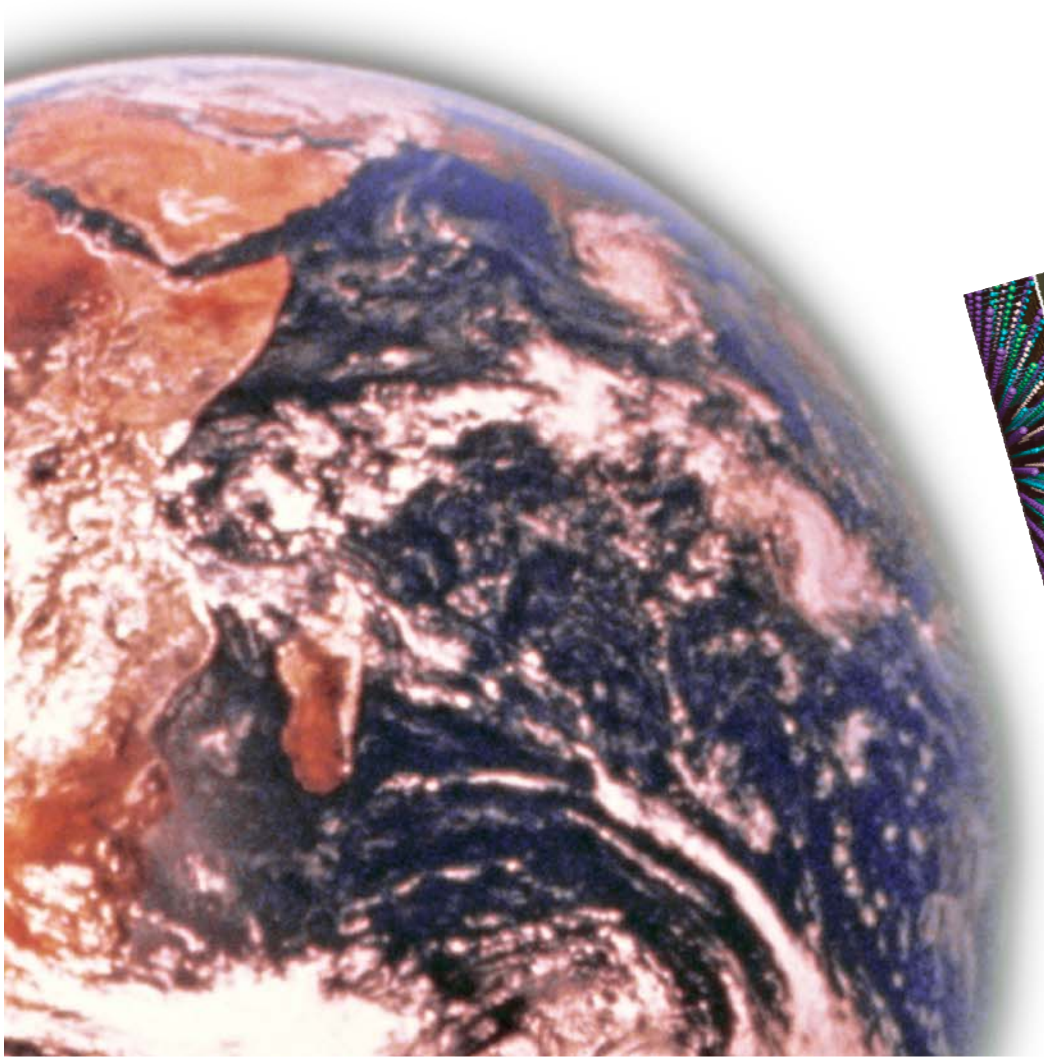
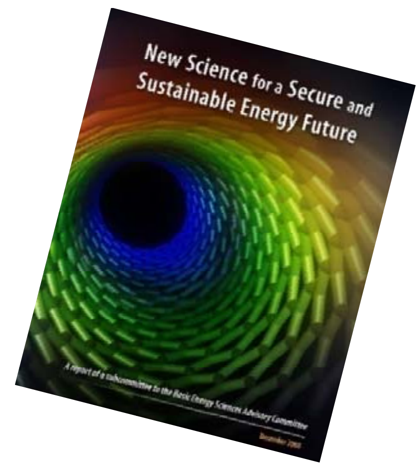
Superconductivity: Challenges and Opportunities for our Energy Future



John Sarrao
Los Alamos National Laboratory



http://www.sc.doe.gov/bes/reports/list.html

Office of Science
U.S. DEPARTMENT OF ENERGY

Outline

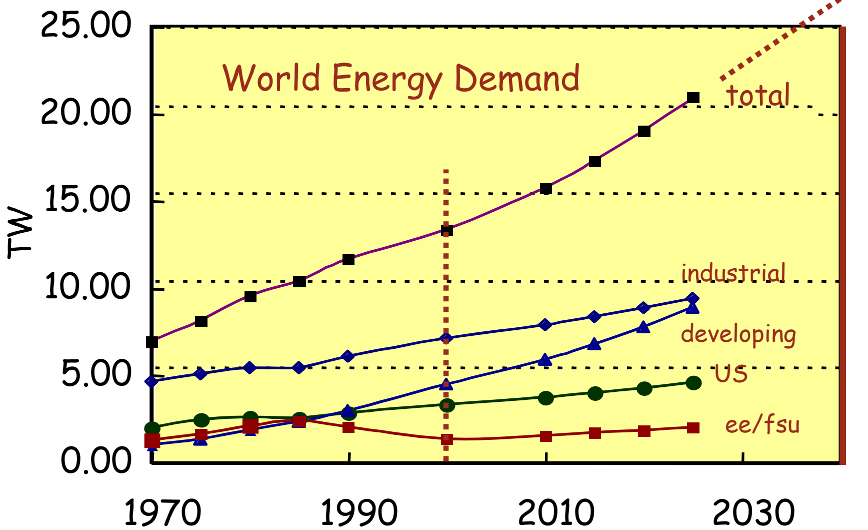
- The Energy Challenge
  - Electricity Distribution and the 21st Century Grid

- Potential for Superconductivity Solutions
  - Capacity
  - Reliability & Power Quality
  - Efficiency
  - (Superconductivity 101)

- Transformational Needs
  - Higher T_c by Design
  - Control "Vortex Matter"

"The intersection of control science with high-functioning materials creates a tipping point for sustainable energy"

The Energy Challenge



Double by 2050

Triple by 2100

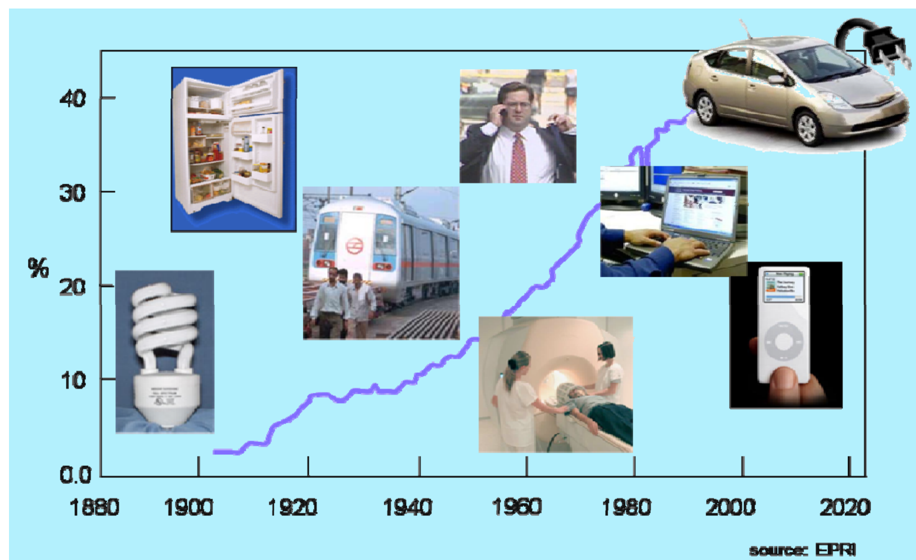
Challenge for production, **DISTRIBUTION**, use

Electricity is an essential energy carrier

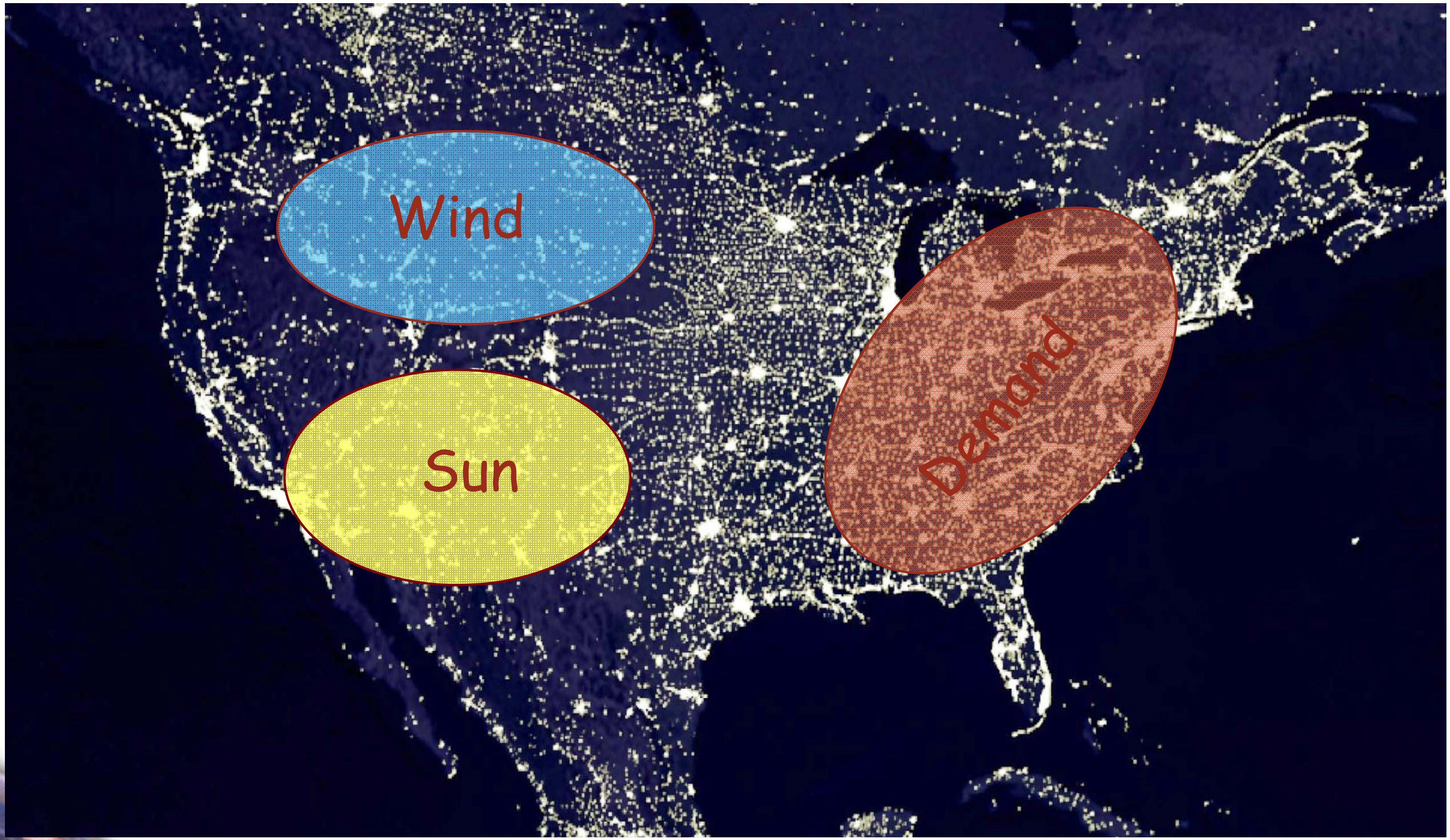
35% of primary energy (& growing)

34% of CO_2 emissions

63% of energy lost



The Grid - Triumph of 20th Century Engineering



Not built for 21st Century Green Energy distribution

Unprecedented 21st Century Challenges for the Grid

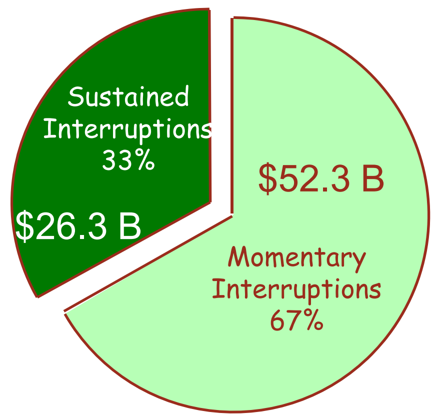
capacity
growing electricity uses
growing cities and suburbs
high people / power density
urban power bottleneck

2030
50% demand growth (US)
100% demand growth (world)

reliability
power quality

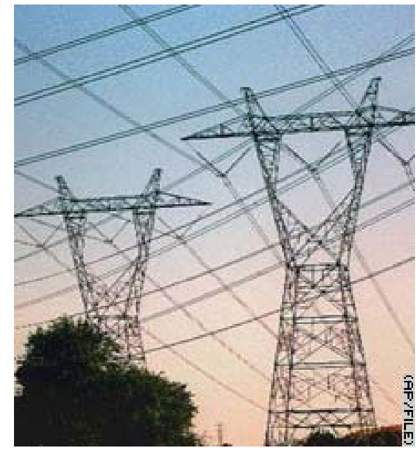
average
power loss/customer
(min/yr)

US	214
France	53
Japan	6



$79 B economic loss (US)
LaCommare & Eto, Energy 31, 1845 (2006)

efficiency
lost energy



62% energy lost in production / delivery

8-10% lost in grid

40 GW lost (US)
~ 40 power plants

2030: 60 GW lost
340 Mtons CO_2

Superconductivity is vital to the solution of these challenges

Superconductivity: Moving Electricity Sustainably

Discovery

High temperature superconductivity 1986

Carry electricity without loss

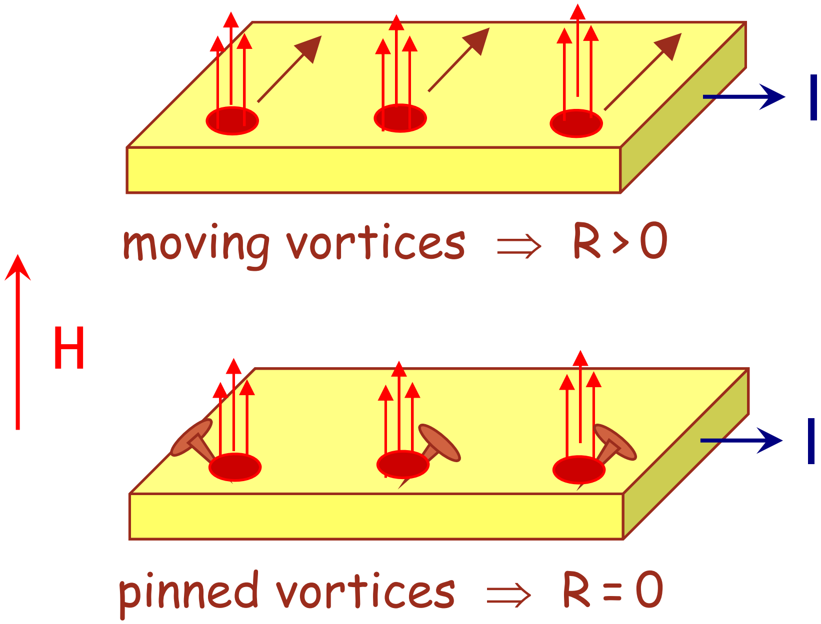
capacity ⇒ high current / low voltage
5 times power in same cross section

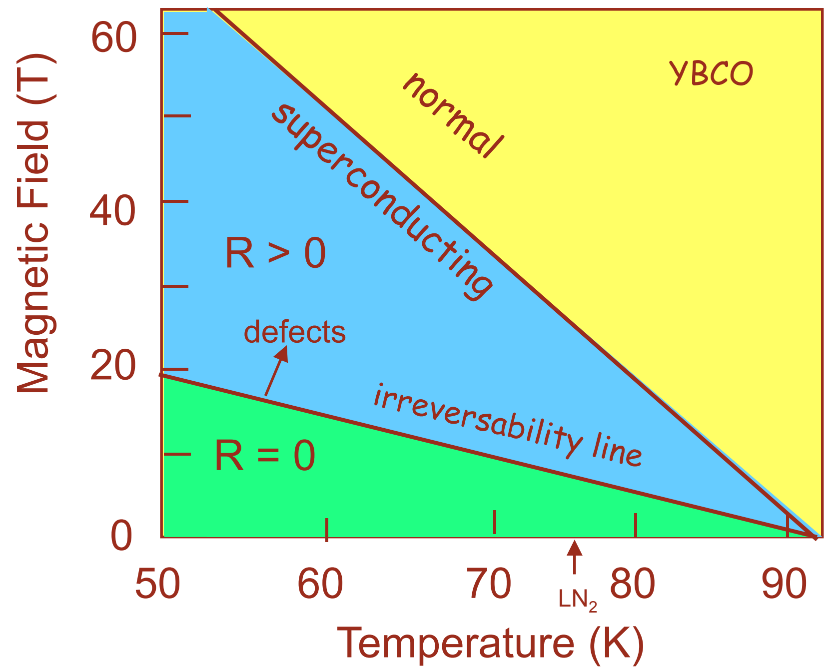
reliability / quality ⇒ smart, self-healing power control

efficiency ⇒ zero resistance (DC)

100 times lower than copper (AC)

Barriers to Superconducting Performance





Performance Barriers

higher transition temperature - new materials

higher currents - control “vortex matter”

A short detour:
Defining Properties of a Superconductor

Pairing Interaction

Long-Range Quantum Mechanical Order
(phase coherence)

Zero Electrical Resistance

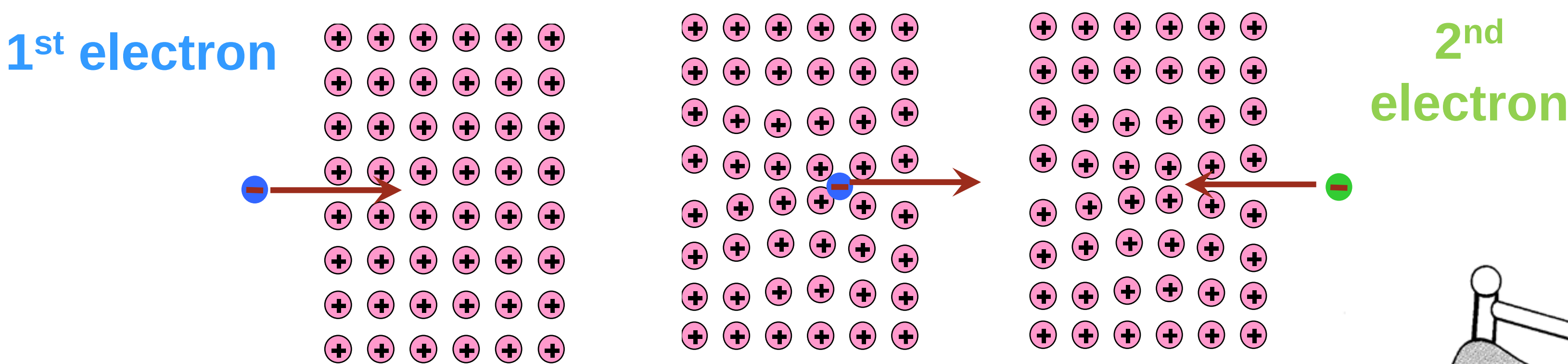
Perfect Diamagnetism

Pairing in conventional superconductors

Electrons repel due to their electrical charge

How do you "repeal Coulomb's Law" ?

1. First electron leaves a
   positive WAKE in the lattice, and
2. Second electron is attracted to that wake:

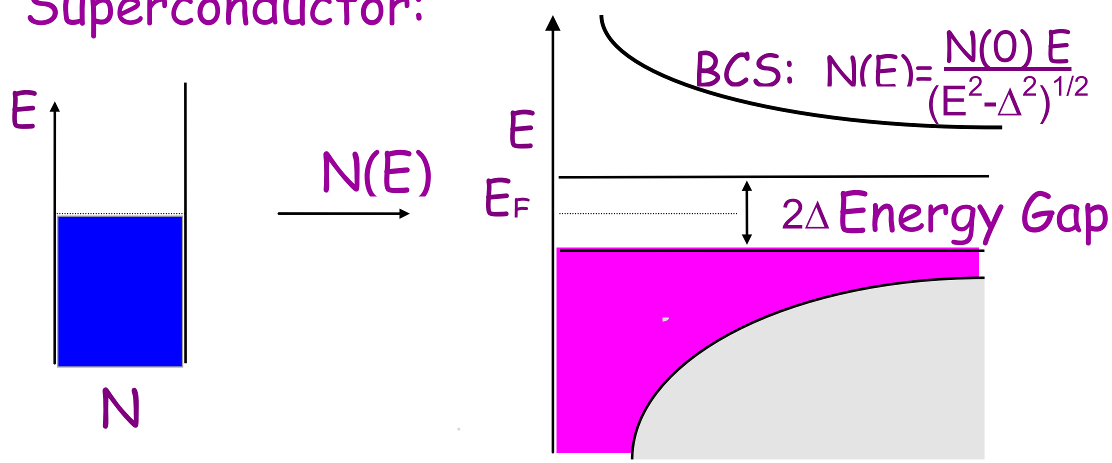


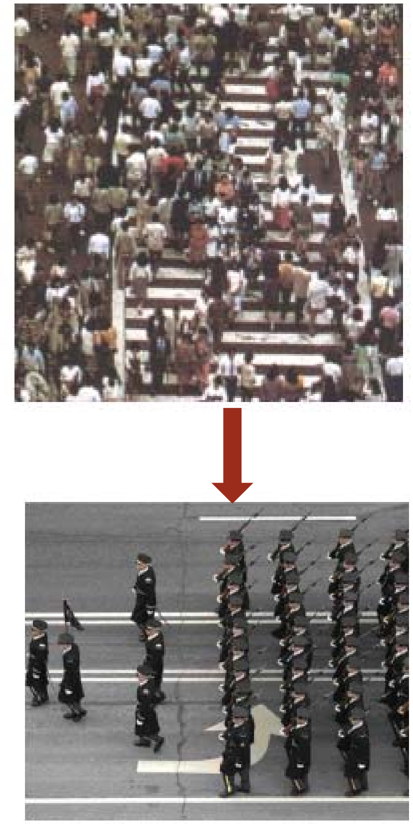
BCS Theory explains conventional superconductors in this framework – Nobel Prize

The paring mechanism in HTS remains elusive !!!

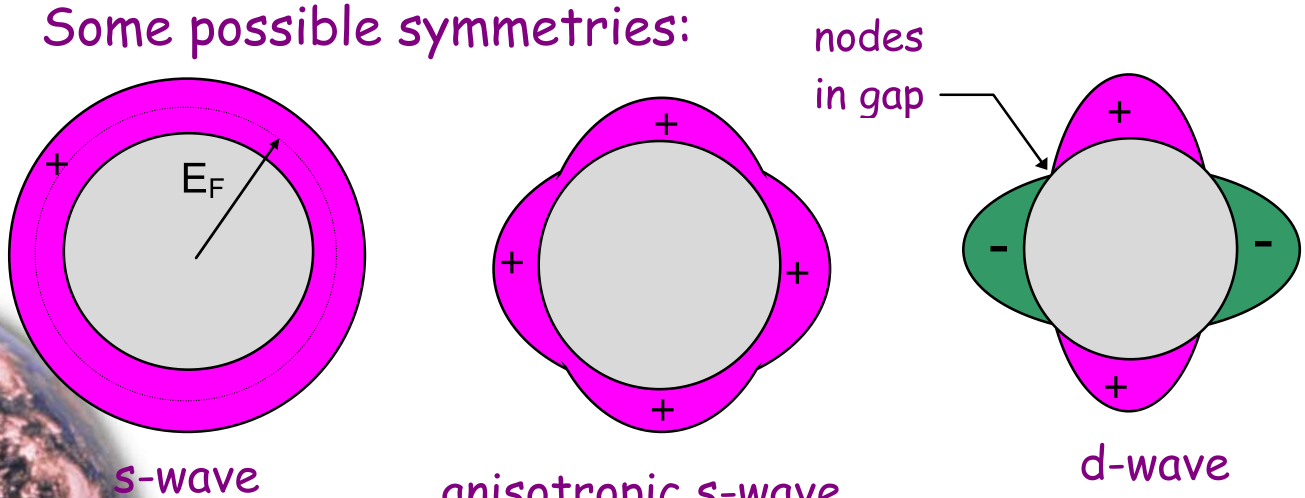
Gap (wave function) Symmetries

Superconductor:





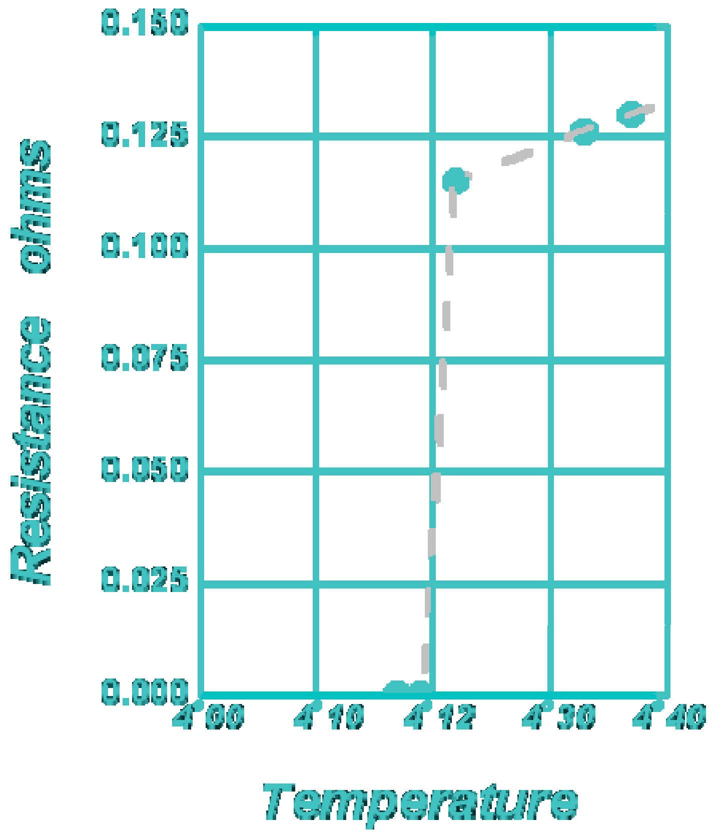
Some possible symmetries:



"Conventional" "Unconventional"

The Discovery of Superconductivity

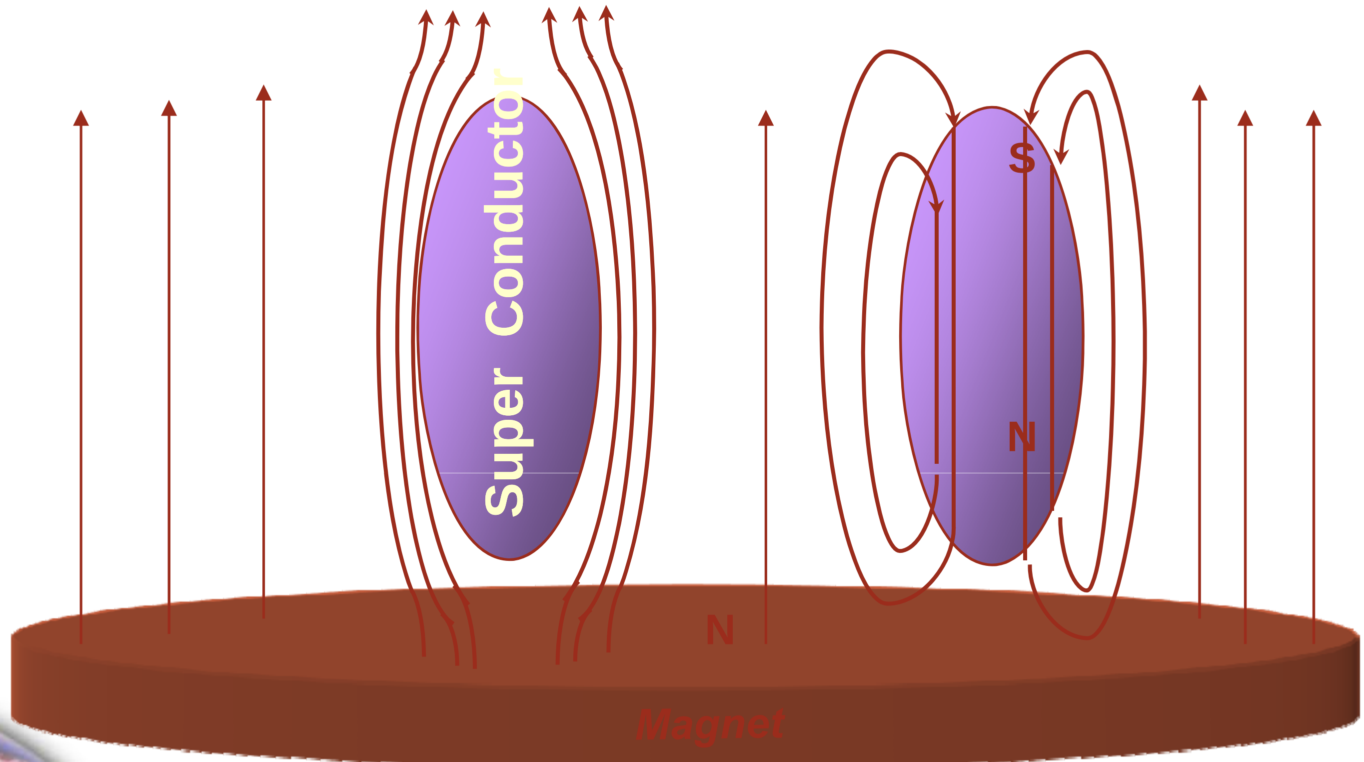
H. Kammerlingh Onnes, 1911, Lieden



Resistance goes to zero below a Critical Temperature, Tc

Defining Properties of a Superconductor:

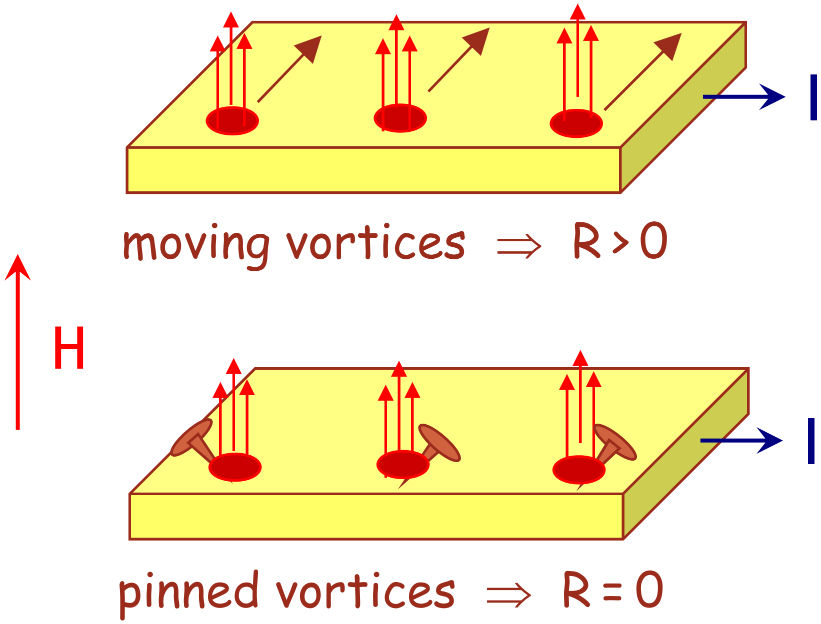
Perfect Diamagnetism: A magnetic field is expelled from a superconductor

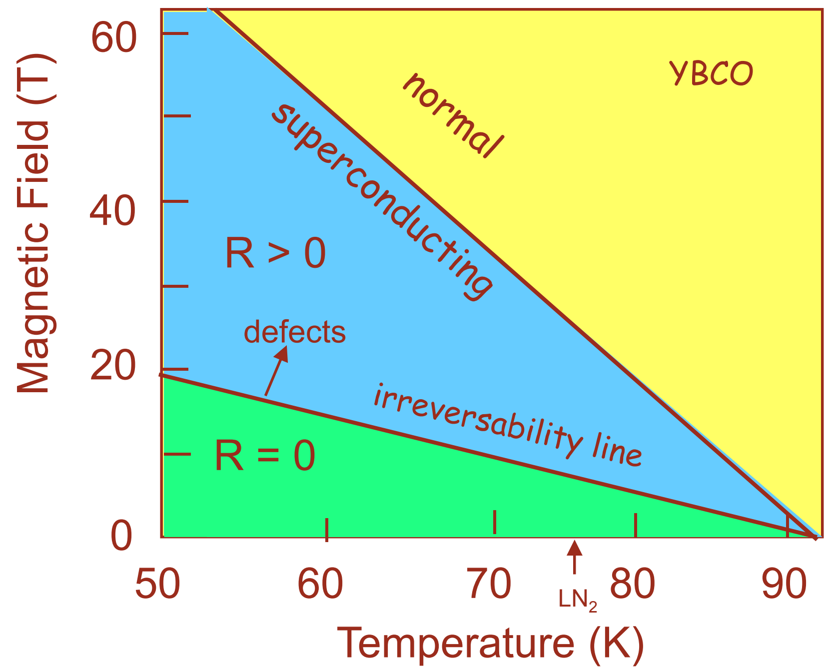


This picture applies to Type 1 superconductors

-Type 2 are somewhat more complicated (and Abrikosov won a Nobel Prize)

Barriers to Superconducting Performance





Performance Barriers

higher transition temperature - new materials

higher currents - control “vortex matter”

A Short History: Two Generations of High Temperature Superconducting Wire

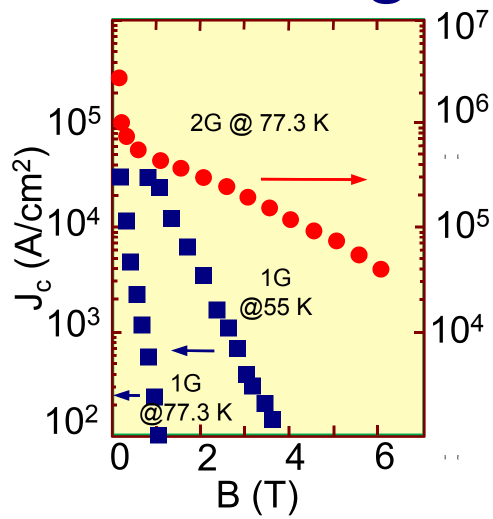
First Generation Wire: 1G

BiSrCaCuO multifilaments

expensive materials - silver sheath

simple architecture

high anisotropy - limited pinning



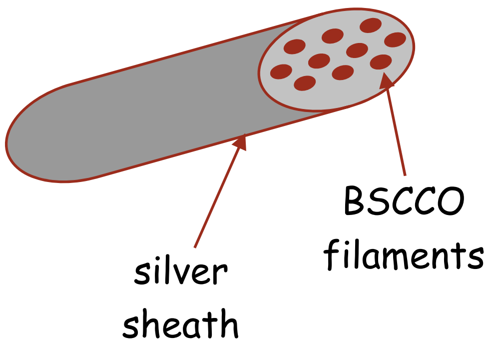
Second Generation Wire: 2G

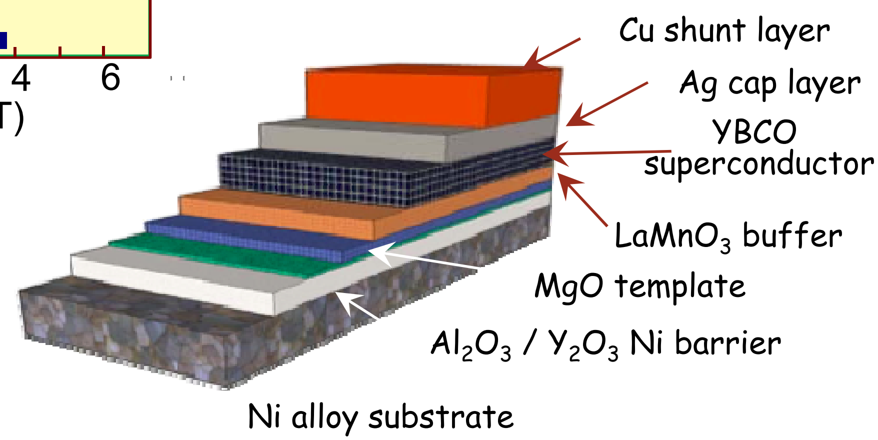
YBaCuO coated conductor

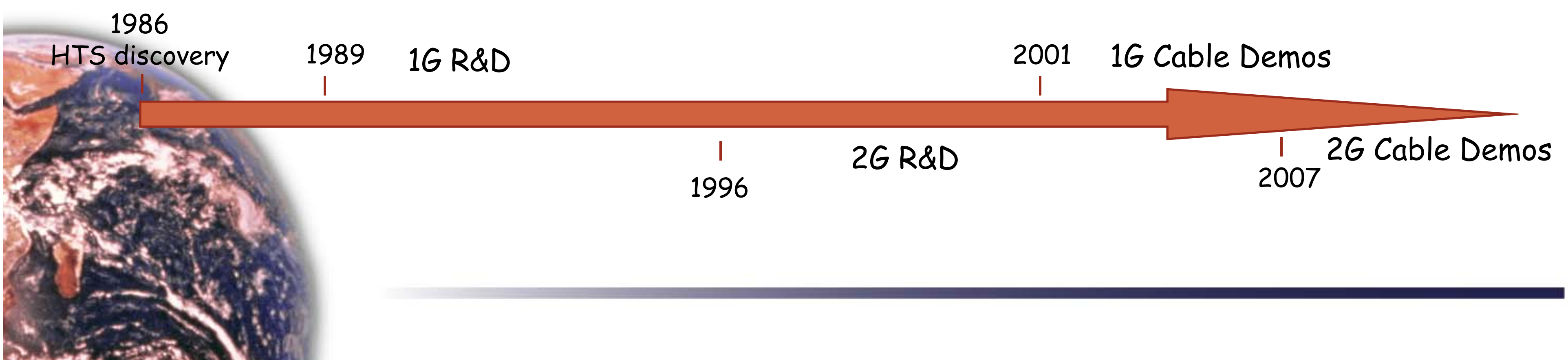
inexpensive materials

complex multilayer architecture

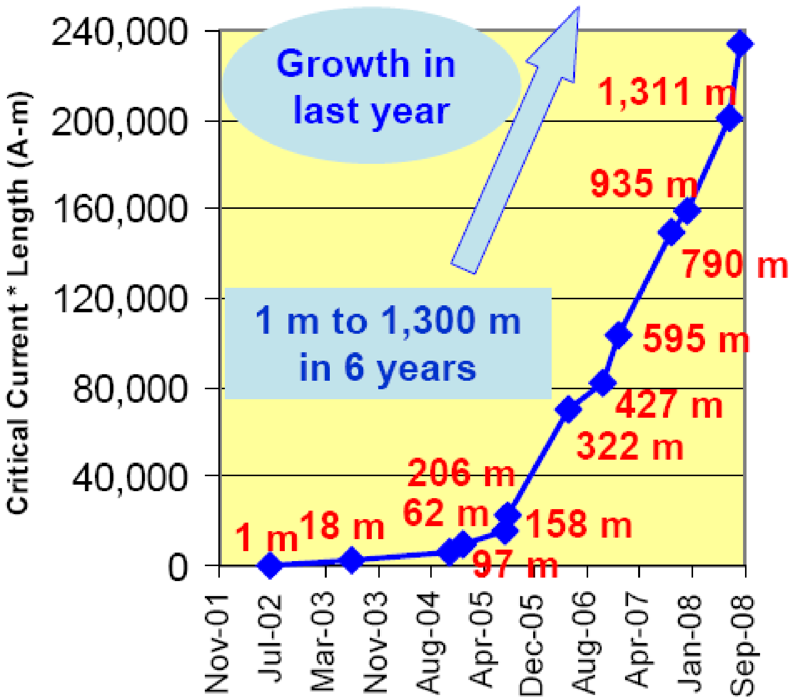
low anisotropy - strong pinning

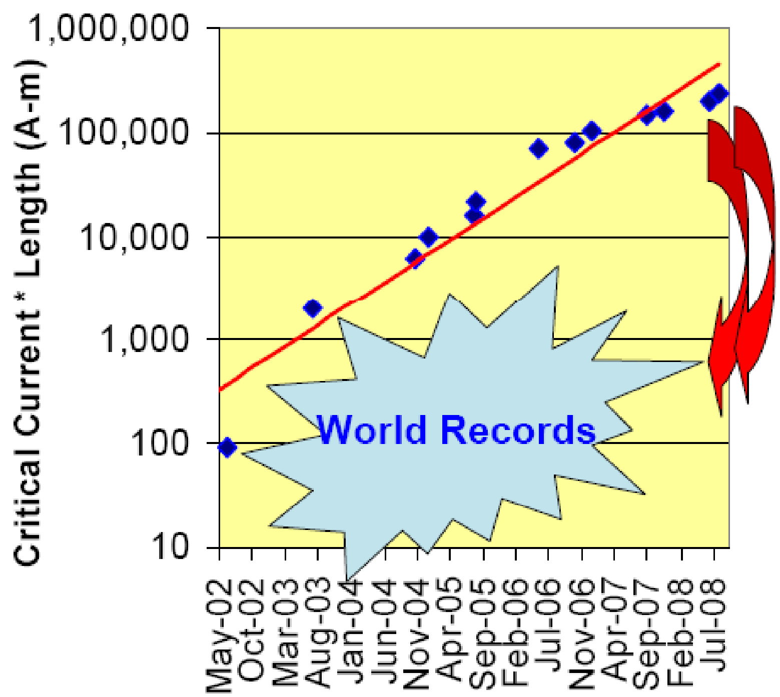






Remarkable progress in being made in 2G HTS wire development…





SuperPower Inc.

… that is impacting the grid today …

Columbus, OH

Albany, NY

Long Island

But significant challenges remain:

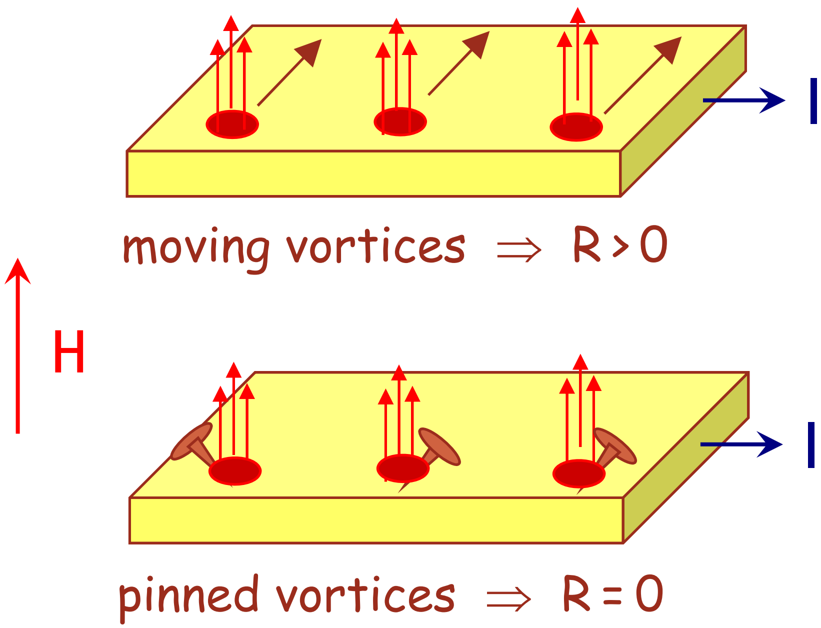
10-fold increase in critical current, 10-100 fold reduction in cost

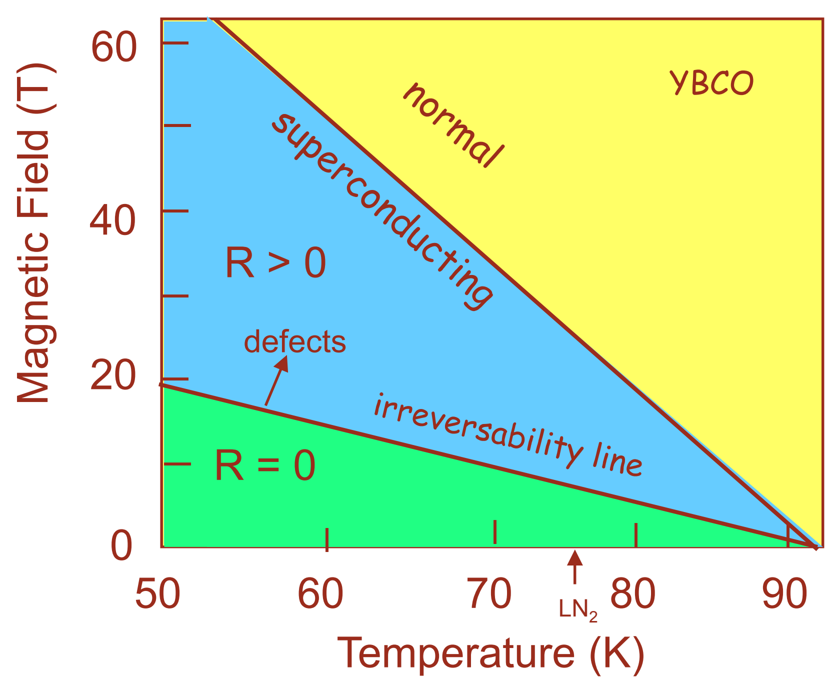
Understand and control dynamics of vortex matter, mechanism of superconductivity

Discover new materials: higher transition temperatures, lower anisotropy

Paradigm shift: superconductors by serendipity $\Rightarrow$ superconductors by design

Barriers to Superconducting Performance





Performance Barriers

higher transition temperature - new materials

higher currents - control “vortex matter”

Discovering the next generation of superconductors

~ 50 copper oxide superconductors

Highest Tc = 164 K under pressure

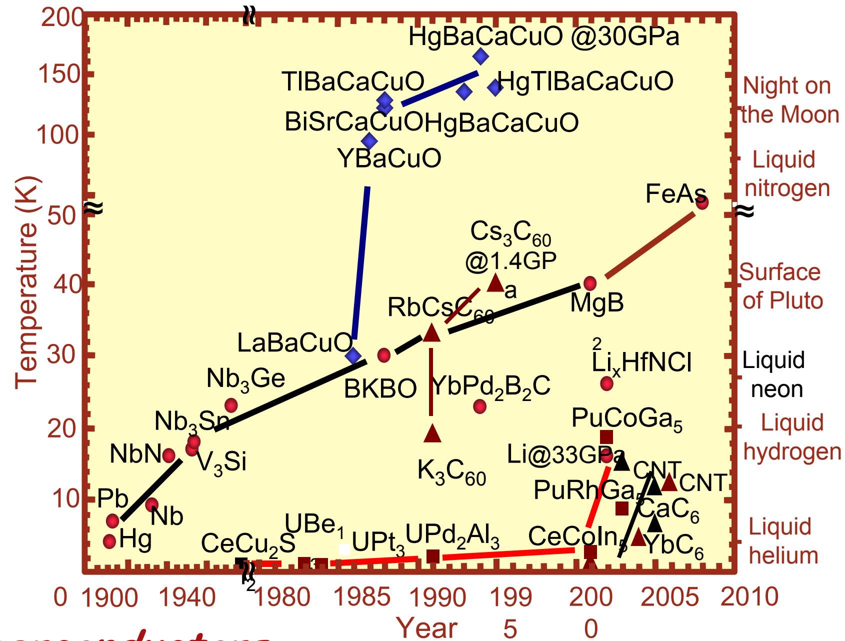
(1/2 Room Temp)

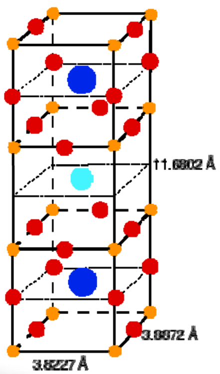
Only class of high T_c superconductors ?

High T_c superconductors $\geq$ 4 elements

55 superconducting elements

-> 55^4 ~ 10 million quaternaries





Search strategies for new superconductors

- Quaternary and higher compounds
- Layered structures
- Highly correlated normal states
- Competing high temperature ordered phases
- Variable valence states

Target Properties

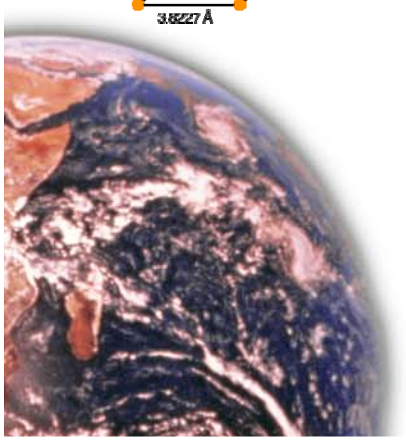
Higher Tc &

Jc

isotropy

Ductility

…



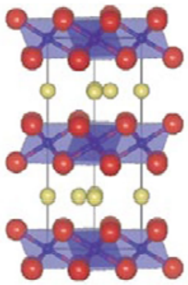
Challenge:

Towards Room Temperature Superconductivity

Superconductors by Design

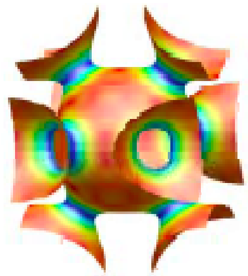
Discovery by serendipity: Hg (1911), copper oxides (1986), MgB_2 (2001), $NaCoO_2$:H_2O (2003)

Discovery by empirical guidelines: competing phases, layered structures, light elements, . . .
B-doped diamond (2004), CaC_6 (2005)



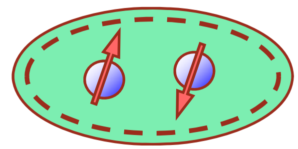
Crystal Structure
Composition

+



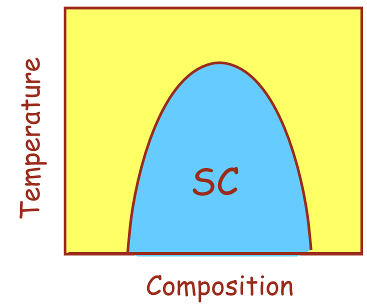
Electronic Structure
Density functional theory

+



Pairing Mechanism
phonons (classical BCS)
spin fluctuations
valence fluctuations

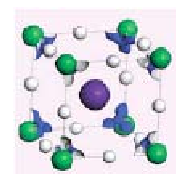
=



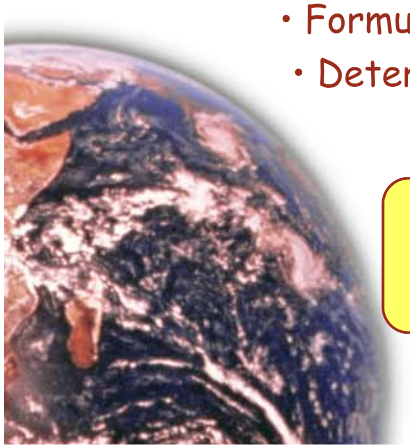
Superconductivity

Computationally designed superconductors

- Electronic structure calculation by density functional theory
- Large scale phonon calculations in nonlinear, anharmonic limit
- Formulate "very strong" electron-phonon coupling (beyond Eliashberg)
- Determine quantitative pairing mechanisms for high temperature SC

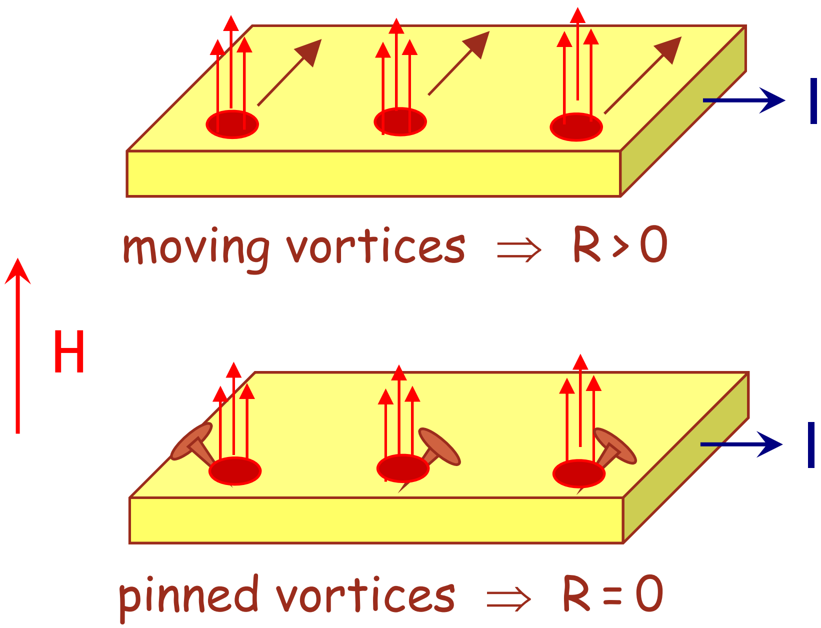


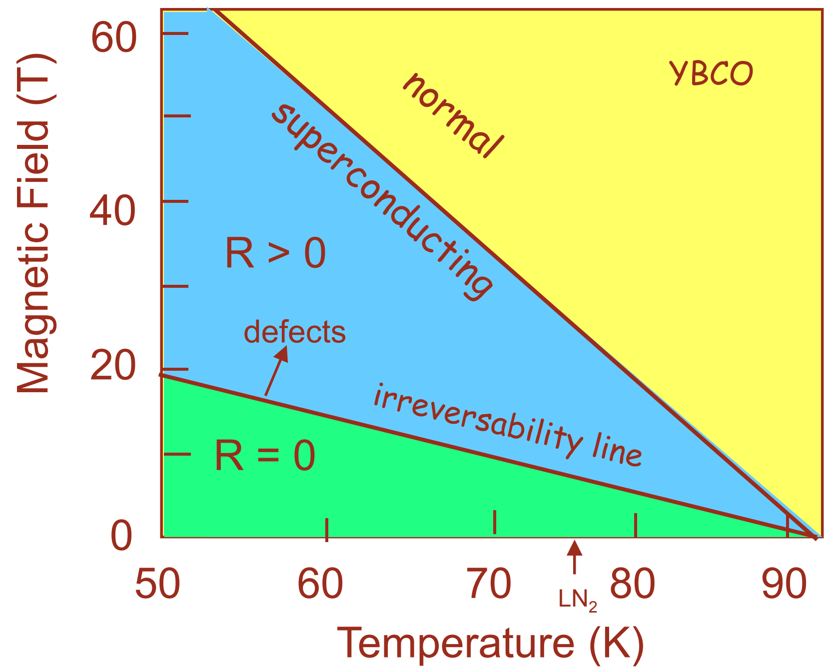
J. Mater. Chem., 2006
Computed metal hydride superconductor



Challenge:
Create a paradigm shift to superconductors by design

Barriers to Superconducting Performance





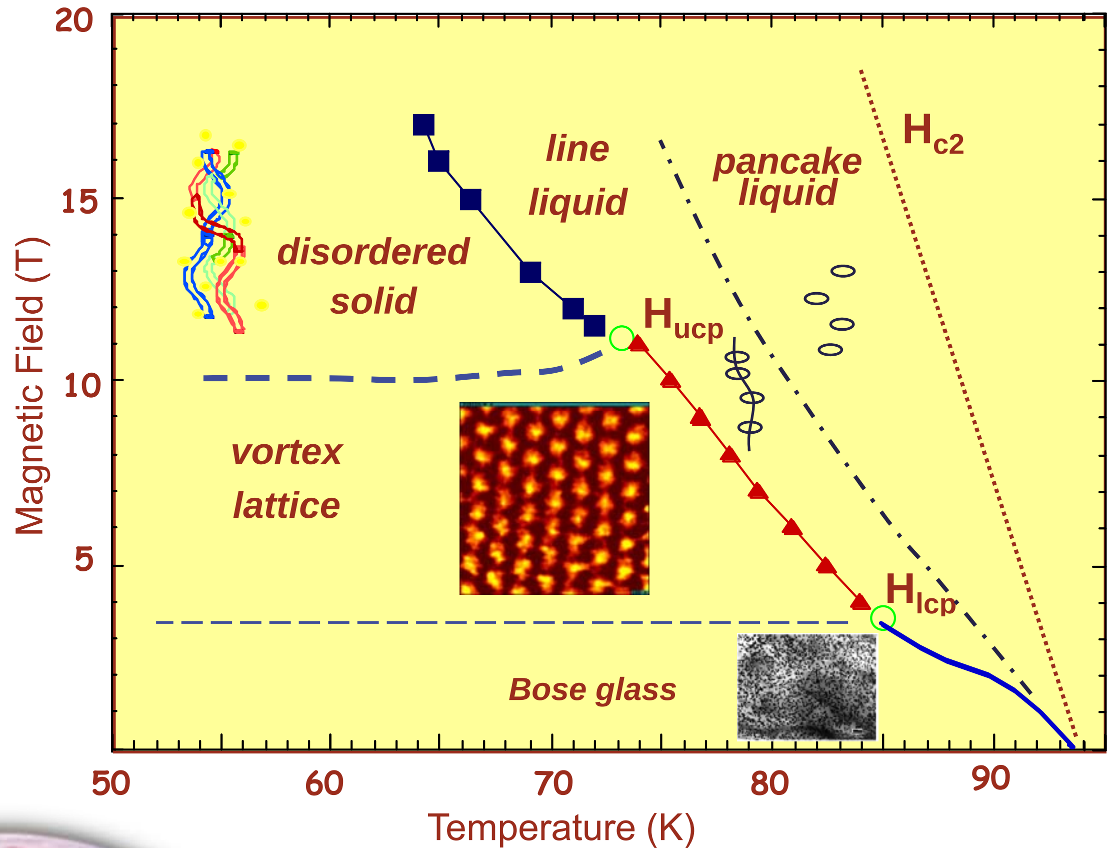
pinning defects:
nanodots, disorder,
2nd phases, dislocations
intergrowths
. . .

Performance Barriers

higher transition temperature - new materials

higher currents - control "vortex matter"

YBCO Vortex Phase Diagram



four competing energies

vortex repulsion ⇒ lattice

thermal ⇒ liquid

pinning ⇒ glass

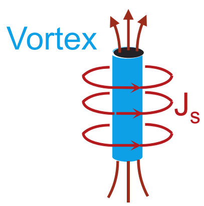
layer coupling ⇒ line tension

moderate anisotropy

rich collective behavior of flexible line objects
mediated by magnetic fields

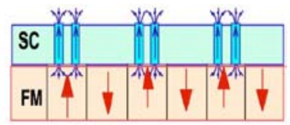
Control Vortex Matter: a multi-scale challenge

Vortex: nano-sized quantum of magnetic flux



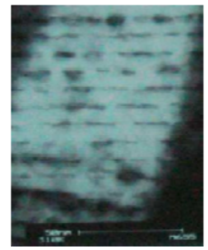
Determines the full electro-magnetic behavior of superconductors

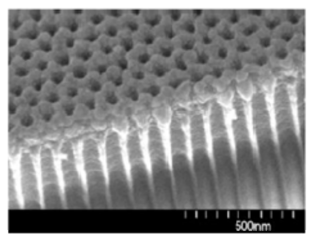
Novel Pinning Schemes



Magnetic pinning arrays

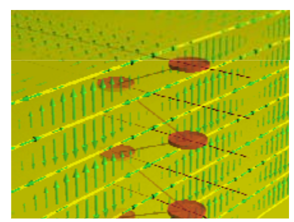
Facilitate isotropic pinning





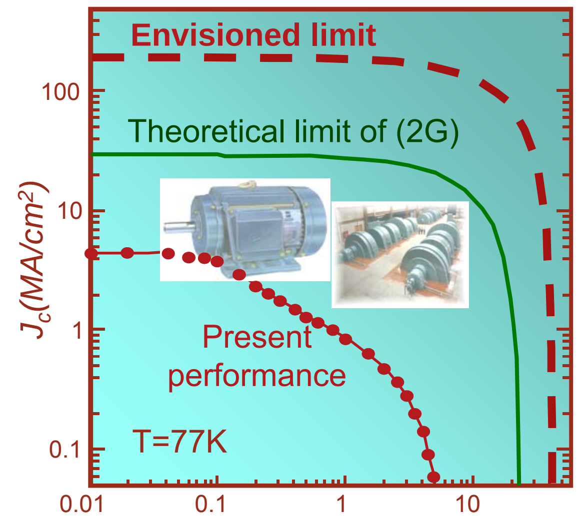
Self-assembled nano pin sites

Crossing vortex lattices

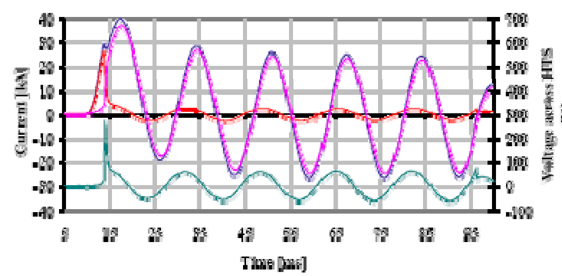


Impact

Achieve highest J_c



Limit faults in grid "smartly"

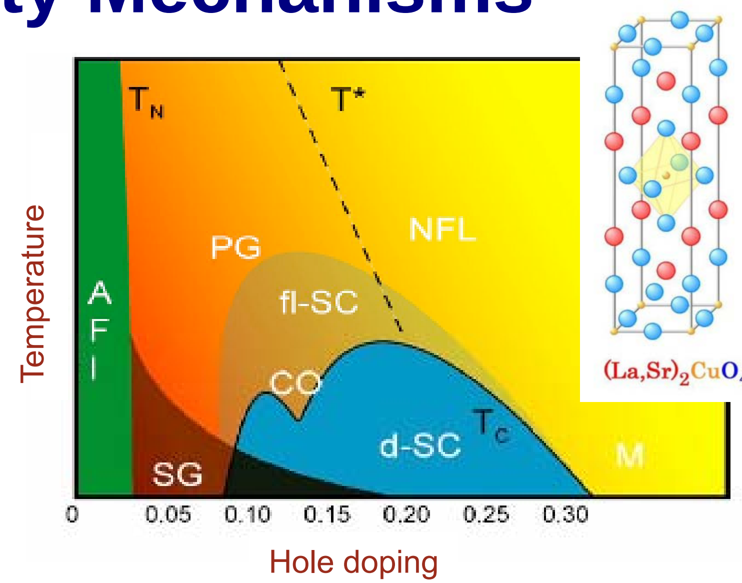


Challenge:
Transformational advances in superconductor performance through vortex manipulation

Find the Superconductivity Mechanisms

Higher T_c / New Mechanisms

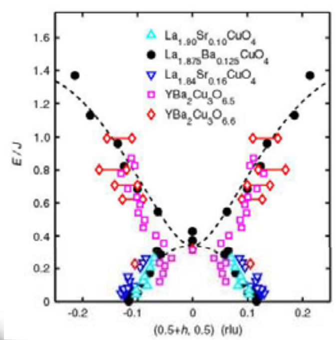
High temperature "fluctuating superconductivity"
in the pseudo-gap region and 'normal state' vortices?
p-, d-wave Cooper pairing
Two band superconductivity
multiple pairing mechanisms
Relate superconductivity to neighboring normal phases



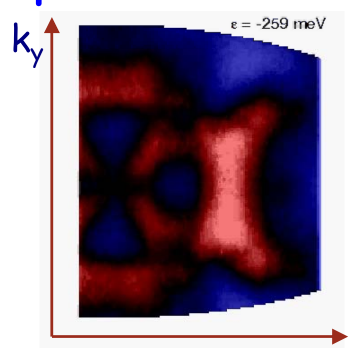
Find the simplifying emergent concepts

"Map the genome" of high T_c: find the controlling factors

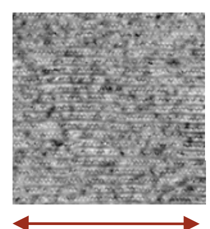
Using new tools with unprecedented resolutions



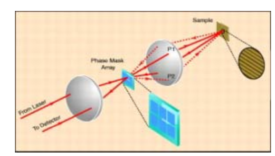
Neutron Scattering



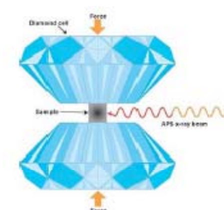
ARPES



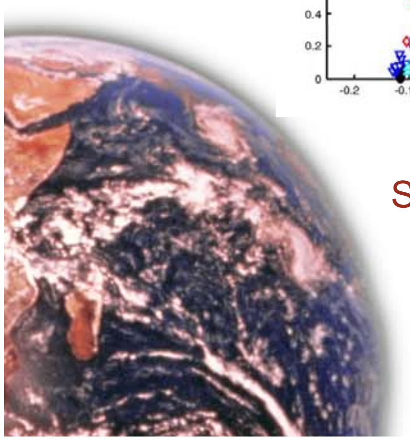
600 Å
STM



Femtosecond Spectroscopy

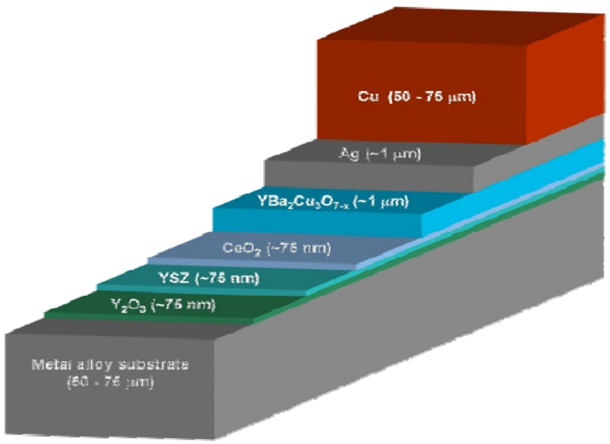


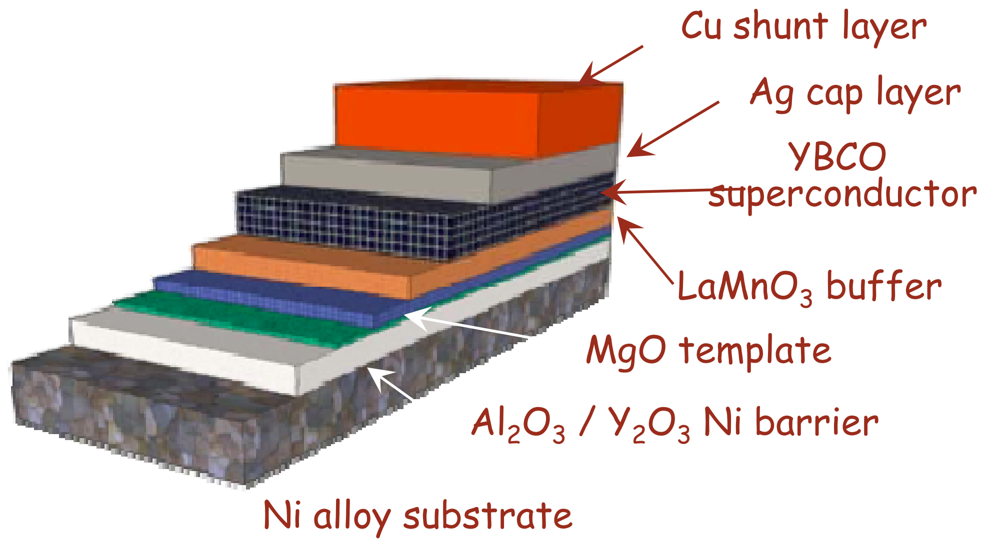
Extreme Environments



Challenge:
Reveal and exploit the essential interactions

The Multi-Functional Materials Challenge





Research Challenges

Hybrid materials for multifunctional layers

Nanoscale integration of high strength, flexibility and crystalline alignment

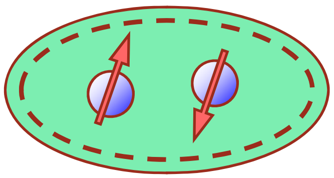
Enhance crystalline alignment between layers without contamination

Simplify layered architecture

Superconductivity - Emergent Nanoscale Science

Superconductivity arises from two emergent building blocks

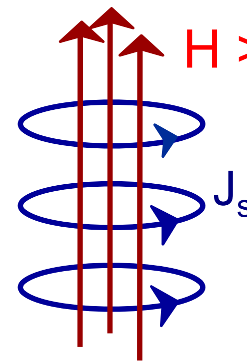
H=0



Cooper pairs
Charge 2 e^-
Spin = 0
ξ ~ 0.1 - 10 nm

Vortices
ξ ~ 0.1 - 10 nm
λ ~ 10 - 100 nm

H > 0



"electron matter"
transition temperature
excitations, fluctuations, stability

Macroscopic Behavior
10^{16} - 10^{23} Cooper pairs
10^{10} vortices

"vortex matter"
lossless / resistive current flow
electromagnetic response

ripe for nanoscale manipulation: confinement, proximity, hybrid structures, . . .

nanoscale architectures
top-down lithography
bottom-up self-assembly
multi-scale integration

characterization
scanning probes
electrons, neutrons, x-rays
smaller length and time scales

theory and modeling
multi-node computer clusters
density functional theory
10 000 atom assemblies

superconductivity embodies the frontier of nanoscale control science

Perspective

Electricity is our most effective energy carrier
- *Clean, versatile, switchable power anywhere*

The grid cannot meet 21st century challenges
- *Capacity, reliability, quality, efficiency*

Superconducting technology is poised to meet the challenge

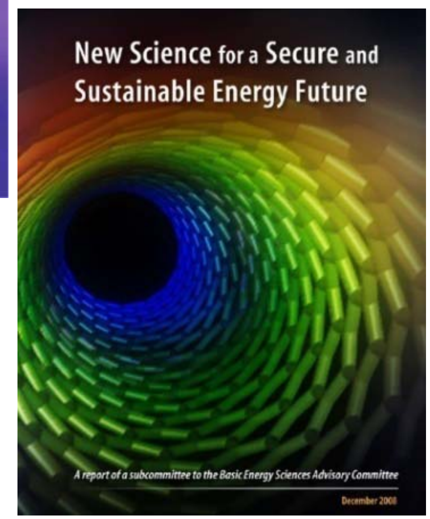
Present generation materials enable grid-connected cables and demonstrate control technology

Basic and applied research needed to lower cost and raise performance

High risk-high payoff discovery research for next-generation supercondcutors

Materials discovery by design

Control vortex matter



http://www.sc.doe.gov/bes/reports/list.html

The Superconductivity Opportunity: Transform the power grid to deliver abundant reliable, high-quality power for the 21st century

"The intersection of control science with high-functioning materials creates a tipping point for sustainable energy"