Humankind 2.0: The Technologies of the Future
5. Nanotech
Superconductivity, Quantum Computing

Piero Scaruffi, 2016

See http://www.scaruffi.com/singular/human20.html for the full text of this discussion
The Future of Technology

• Moore's law has changed our perception of what constitutes a "great" technology: progress now means "smaller", not "bigger."

• A Nvidia GPU is thousands of times smaller than the early computers, and thousands of times faster.

• The future of technology will be invisible: cloud, nano-bots, increasingly small devices and brain-machine interfaces.
The Future of Technology

- Nano-devices will colonize the human body at the same time that the human body will colonize cyberspace through them.
A Brief History of Nanotech

- 1959: Richard Feynman’s speech "There's Plenty of Room at the Bottom": to operate on single atoms
- 1971: Leon Chua introduces memristors
- 1974: Norio Taniguchi coins the term "Nanotechnology"
- 1981: The Scanning Tunneling Microscope is invented
- 1986: The Atomic Force Microscope is invented
- 1986: Foresight Institute in Menlo Park
- 1989: “IBM in atoms” demo
A Brief History of Nanotech

• 1991: Carbon nanotubes are demonstrated
• 1996: Mitsutaka Fujita popularizes graphene nanoribbons
• 2001: Richard Smalley’s article “Of Chemistry, Love and Nanobots”
• 2003: USA’s National Nanotechnology Initiative
• 2004: Kostya Novoselov and Andre Geim popularize graphene
• 2015: Nathan Guisinger synthesizes borophenes
Nanotech bubble of 2006

2000-2005: VCs have invested more than $1 billion in nanotech
2006: 1,200 nanotech startups worldwide 50% in the USA
Harris & Harris: venture capital firm investing only in nanotech
In-Q-Tel (CIA) singles out nanotech as strategic
2000: Bill Clinton doubles national investment in nanotech
2003: George W. Bush further increases national investment
Lux Research's report in 2004: "In 2014 nanotechnology will be incorporated in products worth $2.9 trillion in revenue"
Nanotech bubble of 2006

BusinessWeek’s special edition (February 2005)
2006: Invesco’s Lux Nanotech ETF and Lux Nanotech Index
2006: Steven Edwards’ "The Nanotech Pioneers: Where Are They Taking Us"
2006: Ray Kurzweil’s "The Singularity is Near“: “the advent of full-scale nanotechnology in the 2020s”

Nanotech and immortality

Ray Kurzweil, in "The Singularity is Near" proposes a redesign of cells using nanotechnology that would cure disease...and aging.
Nanotech bubble of 2006

• Nanotechnology is not an industry
• Nanotechnology helps progress in many different industries: biotech, displays, batteries, semiconductors…
• Nanotechnology never had its Facebook, and never will
• Time to market for nanotech inventions is very long
Nanotech bubble of 2006

- Nanotech stocks underperformed

Growth of $10,000

- S&P 500 Index
  - $18,476
- Lux Nanotech Portfolio
  - $5,026
- Lux Nanotech Index
  - $4,389

Data beginning Fund inception and ending Dec. 31, 2013.
A Brief History of Nanotech

- 2006-7: Semiconductors industry moves to a 65-nanometer manufacturing process
- 2013: Andreas Heinrich’s movie “A Boy and His Atom”, the “world’s smallest movie”: the moving dots are single atoms
- 2015: Borophene is synthesized
What is Nanotech

- "Nano": technology that operates at the atomic and molecular scale
- 100 nanometers or smaller (a nanometer is one billionth of a meter)
- The size of an ant is 6 million nanometers
- Bacteria are 2,000 nanometers wide
- The scale of DNA is about 2 nanometers
What is Nanotech

- In theory: to pick one atom at a time and place them in the right place to form the object that we desire
- In practice: molecules self-assemble - they bind together spontaneously in the right place - and then a new material is constructed "bottom-up"
- A very expensive field, that requires very expensive equipment.
- “Molecular manufacturing" is not feasible on a large scale
Progress in Nanotech

The growth of nanotechnology

futuretimeline.net
Applications

• Stronger and lighter materials
• Clean (solar) energy
• Sustainable materials. (materials that can self-decompose)
• Improved battery technology
• Precision biomedicine
• Faster computing
• …
Nanomedicine

Nanomedicine has the potential to develop radical new therapies

- Targeted drug delivery
- Dissolvable sensors
- Issuing orders to cells
- Early detection of cancer
- Antibiotics
Nanomedicine

• Targeted drug delivery
  – Robert Langer’s nanopolymers (MIT)
  – James Swartz’s re-engineered virus (Stanford)
  – Warren Chan’s “smart nanoparticles” (Univ of Toronto)
Nanomedicine

- Targeted drug delivery
Nanomedicine

- Dissolvable sensors
  - Washington Univ in St Louis (Rory Murphy and Wilson Ray) and the Univ of Illinois at Urbana-Champaign (John Rogers)
Nanomedicine

• Early detection of cancer
  – Rajesh Sardar (Indiana Univ)
Nanomedicine

• Issuing orders to cells
  – Daniel Siegwart (Univ of Texas)
  – Peter Ma (Univ of Michigan)

DALLAS – Jan. 25, 2016 – UT Southwestern Medical Center chemists have successfully used synthetic nanoparticles to deliver tumor-suppressing therapies to diseased livers with cancer

The polymer sphere delivers the microRNA into cells already at the wound site, which turns the cells into bone repairing machines. (image: Peter Ma)
Nanomedicine

- Antibiotics
  - Each year antibiotic-resistant bacteria infect two million people and kill at least 23,000 in the USA alone
  - Prashant Nagpal’s light-activated nanoparticles (Univ of Colorado)
Nanobots

- Peer Fischer’s swimming nanobots (Max Planck Inst)
- Charles Cao’s and Chen Liu’s nanozyme (Univ of Florida)
- Joseph Wang and Liangfang Zhang’s self-propelled nanobots (UC San Diego)

Micro- or even nano-robots could someday perform medical tasks in the human body. Researchers from the Max Planck Institute for Intelligent Systems in Stuttgart have now taken a first step towards this goal.

Nanoparticle Completely Eradicates Hepatitis C Virus

By Dexter Johnson
Posted 17 Jul 2012 | 19:37 GMT

Research in the Wang lab falls within the field of nanobioelectronics, focusing mostly on the design of wearable biosensors and nano- and micromotors for drug delivery and microchip diagnostics. The Wang group’s work on nano- and micromotors have advanced the field significantly towards the dream of autonomous machines capable of navigating the circulation to deliver drugs...
Nanobots

• The nano equivalent of the assembly line
  – David Leigh’s nanobots that can pick up a single molecule and move it somewhere else (Univ of Manchester) - Feynman’s dream
Nanotech + Biotech

Biology used to stop at the level of the cell
Nanotech allows Biotech to go even below the atom
Nanotech + Biotech

Trojan horses
Nano-particles can change the way a cell behaves without altering its DNA
"Trojan horses" inside a cell

Using nanoparticles to kill tumor cells inside the eye

ANN ARBOR, Mich. — Researchers at the University of Michigan Kellogg Eye Center have developed a new nanoparticle that uses a tumor cell’s protective mechanism against itself — short-circuiting tumor cell metabolism and killing tumor cells.

“Our work uses a semiconducting nanoparticle with an attached platinum electrode to drive the synthesis of an anti-cancer compound when illuminated by light,” says Howard R. Petty.
Nanotech + Biotech

Synthetic fossils
- DNA stores a lot of information in a tiny space
- DNA can last a very long time
- DNA is a highly optimized storage for data that can last for thousands and thousands of years

Data-storage for eternity

13.02.2015 | News

How can we preserve our knowledge today for the next millennia? ETH researchers have found a way to store information in the form of DNA, preserving it for nearly an eternity.

Robert N. Grass (1979) is lecturer in the group of Prof. Stark at ETH Zürich.
New Materials

• Making new materials is extremely difficult and expensive (except for laser materials, e.g. barcodes)

• Nanotech allows to build
  – Ultra-light hyper-strong materials (carbon nanotubes and graphene)
  – Water-repellent surfaces
  – Self-cleaning surfaces
  – Quantum dots
  – …
New Materials

• The revolution in materials will fuel the revolutions in Consumer Electronics, Biotech, Internet of Things, and Space Exploration
New materials

Nanomaterials (1-100 nm)

- Liposome
- Fullerene
- Carbon nanotube
- Graphene
- Dendrimer

Molecular objects

- Water molecule
- Gold atom: 3 x 10^{-4} nm
- Glucose molecule: 1 nm
- Hemoglobin: 5 nm
- DNA: 10 nm
- Bacteria: 1000 nm
- Hair: 10000 nm
- Red cells: 10000 nm
- Ant: 10^6 nm
- Baseball: 10^8 nm
New Materials

- Graphene: carbon sheets that are only one atom thick
New Materials

• Graphene
  – The lightest material known
  – The strongest material known (200 times stronger than steel)
  – The best conductor of heat at room temperature
  – The best conductor of electricity known (carrying electricity at 1 million meter/sec)
  – Carbon is the 4th most abundant element in the universe (by mass)
Graphene

- Graphene’s applications
  - Mobile phones that the user can roll up and put in the pocket
  - TV sets as thin as wallpaper
  - Bend-able electronic e-readers that the reader can fold away just like the old newspapers
  - Replace silicon in computer chips
Graphene

- Graphene’s applications
  - Fast-charging batteries
  - Ultracapacitors with better performance than today's batteries
  - Storing hydrogen for fuel-cell powered cars
  - Lower cost solar cells

Stanford scientists build the first all-carbon solar cell
Researchers have developed a solar cell made entirely of carbon, an inexpensive substitute for the pricey materials used in conventional solar panels
19 Nov 2012 | Editor

Ultracapacitor (Nankai University, 2013)
Graphene

• Graphene’s applications
  – Batteries

All-graphene-battery: bridging the gap between supercapacitors and lithium ion batteries

Haegyeom Kim, Kyu-Young Park, Jihyun Hong & Kisuk Kang

Received: 02 April 2014
Graphene

- Graphene’s applications
  - Lithium-air batteries
    - Invented in 1996
    - They can store ten times more than today's best batteries
    - But difficult to build
    - 2015: Clare Grey uses graphene electrodes

New design points a path to the ‘ultimate’ battery

Researchers have successfully demonstrated how several of the problems impeding the practical development of the so-called ‘ultimate’ battery could be overcome.
Graphene

• Graphene’s applications
  – Brain implants (2015)
  – Color-tunable LEDs (2015)
  – Low-cost water desalination (2012)

Chinese Scientists Develop Color Tunable Single Graphene-based LEDs

Nanoporous graphene could outperform desalination techniques

June 22, 2012 by Lisa Zyga
Graphene

- Graphene-based foams
  - Graphene Aerogel (Zhejiang Univ, 2013), the lightest material ever made
  - GO-0.5BN (Rice Univ, 2014)
Graphene

Ultrathin Two-Dimensional Nanomaterials
Graphene

Ultrathin 2D nanomaterials have unique properties that are ideal for the manufacturing of electronic and photonic devices:

– mechanical flexibility
– electrical conductivity
– optical transparency
Carbon Materials

Allotropes of Carbon
• a) Diamond
• b) Graphite
• c) Lonsdaleite
• d) C60 – Buckminsterfullerene
• e) C540 Fullerene
• f) C70 Fullerene
• g) Amorphous carbon
• h) Single-walled carbon nanotube

(Source: Michael Ströck)
Carbon Materials

- Carbon Nanotubes
  - A sheet of graphene rolled into a cylinder
  - Discovered in 1991 (Sumio Iijima)
  - Water Desalination (Ben Corry, 2008)

![Strength of various materials chart](chart.png)
Carbon Nanotubes

• Applications of Carbon Nanotubes
  – Fuel cells

'Unzipped' carbon nanotubes could help energize fuel cells and metal-air batteries, Stanford scientists say

Platinum catalysts in fuel cells are too expensive for large-scale production. Stanford scientists have developed a technique that could make carbon nanotubes an attractive, low-cost alternative.
Carbon Nanotubes

- Applications of Carbon Nanotubes
  - Carbon nanotube computers

Stanford Report, September 26, 2013
A first: Stanford engineers build basic computer using carbon nanotubes
Unprecedented feat points toward a new generation of energy-efficient electronics.

Chip test: Each chip on this wafer has 10,000 nanotube transistors on it. IBM hopes to be able to put billions of the devices on a single chip soon after 2020.
Borophene

- Borophene: a single layer of boron atoms that form various crystalline structures.
- A two-dimensional material like graphene
- First synthesized in 2015
  - Andrew Mannix of Northwestern and Xiang-Feng Zhou of Stony Brook, working in the teams of
    - Artem Oganov of Stony Brook University
    - Mark Hersam of Northwestern University
    - Nathan Guisinger of Argonne National Laboratory
- Stronger than graphene and more flexible
- Good conductor of both electricity and heat
- Superconductor
- Promising for storing metal ions in batteries
Borophene

- First synthesized in 2015 by Nathan Guisinger's team in the USA and Kehui Wu's team in China
- Free standing borophene synthesized in 2019 by Nathan Guisinger's team

*Science* 2015 December 18

Synthesis of borophenes: Anisotropic, two-dimensional boron polymorphs

Andrew J. Mannix1,2, Xiang-Feng Zhou3,4, Brian Kiraly1,2, Joshua D. Wood2, Diego Alducin5, Benjamin D. Myers2,6, Xiaolong Liu7, Brandon L. Fisher1, Ulises Santiago5, Jeffrey R. Guest1, Miguel Jose Yacaman5, Arturo Ponce5, Artem R. Oganov8,9,3,* Mark C. Hersam2,7,10,* and Nathan P. Guisinger1,*

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Experimental realization of two-dimensional boron sheets

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Rectennas

- Rectennas: devices that convert AC electromagnetic waves into DC electricity
- Eliminate batteries: convert Wi-Fi signals to electricity
- Traditional rectennas use either silicon or gallium arsenide for the AC-to-DC rectifier
- Traditional rectennas operate at low frequencies: they cannot feed on the gigahertz frequencies of cell phone and Wi-Fi signals
Rectennas

• Tomás Palacios (MIT, 2019): a rectenna made of a 2-D (three atoms thick) semiconducting material, molybdenum disulfide (MoS2), that is flexible and captures high frequencies.
New Materials

- Water-repellent electronics
- Self-cleaning materials
- Self-warming clothes

New paint makes tough self-cleaning surfaces

6 March 2015

Yao Lu
University College London, London
Nanotechnology, Physical Chemistry, Materials Chemistry

Nanowire clothing could keep people warm, without heating everything else

Date: January 7, 2015
Quantum Dots

• Semiconducting nano-particles
• Applications
  – television sets
  – solar batteries
  – electron microscopes
Strong Ultralight Materials

- Julia Greer’s ceramic (Caltech, 2014)
- Xiaochun Li's metal (UCLA, 2015)
- Xudong Wang’s two-dimensional nano-sheets that don't exist in nature (Univ of Wisconsin, 2016)
Making New Materials

- Chad Mirkin (1996): a combination of gold and DNA to create a new material
- Pluripotent matter: a material that can transform itself into different materials

Transmutable nanoparticles with reconfigurable surface ligands

Youngeun Kim¹,², Robert J. Macfarlane²,³,*,†, Matthew R. Jones¹,²,*,‡, Chad A. Mirkin¹,²,³,§
Metamaterials
and the cloak of invisibility

• Metamaterials
  – Victor Veselago (1968): materials that have properties not found in nature
  – David Smith (2006): you can make an object invisible if you cover it with a material that will bend electromagnetic waves
  – Andrea Alu (2012): a metamaterial cloak for a 3D object in free-space (just a few micrometers thick and only for microwaves)
Nano Manufacturing

- Expensive to build nanomaterials and in general to work at the nanoscale.
- Copy Nature: program nano-particles so that they self-assemble into complex structures?
- Ting Xu’s self-assembling nano-particles
Nano Manufacturing

- Colloidal synthesis (e.g., Paul Alivisatos, UC Berkeley)
- Nanoimprint lithography (Stephen Chou, Univ of Minnesota)
- Two-photon-lithography (Jürgen Stampfl, Vienna University of Technology)
- 3D printing (Ho-Young Kim, Seoul National University)
- Colin Raston’s Vortex Fluidic Device
Figure 1. Nanomanufacturing techniques must not only produce structures on a small length scale $L$ but also achieve a high areal throughput $T$. Tennant's law, which states that $T$ scales as the fifth power of $L$, holds approximately over a wide range of technologies discussed in the text, including those based on scanning tunneling microscopes (STMs) and atomic force microscopes (AFMs), optical lithography, electron-beam (e-beam) lithography and reflective e-beam lithography (REBL), nanoimprinting, focused ion beams (FIBs), dip-pen nanolithography (DPN), and atomic calligraphy. Beating that trend (shifting the black curve down and to the right) is the challenge of nanomanufacturing. (Adapted from refs. 4 and 17.)
Superconductivity

- A state of matter in which electrons flow without resistance
- Achieved at absolute zero temperature
- Much harder to achieve at normal temperatures
Superconductivity

• Practical applications:
  – Magnetic Resonance Imaging (MRI) used in hospitals
  – Magnetic-levitating trains
  – Power transmission

• Can Nanotech create superconductors that work at room temperature?
Superconductivity

• A brief history
  – 1911 Heike Onnes (Netherlands) discovers superconductivity.
  – 1933 Walther Meissner and Robert Ochsenfeld (Germany) discovers the Meissner effect
  – 1950 Lev Landau and Vitaly Ginzburg (Russia) propose a theory of superconductivity
  – 1956 Leon Cooper predicts that electrons would attract one another at extreme low temperatures in some materials
  – 1957 John Bardeen, Leon Cooper and John Schrieffer (Univ of Illinois) provide a complete theory of superconductivity
  – 1961 Eugene Kunzler (Bell Labs) discovers that niobium-tin can be used to make supermagnets
Superconductivity

• A brief history
  – 1962 Ted Berlincourt and Richard Hake (Atomics International, California) discover that alloys of niobium and titanium are suitable for industrial applications, and production of superconducting wires begins at Westinghouse
  – 1962 Brian Josephson (Univ of Cambridge) shows that a supercurrent can flow between two pieces of superconductor separated by a thin insulator
  – 1980 Klaus Bechgaard (Denmark) synthesizes an organic (carbon-based) superconductor
  – 1986 Alex Müller and Georg Bednorz (IBM, Switzerland) discover a high-temperature superconductor (at 35K)
  – 1987 Ching-Wu "Paul" Chu (Univ of Houston) discovers YBCO, the first material to exhibit superconductivity at temperatures above the boiling point of liquid nitrogen (77k), thus making liquid nitrogen feasible as a refrigerant
Superconductivity

• A brief history

- 1993 Andreas Schilling (Switzerland) achieves superconductivity at 133 K
- 2000 Jun Akimitsu (Japan) discovers a magnesium diboride superconductor
Superconductivity

• A brief history
  – 2006 Hideo Hosono (Japan) discovers an iron-based superconductor
  – 2008 Maw-Kuen Wu discovers that FeSe is a superconductor
Superconductivity

- A brief history
  - 2014 Andrea Cavalleri (Germany) uses lasers to achieve superconductivity at room temperature (but only for 0.000000000002 seconds)
  - 2015 Mikhail Eremets and Alexander Drozdov (Germany) achieve superconductivity at 203K
  - 2015 Kosmas Prassides (Japan) discovers the Jahn-Teller metal: a substance that exhibits the properties of an insulator, superconductor, metal, and magnet all in one
Superconductivity

• If achieved at room temperature…
  – More efficient transmission of electricity
  – All the railways that use electricity would become magnetic levitation railways
  – Cheaper electronic circuits
  – Fusion at room temperature
Superconductivity

- If they invent superconductivity at room temperature, invest in a recycling company!
- TV sets, computers, phones, transformers and all the electrical devices that exist today in the world would become obsolete.
Nanotech for Electronics

• The limit of Moore’s Law: increasing the clock speed of a chip also increases its electrical consumption which also increases the heat it generates

• Moore’s Law stopped working in 2005: what is increasing exponentially is no longer the “clock speed” but the number of transistors thanks to multiple cores on the same chip

• The cost per transistor has actually been rising since 2011 (the 28-nanometer chip)
Nanotech for Electronics

- The problem: the “Gelsinger syndrome”

In 2001, Patrick Gelsinger, an Intel executive, predicted that unless something changed, computer chips would become hotter than nuclear reactors within a few years. *Illustration by Jenna Luecke*
Nanotech for Electronics

- The solution: multiple cores
Nanotech for Electronics

The Economist’s version of the same graph (2016)
When Moore’s Law stops working, what happens to the progress in devices?

Moore’s Law has resulted in new generations of devices.
Nanotech for Electronics

• Optoelectronics
  – Keep silicon transistors but use light to transfer information
  – Faster speed and lower consumption
  – Rajeev Ram (MIT, 2015)
  – IBM (2015)

IBM announces silicon photonics breakthrough, set to break 100Gb/s barrier

By Joel Hruska on May 14, 2015 at 4:49 pm
Nanotech for Electronics

• The other solution: new materials
  – Graphene "nanoribbons" could replace silicon semiconductors and
    • transport electrons thousands of times faster than a traditional metallic conductor
    • provide microprocessor clock speeds hundreds of times faster than today’s microprocessors
    • increase the density of transistors on a computer chip by as much as 10,000 times
Nanotech for Electronics

• Manufacturing graphene nanoribbons
  – Felix Fischer at UC Berkeley
  – Michael Arnold at the Univ of Wisconsin
  – Paul Weiss at UCLA
Nanotech for Electronics

• Graphene electronics
  – Graphene conducts too well – not ideal to replace silicon
  – Andras Kis (Switzerland): a transistor made of TMDC (2010)
  – Madhu Menon (Britain): a new material that is one-atom thick like graphene, but it is a semiconductor like silicon (2016)
Nanotech for Electronics

- **Storage**
  - Computer memory is made of transistors, which are "volatile"
  - Memristors are a nonvolatile technology: they don't lose their information when the power is turned off (RAM + Hard Disk = Memristor)
  - A memristor is neither a resistor nor a capacitor nor an inductor. It is a fourth fundamental circuit element with properties that cannot be achieved by any combination of the other three.

In 2008 a team lead by [Stanley Williams](https://www.stanleywilliams.com) created the first memristor.
Nanotech for Electronics

• Storage
  – Memristors are similar to synapses, therefore well-suited for neural networks (e.g. Dmitri Strukov, 2015)
  – New Mexico-based Knowm

Startup claims a breakthrough in brain-like computing on chips
Controlling Matter at the Atomic Scale

- IBM
  - 1989: “IBM in atoms” demo
  - 2013: “A Boy and His Atom”, the “world’s smallest movie”

- Michelle Simmons at the University of New South Wales and Gerhard Klimeck at Purdue University created a transistor from a single atom (2012)

One and done: Single-atom transistor is end of Moore's Law; may be beginning of quantum computing
Post-Electronics

- Intel already announced it won’t go below 7nm with silicon
- A 2nm transistor would be made of only 10 atoms
- Quantum effects would make them unreliable

Intel: we'll have to adopt fundamentally new transistor technologies in 4-5 years, Spintronics is a leading candidate

Feb 05, 2016

Intel's technology and manufacturing group leader, William Holt, says that if Intel wants to keep improving its chips, it will soon have to start using fundamentally new technologies. The company does not know which technology will be adopted, but there are two possible candidates at this stage - Spintronics, and tunneling transistors.
Spintronics

- 1988: Albert Fert (France) and Peter Gruenberg (Germany) discover the Giant Magnetoresistive (GMR) effect, that uses the electron spin to increase the rate at which magnetic states can be read, thus enabling the storage of extremely densely-packed information
- 1997: IBM introduces the first hard disk that uses the GMR effect for its read-out head
- 2006: Freescale/Everspin introduces a computer memory based on GMR, Magnetoresistive RAM (MRAM)
Quantum Computing

- 1964: Ford Labs invent Superconducting Quantum Interference Device (SQUID)
- 1982: Richard Feynman shows that a device can store information "qubits" instead of binary bits
- Multiple qubits can be linked in “entangled” states
- A change in one qubit changes the entire system
- A quantum computer could perform multiple calculations at the same time; for example, perform multiple searches at the same time
- 1985: David Deutsch describes a universal quantum computer
Quantum Computing

- 1994: Peter Shor shows that quantum algorithms can run exponentially faster than classical ones
- 1995: Peter Shor shows that quantum error correction is possible
- 1997: Colin Williams’ and Scott Clearwater’s "Explorations in Quantum Computing"
- 1997: David DiVincenzo’s criteria
- 1997: Anton Zeilinger demonstrates quantum teleportation
Quantum Computing

• 2002: Michael Freedman describes a topological quantum computer
• 2006: Christopher Monroe creates a quantum processor
• 2007: D-Wave demonstrates its first quantum computer
• 2009: NIST unveils a universal programmable quantum computer (two qubits)
Quantum Computing

• 2013: The London Centre for Nanotechnology discovers that the electrons in copper phthalocyanine remain in superposition for long times

• 2014: Delft Univ teleports information between two qubits separated by three meters

• 2016: JQI’s five-qubit modules that can be combined together

• 2016: IBM makes a five-qubit computer available on the cloud
Quantum Computing

• Unsolved problems
  – Cooling the superconducting circuits is expensive and cumbersome
  – Superconducting qubits (SQUIDs) are unreliable

• Reliable qubits
Quantum Computing

• Qubits via photon quantum states
  – Photons preserve entanglement over long distances and time periods
Quantum Computing

• Quantum Processors
  – Does quantum mechanics work? The MRI!
  – Difference between the MRI and quantum computing: the MRI measures average properties, we need to measure each spin individually
Quantum Computing

- Quantum Processors
  - How to make quantum materials: engineers “encourage” nature to assemble stable structures, and nature does the rest
  - Problem of entanglement: in order to describe 300 entangled qubits, we need more numbers than particles in the universe
  - Many different techniques… see graph of when we expect to be able to describe n entangled atoms
  - Superconducting circuits
Quantum Computing

• Quantum Processors
  – Superconducting circuits are the most promising platform
  – UC Berkeley

Welcome to the Quantum Nanoelectronics Laboratory!
Quantum Computing

• Superconducting Quantum Processors
Quantum Computing

• Superconducting Quantum Processors
  – Suitable for specific applications
  – Suitable for improving classical algorithms, eg “quantum recommendation systems” for Netflix and Amazon
Quantum Computing

• Peter Wittek (Univ of Toronto): quantum computing and artificial intelligence

• Blackbrane (Toronto, Colin Lupton): Virtual quantum machine (cloud-based 128-qubit quantum computer)
Quantum Computing

• Scott Aaronson, founding director of the Quantum Information Center at the University of Texas at Austin

The University of Texas at Austin
Quantum Information Center
NanoArt

- Cris Orfescu
- Ghim Wei Ho
- Tim Fonseca
- Erik Viktor
NanoArt

- Maiken Lilley
- Victoria Vesna
Bibliography
Contact

- www.scaruffi.com

See http://www.scaruffi.com/singular/human20.html for the full text of this discussion