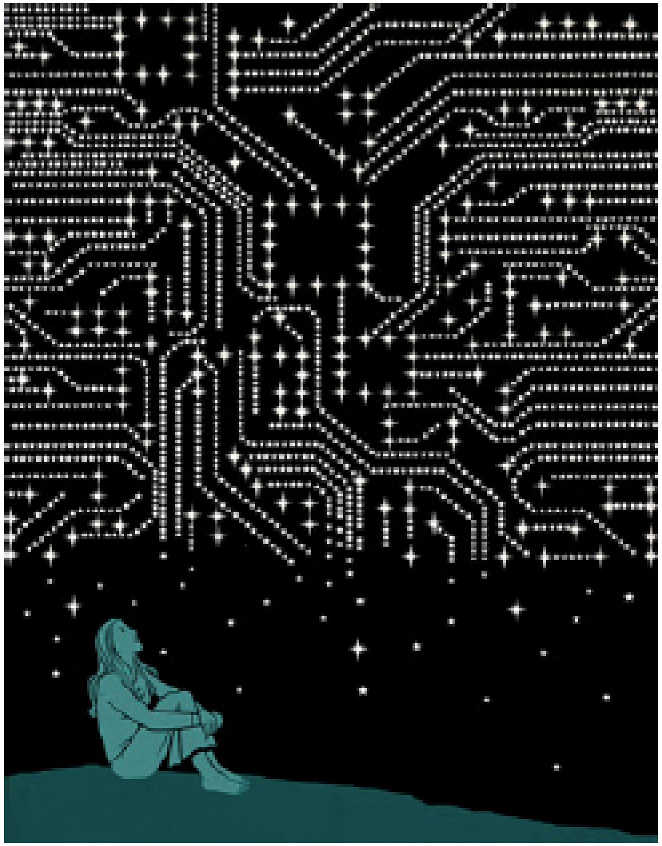
“Personal Computer without ICs”

“… how a home computer could look like in the year 2004... with teletype interface and Fortran language, the computer will be easy to use.” *Popular Mechanics*, 1954

Device research in the 21st Century

Predicting the Great Achievements of the 21st Century

Robert W. Lucky *IEEE Spectrum*, Dec. 2014



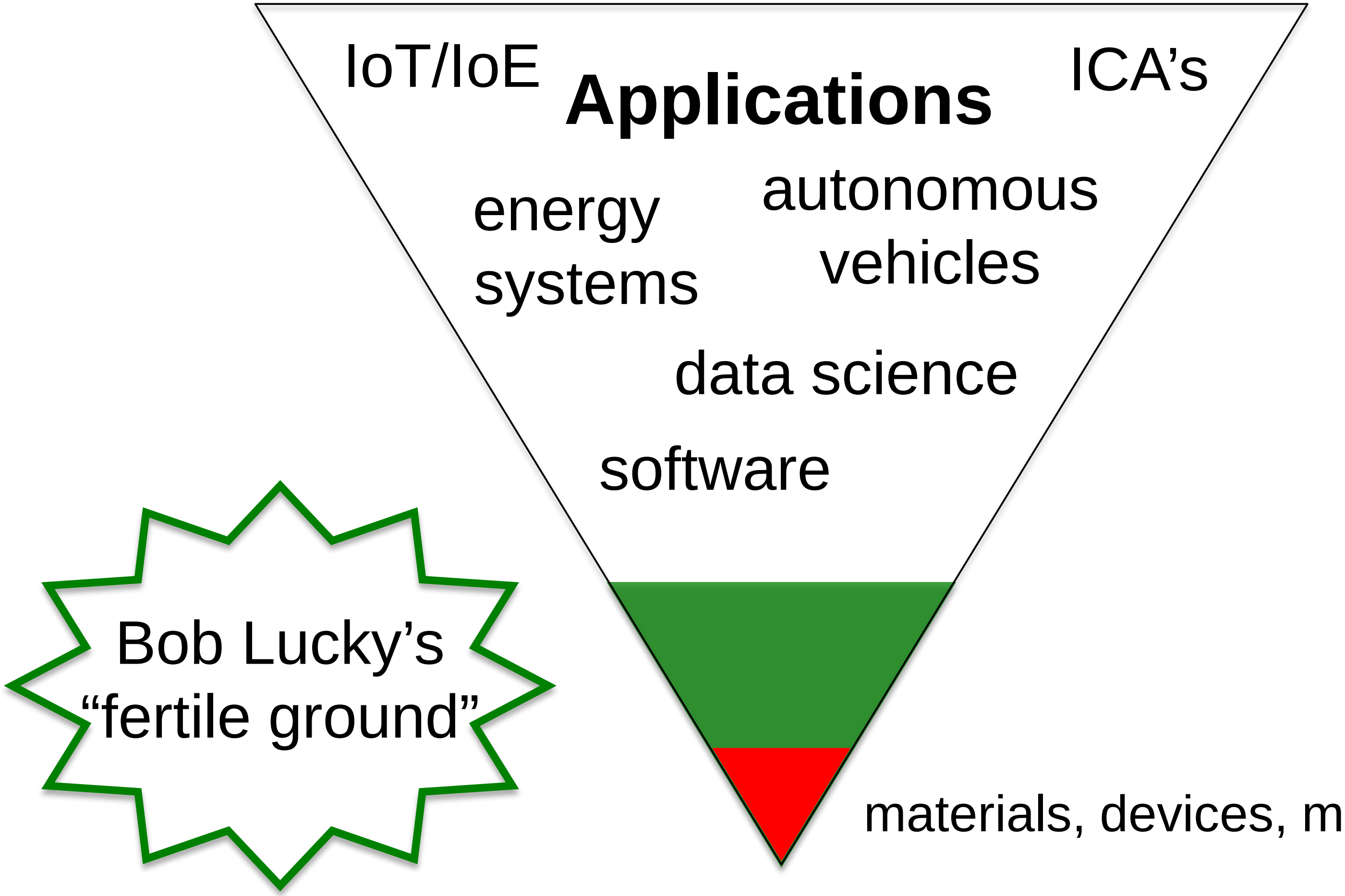
- Things that were happening
- Things that could be anticipated
- Things that no one can could have predicted.

The future

What’s different now, is that we have in place an incredibly sophisticated and pervasive infrastructure.

Is there a new device that will invent its own applications?

21^{st} Century Electronics



IoT/IoE

Applications

ICA's

energy systems

autonomous vehicles

data science

software

materials, devices, manufacturing

Bob Lucky's "fertile ground"

R. W. Lucky, *IEEE Spectrum*, May 1998

The future

How do we prepare students and working engineers to succeed in 21st Century physical electronics?

The challenge in 1960

en.wikipedia.org/wiki/Frederick_Terman

"... education is perhaps the most significant factor affecting the future of electronics."

Frederick Emmons Terman, "**Education** – A basic component of the new electronics," presented at the 16th National Electronics Conference, Chicago, IL, Oct. 12, 1960.

Semiconductor Electronics Education Committee

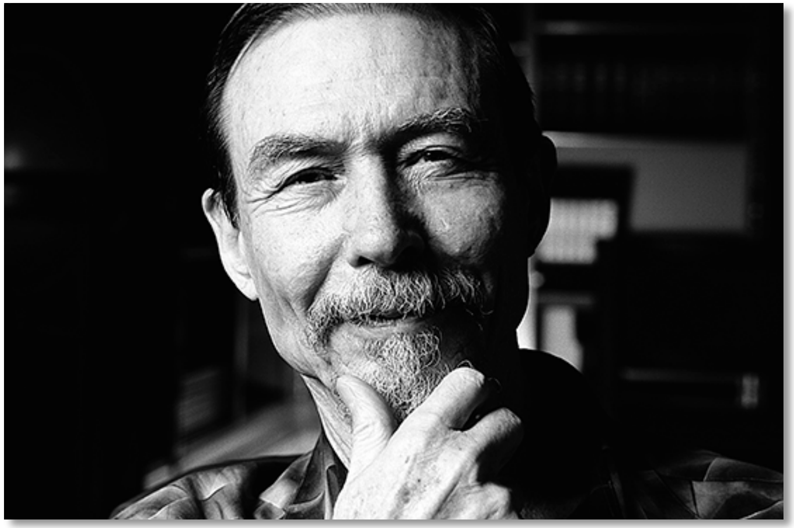
SEEC Notes

“**SEEC was a triumph of engineering science**, with a substantial, lasting impact. The basic ideas influenced many textbooks written in subsequent years. The approaches are still used in EE education throughout the world...”

R.B. Adler, et al., 1960-1967

http://web.mit.edu/klund/www/books/seec.html
http://www-mtl.mit.edu/~penfield/pubs/eb-03.html

Carver Mead’s question

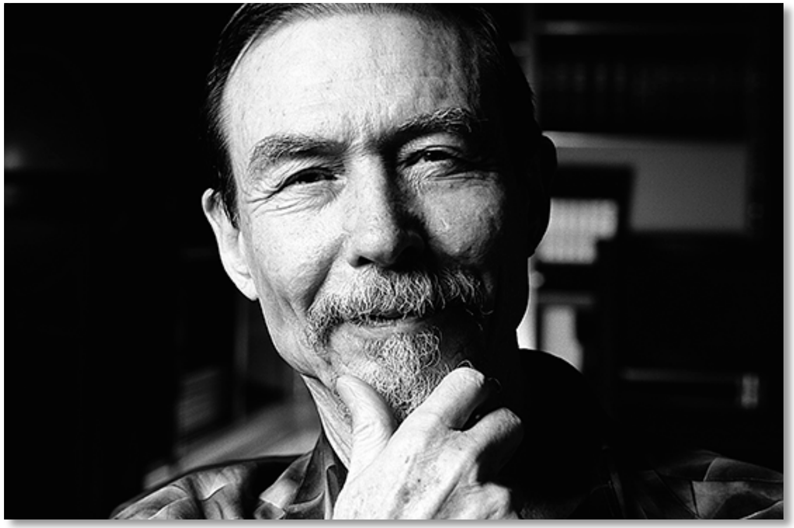


http://www.carvermead.caltech.edu

“How do we, as a human culture, prepare ourselves and our children for this world in which the knowledge base turns over several times within a single human lifetime?”

Carver Mead, *Collective Electrodynamics*, MIT Press, 1999.

“One answer is specialization”

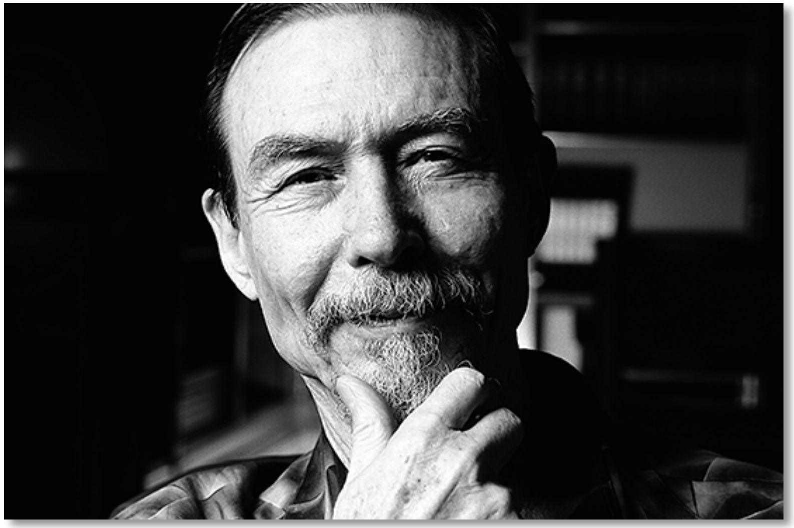


http://www.carvermead.caltech.edu

“If that were to be our only response, I would view our prospects as a culture with deep concern, even with alarm.”

Carver Mead, *Collective Electrodynamics*, MIT Press, 1999.

Carver Mead’s answer

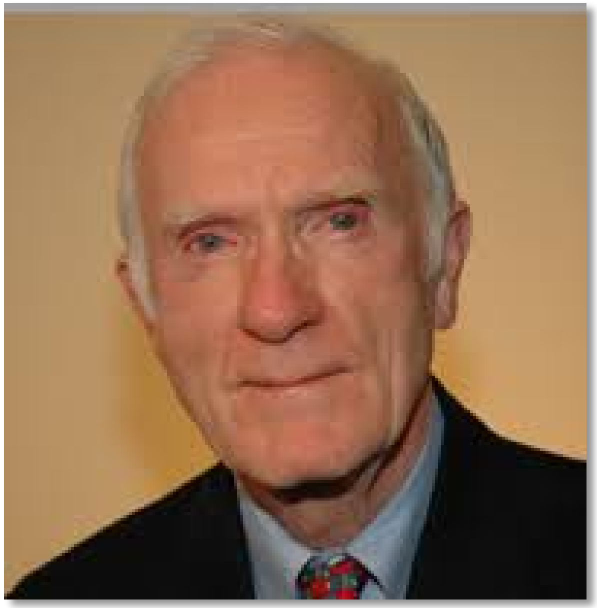


http://www.carvermead.caltech.edu

“It is the **unification and simplification of knowledge** that gives us hope.”

Carver Mead, *Collective Electrodynamics*, MIT Press, 1999.

Simplifying without watering down



Paul Penfield, MIT

“Trying to explain things rigorously, but simply often requires **new organizing principles** and approaches.”

class notes on “Information and Entropy”

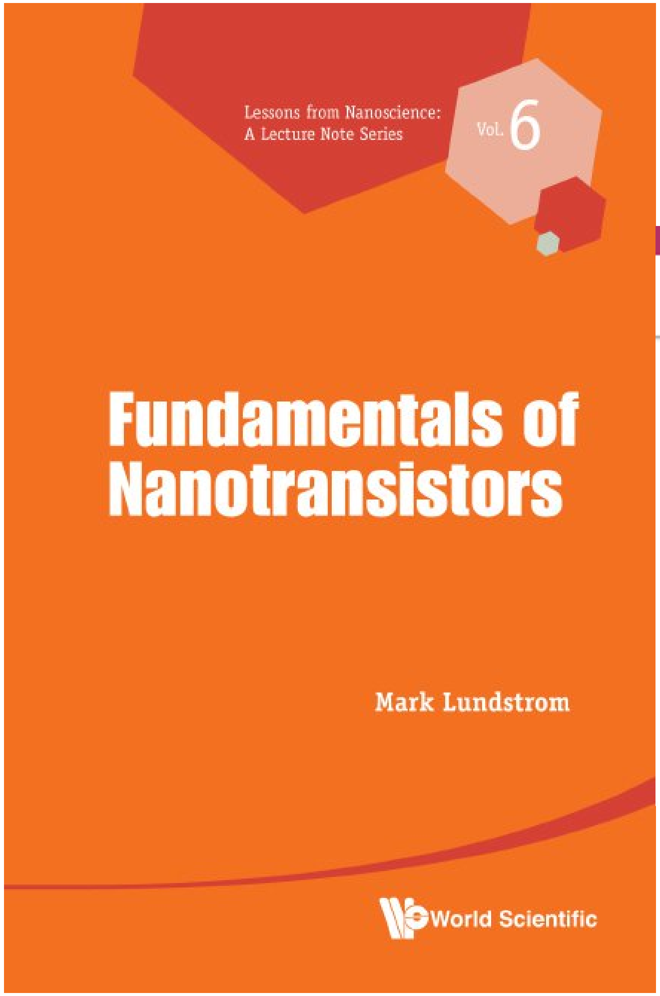
https://ocw.mit.edu/courses/electrical-engineering-and-computer-science/6-050j-information-and-entropy-spring-2008/syllabus/MIT6_050JS08_penfield.pdf

Outline

1) The past
2) The present
3) **The future**

- Essential Physics of Transistors
- Transport Theory for the 21st Century

Essential physics of transistors

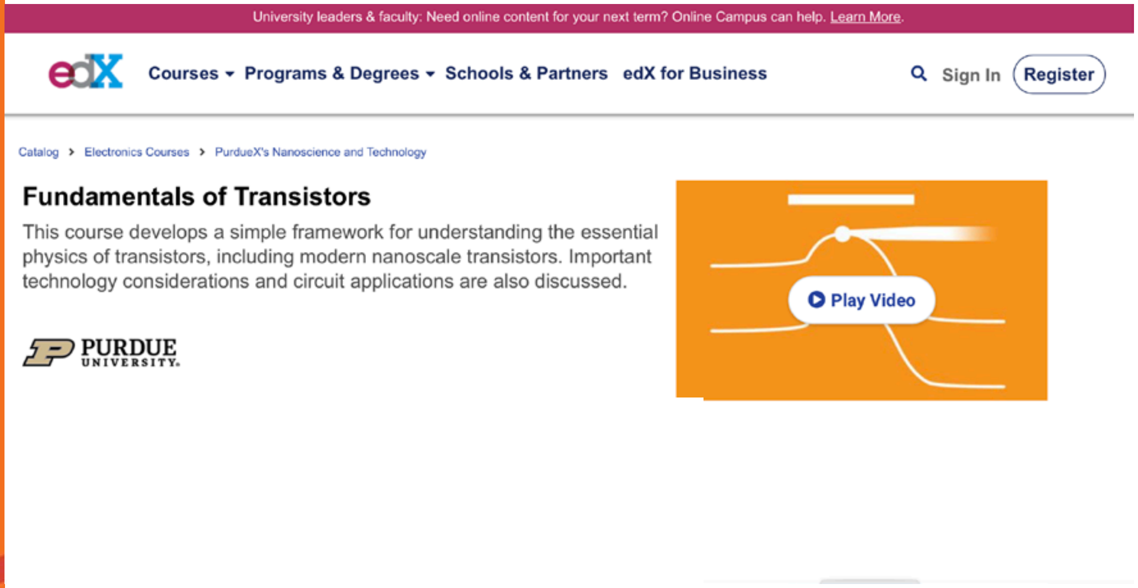


Lessons from Nanoscience:
A Lecture Note Series
Vol. 6

Fundamentals of Nanotransistors

Mark Lundstrom

World Scientific



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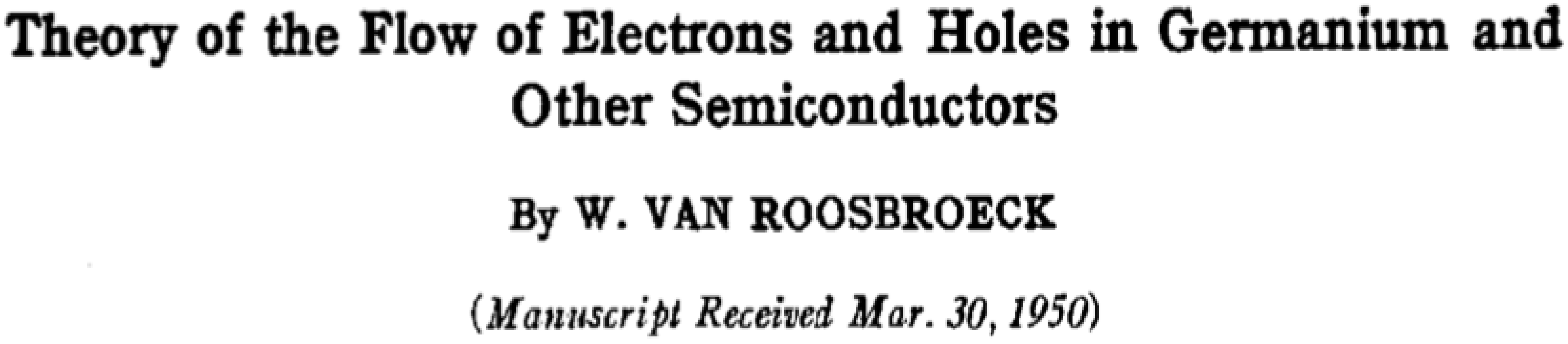
Fundamentals of Transistors

This course develops a simple framework for understanding the essential physics of transistors, including modern nanoscale transistors. Important technology considerations and circuit applications are also discussed.

World Scientific, 2018

Transport theory: Our common knowledge



Theory of the Flow of Electrons and Holes in Germanium and Other Semiconductors

By W. VAN ROOSBROECK

(Manuscript Received Mar. 30, 1950)

Abstract – A theoretical analysis of the flow of added current carriers in homogeneous semiconductors is given...

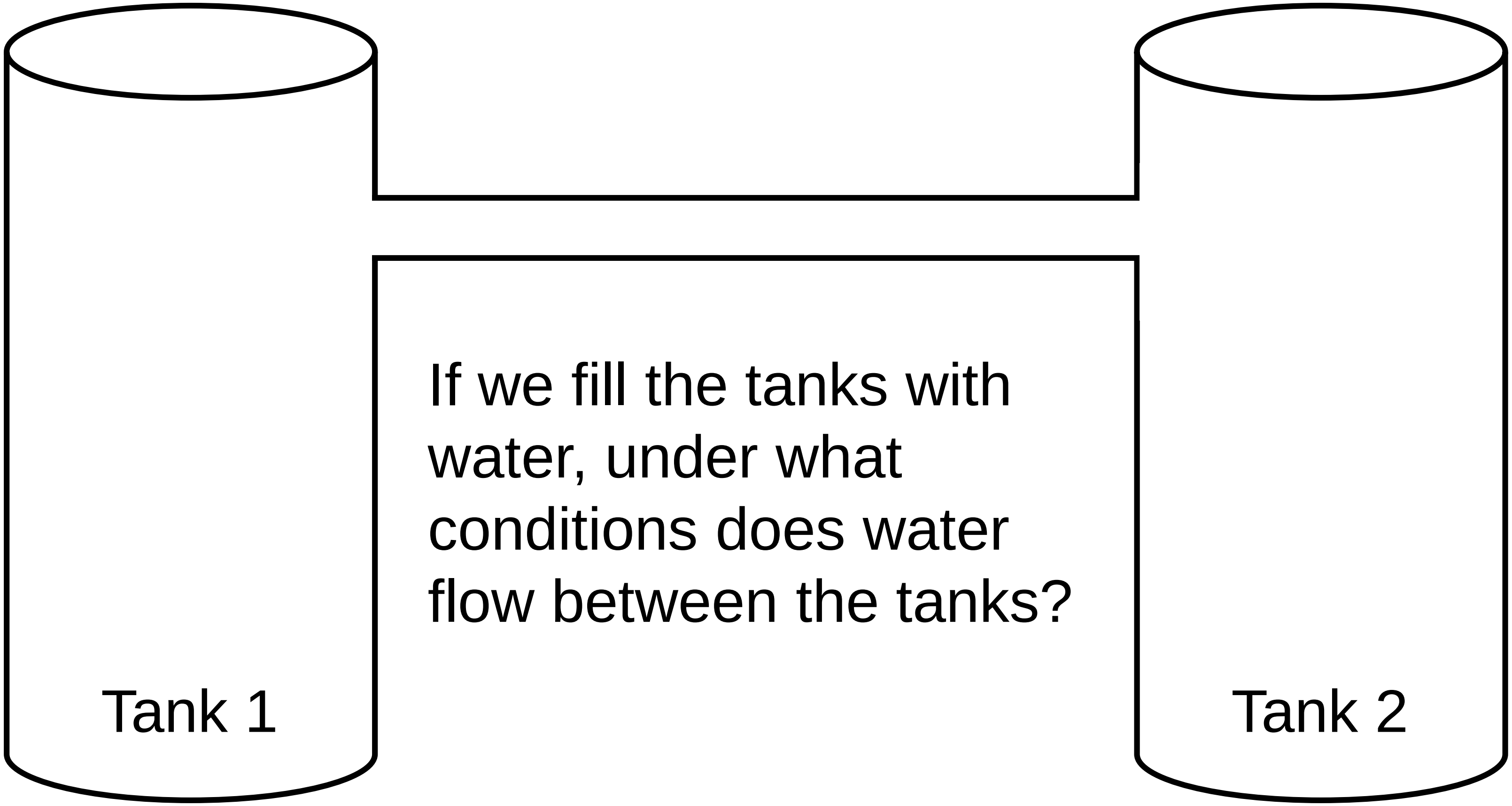
The *Bell System Technical Jou*rnal, **29** (4), pp. 560-607,1950.

What causes a current?

We are interested in what causes charge (and heat) to flow, i.e. what produces electrical (and heat) currents?

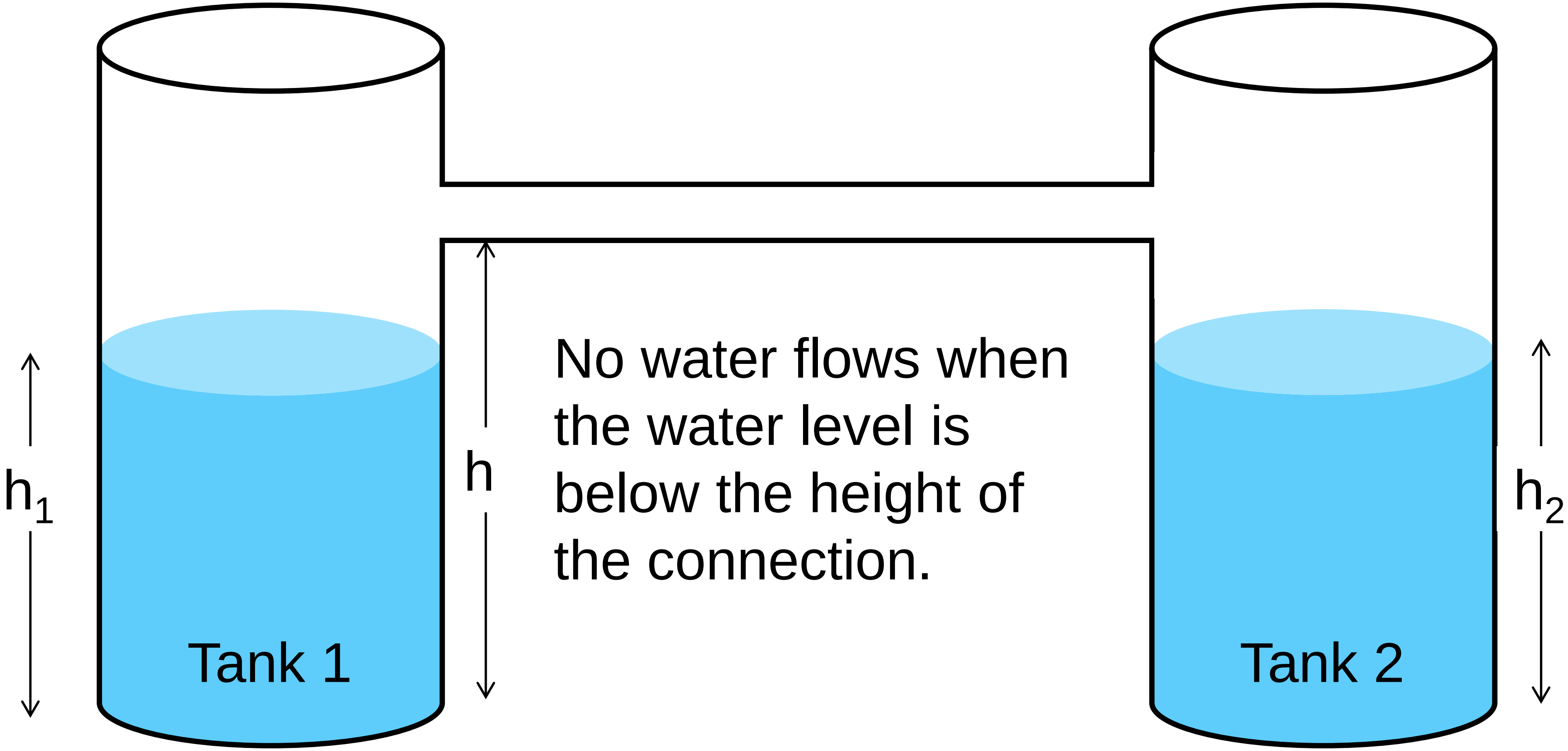
The general concepts can be illustrated with a hydrodynamic analogy, i.e. what causes water to flow?

What causes water to flow?



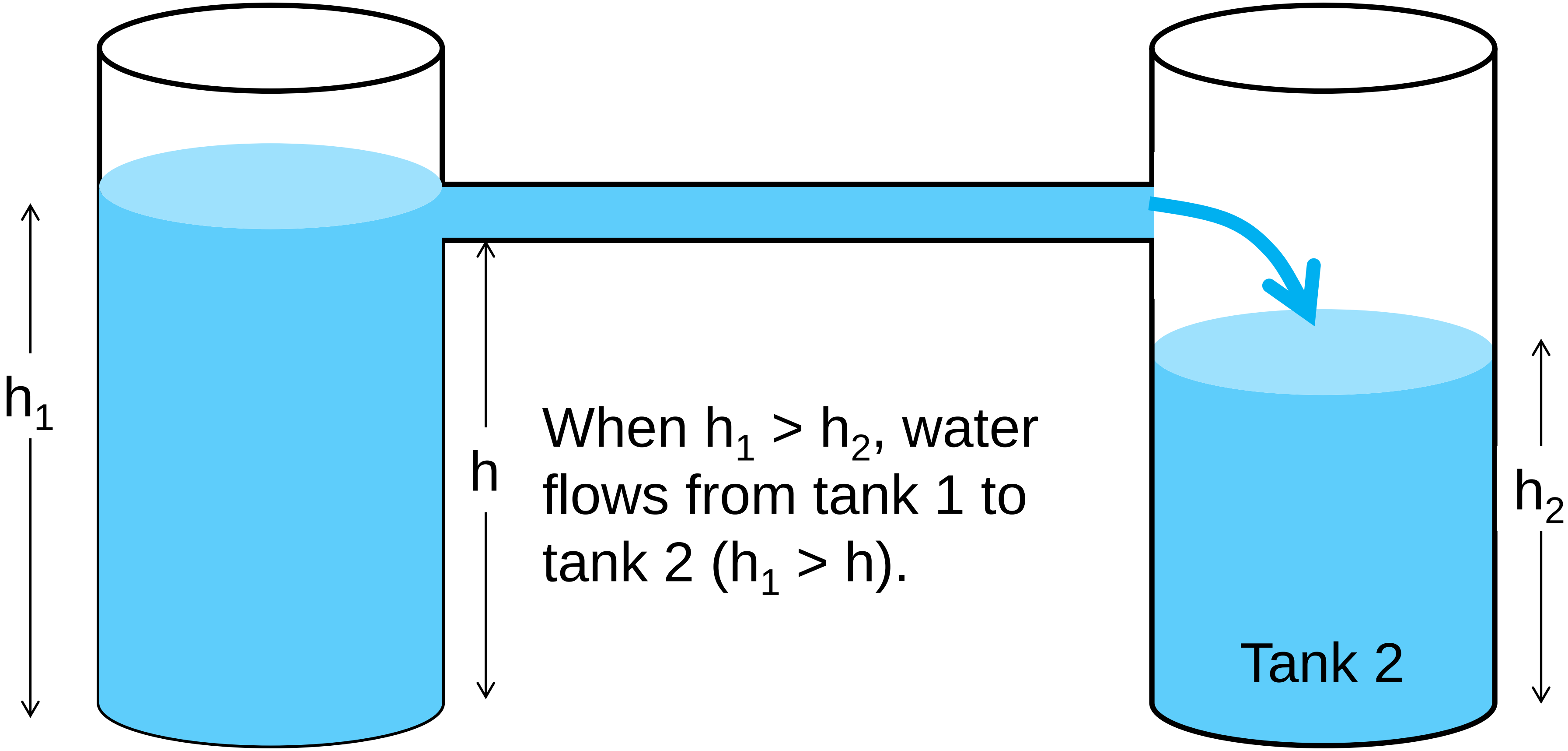
If we fill the tanks with water, under what conditions does water flow between the tanks?

What causes water to flow?



No water flows when the water level is below the height of the connection.

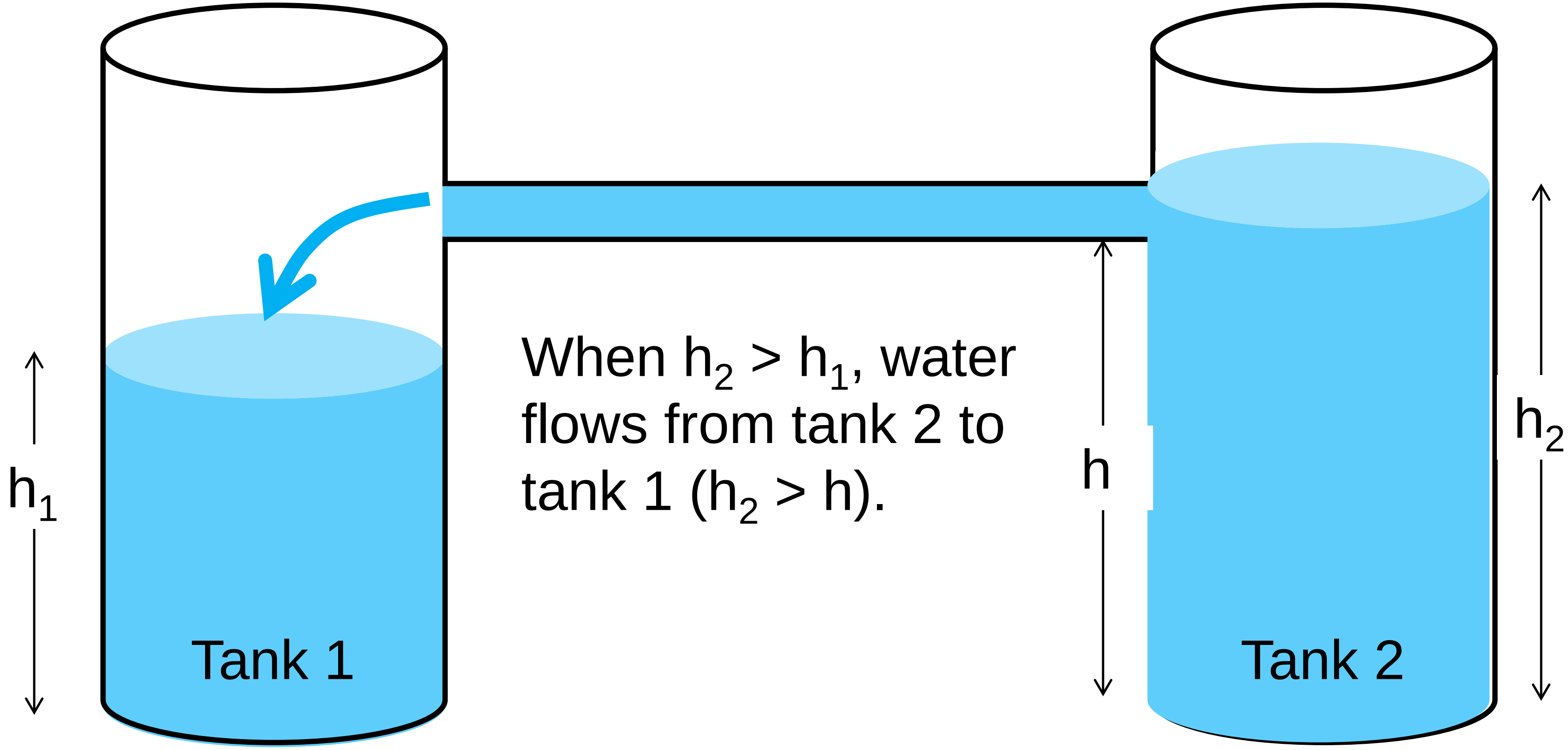
What causes water to flow?



When $h_1 > h_2$, water flows from tank 1 to tank 2 ($h_1 > h$).

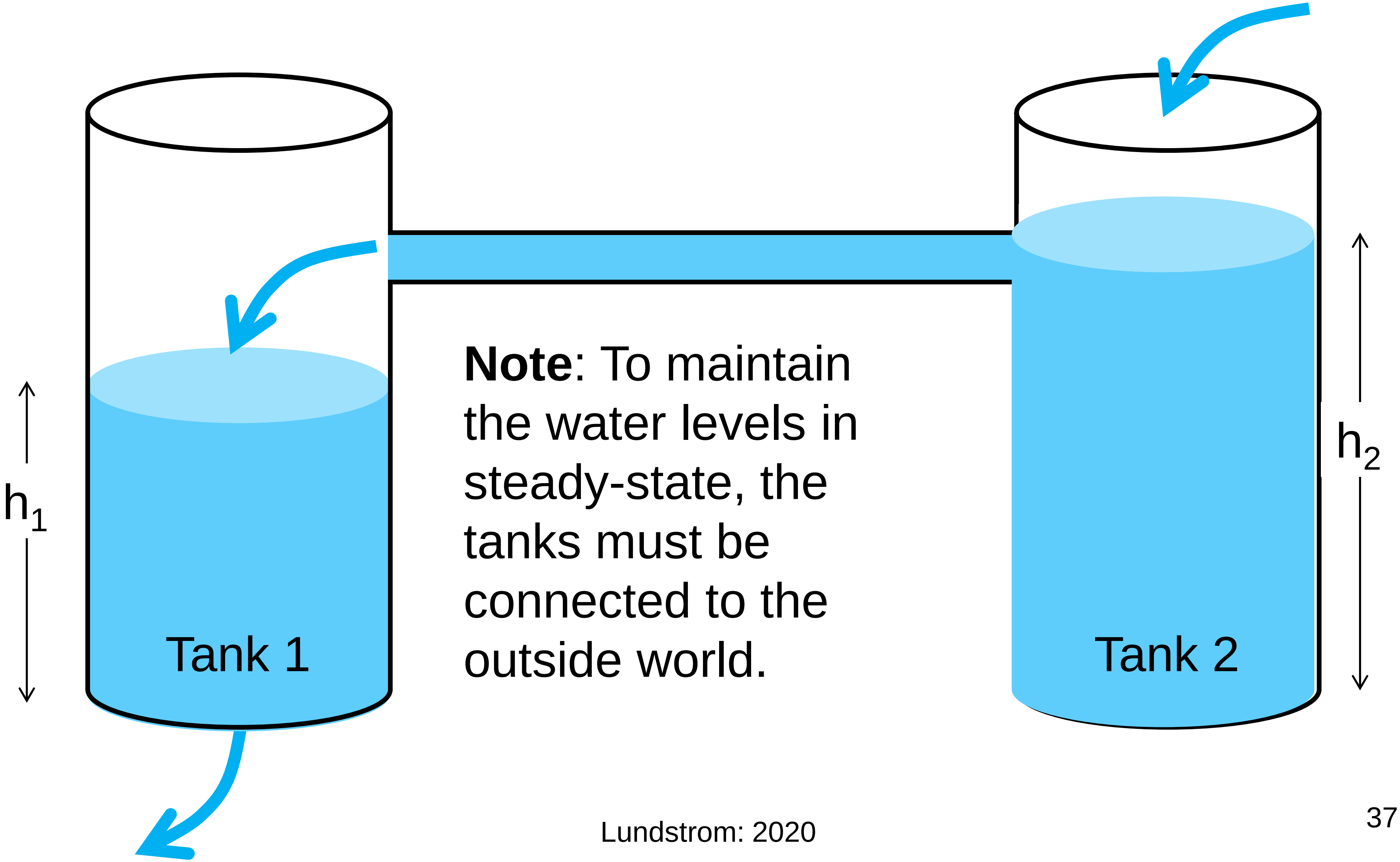
Lundstrom: 2020

What causes water to flow?



When $h_2 > h_1$, water flows from tank 2 to tank 1 ($h_2 > h$).

Connection to the outside



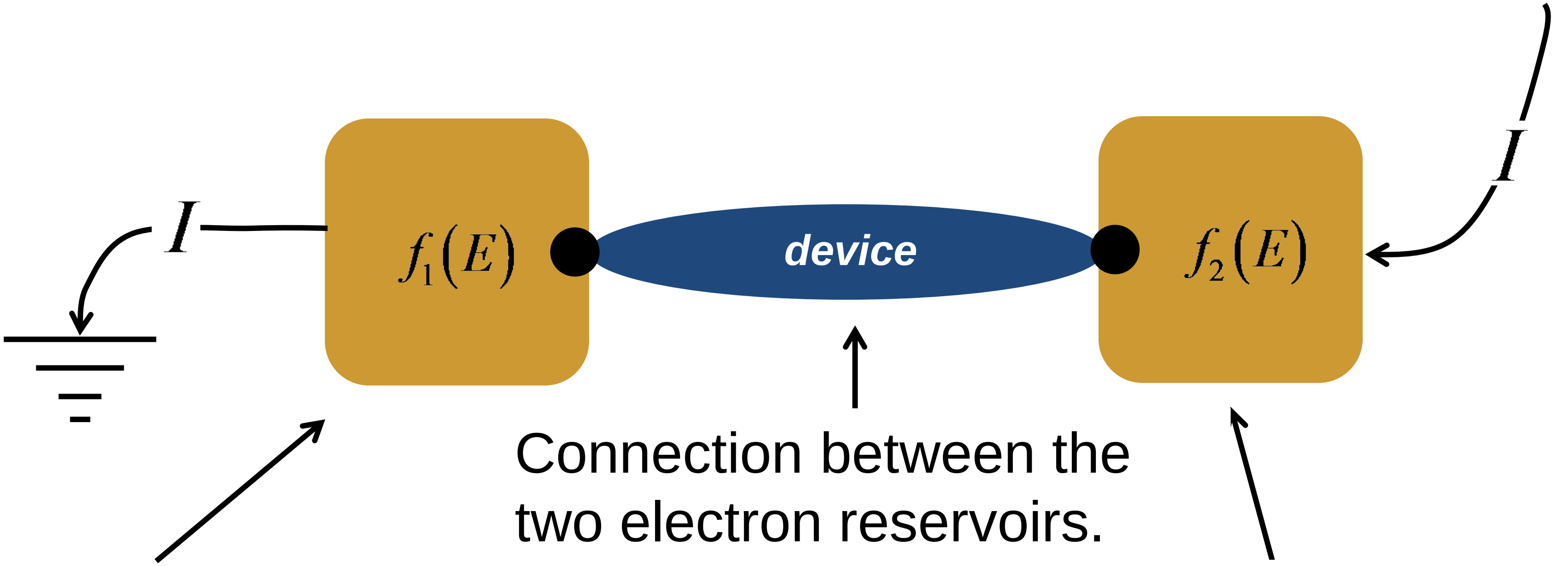
Note: To maintain the water levels in steady-state, the tanks must be connected to the outside world.

Electron transport

In learning chemistry, we begin with the simplest atom – the hydrogen atom and then to proceed to more complex atoms, molecules, compounds, etc.

We will take a similar approach - begin by understanding the current in a small, nanodevice, and then extend that understanding to large, bulk semiconductors.

Current in a nano device



Connection between the two electron reservoirs.

Reservoir of electrons characterized by a Fermi level.

Reservoir of electrons characterized by a Fermi level.

How does the current that flows depend on the voltages on the two contacts?

Current equation

$$I = \frac{2q}{h}\int \mathcal{T}(E)\,M(E)\big(f_1(E) - f_2(E)\big)\,dE$$

Fundamental constants

Transmission:

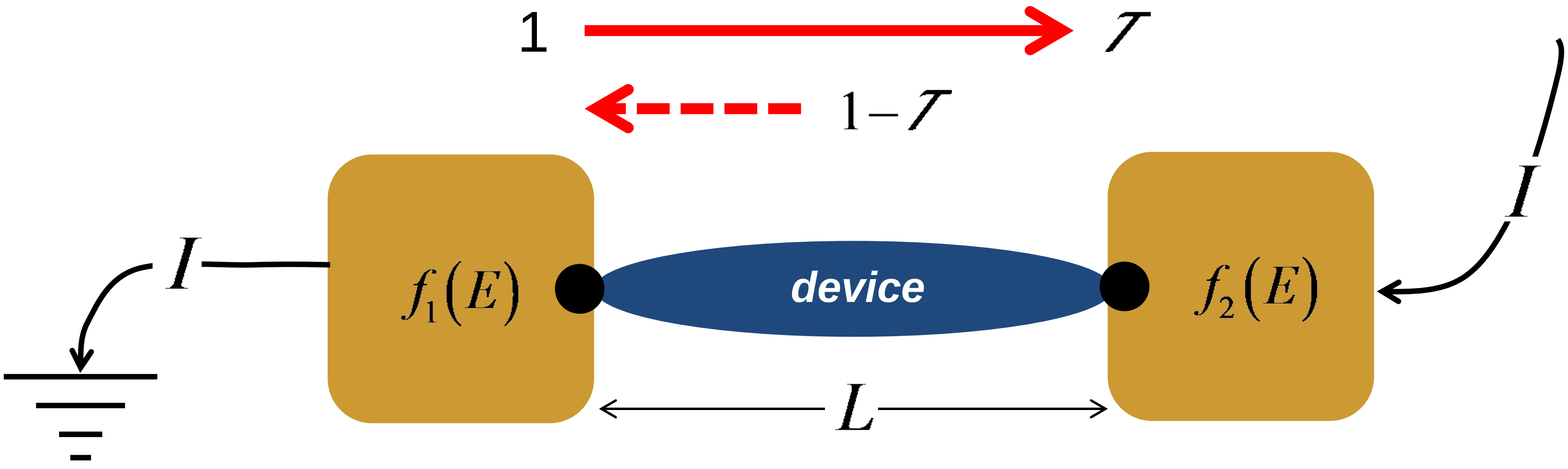
$$0 < \mathcal{T}(E) < 1$$

No. of Channels

Contacts

The integral over energy is analogous to connecting pipes at different heights.

What is transmission?



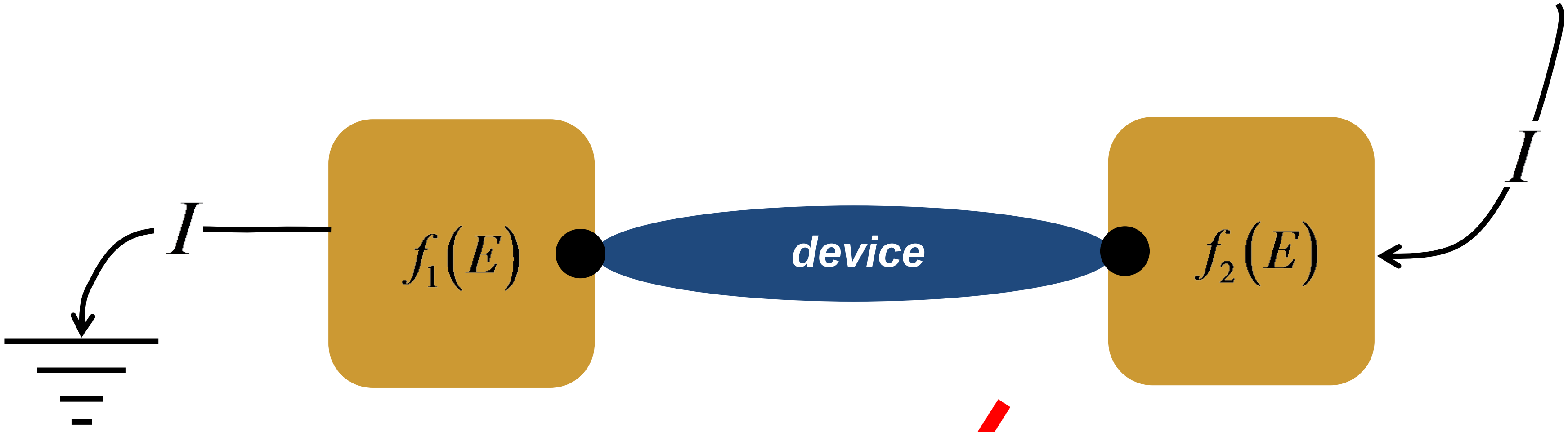
$$\mathcal{T}(E)=\frac{\lambda(E)}{\lambda(E)+L}$$

1) Diffusive: $L >> \lambda \quad \mathcal{T}=\frac{\lambda}{L}<<1$

2) Ballistic: $L << \lambda \quad \mathcal{T}=1$

λ is the “mean-free-path for backscattering”

What is a channel?

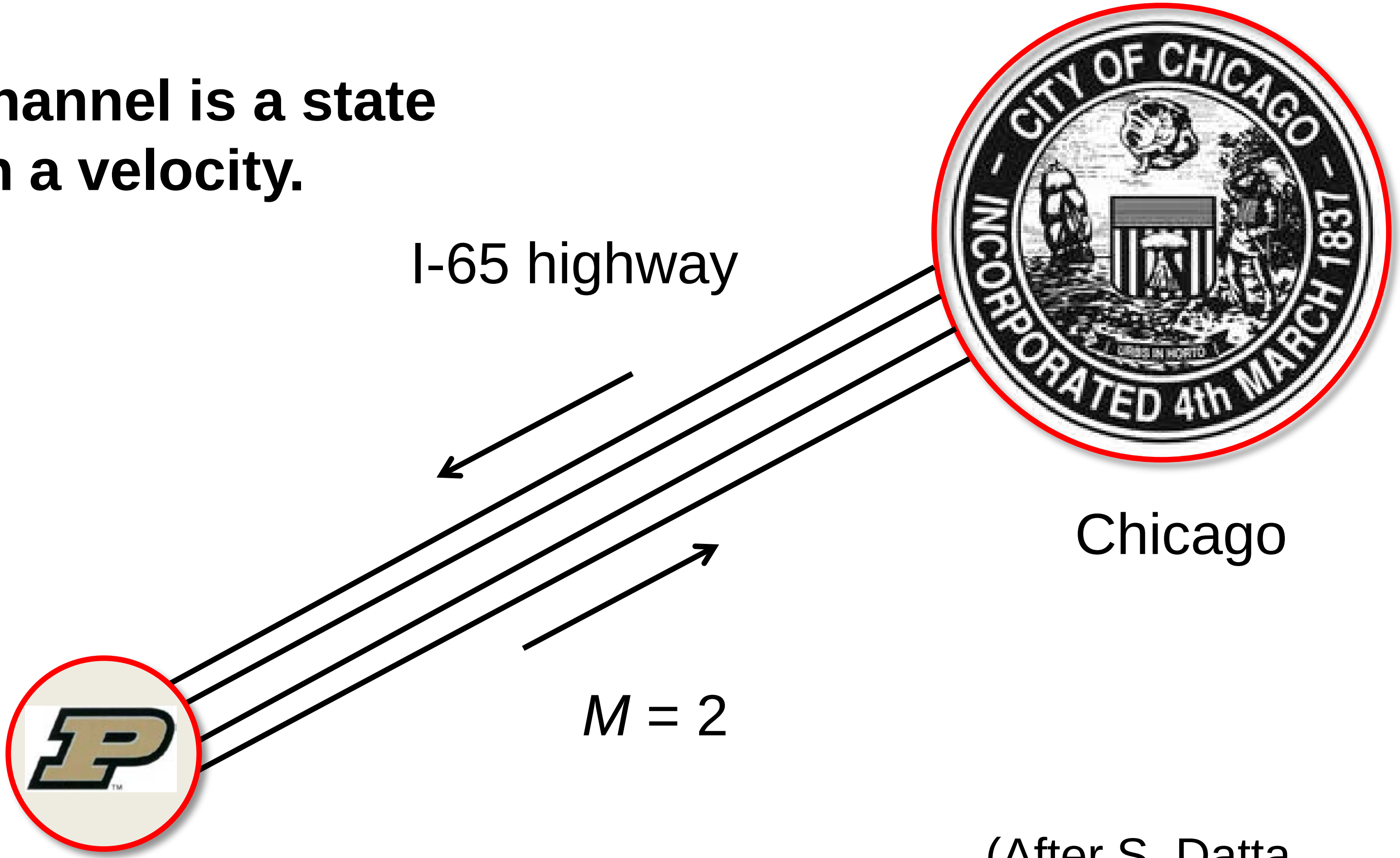


$$I = \frac{2q}{h}\int \mathcal{T}(E)\,M(E)\left(f_1 - f_2\right)dE$$

(channels are also called “modes”)

Channels are like lanes on a highway

A channel is a state with a velocity.



I-65 highway

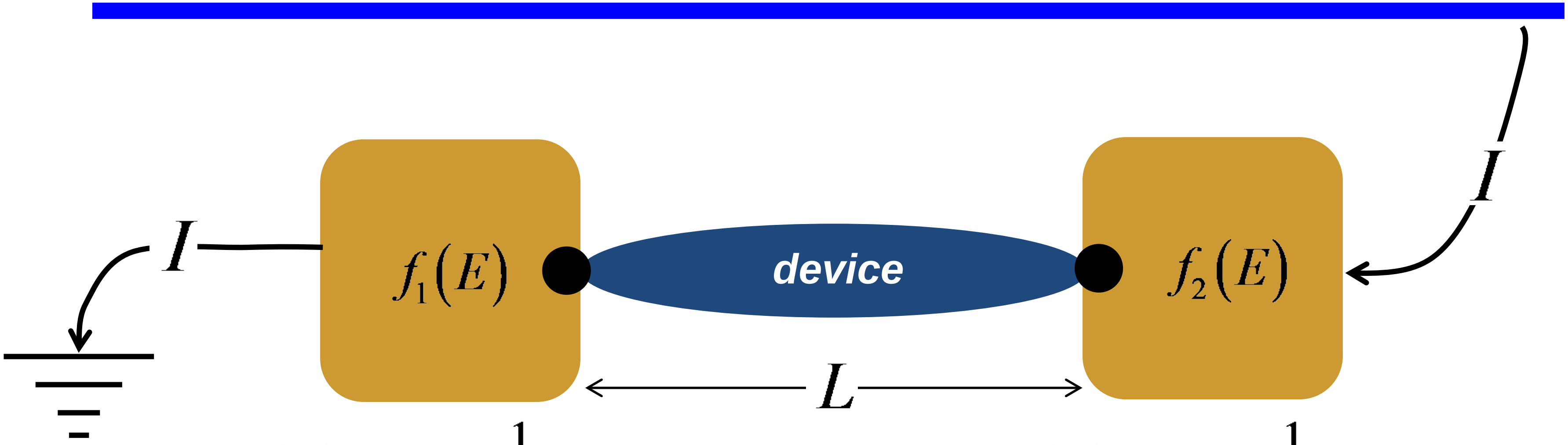
$M = 2$

Chicago

Purdue University

(After S. Datta, Purdue Univ.)

“Fermi window”



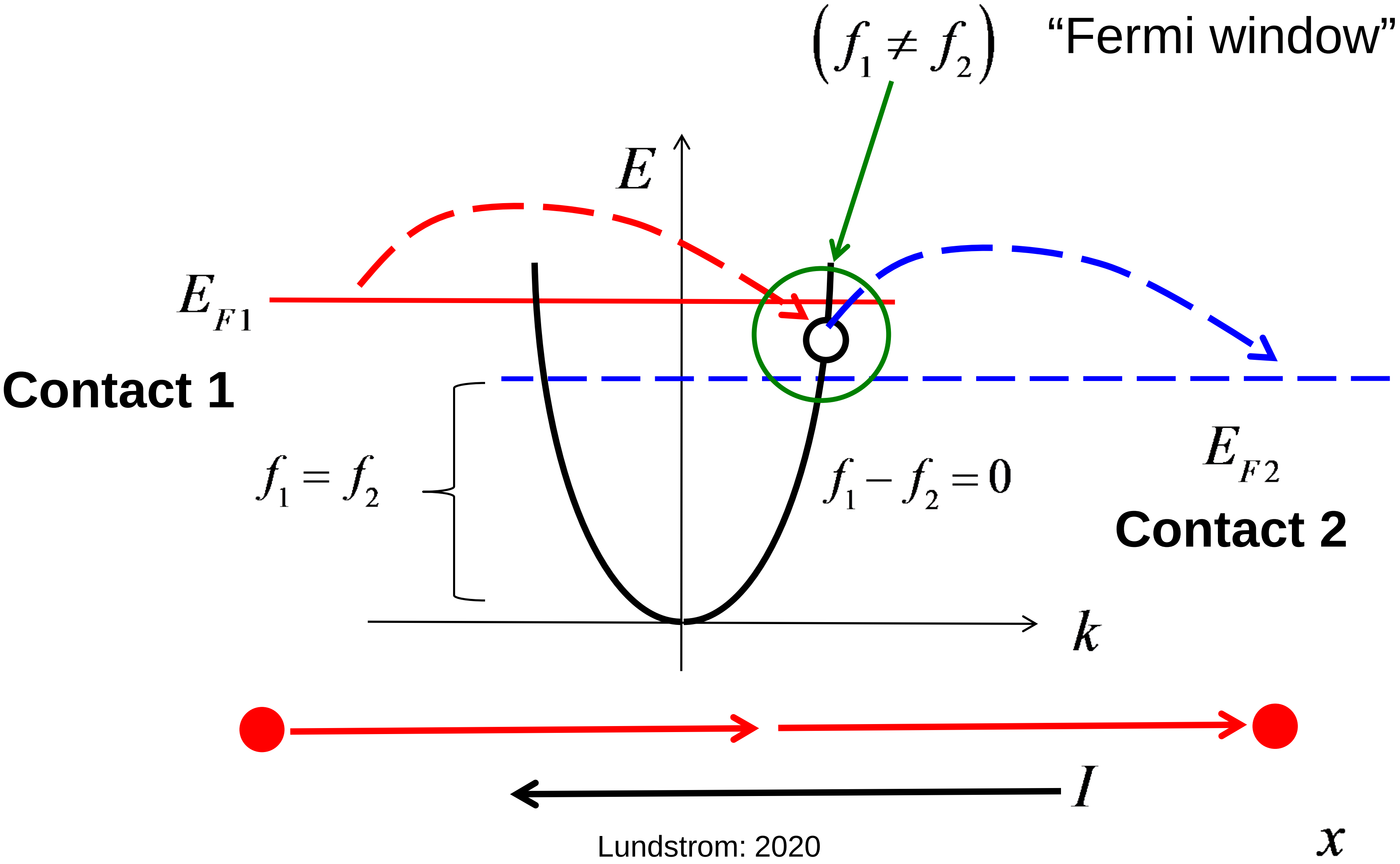
$$f_1(E) = \frac{1}{1 + e^{(E - E_{F1})/k_B T}} \qquad f_2(E) = \frac{1}{1 + e^{(E - E_{F2})/k_B T}}$$

$$I = \frac{2q}{h} \int \mathcal{T}(E) M(E) \left(f_1 - f_2\right) dE$$

The range of energies over which $\left(f_1 - f_2\right) \neq 0$

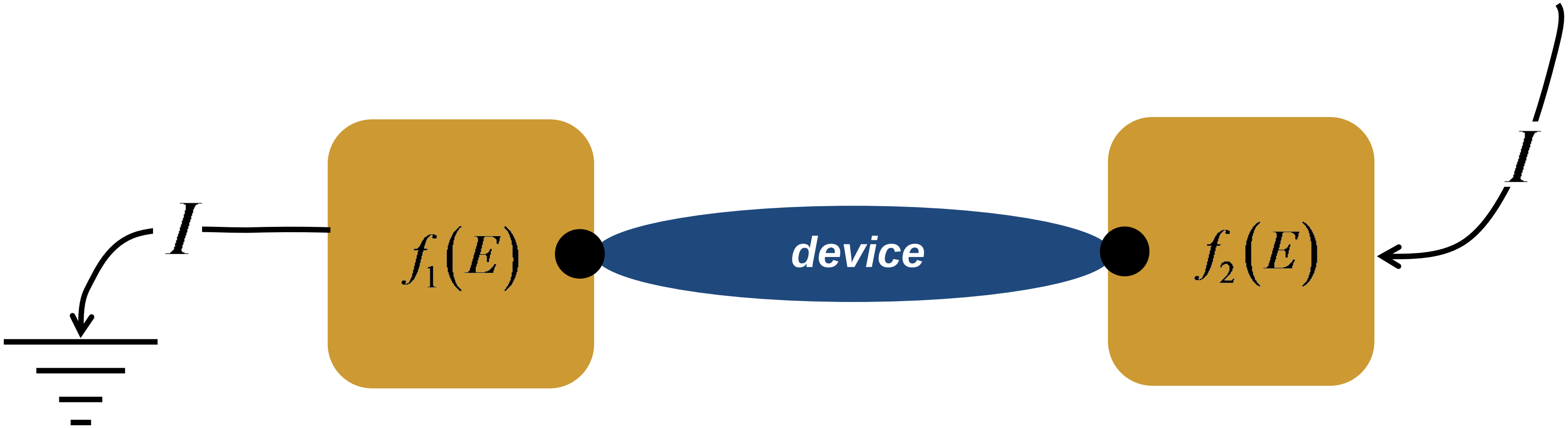
Lundstrom: 2020

How current flows (T = 0 K)



Lundstrom: 2020

What causes a current?



$$I = \frac{2q}{h}\int \mathcal{T}(E)M(E)\left(f_1 - f_2\right)dE$$

Differences in the Fermi level (Fermi function) cause electrical currents.

Lundstrom: 2020

Fermi window under small bias

$$I = \frac{2q}{h}\int \mathcal{T}(E)\,M(E)\left(\underline{f_1(E)-f_2(E)}\right)dE$$

$$f_1(E) = \frac{1}{1+e^{(E-E_{F1})/k_BT}} \approx f_0(E)$$

$$f_2(E) = \frac{1}{1+e^{(E-E_{F2})/k_BT}} \approx f_0(E)$$

$$E_{F2} = E_{F1} + \delta E_F$$

$$\frac{f_2(E)-f_1(E)}{\delta E_F} \approx \frac{\partial f_0}{\partial E_F} = -\frac{\partial f_0}{\partial E}$$

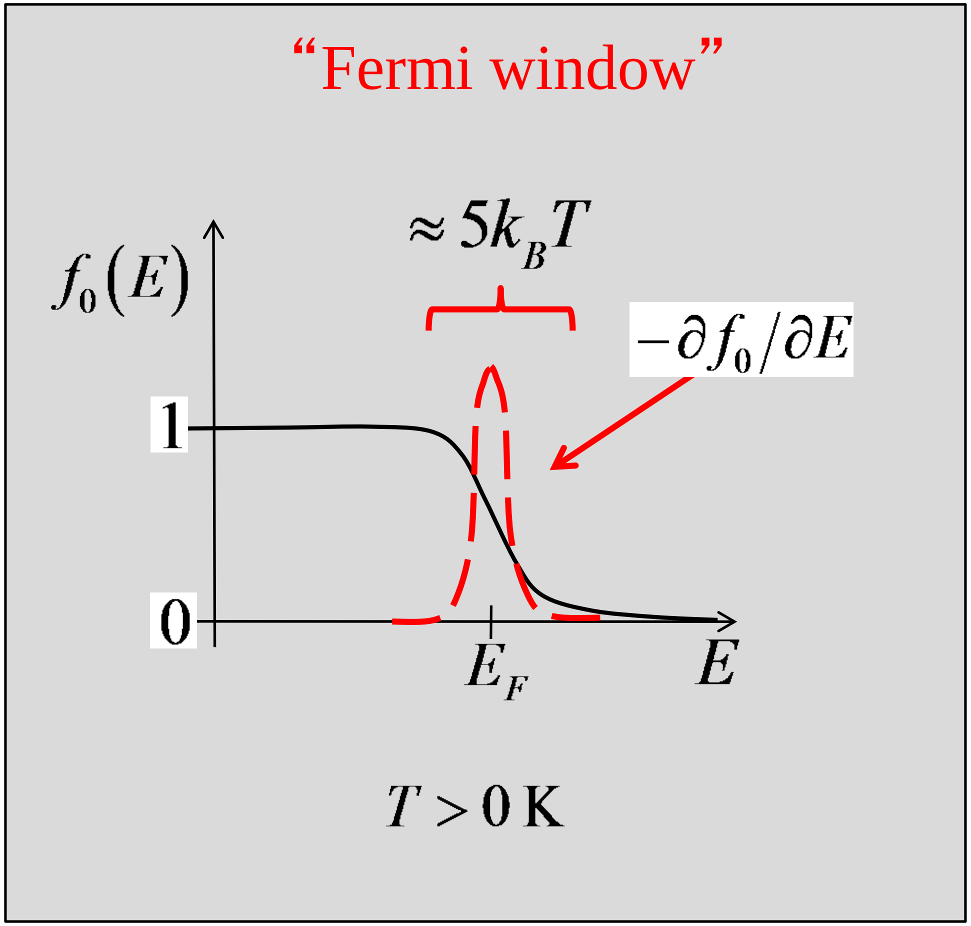
$$f_1(E)-f_2(E) \approx -\left(-\frac{\partial f_0}{\partial E}\right)\delta E_F$$

Fermi window: small bias

$$f_1(E) - f_2(E) \approx -\left(-\frac{\partial f_0}{\partial E}\right)\delta E_F$$

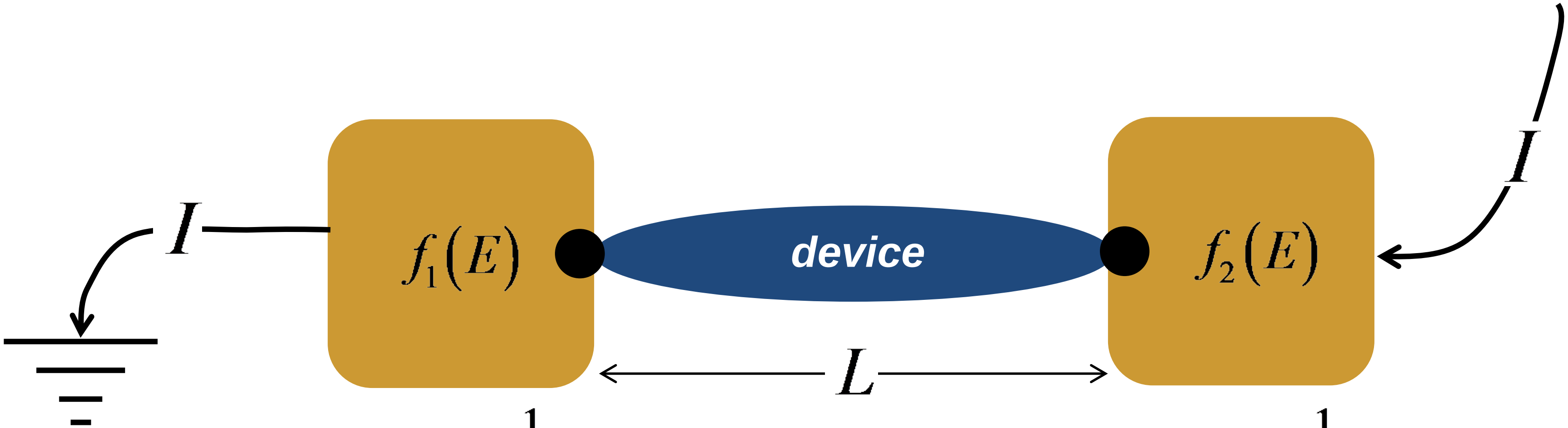
$$\delta E_F = -qV$$

$$\boxed{f_1(E) - f_2(E) = \left(-\frac{\partial f_0}{\partial E}\right)(qV)}$$



Lundstrom: 2020

Current for a small voltage difference



$$f_1(E) = \frac{1}{1 + e^{(E - E_{F1})/k_B T}} \qquad f_2(E) = \frac{1}{1 + e^{(E - E_{F2})/k_B T}}$$

$$I = \frac{2q}{h} \int \mathcal{T}(E) M(E) \underline{\left(f_1 - f_2\right)} dE$$

$$f_1(E) - f_2(E) \rightarrow \left(-\frac{\partial f_0}{\partial E}\right)(qV) \Rightarrow I = GV$$

Ohm's Law!

Lundstrom: 2020

Small bias conductance

$$I = GV \qquad \text{A}$$

$$G = \frac{2q^2}{h} \int \mathcal{T}(E) M(E) \left(-\frac{\partial f_0}{\partial E} \right) dE \qquad \text{S}$$

Case 1: Quantized conductance

$$G = \frac{2q^2}{h} \int \mathcal{T}(E) M(E) \left(-\frac{\partial f_0}{\partial E} \right) dE$$

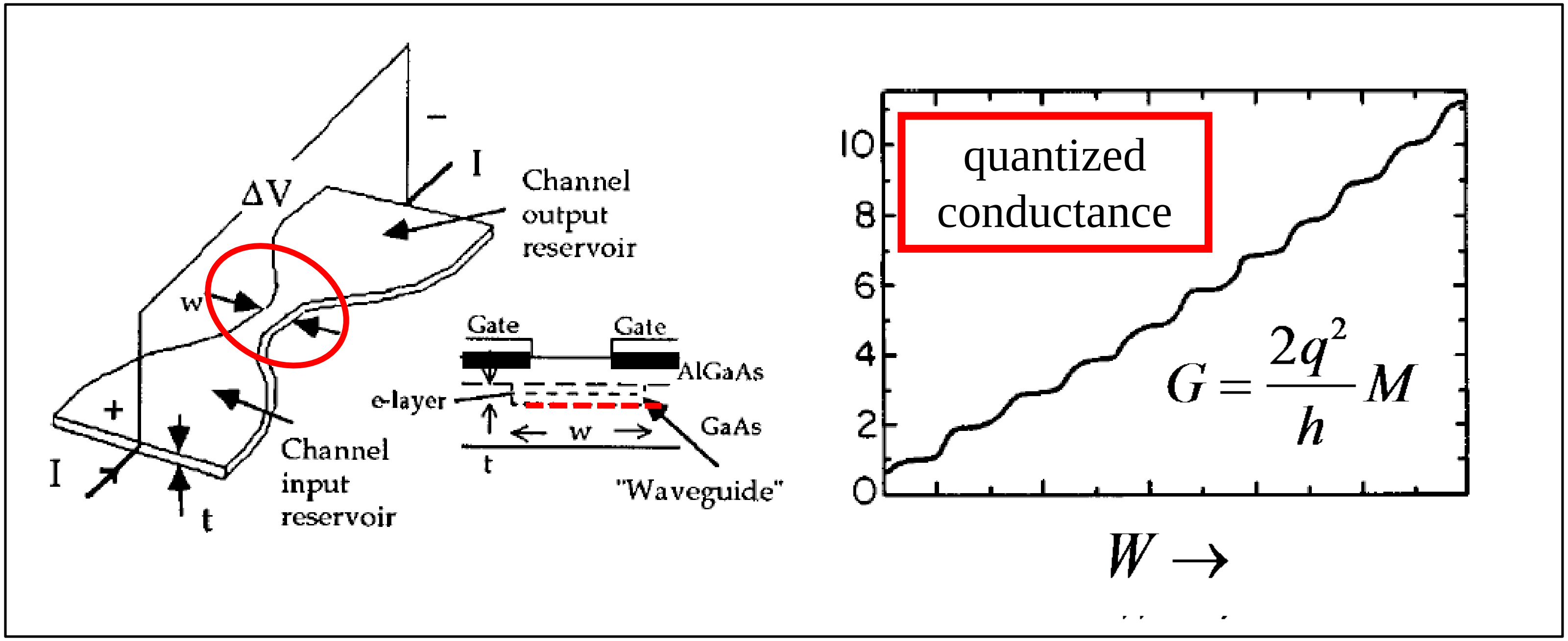
$T \rightarrow 0\,\mathrm{K}$

$\left(-\frac{\partial f_0}{\partial E} \right) \rightarrow \delta(E_F)$

$\mathcal{T}(E) \rightarrow 1$

$$\boxed{G_B(0\,\mathrm{K}) = \frac{2q^2}{h} M(E_F) = \frac{1}{12.9\ \mathrm{k}\Omega} M(E_F)}$$

Case 1: Quantized conductance

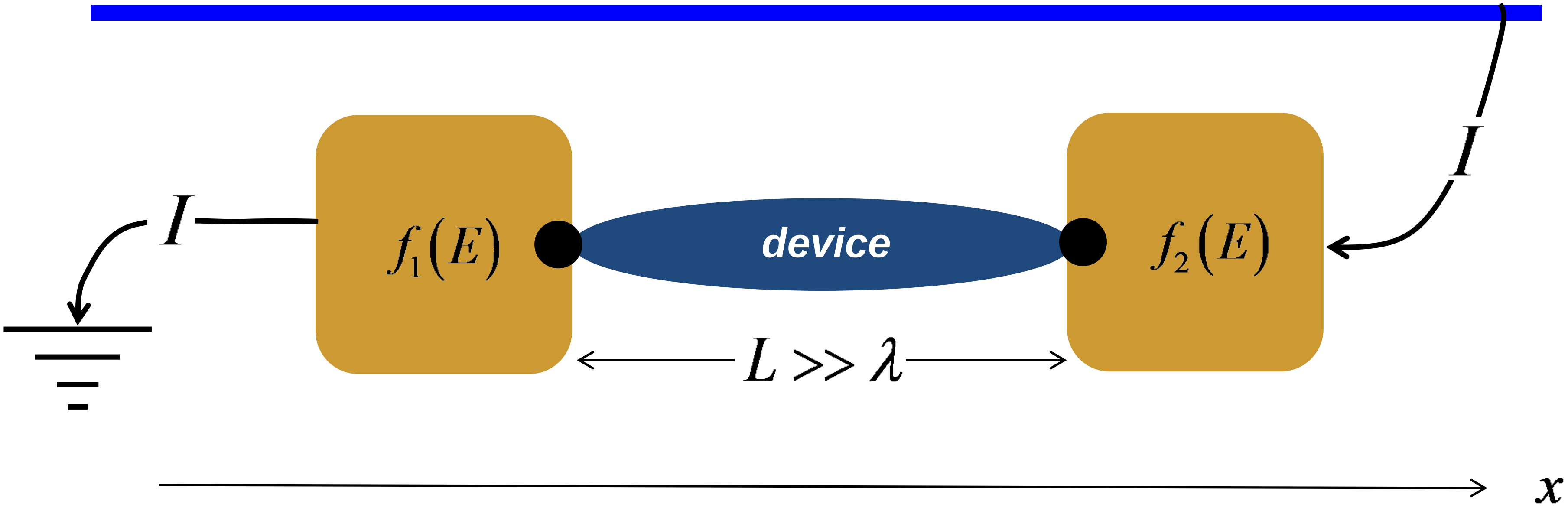


quantized conductance

$$G = \frac{2q^2}{h} M$$

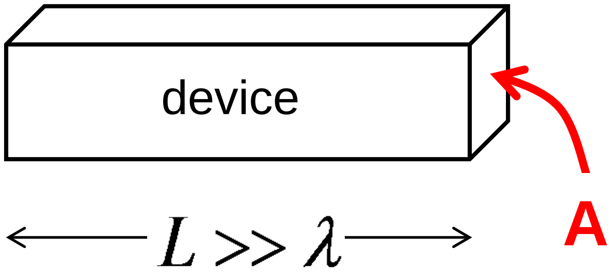
D. Holcomb, *American J. Physics*, **67**, pp. 278-297 1999.
Data from: B. J. van Wees, et al., *Phys. Rev. Lett*. **60**, 848851, 1988.

Case 2: Transport in a bulk semiconductor



We seek an equation for the current density in the +x direction.

In 3D: $J_x = -I/A$



Current equation in the bulk

$$G = \frac{2q^2}{h}\int \mathcal{T}(E)M(E)\left(-\frac{\partial f_0}{\partial E}\right)dE \qquad \mathcal{T}(E) = \frac{\lambda(E)}{\lambda(E)+L} \rightarrow \frac{\lambda(E)}{L}$$

"diffusive"

$$J_x = -I/A = \left\{\frac{2q^2}{h}\int \frac{\lambda(E)}{L}\frac{M(E)}{A}\left(-\frac{\partial f_0}{\partial E}\right)dE\right\}V \qquad \frac{qV}{L} = -\frac{dF_n}{dx}$$

$$\boxed{J_x = \sigma_n \frac{d(F_n/q)}{dx} \qquad \sigma_n = \frac{2q^2}{h}\int \lambda(E)\left(M(E)/A\right)\left(-\frac{\partial f_0}{\partial E}\right)dE}$$

σ_n: Conductivity (S/m)

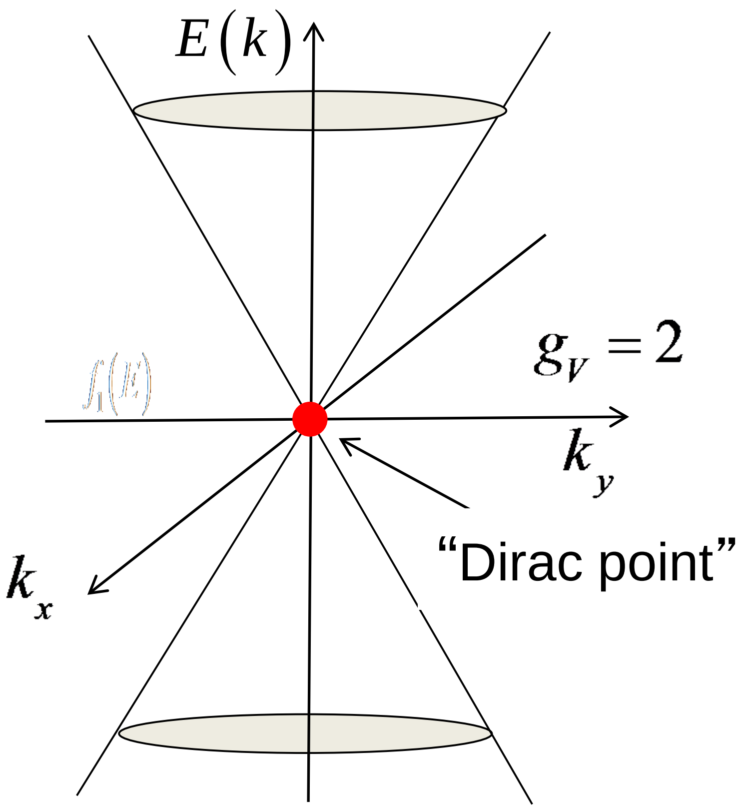
Lundstrom: 2020

Mobility of graphene?

$$\boxed{\mu_n = \frac{q\tau_m}{m_n^*}}$$

$$m^* = \infty ?$$

$$m^* = 0 ?$$

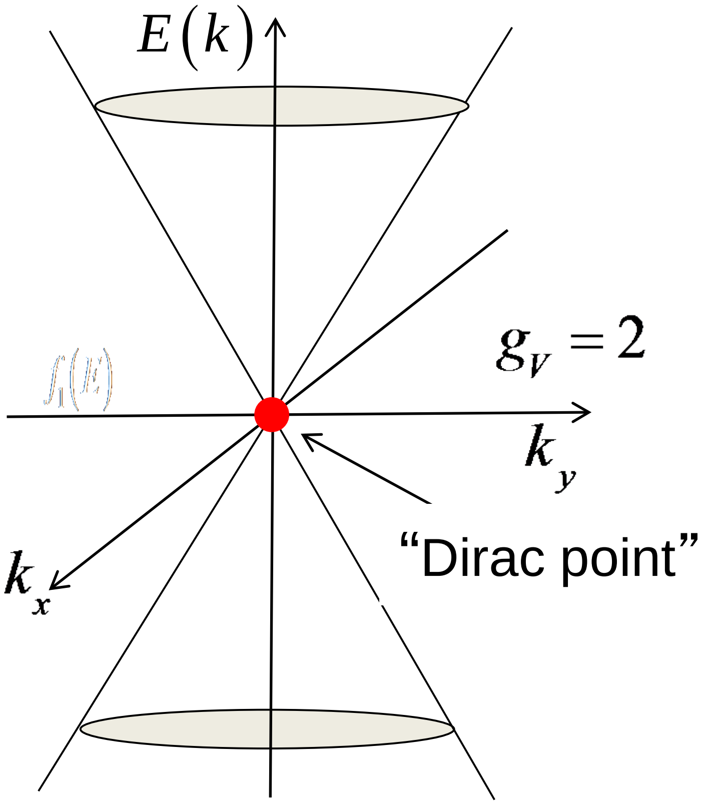


$$E(k) = \pm\hbar\upsilon_F k = \pm\hbar\upsilon_F\sqrt{k_x^2 + k_y^2}$$

Mobility in graphene?

$$\sigma_n = \frac{2q^2}{h}\int \lambda(E)\left(M(E)/A\right)\left(-\frac{\partial f_0}{\partial E}\right)dE$$

$$\sigma_n \equiv nq\mu_n$$



$$E(k) = \pm\hbar\upsilon_F k = \pm\hbar\upsilon_F\sqrt{k_x^2 + k_y^2}$$

Current in the bulk

$$\boxed{\begin{aligned} J_{nx} &= \sigma_n \frac{d\left(F_n/q\right)}{dx} \\[2ex] J_{px} &= \sigma_p \frac{d\left(F_p/q\right)}{dx} \end{aligned}}$$

(Large (bulk) semiconductor under small bias.)

Gradients in the quasi-Fermi level cause current to flow.

Current equation for bulk semiconductors

$$\boxed{J_x = n\mu_n \frac{dF_n}{dx}}$$

$$n = N_C e^{(F_n - E_C)/k_B T}$$

$$F_n = E_C + k_B T \ln\left(\frac{n}{N_C}\right)$$

$$\frac{dF_n}{dx} = \frac{dE_C}{dx} + k_B T \frac{1}{n}\frac{dn}{dx}$$

$$J_x = n\mu_n \frac{dE_C}{dx} + k_B T \mu_n \frac{dn}{dx} \qquad (1)$$

$$E_C(x) = E_{ref} - qV(x)$$

$$\frac{dE_C}{dx} = -q\frac{dV}{dx} = q\mathcal{E}$$

$$k_B T \mu_n = qD_n$$

$$\boxed{J_x = nq\mu_n\mathcal{E} + qD_n\frac{dn}{dx}}$$

Transport from the nanoscale to the macroscale

$$\boxed{I = \frac{2q}{h}\int \mathcal{T}(E)M(E)\left(f_1 - f_2\right)dE}$$

linear transport

$$G = \frac{2q^2}{h}M$$

low T

ballistic

M countable

$$G = \frac{2q^2}{h}\int_{E_C} \mathcal{T}(E)M(E)\left(-\frac{\partial f_0}{\partial E}\right)dE$$

ballistic to diffusive

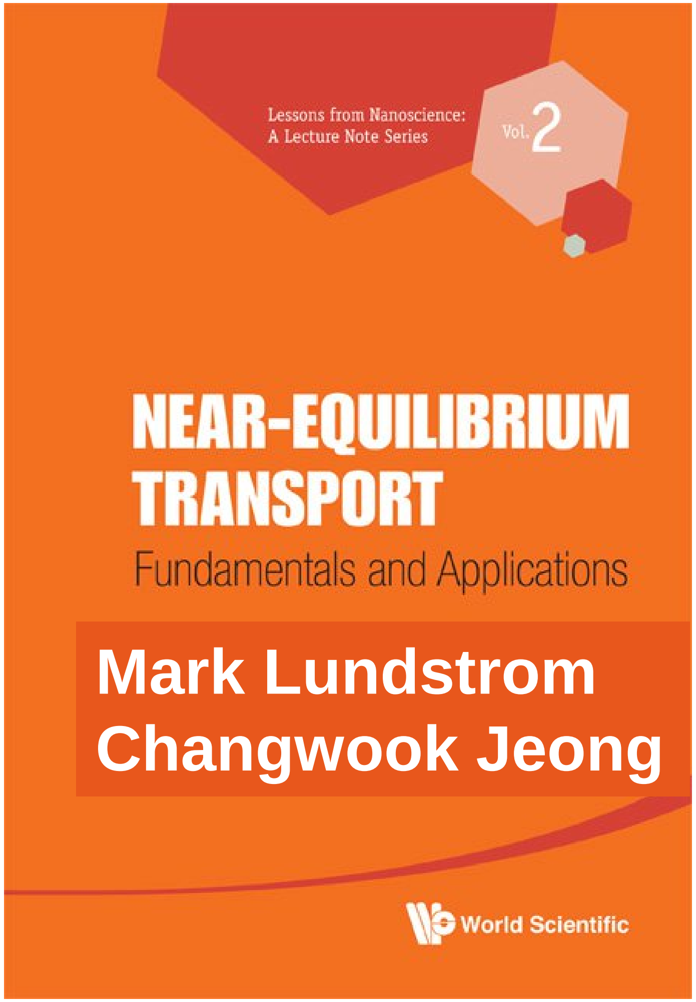
M small or large

$$J_n = \sigma_n \frac{d\left(F_n/q\right)}{dx}$$

diffusive, M large

$$\boxed{J_n = n\mu_n\mathcal{E} + qD_n\frac{dn}{dx}}$$

For more…



Lessons from Nanoscience:
A Lecture Note Series

Vol. 2

NEAR-EQUILIBRIUM TRANSPORT

Fundamentals and Applications

Mark Lundstrom
Changwook Jeong

World Scientific

SEEC for the 21st Century

SEEC Notes

R.B. Adler, et al., 1960-1967

"**SEEC was a triumph of engineering science**, with a substantial, lasting impact. The basic ideas influenced many textbooks written in subsequent years. The approaches are still used in EE education throughout the world..."

http://web.mit.edu/klund/www/books/seec.html
http://www-mtl.mit.edu/~penfield/pubs/eb-03.html

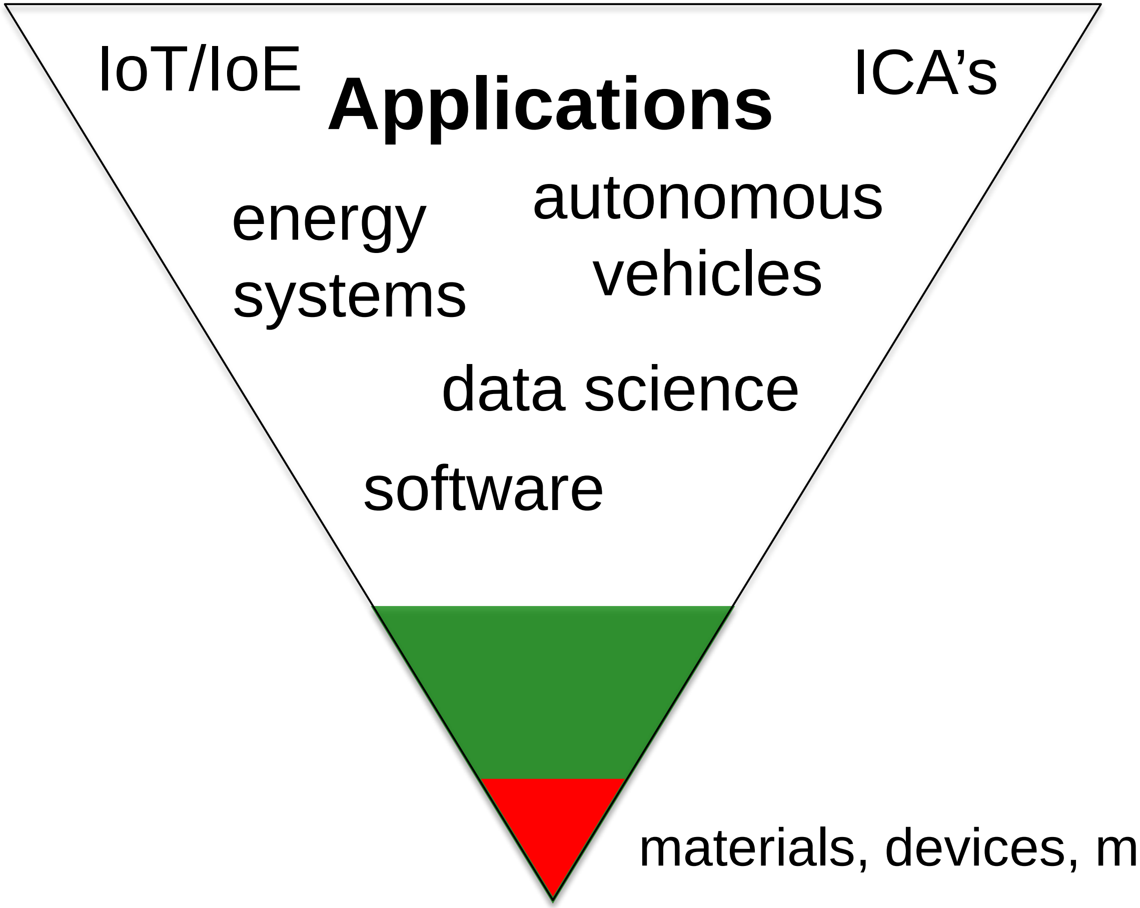
Summary

Semiconductor devices have enabled the powerful electronic systems that we have today.

21st Century device research is system-driven.

To support another 50+ years of innovation in semiconductor electronics, we should re-think how we educate semiconductor technologists.

21st Century Electronics



IoT/IoE

Applications

ICA’s

energy systems

autonomous vehicles

data science

software

materials, devices, manufacturing

R. W. Lucky, *IEEE Spectrum*, May 1998