MEMS and Sensors
a Journey to Mainstream

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Shaping the Future of MEMS and Sensors
Santa Clara, CA, September 12, 2013

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Historical MEMS Drivers

1950s Fundamental research

1960s Defense and Avionics, in response to Sputnik (1958)

1970s Process Control and Automotive

- Automotive CAFE in 1972 drives demand for pressure sensors, later flow sensors

1980s Industrial Controls and Medical

- Disposable blood pressure sensor in 1982

1990s Automotive and Consumer

- Airbags mandatory in 1998, driving acceleration sensors
- DLP and ink jet printes

2000s Mobile and Automotive

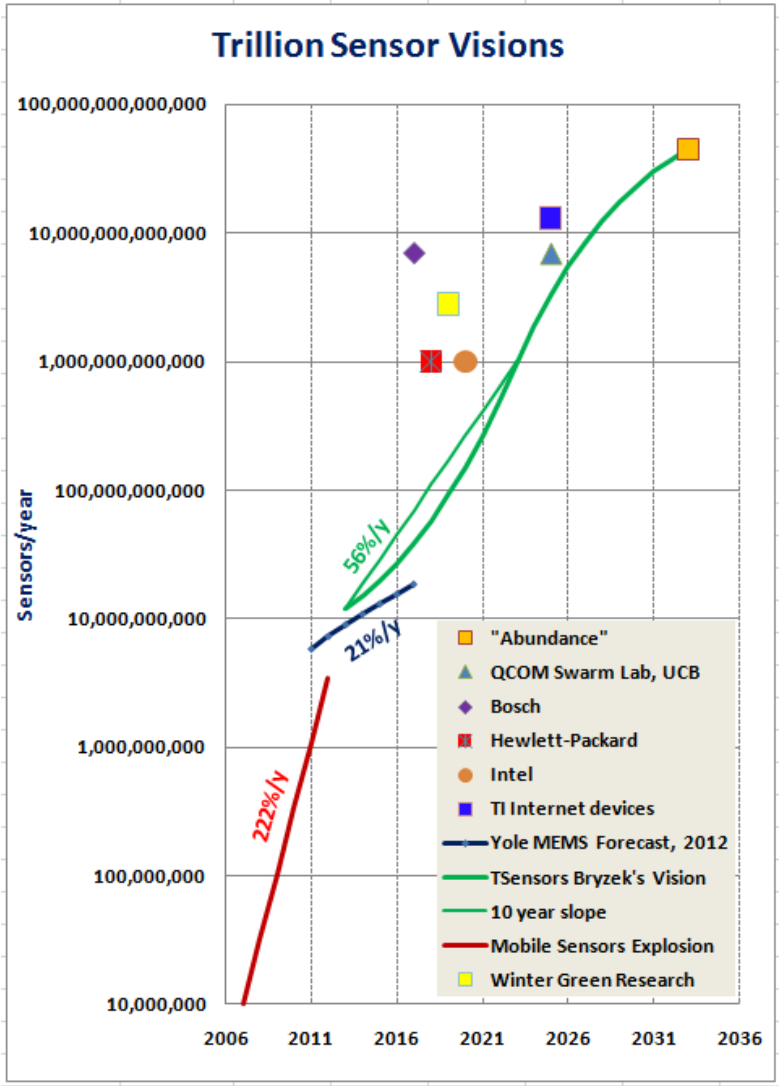
- WII in 2006
- iPhone in 2007
- Microphones, accels, gyros, compass, pressure, …
- FBAR exceed billion units/year
- 10s of sensors in cars

2010s New global tides:

- Wearable, Digital Health, Internet of Things, Context Awareness, CeNSE
- Emergence of Trillion Sensors potential

Trillion Sensors (TSensors) Vision

- Mobile sensor market for volumes *not envisioned* by leading market research organizations in 2007, grew exponentially over 200%/y between 2007 and 2012.
- Several organizations presented their visions for a continued growth to trillion(s).
  - Market research companies don't yet see this growth.
  - So the explosion to trillion(s) is likely to be driven by applications *not yet envisioned* by leading market research organization.
- Global tides supporting growth of sensors to trillions include:
  - Abundance, Smart Systems, Sensory Swarms, Mobile Health, Internet of Things, Context Computing and Central Nervous System for the Earth



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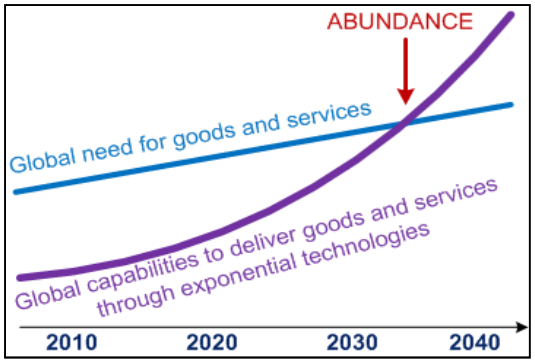
How Big is 1 Trillion Sensors…

- If the ASIC would be 4 mm^2 and MEMS consisting of two wafers 4 mm^2, one trillion sensors would require:
  - 130 million 8” ASIC wafers
  - 260 million 8” MEMS wafers
- For 3D printed sensors, assuming 12x 25 mm strip with sensors and electronics, one trillion sensors would require:
  - 300 million m^2 of substrate.

Boldest Vision: Abundance*

- The biggest global problems, such as hunger and lack of medical care, will be solved in one generation through:
  - Exponential technologies.
    - Biotechnology and bioinformatics
    - Medicine
    - Nanomaterials and nanotechnology
    - Networks and sensors (45 trillion networked sensors in 20 years).
    - Digital manufacturing (3D printing) and infinite computing
    - Computational systems
    - Artificial intelligence
    - Robotics
  - DIY (Do-it-Yourself) Revolution.
    - Power of individual innovators capable of impossibles.
      - E.g., flying into space (Burt Rattan) and sequencing human genome (Craig Venter).
  - Unrivaled in history Technophilanthropic force.
    - Funded by billionaires (Gates, Zuckenberg, Omidyars, etc.).
  - The rising billion,
    - Billion of the very poorest of the poor on earth is being plugged into global economy through a global transportation network, Internet, microfinance and wireless communication.



* http://www.abundancethebook.com/

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Smart Systems

- Harbor Research introduced a concept of ***Smart Systems in the Era of Pervasive Internet***.
  - Defined as a fusion of ***computing***, ***communication*** and ***sensing***.
    - People, devices, ***sensors*** and businesses are connected and able to interact.
- Harbor Research leading markets for smart sensing systems include:
  - Cell phones
  - Health monitoring devices
  - Smart grid infrastructure
  - Automotive
  - IT
  - Industrial systems
- Smart business will enable collective awareness, creativity and better decision making capabilities, driving the **largest growth opportunity in the history of business.**

http://www.harborresearch.com/Home.htm

Qualcomm Swarm Lab at UC Berkeley

- Swarm Lab projects 1000 radios per person on Earth by 2025, with trillions of connected devices as the swarm around the edge of the Cloud, to link the cyber and physical/biological worlds.
- Trillions wireless devices creates a challenging demand for RF bandwidth.
  - Swarm Lab is developing next gen low power radios enabling bandwidth sharing.
  - IPv6 introduced in June 2012 paved a way for sensory swarms.
    - Increased IP addresses from 2^{32} = 4.3 billion to 2^{128}, or 340 undecillion, or…
    - 340 trillion trillion trillion, or…
    - 340,282,366,920,938,463,463,374,607,431,768,211,456

Bosch Sensory Swarms

- Bosch presented a vision for 7 trillion devices consisting of Sensory Swarms connected to the Internet to serve 7 billion people by 2017.
  - Funded development group.
- This vision translates to 1000 sensors per average person.
  - Current applications supported by large number of sensors:
    - Advanced cars have close to 100 sensors.
    - Smart homes use 10s and 100s of sensors.
    - Smart phones use now up to 18 sensors.
    - Medical diagnostics uses 10s of different sensors, which will be migrating to personal use.
  - It is thus not too big of a stretch to foresee the growth outlined by Bosch.

Mobile Health

- Health cost is dramatically increasing.
  - In the US, it reached $2.5 trillion in 2009, representing 18% of the GDP.
- Remote home care emerges as Tornado-in-making to reduce health care cost.
- Wearable (wireless) devices market (ABI Research) is forecasted to grow from 12M devices in 2010, to 420 million wearable health monitors in 2014.
  - 59 million to be used at home.
- Personal wellness and health sensors promise dramatic cost reduction.
  - FDA excluded wellness sensors from their regulations in March 2013.
- 500M people forecasted to be using mobile health apps by 2015 (www.alivecor.com)
- 2013 CES Show in Las Vegas:
  - 19 Digital Health Sessions
  - 350 exhibitors in Digital Health section
- By 2023, 10s or 100s of medical sensors might be connected ON and IN the body for diagnostics and therapeutics apps.
  - Many disposable.

Internet of Things (IoT)

- Internet of Things: sensors and actuators embedded in physical objects and linked through wired and wireless networks often using IP.
- Revolutionary aspects:
  - Deployment of *physical information systems* and *ability to work without human intervention*.
- In China's 12th 5 year plan, IoT is one of the seven Strategic Emerging Industries with 5Billion RMB of government funding allocated during the next five years.

  http://technode.com/2012/05/14/internet-of-things-not-just-a-concept-for-fund-raising/
- Major Applications:
  - Information and analysis, such as
    - Tracking behavior of persons, things and data through space and time,.
    - Enhanced real time situational awareness of physical environment.
    - Sensor driven decision analytics through deep analysis and data visualization.
  - Automation and control.

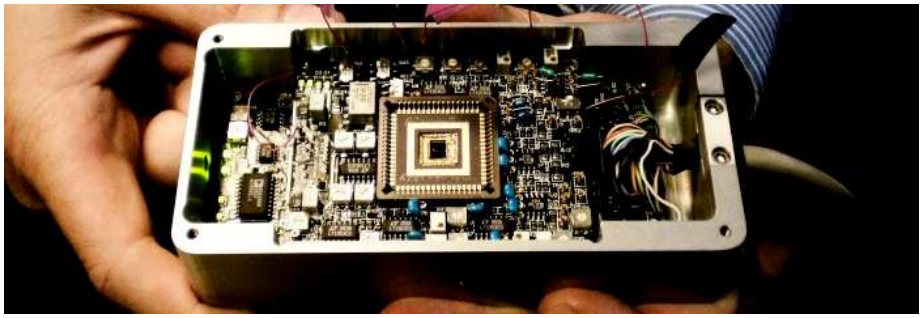
Source: McKinsey Quarterly 2010 Number 2

Intel Context Computing

- Sensors are key to the success of Context-Aware Computing to sense e.g.:
  - All around me and my needs
    - Understanding situations (e.g., mood of the person you meet).
  - All around devices
  - Personal health
  - Social interactions
  - Planet context
  - Universe context
- Context-aware algorithm development needs huge processing power.
  - 100s of servers at HP.
- Out of trillion sensors by 2020-2022.
  - 70% of sensors will be solving problems.
  - 30% of sensors will create lifestyle enhancements.

Central Nervous System for the Earth

- CeNSE is expected to deploy a trillion micro/nano sensors and actuators by 2018.
- Markets for CeNSE:
  - Climate monitoring
  - Oil exploration and production
  - Assets and supply chain tracking
  - Smart highway infrastructure
  - Tsunami and earthquake warning
  - Smart grid and homes
  - Structural health monitoring
- Processing sensor information will require increasing the size of Internet 1000 times creating:
  - $70B global market for sensing systems,
  - $290B market for value added sensing services.



http://www.hpl.hp.com/news/2009/oct-dec/cense.html

Harbor Research performed a market research for HP resulting in CeNSE.

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Sensor Fusion and Data Fusion

- In addition to unit volumes, equally challenging will be the massive real-time sensor data traffic from trillions of connected devices.
  - Some forecast sensors generating brontobytes of data (10^{27} bytes) by 2023.
  - That data will need to be processed, stored, analyzed and visualized.
- The feeder of these data will be sensor and sensor data fusion, enabling significant data compression.
  - *Sensor fusion*: combining multiple sensors data such that the resulting information is in some sense *better* than would be possible from individual sensors.
  - *Multisensor data fusion:* process of acquiring multiple data sets from multiple sensors with the intent of building a more precise data set.

Sensor Hubs

- Sensor data processing will be distributed across the system.
- Sensor Hub performing sensor and data fusion had been demonstrated at:
  - Sensor itself (e.g., Bosch)
  - Dedicated uC (e.g., ST)
  - Dedicated sensor uC integrated onto AP (e.g., Qualcomm)
  - AP (e.g., Apple)
- Each of these approaches has strengths and weaknesses, with extremes:
  - Embedded sensor processors have least processing power and lack direct access to data from remote sensors, such as GPS.
    - Functions embedded at sensor processors, however, have potential to deliver the lowest implementation power due to 1000x less transistors.
  - AP have the most processing power and direct access to other sensing resources.
    - Functions performed by APs are likely to be the most power hungry.
- Cloud is likely to be the location of choice for Large Data storage and processing.

Why TSensors Needs Roadmap

- Historically, sensor technologies have had long development cycles, about 20 years to volume production due to:
  - Deployed “multi-physics” and “multi-bio-chemistry” complexity.
  - Lack of standardization (one product–one process–one ASIC-one package-one test system).
- Once visibility of likely ultra high volume applications emerges, focused commercialization efforts could be deployed.
- Motivations for academia, Governments and industry to focus on accelerated sensor development:
  - Acceleration of very large market growth.
  - Acceleration of Abundance.
  - Acceleration of new jobs creation.

MEMS/MSTCOMMERCIALIZATION TIMETABLE

Product	Discovery	Product Evolution	Cost Reduction	Full Commercialization	Elapsed Time in Years
Pressure Sensors	1954-1960	1960-1975	1975-1990	1990	36
Accelerometers	1974-1985	1985-1990	1990-1998	1998	24
Gas Sensors	1986-1994	1994-1998	1998-2005	2005	29
Valves	1980-1988	1988-1996	1996-2002	2002	22
Nozzles	1972-1984	1984-1990	1990-2002	2002	24
Photonics/Displays	1980-1986	1986-1998	1998-2005	2005	25
Bio/Chemical Sensors	1980-1994	1994-2000	2000-2012	2012	30
Radio Frequency (R.F.)	1994-1998	1998-2001	2001-2008	2008	13
Rate Sensors	1982-1990	1990-1996	1996-2006	2006	22
Micro Relays	1977-1993	1993-1998	1998-2012	2012	32
Oscillators	1965-1980	1980-1995	1995-2011	2011	46
				Median	**28**

ROGER GRACE ASSOCIATES MARKETING COUNSEL

http://www.rgrace.com/

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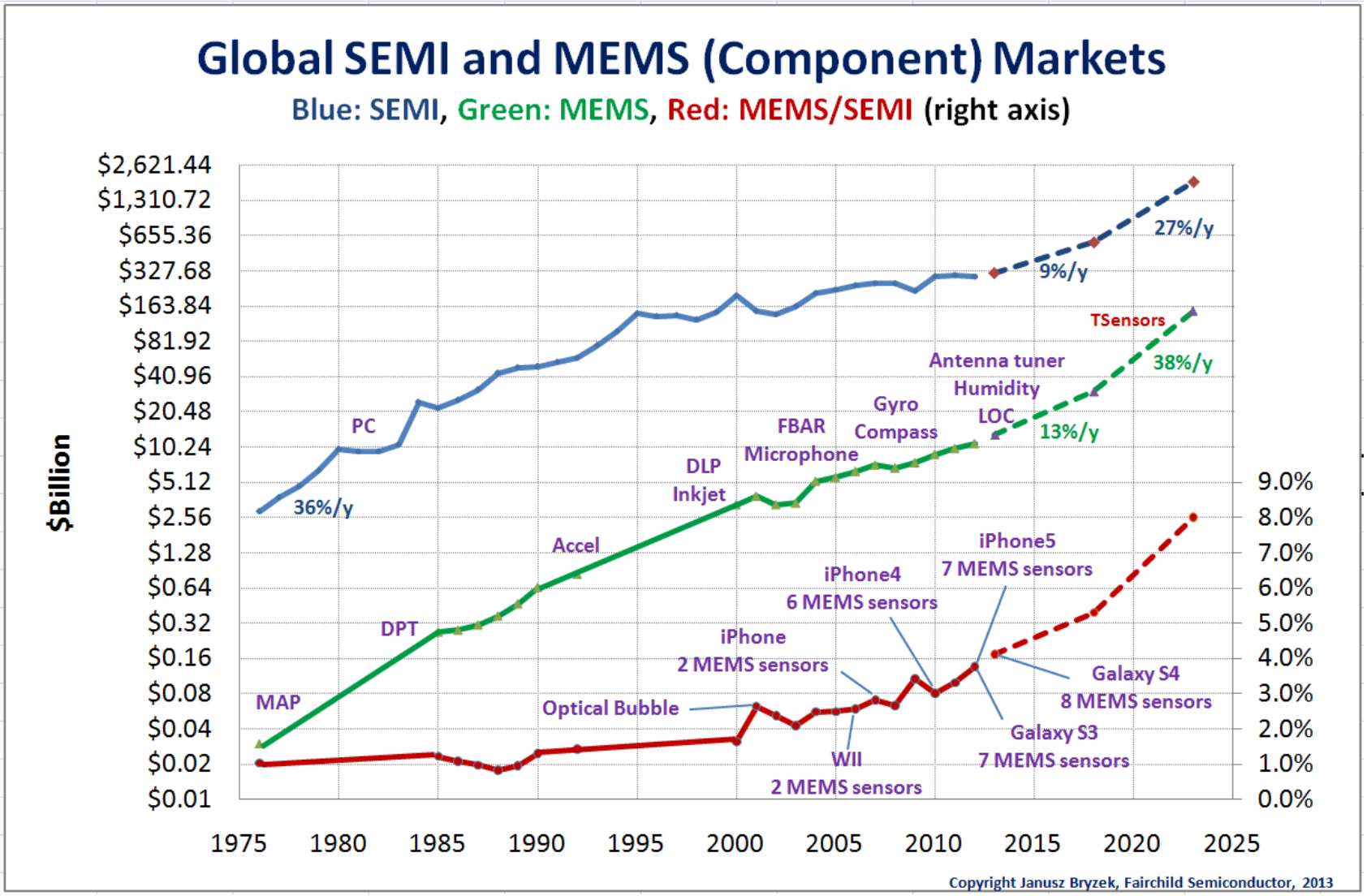
TSensors Summit

- Emerging applications for sensors need to come from sensor visionaries, not market analysts.
- TSensors Summit is being organized at Stanford University, October 23-25, to provide a peek into the future:
  - 42 sensor visionaries were invited to present their vision on the emerging large volume (>1B/y) applications.
- Based on their vision, we plan to select sensors which are not likely to be brought to high volume in 5 years without a dedicated acceleration effort, and launch development acceleration.
- Development acceleration may be in the form of, for example:
  - Facilitating a focused joint industry-academia-government-customers development, funded by industry, customers and governments.
  - Development of standardized manufacturing processes by Cooptition, cooperating competitors to increase market size.
- More information and registration:
  - http://www.tsensorssummit.org/

MEMS Journey to Mainstream



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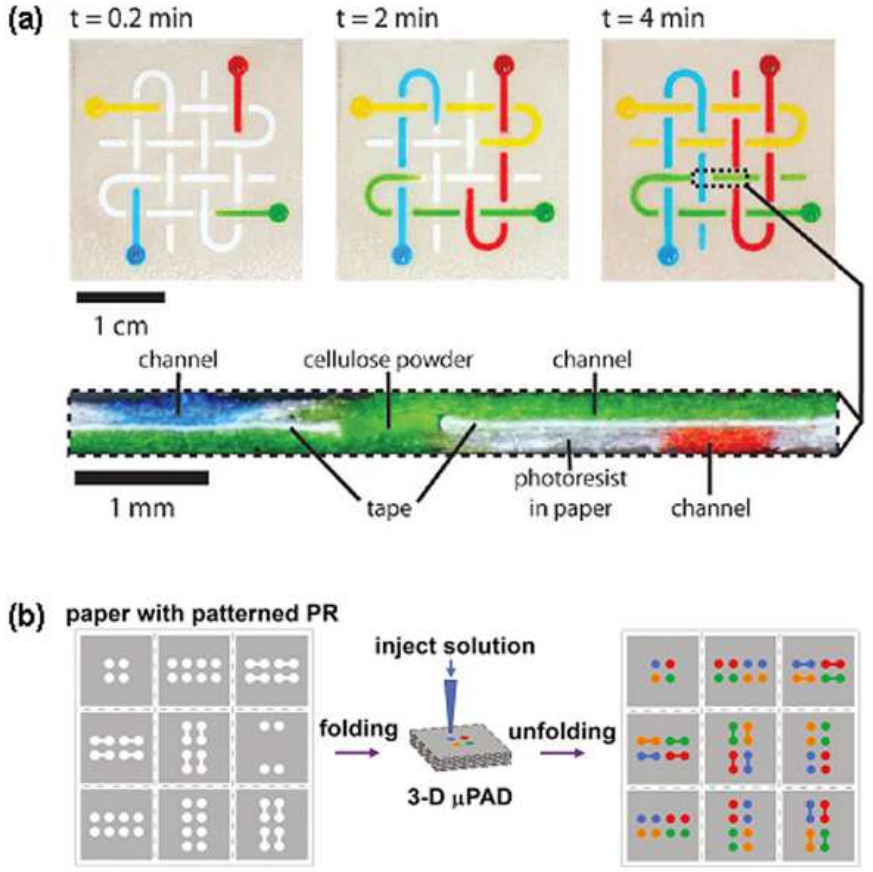
MEMS Based Product Sampler

Paper Microfluidics

Health diagnostics (e.g., urinalysis, saliva analysis, sputum analysis, pregnancy test, blood type)
Biochemical analysis (e.g., enzyme activity)
Environment monitoring
Food quality control
Biomedical analysis
Forensic (e.g., detection of blood)



http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3365319/#c19

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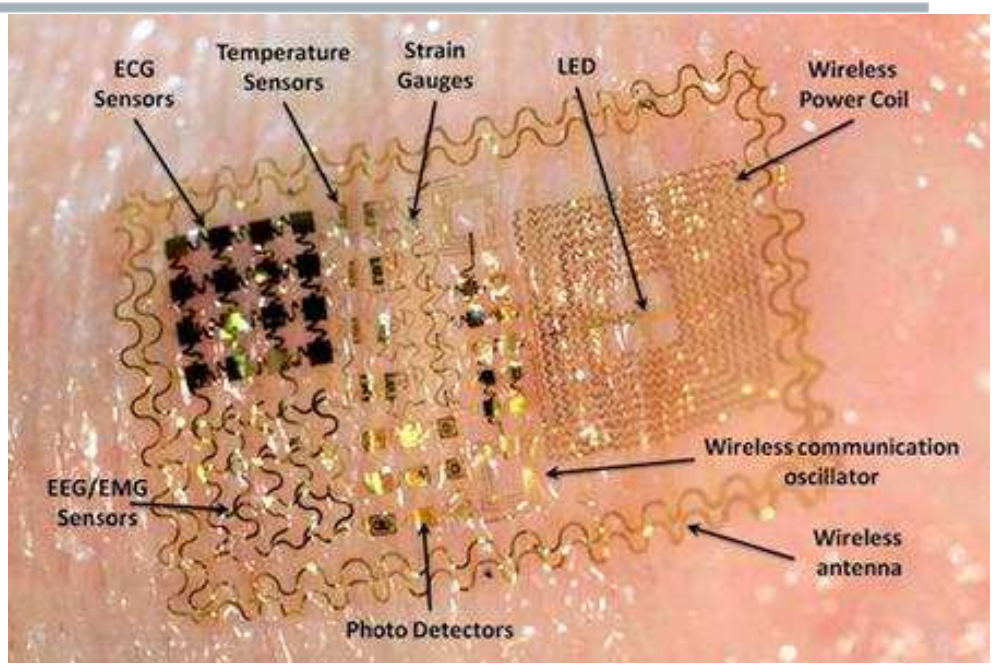
Tattoo Sensors Printed on Skin

Sensing temperature, strain, and the hydration state of the skin, all of which are useful in tracking general health and wellness, and monitoring wound healing (UoI).



Sensing multiple variables (UCSD)

http://www.technologyreview.com/news/512061/electronic-sensors-printed-directly-on-the-skin/

http://forum.eetasia.com/thread!printPreview.jspa?threadID=1200250860&start=0

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On-Body Monitoring System

- Tracks how many calories you've consumed and burned throughout the day.
- Monitors exercise intensity.
- Tracks Sleep Monitoring to gives you a clear understanding of the quality and efficiency of your sleep.
- Includes the following sensors:
  - Acceleration
  - Body heat flux
  - Galvanic skin response
  - Skin temperature

http://www.bodymedia.com/

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NIKE Sensory Overload

8 sensors

4 accelerometers
4 pressure sensors
Bluetooth Smart (aka Bluetooth LE)
Embedded Processor
Battery

http://nikeplus.nike.com/plus/what_is_fuel/

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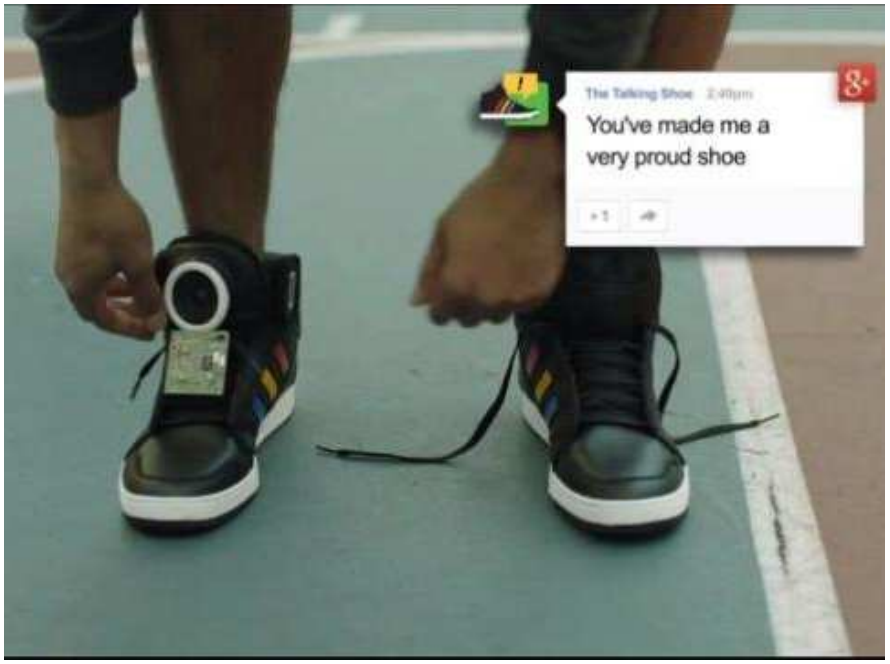
Google Smart Shoes

- Internet-connected sneakers unveiled at 2013 at SXSW conference.
- Include accelerometer, gyroscope, pressure sensor.
- Can monitor physical activity and track a user's every movement, and push that information to a social network.
- Can shout encouraging messages…
  - Through a rather large conical speaker from which up to 250 different spoken phrases can be broadcast.
  - These phrases include gems such as "if standing still were a sport, you'd be world champion!"
- Could just as easily deliver audio commercials to all of the other runners on a track or members of a gym.



http://www.nydailynews.com/life-style/google-unveils-smart-shoes-sxsw-article-1.1287259#ixzz2WbhvEwMn

Freakishly Smart Sensor Basketballs

- **Shooting accurately *and* quickly**
  - Great shooters can shoot the ball after the catch in less than .75 seconds with great accuracy.
- **Shooting with ideal arc**
  - Ideal shot has an entry angle between 42° and 48° to the basket.
- **Shooting with proper release and backspin**
  - Ideal backspin generated on a shot is between 135 and 150 rpm.
- **Dribbling with force/confidence**
  - Great ballhandlers dribble with forces greater than 6 g's with either hand.
- **Dribbling with speed**
  - Putting down 150 dribbles in less than 20 seconds puts you at the top limits of human hand speed.

http://www.infomotionsports.com/products/94fifty-sensor-basketball/

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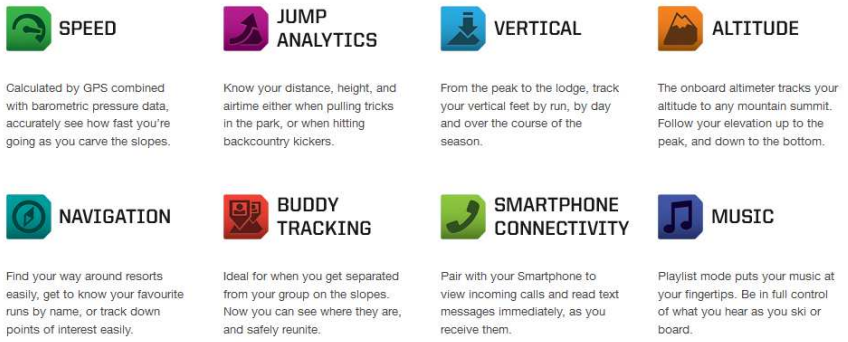
Sensor based Appcessories Sampler

Augmented Reality
(Google Glasses)

Headset with brain interface



Recon Goggles with heads-up display, GPS and IMU for skiers

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Sensor based Appcessories, Sampler

Lapka: gathers:

- Humidity
- Temperature
- Radiation
- Electromagnetic frequencies (EMF)
- Organicity (checks for nitrates, which are commonly used in chemical fertilizers).

Node: includes

- Motion sensors for wakeup
- Temperature gauge
- Barometer
- Ambient light
- Humidity
- Point-and-shoot temperature sensor
- Color sensor for matching colors
- Forthcoming range of gas sensors.

http://www.fastcodesign.com/1670479/iphone-sensors-test-if-your-food-really-is-organic#1

http://www.tuaw.com/2012/12/11/node-gives-your-iphone-sensory-input/

Medical Appcessories Sampler

Proteus digestible sensors send wireless signal through the body to a receiver.
Records type of drug, the dose, and the place of manufacture.
Measures an heart rate, activity, and respiratory rate.

Low cost DNA chips containing up to 64 reactions of less than 1 µl volume.
Assay time is 10-30 minutes, cost < $1,000, assay cost $5-$10 per chip.

Alcohol breathalyzer, $79 accessory.

Uchek (MIT) can detect up to 25 diseases, such as diabetes, urinary tract infections, and pre-clampsia based cell phone camera reading.
It can also measure the levels of glucose, proteins, ketones, and more.

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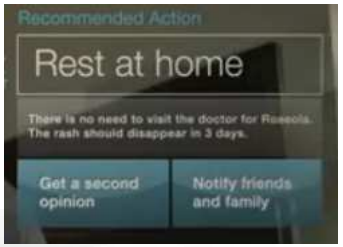
“Doctor in a pocket”

Scanadu is a 2010 startup based at NASA-Ames Research Center.

Introduces in 2013 three home diagnostic tools based on imaging, sound analysis, molecular diagnostics, data analytics and a suite of algorithms to create a comprehensive, real-time picture of your health.

- Uploadable to Scanadu smartphone app via Bluetooth.



SCOUT: collects vital signs In less than 10 seconds contact with the temple:

- Pulse transit time
- Heart rate (pulse rate)
- Electrical heart activity
- Temperature
- Heart rate variability
- Blood oxygenation (pulse oximetry)

ScanaFlo: uses smartphone as a urine analysis reader.

- Designed to be sold over-the-counter as a disposable cartridge, will test for pregnancy complications, preeclampisa, gestational diabetes, kidney failure and urinary tract infections.
- For pregnant women, is the first to provide a healthfeed throughout the duration of a pregnancy.

ScanaFlu

- Assesses cold-like symptoms, removing guess work from early diagnosis of upper respiratory infections.
- By testing saliva, the disposable cartridge will provide early detection for Strep A, Influenza A, Influenza B, Adenovirus and RSV.

http://www.scanadu.com/news/#sthash.oeuESQSK.dpuf

ECG Monitor

- Single channel ECG monitor developed by AliveCor has a standby physician to interpret the results.
- List price $199.

http://www.alivecor.com/

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Ultrasound Imaging

- Ultrasound machine from Mobisante went on sale in October 2011.
  - List price $7500.
  - Single ultrasound transducer made in Silicon Valley.
- Silicon Valley startup Sensant developed a 1000 transducer MEMS chip enabling 3D imaging.
  - Acquired by Siemens in 2005.
  - In hand held devices next year?

http://www.mobisante.com/

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Conclusions

- Future of MEMS and Sensors seems to be very bright.
  - MEMS component market entered the mainstream.
    - Is on its way to reach $100B mark within 10 years.
  - MEMS market growth is driven by several global tides:
    - Abundance, Smart Systems, Digital Health, Internet of Things and Everything, SeNSE, Context Computing.
  - These global tides will drive the growth of semiconductor industry as well.
- Byproduct of the global tides driving market growth:
  - All of us will live longer and healthier.
  - All of us will live in less polluted and more energy efficient world.
  - We will have more fun than ever.
  - First MEMS Billionaires?

Thank You

See the future of sensors
at TSensors Summit at Stanford in October
www.TSensorsSummit.org

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