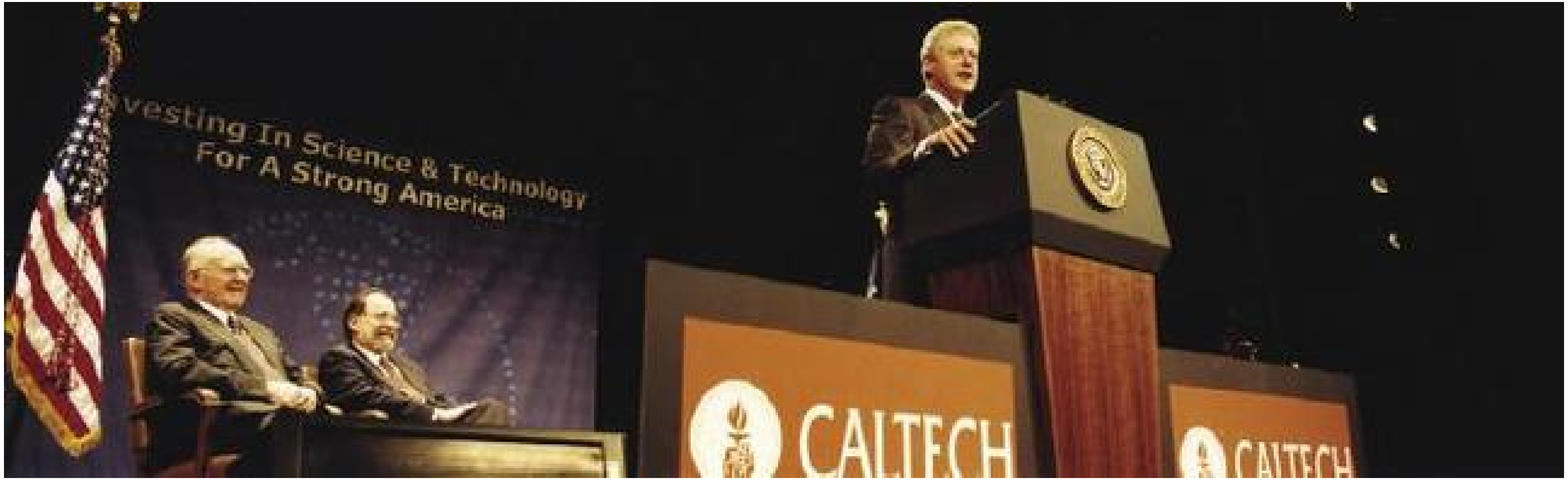
Jan. 21, 2000 - President Clinton announced his FY 2001 budget will include a National Nanotechnology Initiative (NNI):

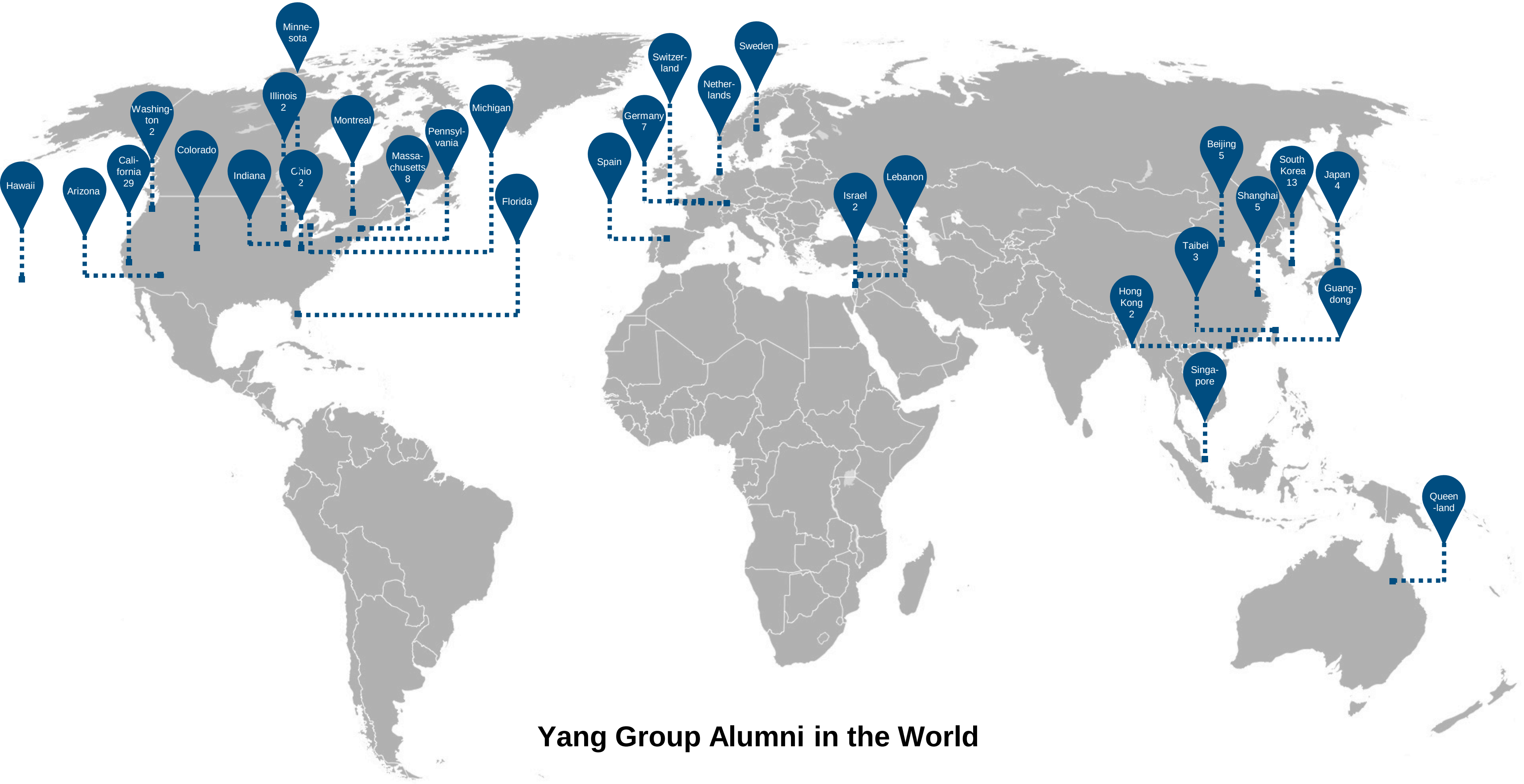


"My budget supports a major new National Nanotechnology Initiative, worth $500 million. ….Imagine the possibilities: materials with ten times the strength of steel---.shrinking all the information housed at the Library of Congress into a device the size of a sugar cube---detecting cancerous tumors when they are only a few cells in size.

“The vision of the National Nanotechnology Initiative (NNI) is a future in which the ability to understand and control matter at the nanoscale leads to a revolution in technology and industry that benefits society.”
https://www.nano.gov/

My 20 years @Berkeley, 1999-

Talent Output: 120 GSR +Postdoc; 75 Faculties



Yang Group Alumni in the World

Supported by

NSF

NASA

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

DARPA

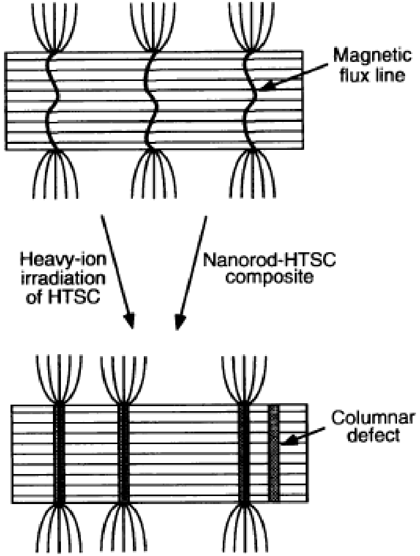
Also Industries & Foundations

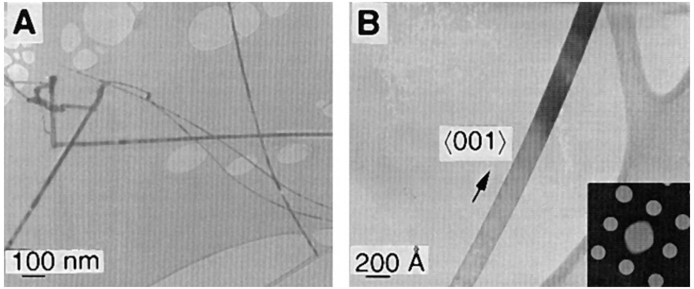
My first Experiment with Nanowires: 1993-96

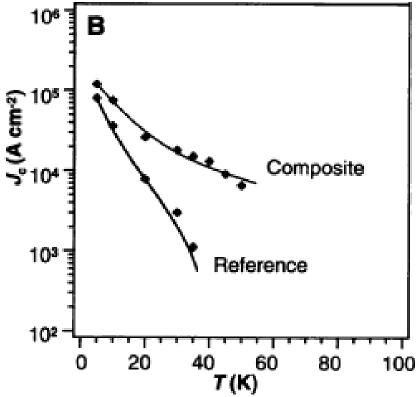
Nanorod-Superconductor Composites: A Pathway to Materials with High Critical Current Densities

Peidong Yang and Charles M. Lieber*

SCIENCE • VOL. 273 • 27 SEPTEMBER 1996







Nanowires as columnar defects in HTSC,
pin magnetic flux lines,
and enhance critical current density

My first Experiment with Nanowires: 1993-96

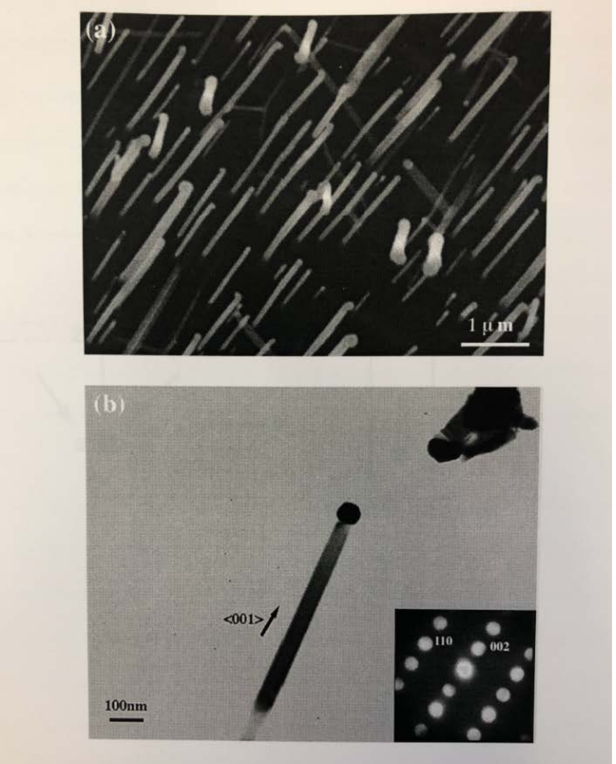


Fig. 2.15 SEM and TEM images of ZnO nanorods. A CBED pattern along [1-10] zone axis is shown in (b) inset.

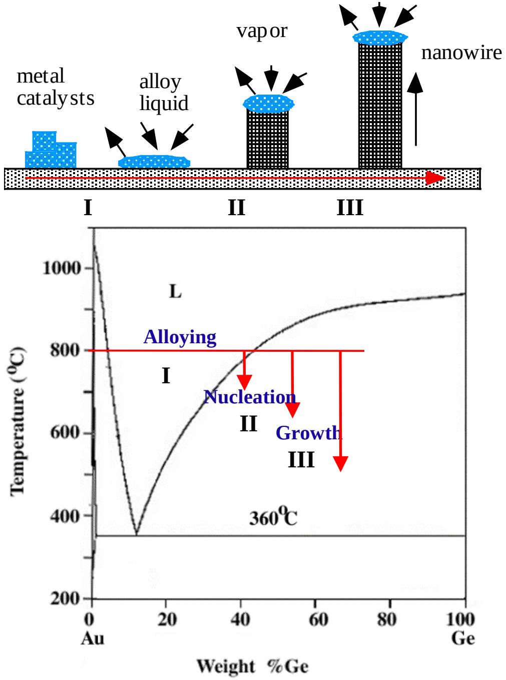
Metal oxide nanorods and composite materials containing such nanorods. **The metal oxide nanorods have diameters between 1 and 200 nm and aspect ratios between 5 and 2000.**

Nanorod
Nanowhisker
..
Nanowire

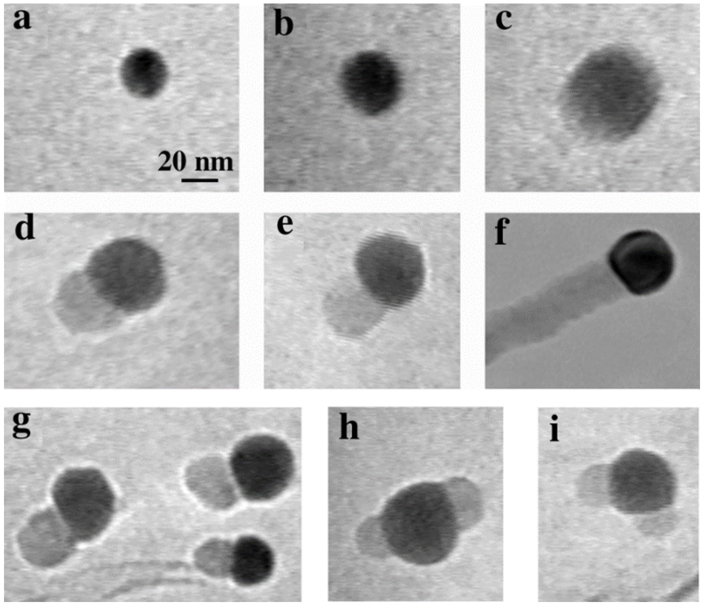
Metal oxide nanorods;
US 5,897,945, April 27, 1999.

Priority date
1996-02-26

Growth Mechanism: Vapor-Liquid-Solid



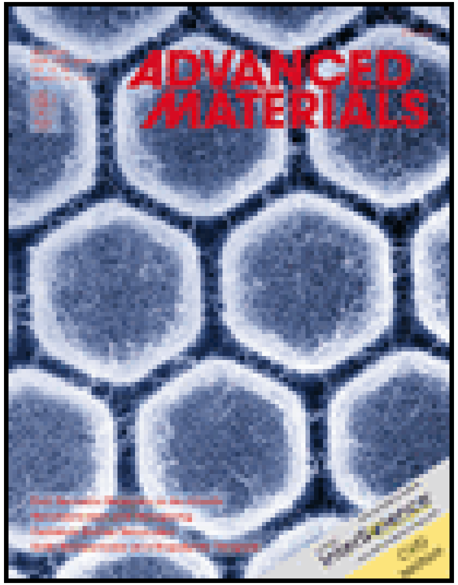
800 deg. In-situ TEM

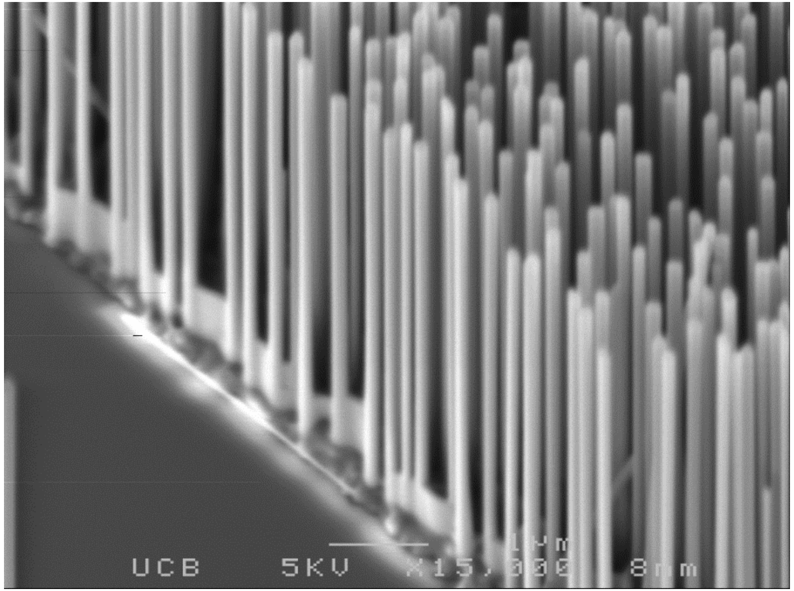


Unidirectional growth is the consequence of an anisotropy in solid-liquid interfacial energy.

Y. Wu, P. Yang ***J. Am. Chem. Soc.*** **2001**, *123*, 3165

ZnO Nanowire & Nanolaser





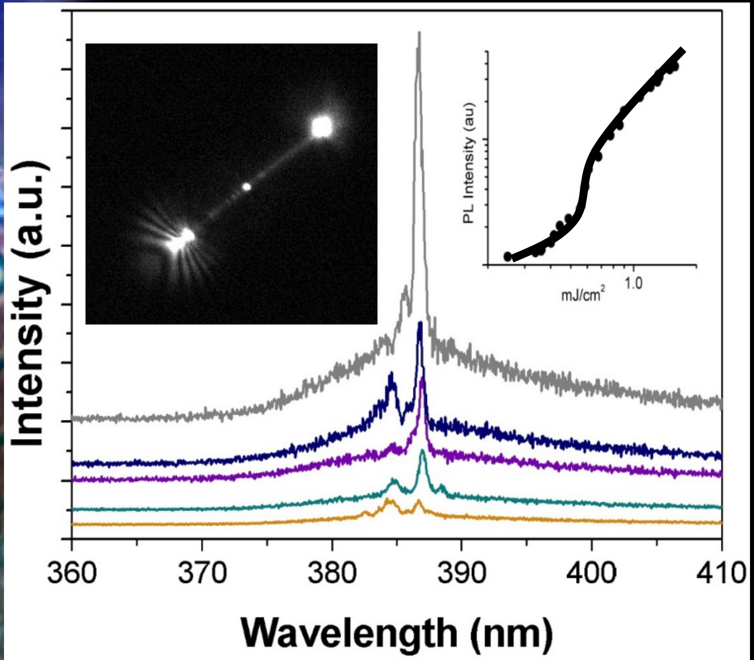
"Catalytic growth of zinc oxide nanowires through vapor transport",
M. Huang, Y. Wu, H. Feick, N. Tran,E. Weber, P. Yang, ***Adv. Mater.*13(2), 113**,2001.

"Room-temperature ultraviolet nanowire nanolasers",
M. Huang, S. Mao, H. Feick, H. Yan, Y. Wu, H. Kind, E. Weber,
R. Russo, P. Yang, ***Science*, 292, 1897, 2001.**

Nanowire Lasers

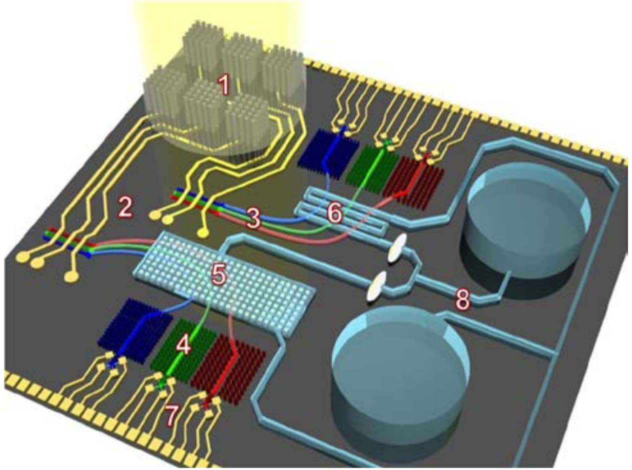
A nanoscopic room temperature UV laser with Fabry-Perot cavity along the third dimension

M. Huang et al. ***Science****, 292, 1897, 2001*



J. Johnson et al. Nature Materials, 1,101, 2002. T. Kuykendall et al. Nature Mater, 3, 528, 2004
P. Pauzauskie et al.Phys. Rev. Lett. 96, 143903, 2006.

Nanowire Photonics

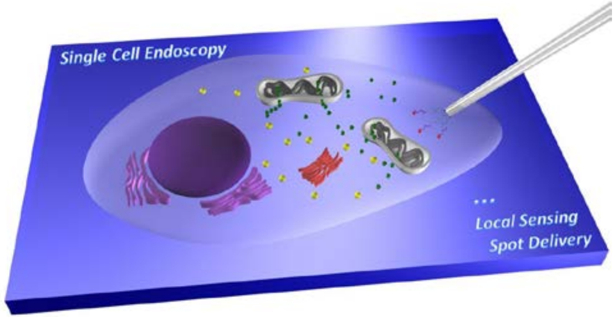


Integrated Nanophotonics

Integrated flexible nanowire sensory system, including light sources, waveguide, detectors, sensors, micro-nanofluidics and embedded energy sources.

Nanowire Single Cell Endoscopy

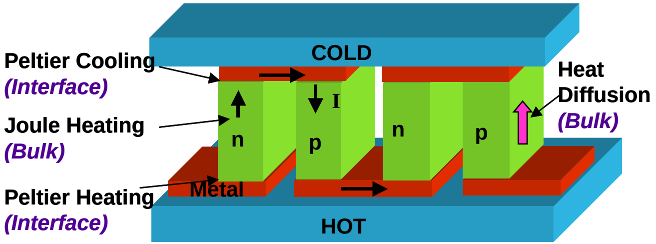
- **Interrogating individual cells**
- **Delivering light, Imaging**
- **Delivering DNA, drug**
- **Extraction**
- **Stimulation, optical/electrical**

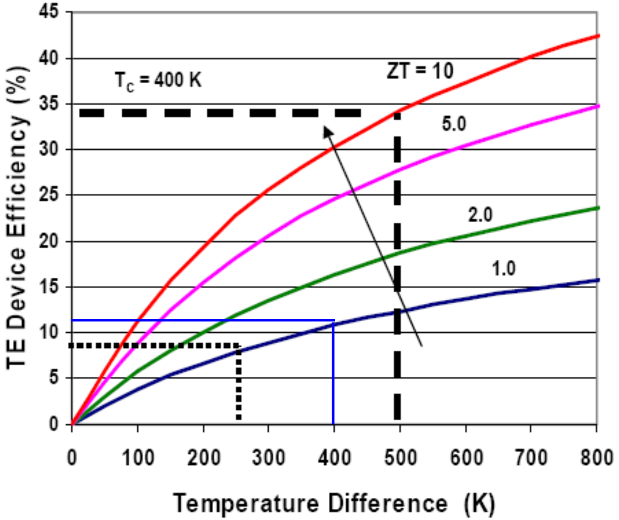


Nature Photonics (invited review), R. Yan, D. Gargas, P. Yang, 3, 569, 2009.

Nature Mater. Rev, *1, 16028, 2016*

Better Semiconductor Thermoelectrics





Thermoelectric Figure of Merit

$$ZT = \frac{S^2 \sigma T}{k}$$

$$\eta(T_h, T_c) = \frac{T_h - T_c}{T_h} \frac{\sqrt{1 + Z\bar{T}} - 1}{\sqrt{1 + Z\bar{T}} + T_c/T_h}$$

Carnot Efficiency

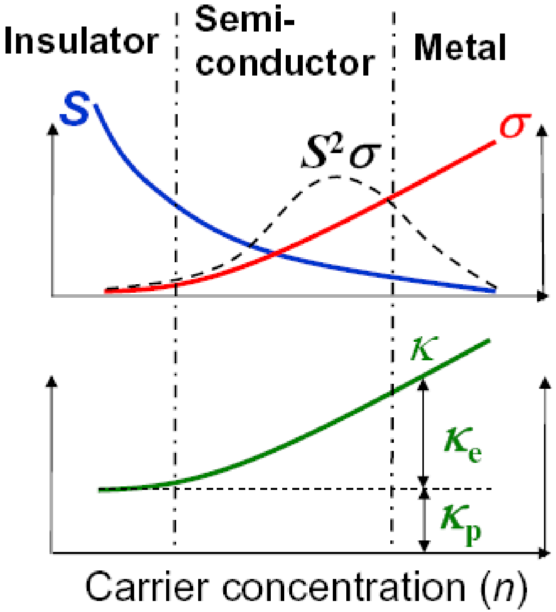
T_h = Hot side temperature
T_c = Cold Side Temperature
ZT = Figure of merit at $T = (T_h+T_c)/2$

S: Seebeck Coeff.
σ: Electrical Conductivity
k: thermoconductivity

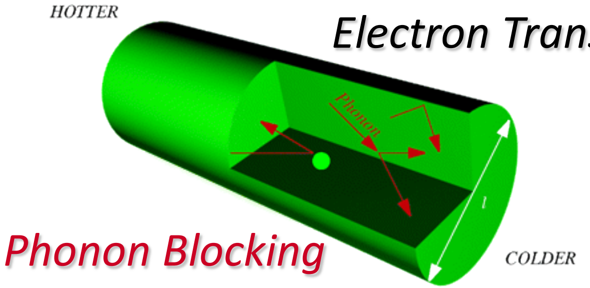
Thermoelectric Figure of Merit: the difficult part

- **Difficulties in increasing ZT in bulk materials.**
- **So far the best bulk materials $Bi_{0.5}Sb_{1.5}Te_3$ has ZT ~ 1 at 300K**

$$ZT = \frac{S^2 \sigma T}{k}$$

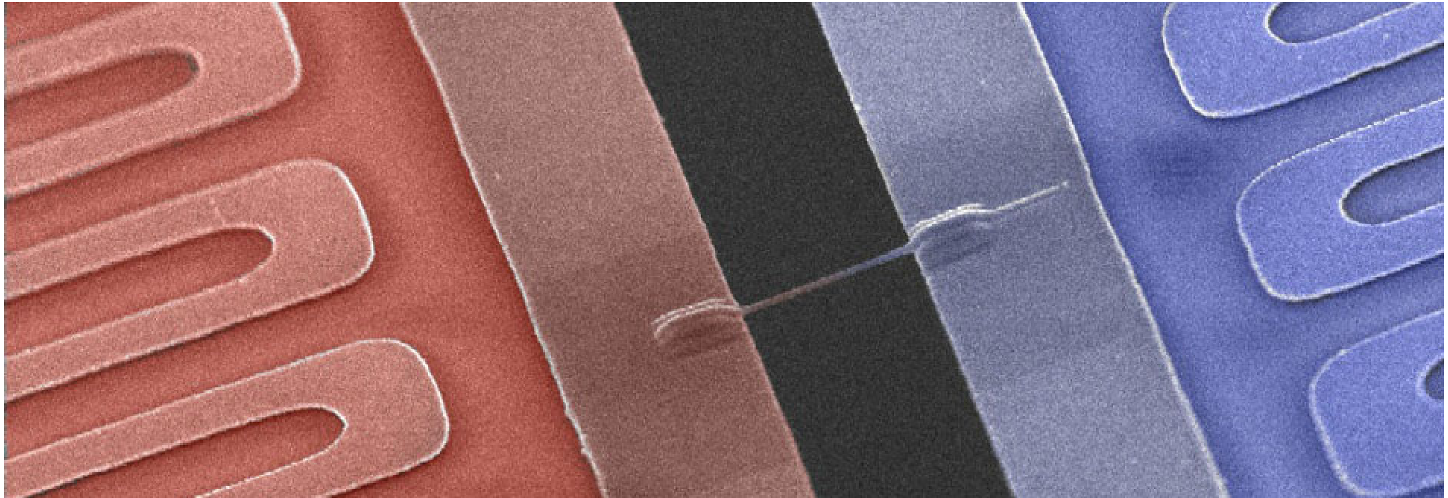


Silicon Nanowires as High Performance Thermoelectrics



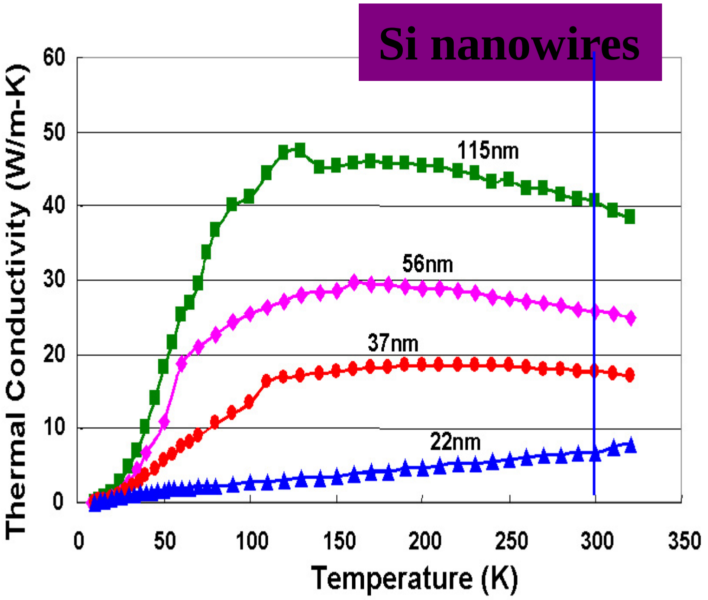
$$ZT = \frac{S^2 \sigma T}{k}$$

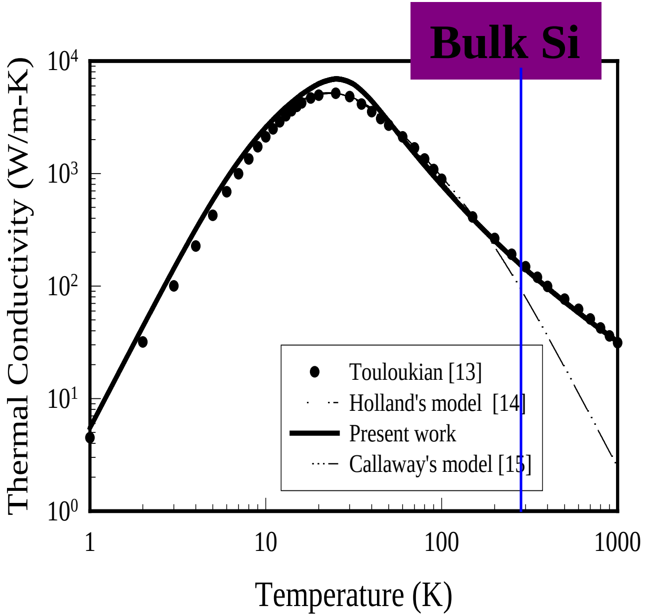
Phonon mean free path ~ > wire diameter > e mfp



Size-dependent Thermal Conductivity

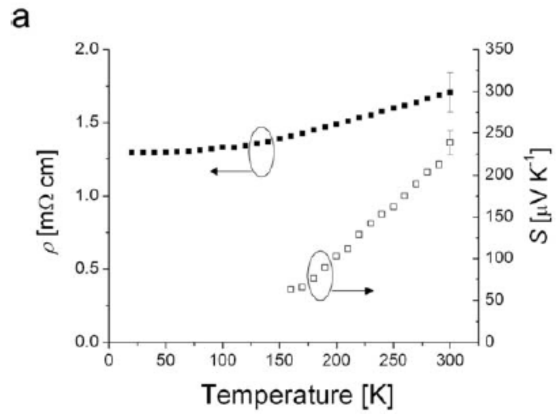
Boundary Phonon Scattering

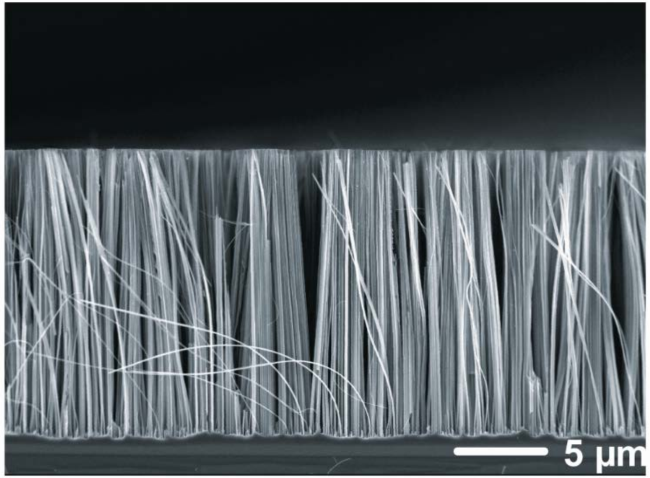


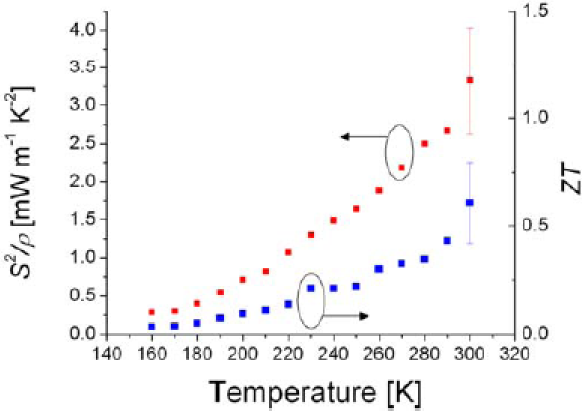


*D. Li, Y. Wu, **Appl. Phys. Lett**. 2003*

ZT of solution-processed rough Si nanowires

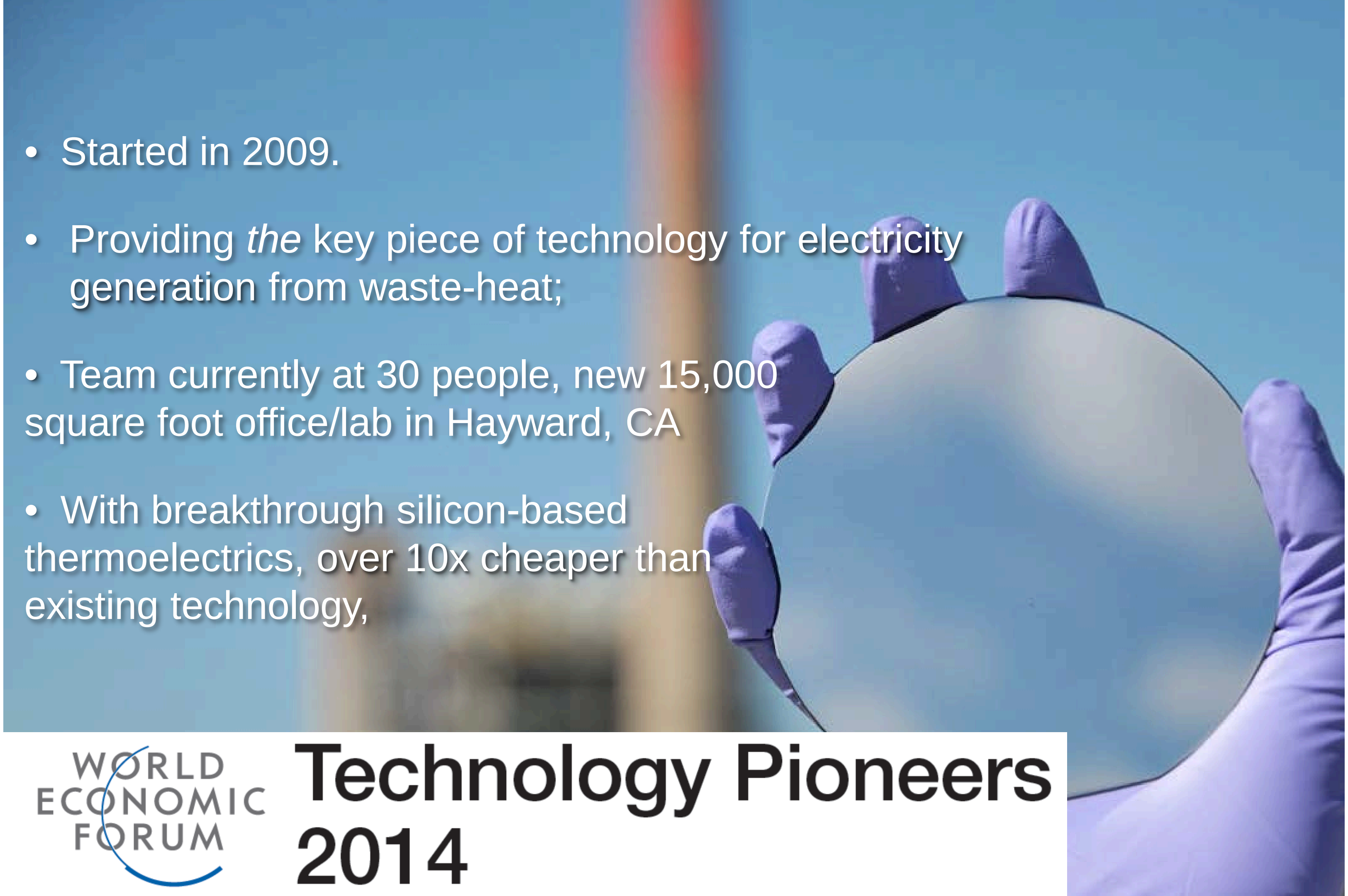






Nanowire *ZT* is 100-fold greater than optimal doped bulk Si!

A. Hochbaum et al. Nature, 2008



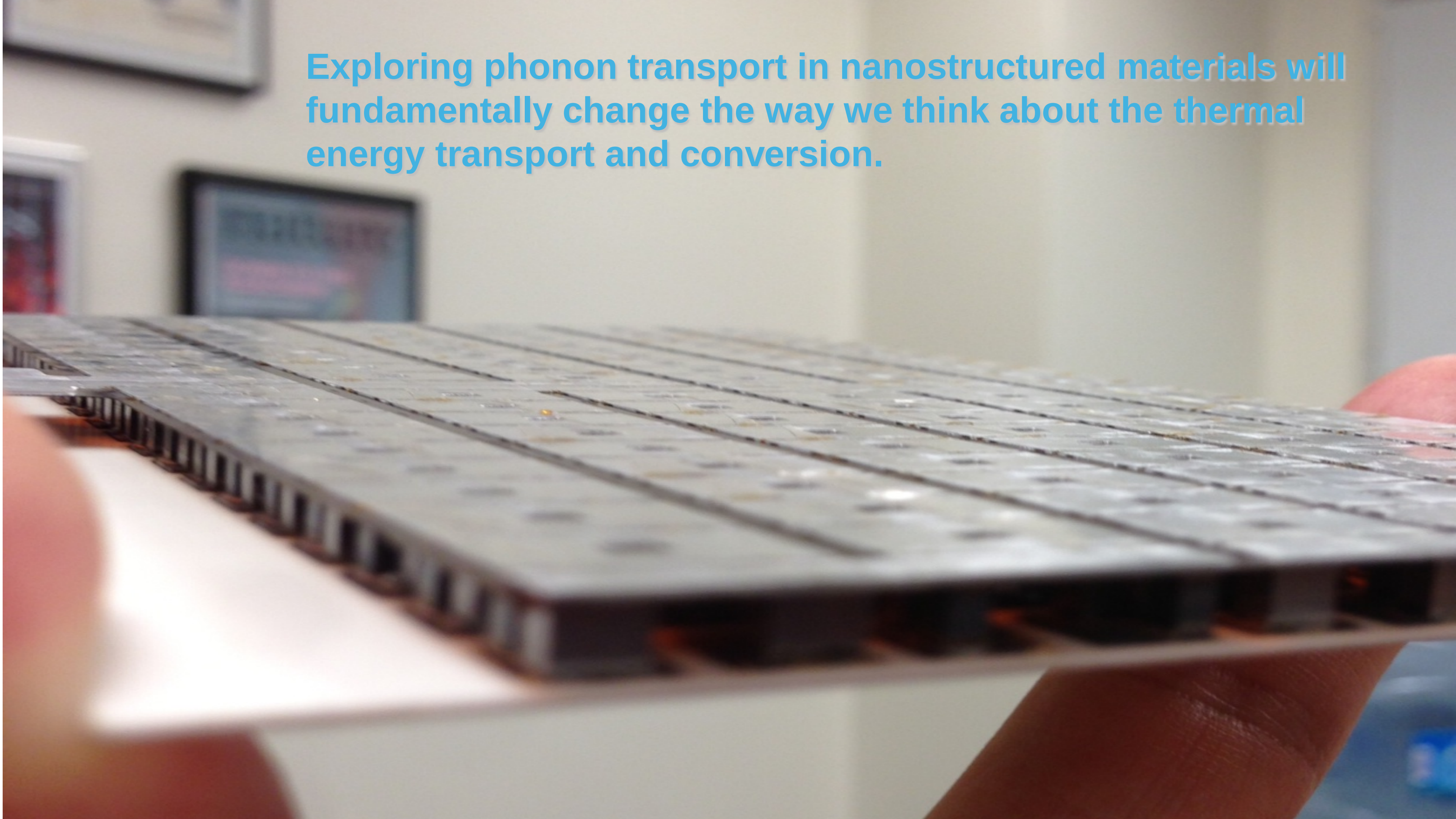
- Started in 2009.
- Providing *the* key piece of technology for electricity generation from waste-heat;
- Team currently at 30 people, new 15,000 square foot office/lab in Hayward, CA
- With breakthrough silicon-based thermoelectrics, over 10x cheaper than existing technology,

WORLD ECONOMIC FORUM

Technology Pioneers 2014

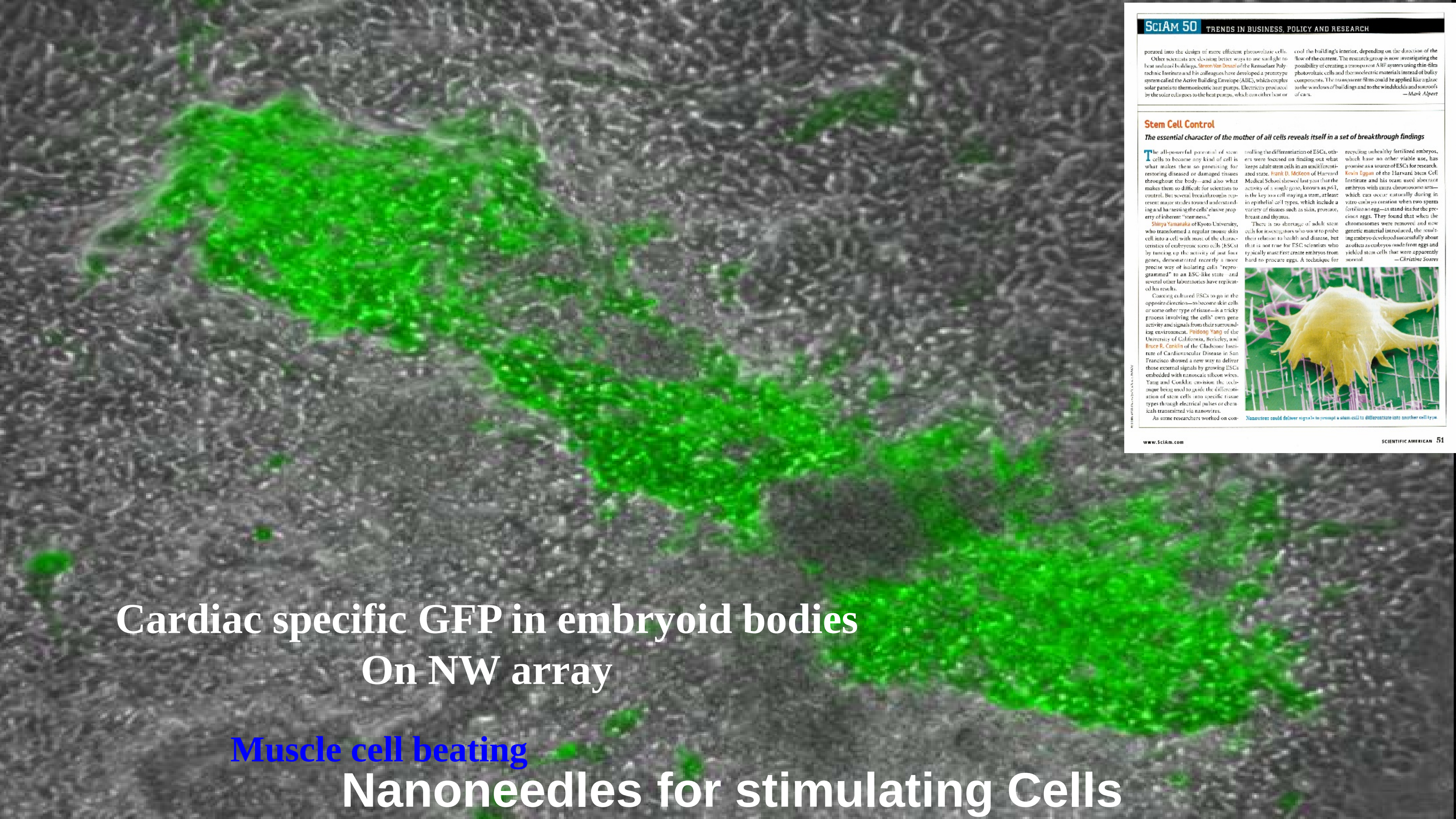
E1 thermoelectric generators

Up to 25 kW per 1,000 kW engine, saving 52,500 liters of diesel fuel per year, per engine


Exploring phonon transport in nanostructured materials will fundamentally change the way we think about the thermal energy transport and conversion.

Cells grow on a bed of nails

Woong Kim et al, JACS, 2007



Cardiac specific GFP in embryoid bodies
On NW array

Muscle cell beating

Nanoneedles for stimulating Cells

porated into the design of more efficient photovoltaic cells.

Other scientists are devising better ways to use sunlight to heat and cool buildings. Steven Van Dessel of the Rensselaer Polytechnic Institute and his colleagues have developed a prototype system called the Active Building Envelope (ABE), which couples solar panels to thermoelectric heat pumps. Electricity produced by the solar cells goes to the heat pumps, which can either heat or cool the building's interior, depending on the direction of the flow of the current. The research group is now investigating the possibility of creating a transparent ABE system using thin-film photovoltaic cells and thermoelectric materials instead of bulky components. The transparent films could be applied like a glaze to the windows of buildings and to the windshields and sunroofs of cars.

—Mark Alpert

Stem Cell Control

The essential character of the mother of all cells reveals itself in a set of breakthrough findings

The all-powerful potential of stem cells to become any kind of cell is what makes them so promising for restoring diseased or damaged tissues throughout the body—and also what makes them so difficult for scientists to control. But several breakthroughs represent major strides toward understanding and harnessing the cells' elusive property of inherent "stemness."

Shinya Yamanaka of Kyoto University, who transformed a regular mouse skin cell into a cell with most of the characteristics of embryonic stem cells (ESCs) by turning up the activity of just four genes, demonstrated recently a more precise way of isolating cells "reprogrammed" to an ESC-like state—and several other laboratories have replicated his results.

Coaxing cultured ESCs to go in the opposite direction—to become skin cells or some other type of tissue—is a tricky process involving the cells' own gene activity and signals from their surrounding environment. Peidong Yang of the University of California, Berkeley, and Bruce R. Conklin of the Gladstone Institute of Cardiovascular Disease in San Francisco showed a new way to deliver those external signals by growing ESCs embedded with nanoscale silicon wires. Yang and Conklin envision the technique being used to guide the differentiation of stem cells into specific tissue types through electrical pulses or chemicals transmitted via nanowires.

As some researchers worked on controlling the differentiation of ESCs, others were focused on finding out what keeps adult stem cells in an undifferentiated state. Frank D. McKeon of Harvard Medical School showed last year that the activity of a single gene, known as *p63*, is the key to a cell staying a stem, at least in epithelial cell types, which include a variety of tissues such as skin, prostate, breast and thymus.

There is no shortage of adult stem cells for investigators who want to probe their relation to health and disease, but that is not true for ESC scientists who typically must first create embryos from hard-to-procure eggs. A technique for recycling unhealthy fertilized embryos, which have no other viable use, has promise as a source of ESCs for research. Kevin Eggan of the Harvard Stem Cell Institute and his team used aberrant embryos with extra chromosome sets—which can occur naturally during in vitro embryo creation when two sperm fertilize an egg—as stand-ins for the precious eggs. They found that when the chromosomes were removed and new genetic material introduced, the resulting embryo developed successfully about as often as embryos made from eggs and yielded stem cells that were apparently normal.

—Christine Soares

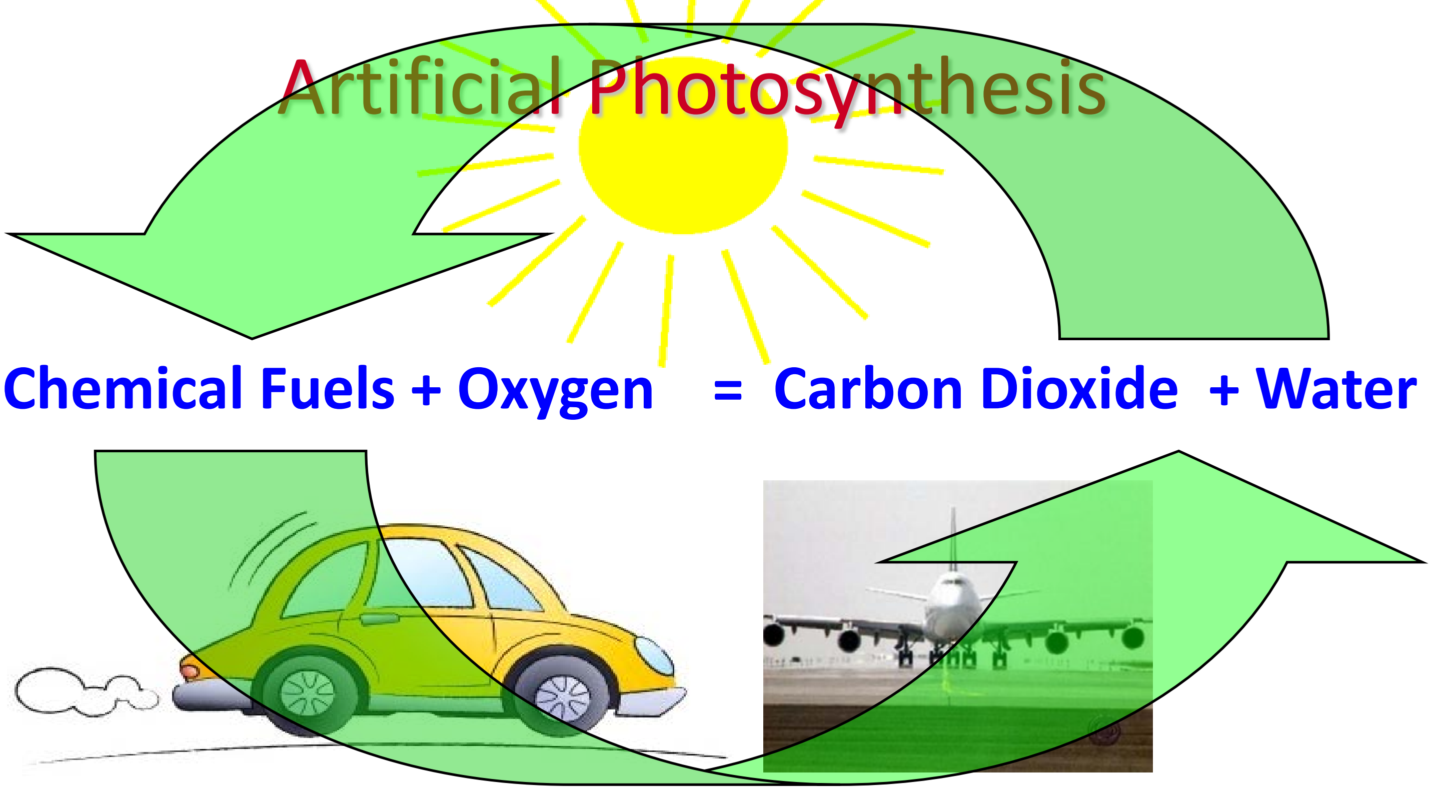
Nanowires could deliver signals to prompt a stem cell to differentiate into another cell type.

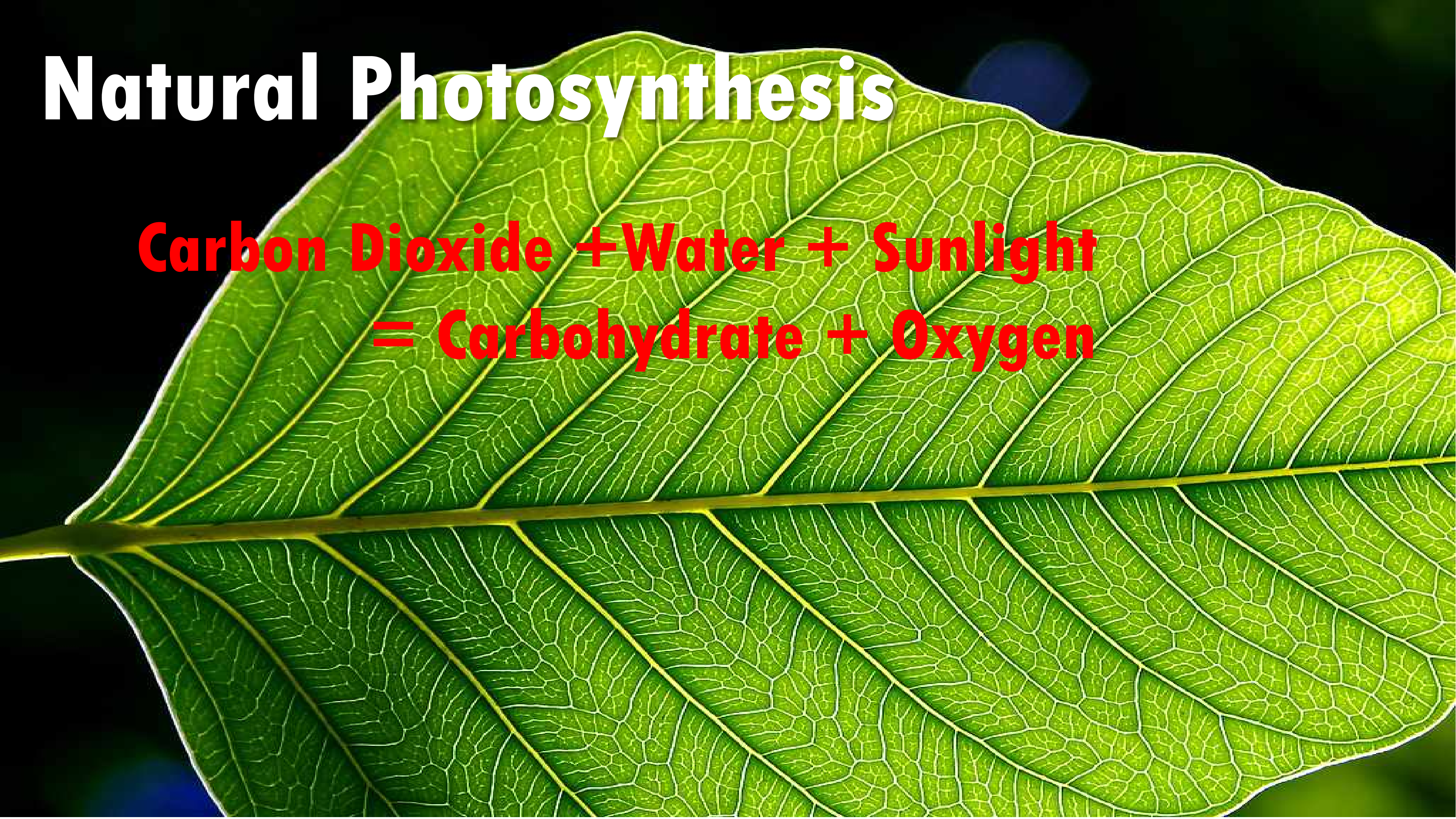
JCAP

JOINT CENTER FOR ARTIFICIAL PHOTOSYNTHESIS

Solar to fuel/chemical

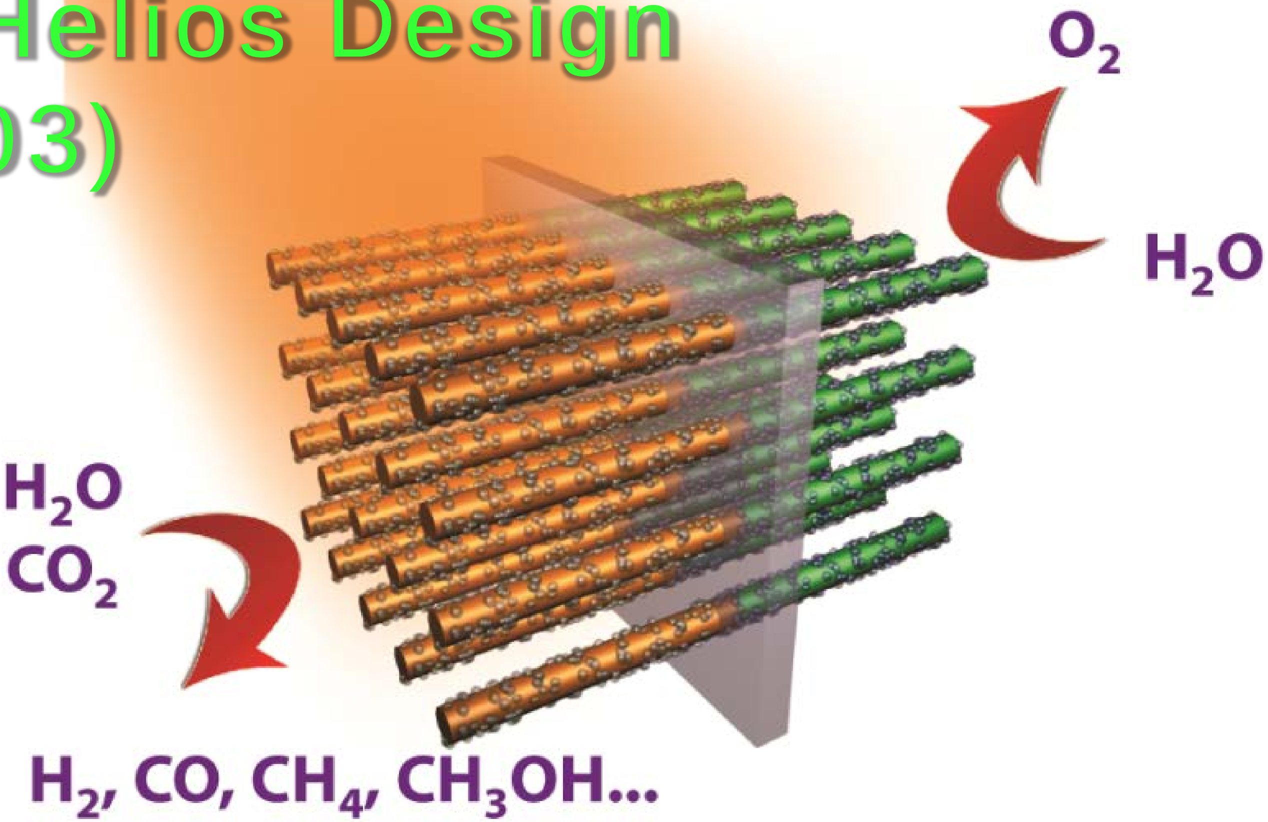
Carbon-Neutral Solution

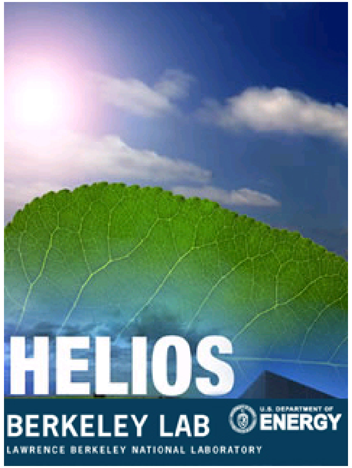



Natural Photosynthesis
Carbon Dioxide +Water + Sunlight
= Carbohydrate + Oxygen

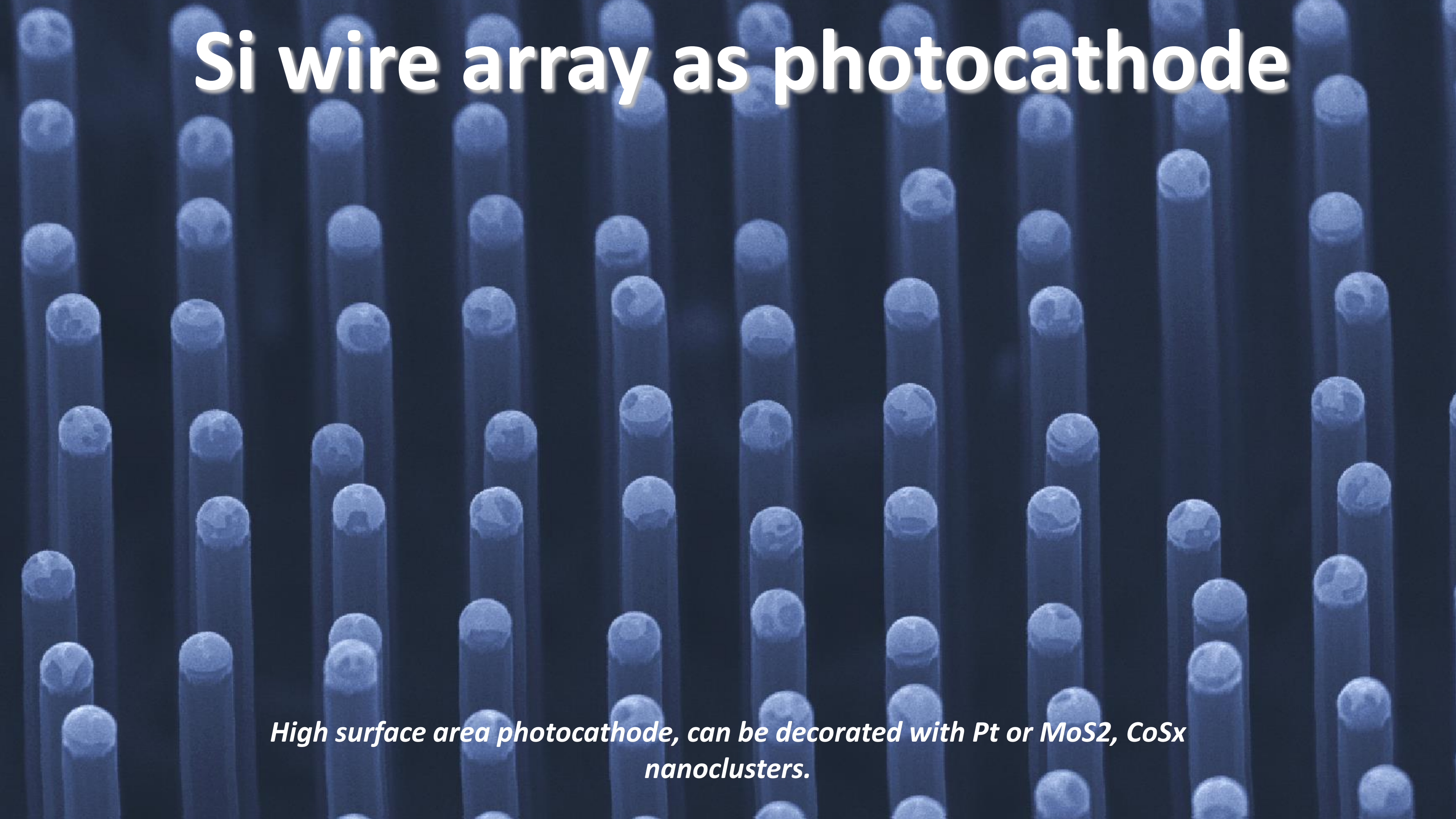
Artificial Photosynthesis

The Helios Design (~2003)

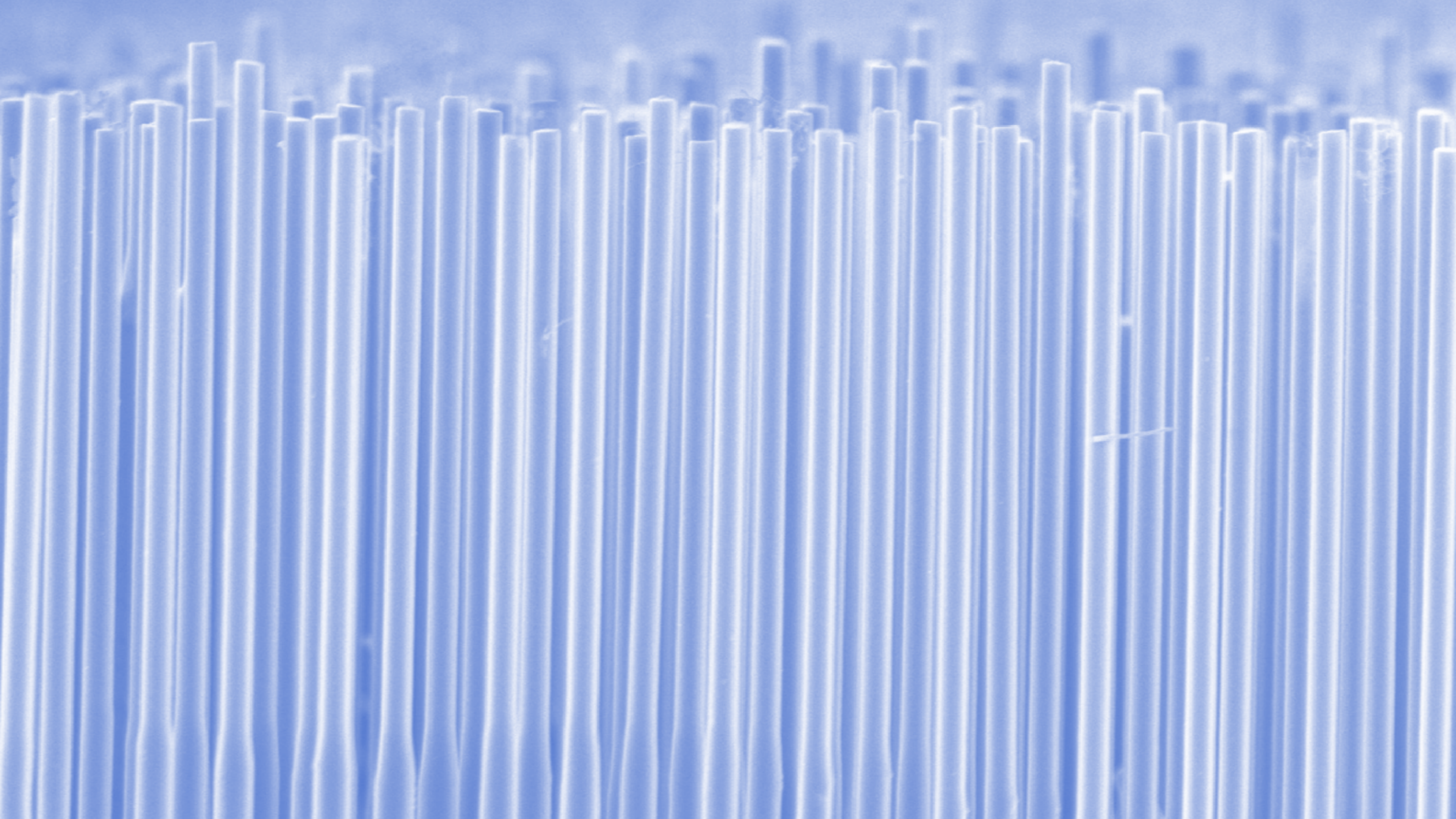




Si wire array as photocathode



High surface area photocathode, can be decorated with Pt or MoS2, CoSx nanoclusters.



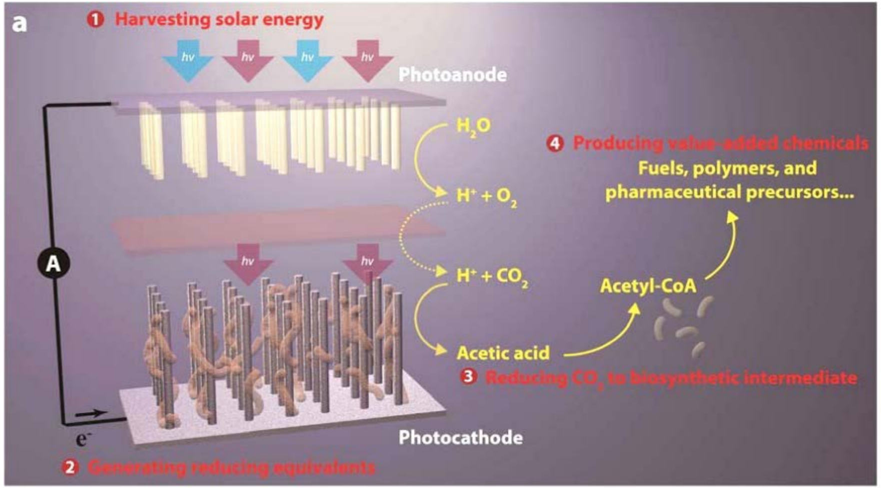
Biotic-Abiotic systems

Nanowire-Bacteria Bio-hybrids

Feeding microbes with electrons for CO2 reduction

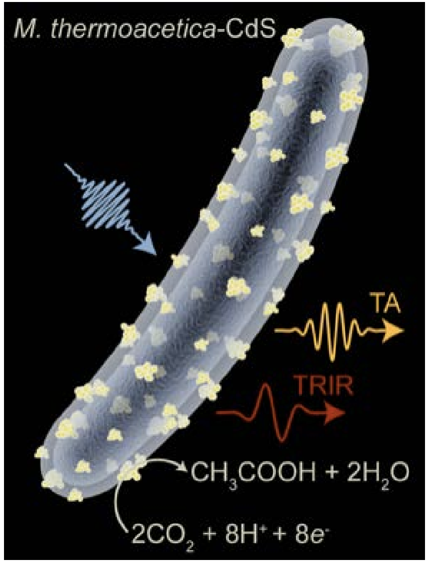
Semiconductor-Microorganism Interface for CO2 fixation

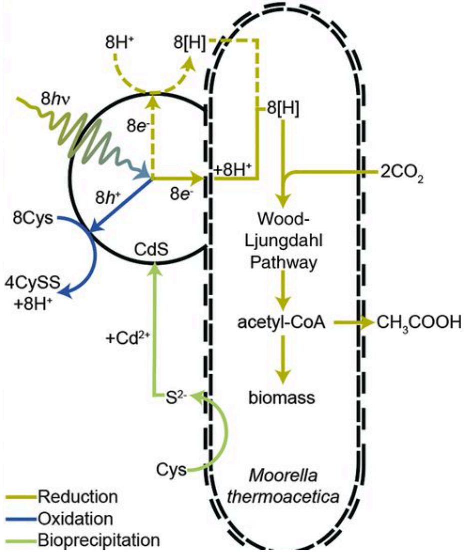
Integrated semiconductor-bacteria hybrid system



The high-surface-area silicon nanowire array harvests light energy to provide reducing equivalents to the anaerobic bacterium, Sporomusa ovata, for the photoelectrochemical production of acetic acid with low overpotential, high Faradaic efficiency and long-term stability.

Self-Photosensitization

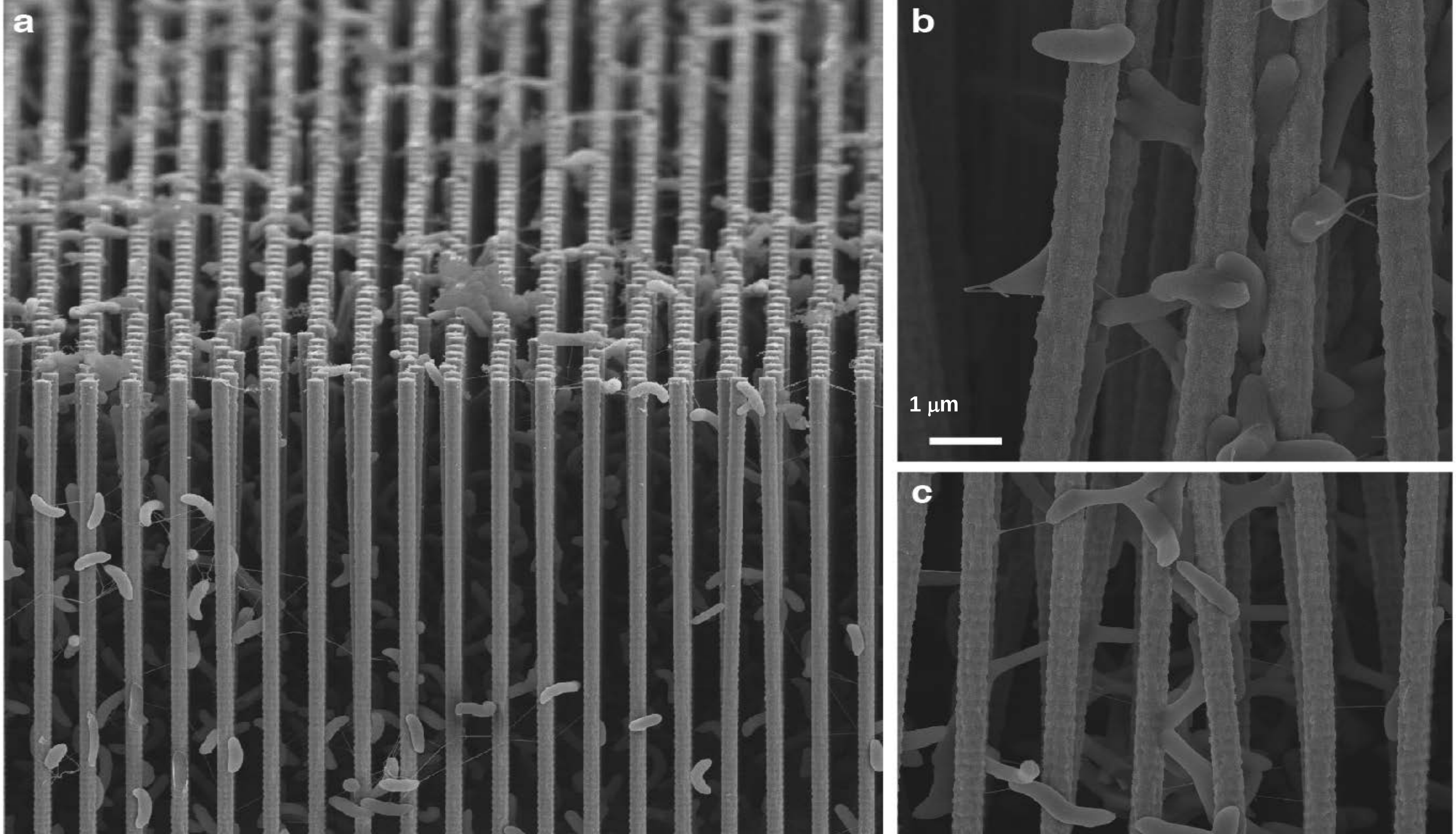


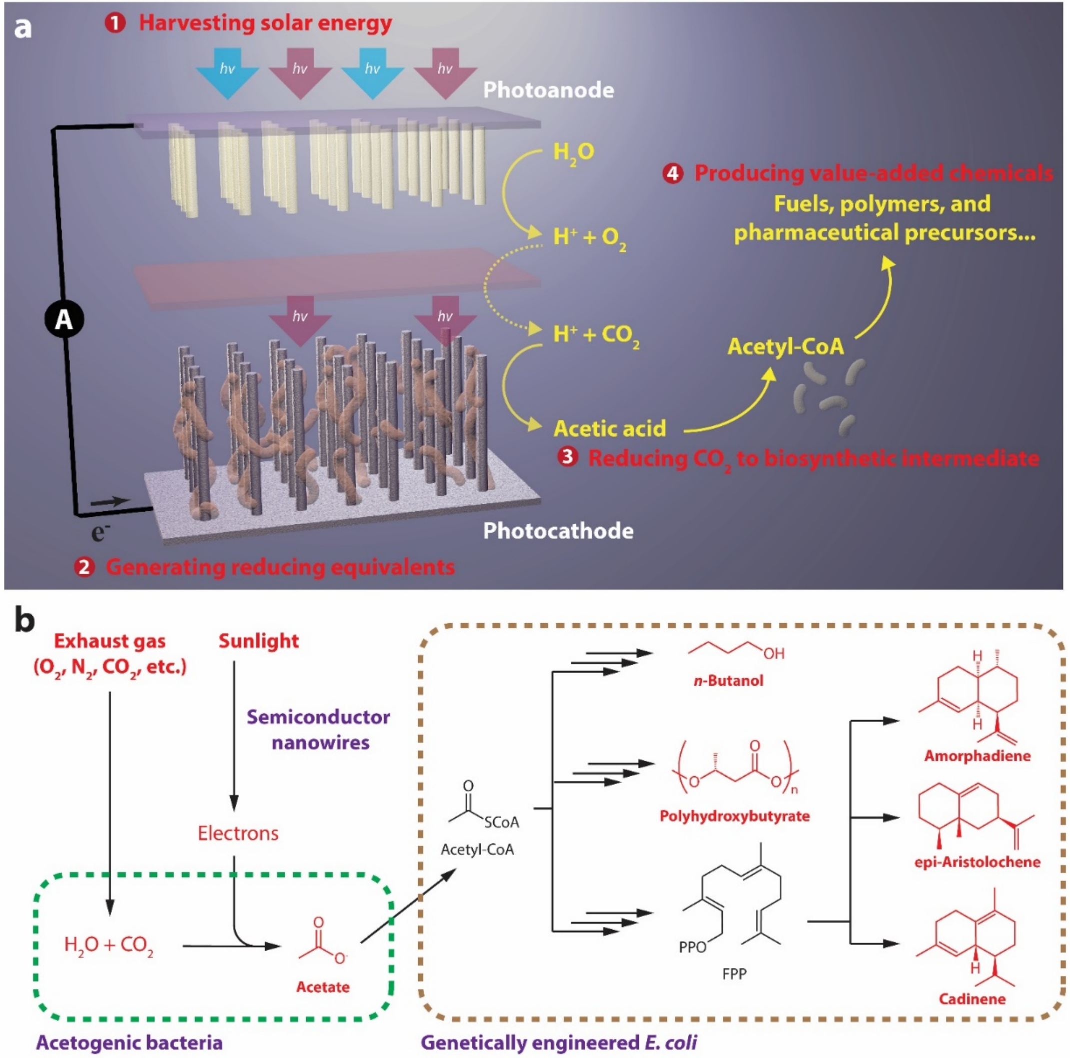


The hybrid approach combined the light harvesting CdS particle with the self-replication biocatalysts a nonphotosynthetic bacterium, Moorella thermoacetica, enabling the photosynthesis of acetic acid from carbon dioxide.

Liu C, et al. *Nano Lett.* **2015**, *15*, 3634.

Sakimoto, K. K., Wong, A. B. & Yang,. *Science* **351,** (2016).


a
b
1 μm
c

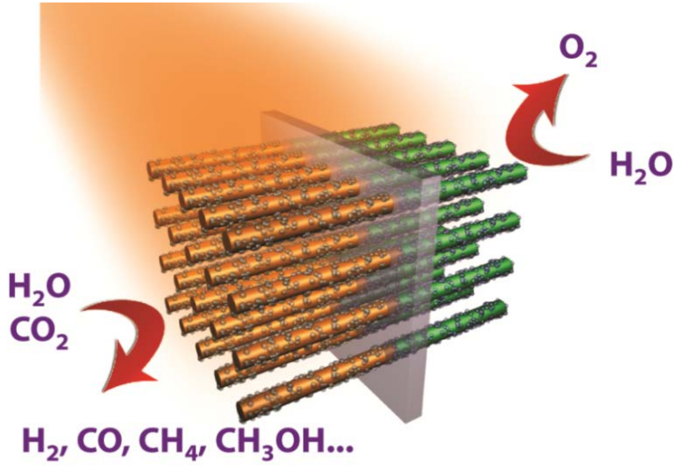


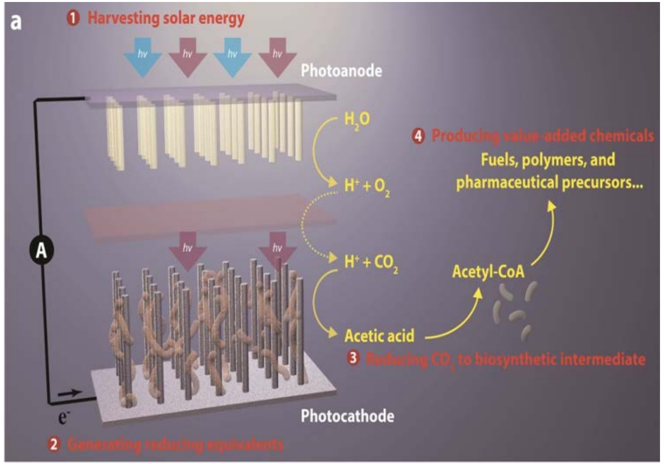
a
1 Harvesting solar energy
hv
Photoanode
H2O
H+ + O2
H+ + CO2
Acetic acid
A
e-
Photocathode
4 Producing value-added chemicals
Fuels, polymers, and
pharmaceutical precursors...
Acetyl-CoA
3 Reducing CO2 to biosynthetic intermediate
2 Generating reducing equivalents
b
Exhaust gas
(O2, N2, CO2, etc.)
Sunlight
Semiconductor
nanowires
Electrons
H2O + CO2
Acetate
SCoA
Acetyl-CoA
n-Butanol
Polyhydroxybutyrate
PPO
FPP
Amorphadiene
epi-Aristolochene
Cadinene
Acetogenic bacteria
Genetically engineered E. coli

Liquid Sunlight

Carbon Dioxide +Water + Sunlight

= Oxygen + Fuels
Pharmaceuticals
Commodity Chemicals



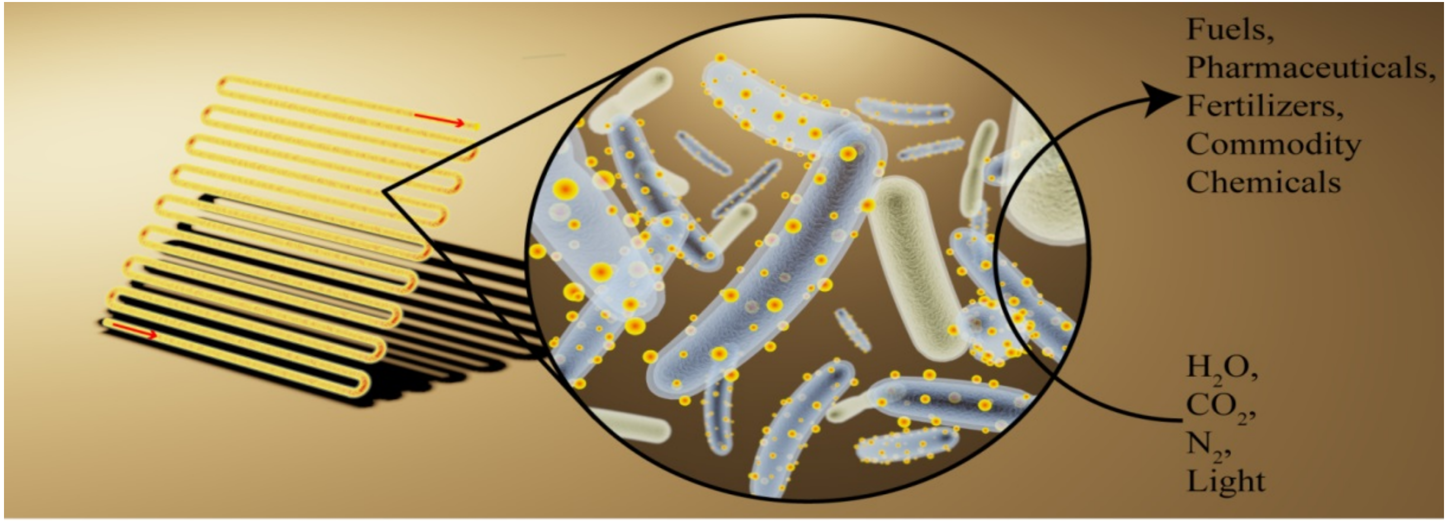


Mimicking the Nature & Better than the Nature

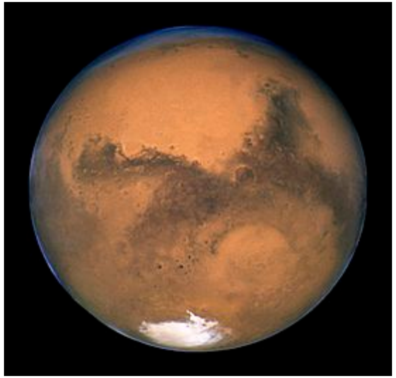
NASA Selects Proposals for First-Ever Space Technology Research Institutes

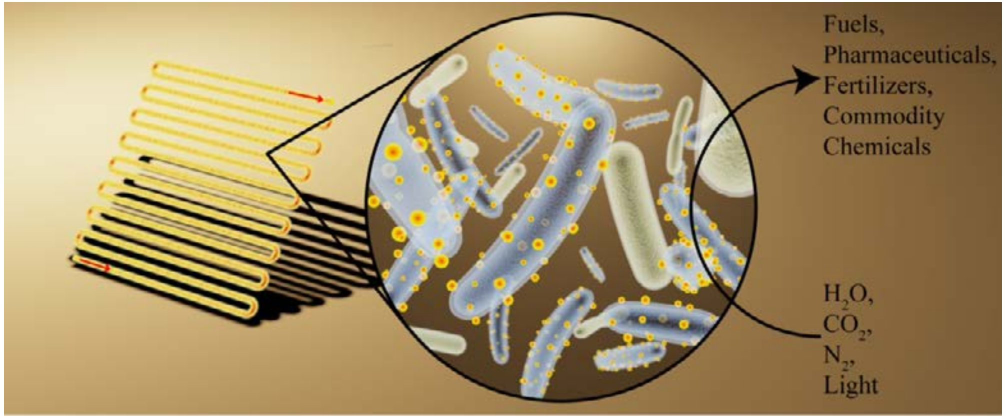
Center for the Utilization of
Biological Engineering in Space (CUBES)
UC, Berkeley

CUBES



Solar Foundry on Mars





Mars Resources: Opportunities and Challenges

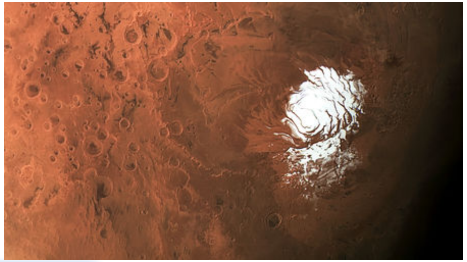
Earth

78% (78 kPa) N_2
21% (21 kPa) O_2
0.04% (0.04 kPa) CO_2
100% Light
H_2O

Mars

2.7% (0.016 kPa) N_2
0.13% (0.8 Pa) O_2
95.3% (0.57 kPa) CO_2
~60% Light
H_2O

Mars's south pole

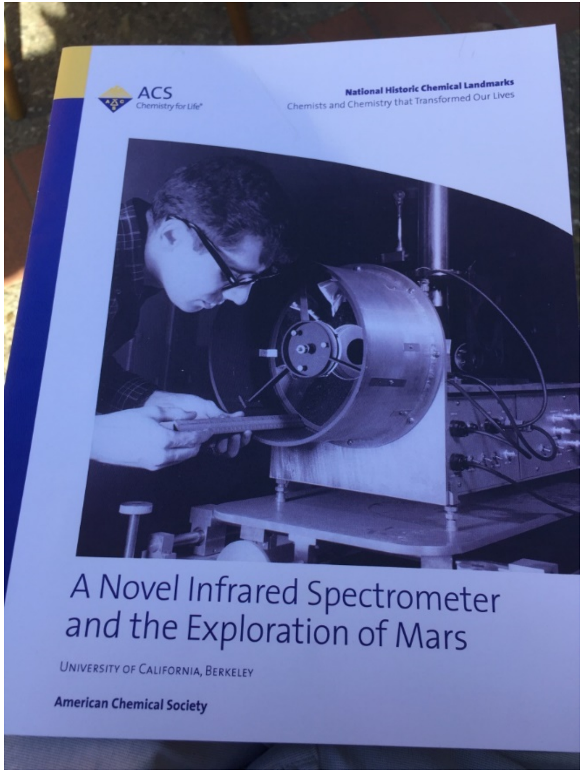


0.6 kPa pressure

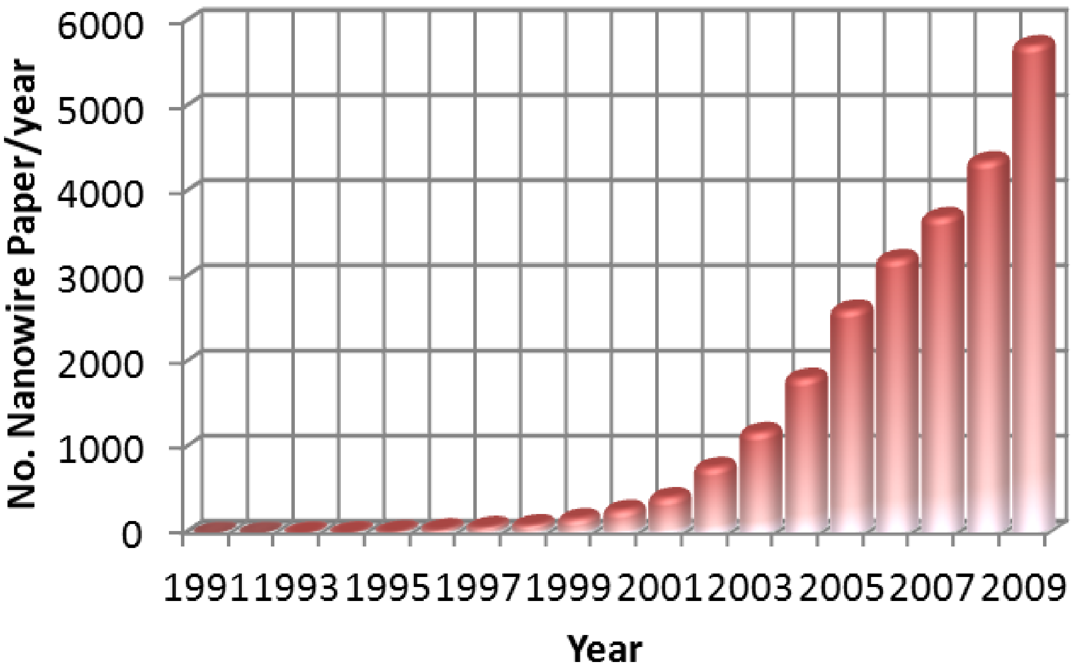
6.7×10^{14} kg N

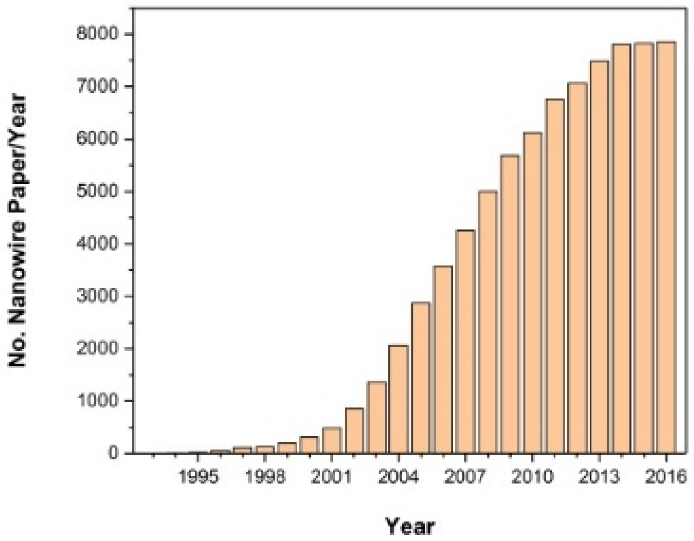
https://nssdc.gsfc.nasa.gov/planetary/factsheet/marsfact.html

George Pimentel, Mariner 6 1969



Semiconductor Nanowires: 1990-2010

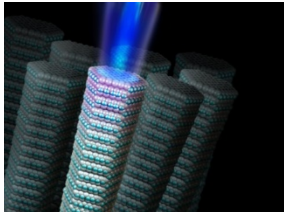


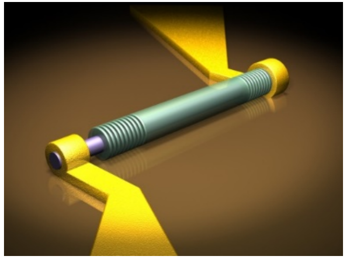


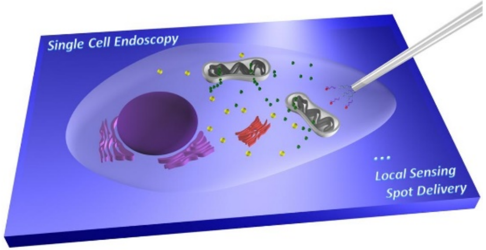
Source: ISI Web of Science, Keyword: Nanowires

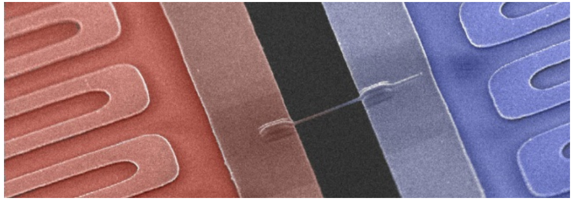
Semiconductor Nanowires

- Nanowire Photonics
- Nanowire Electronics
- Thermoelectrics
- Energy Storage, Battery
- Photovoltaics
- Catalysis
- Bio-nano interface
- [Artificial Photosynthesis]

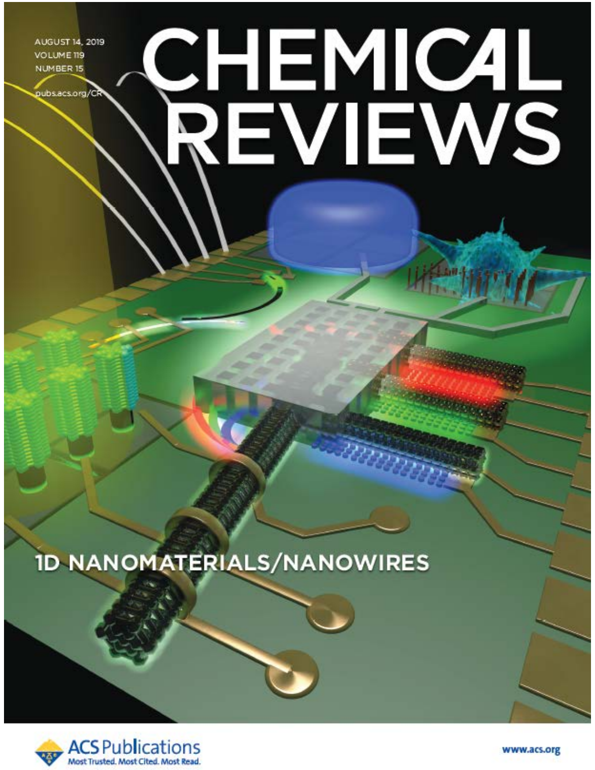


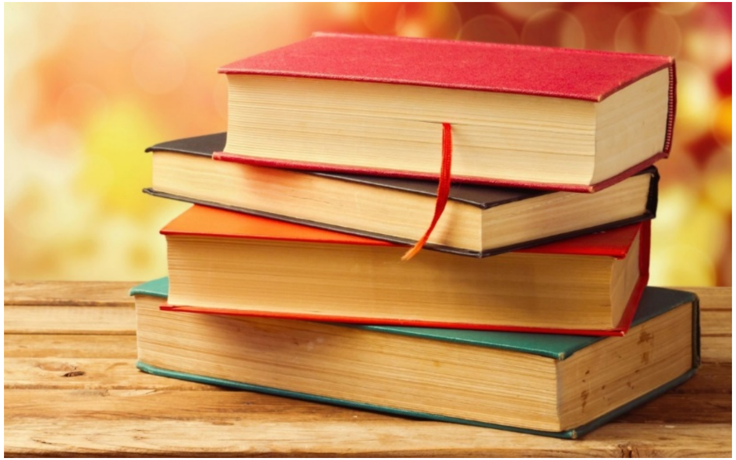






25 years of Nanowire Research





To be published in Oct 2019


Talent

Top Chemists of the Past Decade, 2000-2010

TOP CHEMISTS OF THE PAST DECADE

Data provided by Thomson Reuters from its Essential Science Indicators, 1 January 2000-31 October 2010

Rank in chemistry	Rank in materials science	Scientist	Papers	Citations	Impact
1		**Charles M. Lieber** Harvard University	74	17,776	240.22
2		**Omar M. Yaghi** Univ of California, Los Angeles	90	19,870	220.78
3		**Michael O'Keeffe** Arizona State University	73	12,910	176.85
4		**K. Barry Sharpless** Scripps Research Institute	60	9,754	162.57
5		**A. Paul Alivisatos** University of California, Berkeley	93	14,589	156.87
6		**Richard E. Smalley †** formerly Rice University	60	9,217	153.62
7		**Hongjie Dai** Stanford University	88	12,768	145.09
8		**Xiaogang Peng** University of Arkansas	59	8,548	144.88
9		**Valery V. Fokin** Scripps Research Institute	54	6,853	126.91
10	1	**Peidong Yang** University of California, Berkeley	95	11,167	117.55
11		**Benjamin List** Max Planck Inst of Coal Research	81	8,808	108.74
12	50	**Mark E. Thompson** Univ of Southern California	53	5,394	101.77
13		**Robert H. Hauge** Rice University	55	5,566	101.20
14		**Eric N. Jacobsen** Harvard University	81	7,985	98.58
15		**Banglin Chen** University of Texas at San Antonio	61	5,929	97.20
16		**David W. C. Macmillan** Princeton University	55	5,267	95.76
17		**Mostafa El-Sayed** Georgia Institute of Technology	111	10,135	91.31
18		**Ezio Rizzardo** Commonwealth Scientific and Research Organisation (CSIRO), Australia	52	4,747	91.29
19		**Michael S. Strano** Massachusetts Institute of Technology	54	4,843	89.69
20		**Michael J. Zaworotko** University of South Florida	83	7,403	89.19
21		**Dmitri V. Talapin** University of Chicago	56	4,981	88.95
22		**Ryoji Noyori** Nagoya University	62	5,486	88.48
23		**Chad A. Mirkin** Northwestern University	233	20,505	88.00
24		**Liberato Manna** Italian Institute of Technology	62	5,431	87.60
25		**Richard P. Van Duyne** Northwestern University	88	7,690	87.39
26		**Robert H. Grubbs** California Institute of Technology	170	14,617	85.98
27		**Carlos F. Barbas** Scripps Research Institute	95	8,029	84.52
28		**James R. Heath** California Institute of Technology	69	5,830	84.49
29		**Moungi G. Bawendi** MIT	52	4,364	83.92
30		**David A. Case** Rutgers University	60	5,007	83.45
31		**Shouheng Sun** Brown University	84	6,970	82.98
32	10	**Catherine J. Murphy** University of Illinois at Urbana-Champaign	69	5,717	82.86
33		**M. G. Finn** Scripps Research Institute	76	6,286	82.71
34		**Stephen L. Buchwald** MIT	169	13,941	82.49
35	4	**Younan Xia** Washington University in St Louis	161	13,120	81.49
36		**Stuart L. Schreiber** Harvard University	66	5,369	81.35
37	19	**Taeghwan Hyeon** Seoul National University	82	6,587	80.33
38		**George M. Whitesides** Harvard University	228	18,237	79.99
39		**Ryong Ryoo** Korea Advanced Institute of Science and Technology	77	6,057	78.66
40		**Michael F. Rubner** MIT	51	4,004	78.51
41	20	**Xiangfeng Duan** Univ of California, Los Angeles	64	5,022	78.47
42	48	**Michael Grätzel** Swiss Federal Institute of Technology, Lausanne	187	14,602	78.09
43		**Gregory C. Fu** MIT	111	8,384	75.53
44	89	**Horst Weller** University of Hamburg	73	5,428	74.36
45		**Joan F. Brennecke** University of Notre Dame	65	4,827	74.26
46		**Kenneth R. Seddon** Queen's University Belfast	94	6,916	73.57
47	8	**Alan J. Heeger** Univ of California, Santa Barbara	66	4,758	72.09
48		**Andreas Manz** Korea Institute of Science and Technology Europe	70	5,030	71.86
49		**Hua Chun Zeng** National University of Singapore	53	3,673	69.30
50		**Suprakas Sinha Ray** Council for Scientific and Industrial Research (CSIR), South Africa	50	3,411	68.22
51		**Mikhail E. Itkis** University of California, Riverside	60	4,069	67.82
52		**Osamu Terasaki** Stockholm University	92	6,198	67.37
53	29	**Shaik M. Zakeeruddin** Swiss Federal Institute of Technology, Lausanne	63	4,204	66.73
54		**Wenbin Lin** Univ of North Carolina at Chapel Hill	104	6,930	66.63
55	2	**Yadong Yin** University of California, Riverside	57	3,787	66.44
56		**John R. Yates** Scripps Research Institute	86	5,696	66.23
57		**Samuel I. Stupp** Northwestern University	62	4,073	65.69
58		**Prashant V. Kamat** University of Notre Dame	99	6,426	64.91
59		**John D. Holbrey** Queen's University Belfast	63	4,016	63.75
60		**Jens K. Nørskov** Technical University of Denmark	122	7,736	63.41
61	5	**Yugang Sun** Argonne National Laboratory	93	5,896	63.40
62		**Evgeny Katz** Clarkson University	97	6,147	63.37
63	75	**Craig J. Hawker** Univ of California, Santa Barbara	141	8,893	63.07
64		**Christian Serre** Versailles Saint-Quentin-en-Yvelines University	72	4,517	62.74
65	71	**Richard H. Friend** University of Cambridge	74	4,642	62.73
=66		**Jean M. J. Fréchet** Univ of California, Berkeley	209	12,985	62.13
=66		**James M. Tour** Rice University	134	8,325	62.13
68		**Robert C. Haddon** Univ of California, Riverside	84	5,191	61.80
69		**Peter J. Stang** University of Utah	103	6,356	61.71
70	24	**Nicholas A. Kotov** University of Michigan	78	4,809	61.65
71		**F. Dean Toste** University of California, Berkeley	84	5,163	61.46
72		**Michal Kruk** City University of New York	54	3,315	61.39
73		**Didier Astruc** University of Bordeaux I	114	6,883	60.38
74	83	**Michael Giersig** Free University of Berlin	55	3,310	60.18
75		**George C. Schatz** Northwestern University	202	12,116	59.98
76		**Harold G. Craighead** Cornell University	51	3,042	59.65
77		**Keith Fagnou †** University of Ottawa	63	3,747	59.48
78		**Milan Mrksich** University of Chicago	54	3,168	58.67
79		**Alois Fürstner** Max Planck Inst of Coal Research	151	8,858	58.66
80		**Karl Anker Jørgensen** Aarhus University	152	8,893	58.51
81		**Rustem F. Ismagilov** University of Chicago	59	3,437	58.25
82		**Richard A. Friesner** Columbia University	98	5,697	58.13
83		**Jairton Dupont** Federal University of Rio Grande do Sul	120	6,964	58.03
84		**John F. Hartwig** University of Illinois at Urbana-Champaign	167	9,638	57.71
85		**Robert Langer** MIT	98	5,632	57.47
86		**Mark E. Davis** California Institute of Technology	66	3,791	57.44
=87		**Manos Mavrikakis** Univ of Wisconsin-Madison	56	3,205	57.23
=87		**Adi Eisenberg** McGill University	65	3,720	57.23
89		**Maurice Brookhart** University of North Carolina at Chapel Hill	87	4,978	57.22
90		**Amir H. Hoveyda** Boston College	122	6,967	57.11
91		**Charles R. Martin** University of Florida	58	3,312	57.10
92		**Alexander Zapf** University of Rostock	60	3,407	56.78
93		**Jeffrey R. Long** University of California, Berkeley	98	5,563	56.77
94		**Neil R. Champness** University of Nottingham	86	4,877	56.71
95		**Naomi J. Halas** Rice University	73	4,131	56.59
96		**Abraham Nitzan** Tel Aviv University	51	2,879	56.45
97		**Charles L. Brooks** University of Michigan	67	3,778	56.39
98		**Helmut Cölfen** Max Planck Institute of Colloids and Interfaces	82	4,595	56.04
99		**Jérôme Cornil** University of Mons	65	3,640	56.00
100		**Geoffrey W. Coates** Cornell University	90	5,029	55.88

The United Nations Educational, Scientific and Cultural Organisation (Unesco) and the International Union of Pure and Applied Chemistry (IUPAC) have proclaimed this to be the International Year of Chemistry. During 2011, celebrations and special events will be held around the globe "to increase the public appreciation of chemistry in meeting world needs, to encourage interest in chemistry among young people, and to generate enthusiasm for the creative future of chemistry".

The table presented here is intended to celebrate the achievements of 100 chemists who achieved the highest citation impact scores for chemistry papers (articles and reviews) published since January 2000. Citation impact (citations per paper) is a weighted measure of influence that seeks to reveal consistently superior performance. To ensure that a high score could not be achieved by a few highly cited papers, a threshold of 50 papers was used in the analysis.

The average citation impact in chemistry for the period was 11.07, so all the researchers listed above achieved more than five times that mark. Given that about 1 million chemists were recorded in the journals indexed by Thomson Reuters during the past decade, these 100 represent the top 0.01 of 1 per cent. Sixteen of those listed also ranked in the top 100 by citation impact in materials science, among those who published 25 or more papers in that field during the past decade. Their materials science ranks are noted beside their ranks in chemistry.

Nanotechnology in all its aspects is strongly in evidence when one surveys the research interests of the chemists listed. While the rubric covers much and some sceptics call "nano" the latest fad in chemistry, there is no denying the message of the citation indicators. The field has attracted enormous interest in the past 10 years. Of the 100 chemists listed, 60 identify nanotechnology as their main focus or a significant research topic.

The national affiliations of the authors are: 70 for the US, seven for Germany, four for the UK, two each for Canada, France, Denmark, Switzerland and South Korea, and one apiece for Australia, Belgium, Sweden, Italy, Israel, South Africa, Brazil, Japan and Singapore. The institutions appearing three or more times are: Massachusetts Institute of Technology (6), the Scripps Research Institute (5), the University of California, Berkeley (5), Harvard University (4), Rice University (4), Northwestern University (4), the California Institute of Technology (3), the University of California, Riverside (3) and the University of Chicago (3).

To provide a more comprehensive view of high-impact researchers in chemistry, lists of the top 100 researchers in materials science and biochemistry will appear during the year in these pages.

For more information on Thomson Reuters Essential Science Indicators, see http://science.thomsonreuters.com/products/esi/

Next week: Chinese universities of the C9 League

Top Materials Scientists of the Past Decade, 2000-2010

TOP MATERIALS SCIENTISTS OF THE PAST DECADE

Data provided by Thomson Reuters from its Essential Science Indicators, 1 January 2000-31 October 2010

Rank in materials science	Rank in chemistry	Scientist	Papers	Citations	Impact
1	10	**Peidong Yang** Univ of California, Berkeley	36	13,900	386.11
2	55	**Yadong Yin** Univ of California, Riverside	32	6,387	199.59
3		**Michael H. Huang** National Tsing Hua University	34	5,439	159.97
4	35	**Younan Xia** Washington University in St Louis	83	11,936	143.81
5	61	**Yugang Sun** Argonne National Laboratory	37	5,231	141.38
6		**Yiying Wu** Ohio State University	74	9,590	129.59
7		**Jan C. Hummelen** University of Groningen	38	4,643	122.18
8	47	**Alan J. Heeger** Univ of California, Santa Barbara	49	5,788	118.12
9		**Oomman K. Varghese** Pennsylvania State University	28	3,021	107.89
10	32	**Catherine J. Murphy** University of Illinois at Urbana-Champaign	31	3,313	106.87
11		**Michael D. McGehee** Stanford University	26	2,651	101.96
12		**Christoph J. Brabec** Univ of Erlangen-Nuremberg	43	4,242	98.65
13		**Stephen R. Forrest** University of Michigan	25	2,417	96.68
14		**N. Serdar Sariciftci** Johannes Kepler University of Linz	74	6,444	87.08
15		**Herbert Gleiter** Karlsruhe Institute of Technology	29	2,440	84.14
16		**Rodney S. Ruoff** University of Texas at Austin	25	2,060	82.40
17		**Frank Caruso** University of Melbourne	74	5,589	75.53
18		**Philippe Dubois** University of Mons	36	2,628	73.00
19	37	**Taeghwan Hyeon** Seoul National University	37	2,685	72.57
20	41	**Xiangfeng Duan** Univ of California, Los Angeles	39	2,825	72.44
21		**Rachel A. Caruso** University of Melbourne	27	1,948	72.15
22		**Galen D. Stucky** Univ of California, Santa Barbara	72	5,095	70.76
23		**Igor V. Alexandrov** Ufa State Aviation Technical University	38	2,555	67.24
24	70	**Nicholas A. Kotov** University of Michigan	36	2,388	66.33
25		**Craig A. Grimes** Pennsylvania State University	55	3,626	65.93
26		**Ullrich Scherf** University of Wuppertal	64	4,099	64.05
27		**Andreas Stein** University of Minnesota	47	2,985	63.51
28		**Subra Suresh** Massachusetts Institute of Technology	64	4,024	62.88
29	53	**Shaik M. Zakeeruddin** Swiss Federal Institute of Technology, Lausanne	27	1,670	61.85
30		**Ray H. Baughman** University of Texas at Dallas	25	1,503	60.12
31		**Paul W. M. Blom** University of Groningen	37	2,176	58.81
32		**Jenny Nelson** Imperial College London	31	1,821	58.74
33		**David J. Mooney** Harvard University	43	2,512	58.42
34		**Tsu-Wei Chou** University of Delaware	33	1,915	58.03
35		**Iain McCulloch** Imperial College London	30	1,725	57.50
36		**Andreas Greiner** University of Marburg	30	1,716	57.20
37		**Ferdi Schüth** Max Planck Inst for Coal Research	60	3,395	56.58
38		**Henning Sirringhaus** University of Cambridge	39	2,173	55.72
39		**Samson A. Jenekhe** University of Washington	27	1,490	55.19
40		**C. Suryanarayana** University of Central Florida	33	1,801	54.58
41		**James R. Durrant** Imperial College London	31	1,669	53.84
42		**Guillermo C. Bazan** UC, Santa Barbara	55	2,960	53.82
43		**Meixiang Wan** Chinese Academy of Sciences, Institute of Chemistry, Beijing	29	1,557	53.69
44		**Pierre-Antoine Albouy** University of Paris-Sud 11	28	1,503	53.68
45		**Dietmar W. Hutmacher** Queensland University of Technology	39	2,092	53.64
46		**Anders Hagfeldt** Uppsala University	26	1,385	53.27
47		**Dago M. De Leeuw** University of Groningen and Philips Research Laboratories	32	1,704	53.25
48	42	**Michael Grätzel** Swiss Federal Institute of Technology, Lausanne	52	2,763	53.13
49		**Zhifeng Ren** Boston College	37	1,963	53.05
50	12	**Mark E. Thompson** Univ of Southern California	28	1,482	52.93
51		**Andrey L. Rogach** City University of Hong Kong	34	1,781	52.38
52		**Rinat K. Islamgaliev** Ufa State Aviation Technical University	37	1,926	52.05
53		**Mats R. Andersson** Chalmers Univ of Technology	28	1,449	51.75
54		**Mietek Jaroniec** Kent State University	54	2,771	51.31
55		**Fujio Izumi** National Institute for Materials Science, Japan	25	1,277	51.08
56		**Simon R. Phillpot** University of Florida	29	1,481	51.07
57		**Neil Coombs** University of Toronto	25	1,269	50.76
58		**Terry C. Lowe** Manhattan Scientifics	28	1,416	50.57
59		**Wolfgang J. Parak** University of Marburg	27	1,365	50.56
60		**Marie-Paule Pileni** Pierre and Marie Curie University	32	1,612	50.38
61		**Jonathan N. Coleman** Trinity College Dublin	30	1,507	50.23
62		**Zhenan Bao** Stanford University	38	1,907	50.18
63		**Dieter Neher** University of Potsdam	30	1,499	49.97
64		**Dieter Wolf** Idaho National Laboratory	26	1,285	49.42
65		**Kornelius Nielsch** University of Hamburg	27	1,322	48.96
66		**Yet-Ming Chiang** MIT	26	1,254	48.23
67		**Joachim H. Wendorff** University of Marburg	30	1,430	47.67
68		**Antonios G. Mikos** Rice University	95	4,507	47.44
69		**John R. Reynolds** University of Florida	45	2,131	47.36
70		**David Grosso** Pierre and Marie Curie University	55	2,548	46.33
71	65	**Richard H. Friend** University of Cambridge	60	2,775	46.25
72		**Paula T. Hammond** MIT	42	1,927	45.88
73		**Richard W. Siegel** Rensselaer Polytechnic Institute	31	1,419	45.77
74		**Fred Wudl** Univ of California, Santa Barbara	25	1,141	45.64
75	63	**Craig J. Hawker** Univ of California, Santa Barbara	34	1,548	45.53
76		**Peter X. Ma** University of Michigan	30	1,352	45.07
77		**Karine Alselme** Upper Alsace University	25	1,122	44.88
78		**David L. Kaplan** Tufts University	77	3,408	44.26
79		**Donal D. C. Bradley** Imperial College London	57	2,522	44.25
80		**Kam W. Leong** Duke University	45	1,991	44.24
81		**Yeshayahu Lifshitz** Technion – Israeli Institute of Technology	25	1,097	43.88
82		**John A. Rogers** Univ of Illinois, Urbana-Champaign	61	2,671	43.79
83	74	**Michael Giersig** Free University of Berlin	36	1,570	43.61
84		**Jean-Luc Brédas** Georgia Institute of Technology	50	2,177	43.54
85		**Thomas E. Mallouk** Pennsylvania State University	35	1,523	43.51
86		**Caroline A. Ross** MIT	27	1,174	43.48
87		**John W. Hutchinson** Harvard University	42	1,824	43.43
88		**David Beljonne** University of Mons	25	1,085	43.40
89	44	**Horst Weller** University of Hamburg	25	1,082	43.28
90		**Frederik C. Krebs** Risø DTU National Laboratory for Sustainable Energy	48	2,077	43.27
91		**Linda S. Schadler** Rensselaer Polytechnic Institute	42	1,817	43.26
92		**René A. J. Janssen** Eindhoven Univ of Technology	61	2,633	43.16
93		**Young-Woo Heo** Kyungpook National University	30	1,294	43.13
94		**Alan H. Windle** University of Cambridge	36	1,552	43.11
95		**Andrew I. Cooper** University of Liverpool	30	1,284	42.80
96		**Markus Niederberger** Swiss Federal Institute of Technology, Zurich	36	1,537	42.69
97		**Antonio Facchetti** Northwestern University and Polyera Corporation	37	1,579	42.68
98		**Nicola Pinna** University of Aveiro and Seoul National University	25	1,057	42.28
99		**Xiang Min Meng** Chinese Academy of Sciences, Technical Institute of Physics and Chemistry, Beijing	31	1,309	42.23
100		**William D. Nix** Stanford University	49	2,065	42.14

In recognition of 2011 being named the International Year of Chemistry, *Times Higher Education* previously featured a list of the top 100 chemists over the past decade according to citation impact (citations per paper). In that analysis, a set of discipline-specific journals defined the field of chemistry; as a supplement, selected papers in multidisciplinary journals such as *Science* and *Nature* were also counted. But it must be admitted that chemistry is difficult to define precisely. To supplement the previous treatment, the current table presents data on high-impact researchers in materials science, a realm that overlaps with chemistry as well as physics, engineering and other areas. Once again, the field was defined by a set of discipline-specific journals plus papers dealing with materials science from multidisciplinary titles. Influential biochemists will be the focus of a future analysis to round out our celebration of chemistry.

The table above lists the 100 researchers in material science who achieved the highest citation-impact scores for papers (articles and reviews) published since January 2000. Impact is a weighted measure of influence that seeks to reveal consistently superior performance. To ensure that high scores could not be achieved by a few highly cited papers, a threshold of 25 papers was used in the analysis. The average citation impact in materials science for the period was 6.93, so all the researchers listed above achieved more than six times that mark.

Since approximately 500,000 materials scientists were recorded in the journal publications indexed by Thomson Reuters during the past decade, those listed above represent the top 0.02 of 1 per cent in the field. Sixteen of those listed also ranked in the top 100 by citation impact in chemistry, among those who published 50 or more papers in that field during the past decade. Their ranks in chemistry are noted.

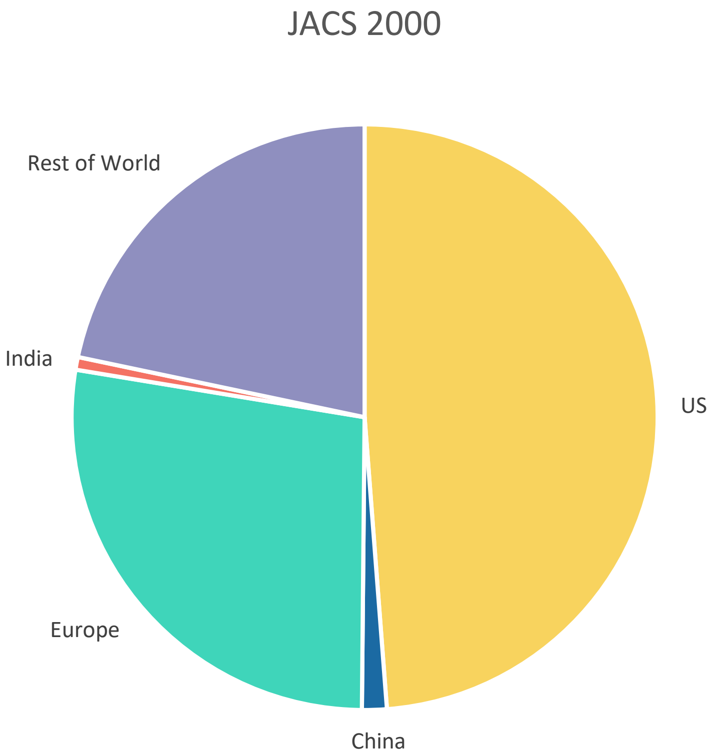
As with the chemistry table, this list includes many researchers who state that a main or significant focus of their research is nanotechnology – by our count, 78 per cent of the scientists featured.

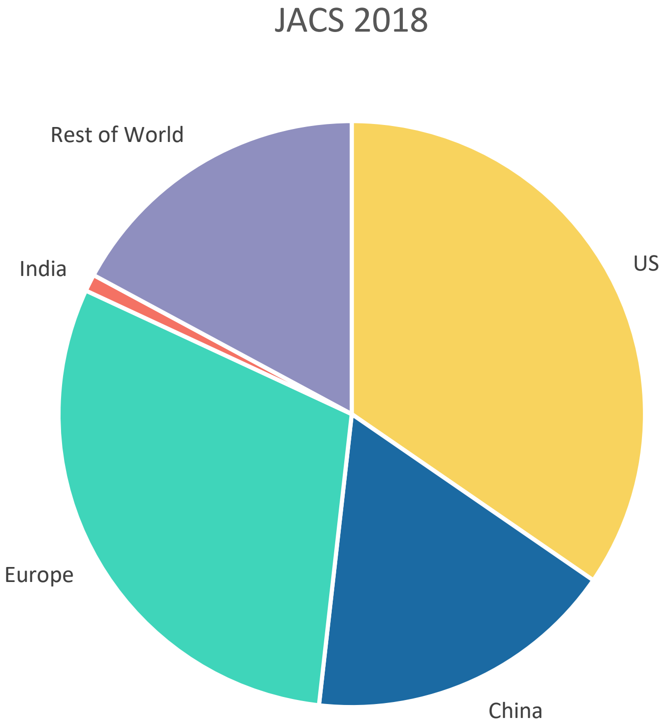
The authors' national affiliations are: 48 for the US; 11 for Germany; eight for the UK; four each for France and the Netherlands; three for Australia, China (including Hong Kong), South Korea and Switzerland; two for Belgium, Russia and Sweden; and one apiece for Austria, Canada, Denmark, the Republic of Ireland, Israel, Japan, Portugal and Taiwan (which comes to 101 owing to Nicola Pinna's appointments in Portugal and South Korea). The institutions appearing three or more times are: University of California, Santa Barbara (5); Imperial College London (4); Massachusetts Institute of Technology (4); Pennsylvania State University (3); Stanford University (3); the University of Cambridge (3); the University of Groningen (3); the University of Marburg (3); and the University of Michigan (3).

For more information, see http://science.thomsonreuters.com/products/esi/

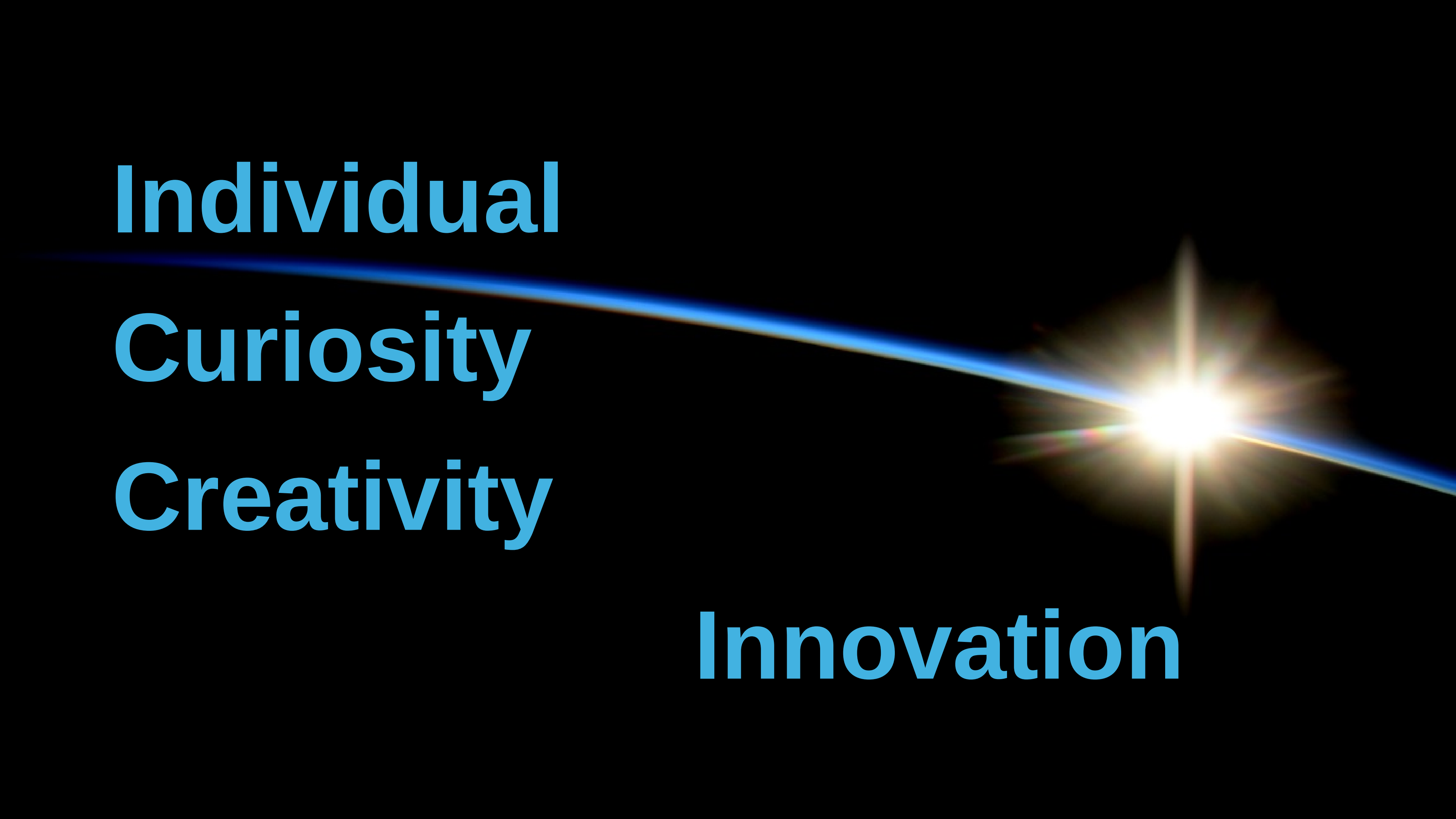
Next week: top 25 nations in agricultural sciences, 2000-10

JACS Associate Editor, 2002-





Interdisciplinary Opportunity


Individual
Curiosity
Creativity
Innovation

https://doi.org/10.1038/s41586-019-0941-9

Large teams develop and small teams disrupt science and technology

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One of the most universal trends in science and technology today is the growth of large teams in all areas, as solitary researchers and small teams diminish in prevalence[1–3]. Increases in team size have been attributed to the specialization of scientific activities[3], improvements in communication technology[4,5], or the complexity of modern problems that require interdisciplinary solutions[6–8]. This shift in team size raises the question of whether and how the character of the science and technology produced by large teams differs from that of small teams. Here we analyse more than 65 million papers, patents and software products that span the period 1954–2014, and demonstrate that across this period smaller teams have tended to disrupt science and technology with new ideas and opportunities, whereas larger teams have tended to develop existing ones. Work from larger teams builds on more-recent and popular developments, and attention to their work comes immediately. By contrast, contributions by smaller teams search more deeply into the past, are viewed as disruptive to science and technology and succeed further into the future—if at all. Observed differences between small and large teams are magnified for higher-impact work, with small teams known for disruptive work and large teams for developing work. Differences in topic and research design account for a small part of the relationship between team size and disruption; most of the effect occurs at the level of the individual, as people move between smaller and larger teams. These results demonstrate that both small and large teams are essential to a flourishing ecology of science and technology, and suggest that, to achieve this, science policies should aim to support a diversity of team sizes.

Advocates of team science have claimed that a shift to larger teams in science and technology fulfils the essential function of solving problems in modern society that are complex and which require interdisciplinary solutions[6–8]. Although much has been demonstrated about the professional and career benefits of team size for team members[9], there is little evidence that supports the notion that larger teams are optimized for knowledge discovery and technological invention[9]. Experimental and observational research on groups reveals that individuals in large groups think and act differently—they generate fewer ideas[10,11], recall less learned information[12], reject external perspectives more often[13] and tend to neutralize each other's viewpoints[14]. Small and large teams may also differ in their response to the risks associated with innovation. Large teams, such as large business organizations, may focus on sure bets with large potential markets, whereas small teams that have more to gain and less to lose may undertake new, untested opportunities with the potential for high growth and failure[15], leading to markedly different outcomes. These possibilities led us to explore the consequences of smaller and larger teams for scientific and technological advance, and how such teams search and assemble knowledge differently.

Previous research demonstrates that large article and patent teams receive slightly more citations[2,16]. However, citation counts alone cannot capture distinct types of contribution. This can be seen in the difference between two well-known articles: one about self-organized criticality[17] (the BTW model, after the authors' initials) and another about Bose–Einstein condensation[18] (for which Wolfgang Ketterle was awarded the 2001 Nobel Prize in Physics) (Fig. 1, Extended Data Fig. 1b). The two articles have received a similar number of citations, but most research subsequent to the BTW-model article has cited only the model itself without mentioning references from the article. By contrast, the Bose–Einstein condensation article is almost always co-cited with Bose[19], Einstein[20] and other antecedents. The difference between the two papers is reflected not in citation counts but in whether they suggested or solved scientific problems—whether they disrupted or developed existing scientific ideas, respectively[21]. The BTW model launched new streams of research, whereas the experimental realization of Bose–Einstein condensation elaborated upon possibilities that had previously been posed.

To systematically evaluate the role that small and large teams have in unfolding scientific and technological advances, we collected large-scale datasets from three related but distinct domains (see Methods): (1) the Web of Science (WOS) database that contains more than 42 million articles published between 1954 and 2014, and 611 million citations among them; (2) 5 million patents granted by the US Patent and Trademark Office from 1976 to 2014, and 65 million citations added by patent applicants; (3) 16 million software projects and 9 million forks to them on GitHub (2011–2014), a popular web platform that allows users to collaborate on the same code repository and 'cite' other repositories by copying and building on their code.

For each dataset, we assess the degree to which each work disrupts the field of science or technology to which it belongs by introducing something new that eclipses attention to previous work upon which it has built. We use a measure that was previously designed[22] to identify destabilization and consolidation in patented inventions; this measure varies between −1 and 1, which corresponds to science and technology that develops or disrupts, respectively (Fig. 1a). We validate the disruption measure in several ways. First, we investigate the distribution of disruption across scientific papers (Fig. 1b); the disruptive BTW-model article is located in the top 1%, whereas the developmental Bose–Einstein condensation paper is in the bottom 3% of the disruption distribution. We also find that, on average, Nobel-prize-winning papers register among the 2% most disruptive articles. Review articles are developmental with a negative mean of disruption (bottom 46%), whereas the original research works that they review have a positive mean (top 23%). Articles that headline prominent prior work—such as the Bose–Einstein condensation article—lie in the bottom 25% (Supplementary Table 1). We further confirmed these results with a survey in which we asked scholars from diverse fields to propose disruptive and developmental articles; this symmetrically confirmed the disruption measure (Supplementary Table 2). Finally, we find that in the titles of articles different words associate with disruptive ('introduce', 'measure', 'change' and 'advance') versus developing ('endorse', 'confirm', 'demonstrate', 'theory' and 'model') papers (Fig. 1c, Supplementary Table 3).

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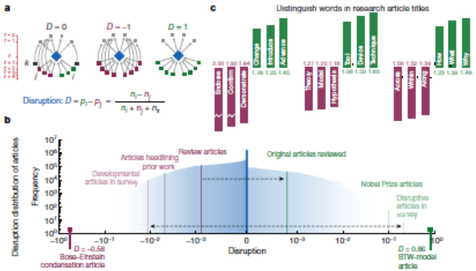

Fig. 1 | Quantifying disruption. a, Simplified illustration of disruption. Three citation networks comprising focal papers (blue diamonds), references (grey circles) and subsequent work (rectangles). Subsequent work may cite the focal work (i, green), both the focal work and its references (j, red) or just its references (k, black). Disruption, D, of the focal paper is defined by the difference between the proportion of type i and j papers $p_i - p_j$, which equals the difference between the observed number of these papers $n_i - n_j$ divided by the number of all subsequent works $n_i + n_j + n_k$. A paper may be disrupting ($D = 1$), neutral ($D = 0$) or developing ($D = -1$). **b,** The distribution of disruption across 25,988,101 WOS journal articles published between 1900 and 2014. On this distribution, we mark the BTW-model ($D = 0.86$, top 1%) and Bose–Einstein condensation articles ($D = -0.58$, bottom 3%) along with several samples used to validate D (Methods, Supplementary Tables 1–3). This includes (1) 104 'disruptive' articles (disruption mean $E(D) = 0.215$, top 2%) and 86 'developing' articles ($E(D) = -0.011$, bottom 13%) nominated by a surveyed panel of 20 scholars across fields; (2) 877 Nobel-prize-winning papers published between 1902 and 2009 ($E(D) = 0.10$, top 2%); (3) 22,672 review articles ($E(D) = -0.0009$, bottom 46%) and 1,338,808 original research articles that they review ($E(D) = 0.0008$, top 23%); and (4) 148,303 articles that headline prominent prior work by mentioning one or more cited authors in the title ($E(D) = -0.0049$, bottom 24%). **c,** We select titles from 24,174,022 articles published between 1954 and 2014 and assign them to one of two groups, disrupting ($D > 0$) or developing ($D < 0$) articles. For the 1,033,879 words observed in both groups, we calculate the ratio of frequency in disrupting versus developing articles, r. We visualize differences in the content and writing style between these two groups in terms of verbs, nouns, and adverbs and prepositions (from left to right). To facilitate comparison, we visualize r in green if $r > 1$, and $1/r$ in red otherwise.

We predict that work by small teams will be substantially more disruptive than work by large teams. Our databases of papers, patents and software strongly confirm this prediction. Our sources differ in scope and domain, but we consistently observe that over the past 60 years, larger teams produce articles, patents and software with a disruption score that markedly and monotonically declines with each additional team member (Fig. 2a–c, Extended Data Fig. 3). Specifically, as teams grow from 1 to 50 team members, their papers, patents and products drop in percentiles of measured disruption by 70, 30 and 50, respectively (Extended Data Fig. 3a). In every case, this highlights a transition from disruption to development. These results support the hypothesis that large teams may be better designed or incentivized to develop current science and technology, and that small teams disrupt science and technology with new problems and opportunities.

This phenomenon is amplified when we focus on the most disruptive and impactful work (Fig. 2d–f). We measure the impact of each article, patent and software using the number of citations each work received. As shown in Fig. 2d, solo authors are just as likely to produce high-impact papers (in the top 5% of citations) as teams with five members, but solo-authored papers are 72% more likely to be highly disruptive (in the top 5% of disruptive papers). By contrast, ten-person teams are 50% more likely to score a high-impact paper, yet these contributions are much more likely to develop existing ideas already prominent in the system, which is reflected in the very low likelihood they are among the most disruptive. By repeating the same analyses for patents (Fig. 2e) and software development (Fig. 2f), we find that disruption and impact consistently diverge as teams grow in size.

Differences in disruption between works produced by small and large teams are magnified as the impact of the work increases (Fig. 3a); high-impact papers produced by small teams are the most disruptive, and high-impact papers produced by large teams are the most developmental. As article impact increases, the negative slope of disruption as a function of team size steepens sharply. Even within the pool of high-impact articles and patents (Fig. 3a, top 5% of citations), which are statistically more likely produced by large teams (Fig. 2d), small teams have disrupted the current system with substantially more new ideas. We further split papers by time period (Extended Data Fig. 3c) and scientific field (Fig. 3b, Extended Data Fig. 4), and found that these patterns linking disruption and team size are stable for all eras and for 90% of disciplines. The only consistent exceptions were observed for engineering and computer science, in which conference proceedings rather than journal articles are the publishing norm (the WOS database indexes only journal articles).

We considered whether observed differences between the work of small and large teams could simply be attributed to differences in disruptive potential for the different types of articles that they produce; for example, small teams may generate more theoretical innovations and large teams more empirical analyses. Drawing on a previous approach[23], we matched papers from www.arXiv.org with the WOS database and repeated our analyses controlling for the number of figures in each article (Extended Data Fig. 5a), as empirical papers tend to have more figures than theoretical ones. Our results suggest that most of the difference in disruption between work from smaller and larger teams is not driven by differences in whether they contributed theoretical versus empirical papers (that is, had more or less figures). The association remains the same when we consider other distinctions, including review versus original research articles. Review articles with fewer authors are more disruptive than those with more, just as with original research articles (Extended Data Fig. 5b).

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