Union College and
IEEE Schenectady Section present
The Steinmetz Memorial Lecture for 2015

Our Travels Through Time:
Envisioning Historical Waves of Technological Innovation

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University of Michigan, Ann Arbor

A lecture in memory of
Charles Proteus Steinmetz
Apr 9, 1865 – Oct 26, 1923

Legendary pioneer of
electrical engineering,

On the 150th anniversary
of his birth

Wiki Commons

I'm especially honored to have been invited to give this lecture for Steinmetz has been a powerful role model for me, because of his:

(i) Pivotal role in the "AC revolution",
(ii) Creatively living a wonderfully full life,
(iii) And doing all this in the face of hardships that could have crushed a lesser soul.

Back in 1978 at MIT, as I struggled to launch a later revolution, I kept a his photo on my office wall (see at right, just above the chair) . . .

Lynn's office at MIT, 1978

As we travel through time . . .

Link

Keep these words in mind . . . *"The farther backward you can look, the farther forward you can see."* – Winston Churchill

We'll first step back and reflect on some early waves of innovation

Then we'll zoom-in on the AC electricity revolution
involving Steinmetz

And on the later VLSI microchip design revolution
that I participated in

We'll then envisioning the huge incoming wave of innovation
as ever-smaller, ever-more-empowering microsystems
become embedded into almost everything.

Note: This slide-show (with links) will be posted online, for later reference.

To set the stage, let's visualize some past waves of disruptive innovation . . .

Link

We'll begin in the 1400s during the Renaissance, a time of transformational cultural advances . . .

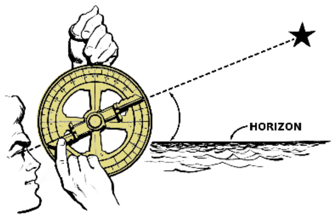
Prague Astronomical Clock, c. 1410:

The mechanization of astronomical calculations during the Renaissance:

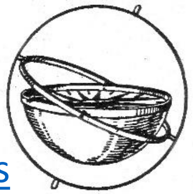
A stunning confluence of the Mathematics, Science, Engineering Architecture and Art of the time . . .

Photo by Hector Zenil (www.hectorzenil.net)

Towards the end of the 1400's a commingling cluster of advances in shipbuilding, navigation and map-making reached a '[tipping point]', triggering the onset of the **[Age of Discovery]** . . .

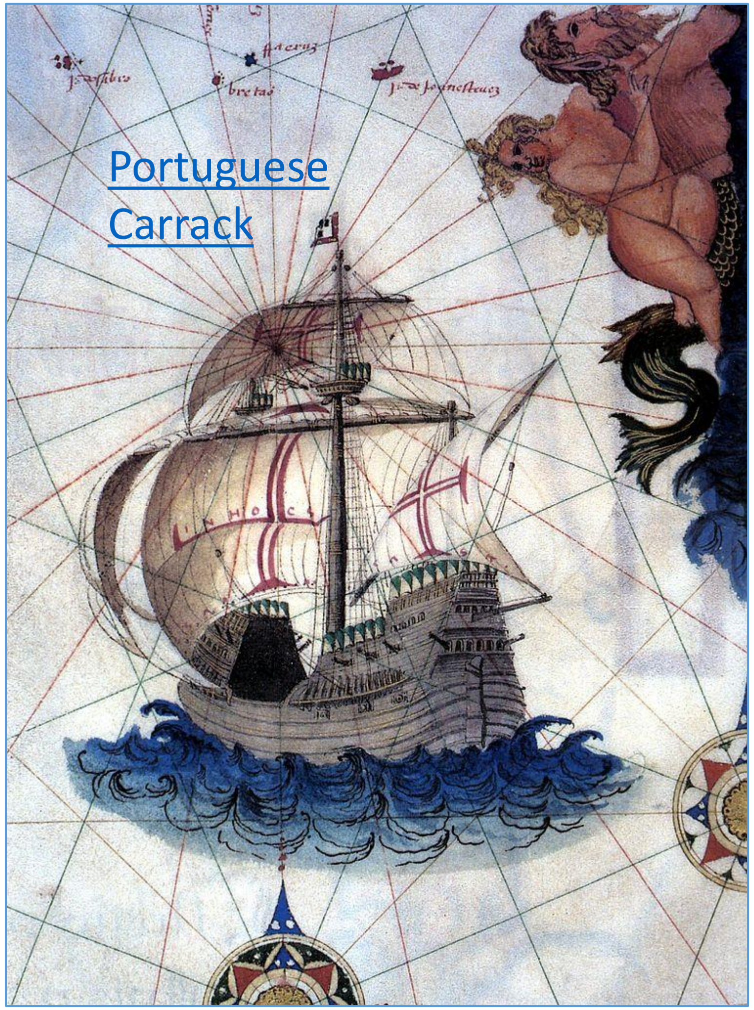


Mariner's Astrolabe



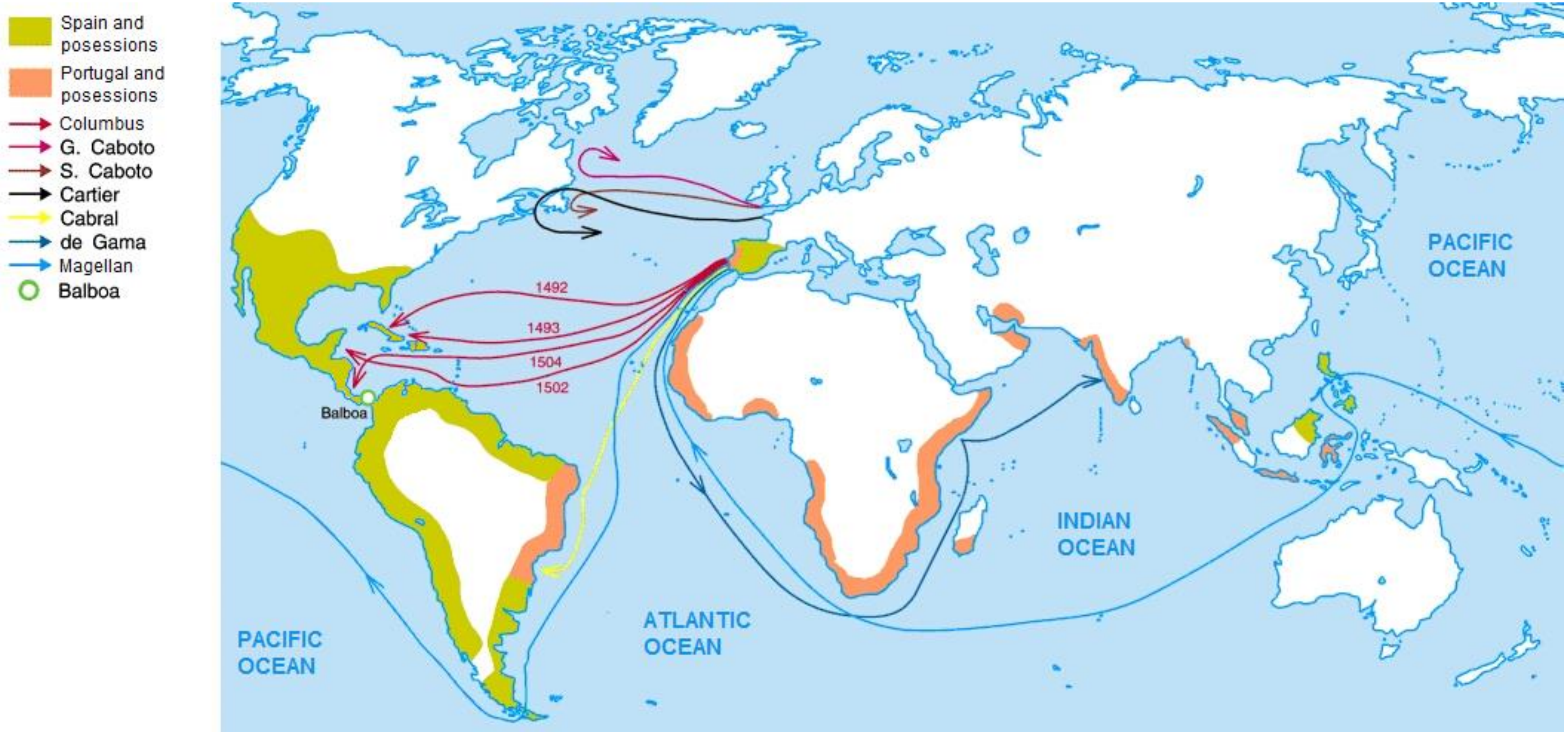
Gimbal Compass

Cantino planisphere (1502)



Portuguese Carrack

Thus it begins: Charting the Early Voyages during the Age of Discovery, c.1492-1522 . . .



[Wiki Commons]

Exploration rates escalated as mass-communication by printing also spread in the late-1400s, enabling adventurers to ever more quickly propagate news of what they'd found and how they'd found it . . .

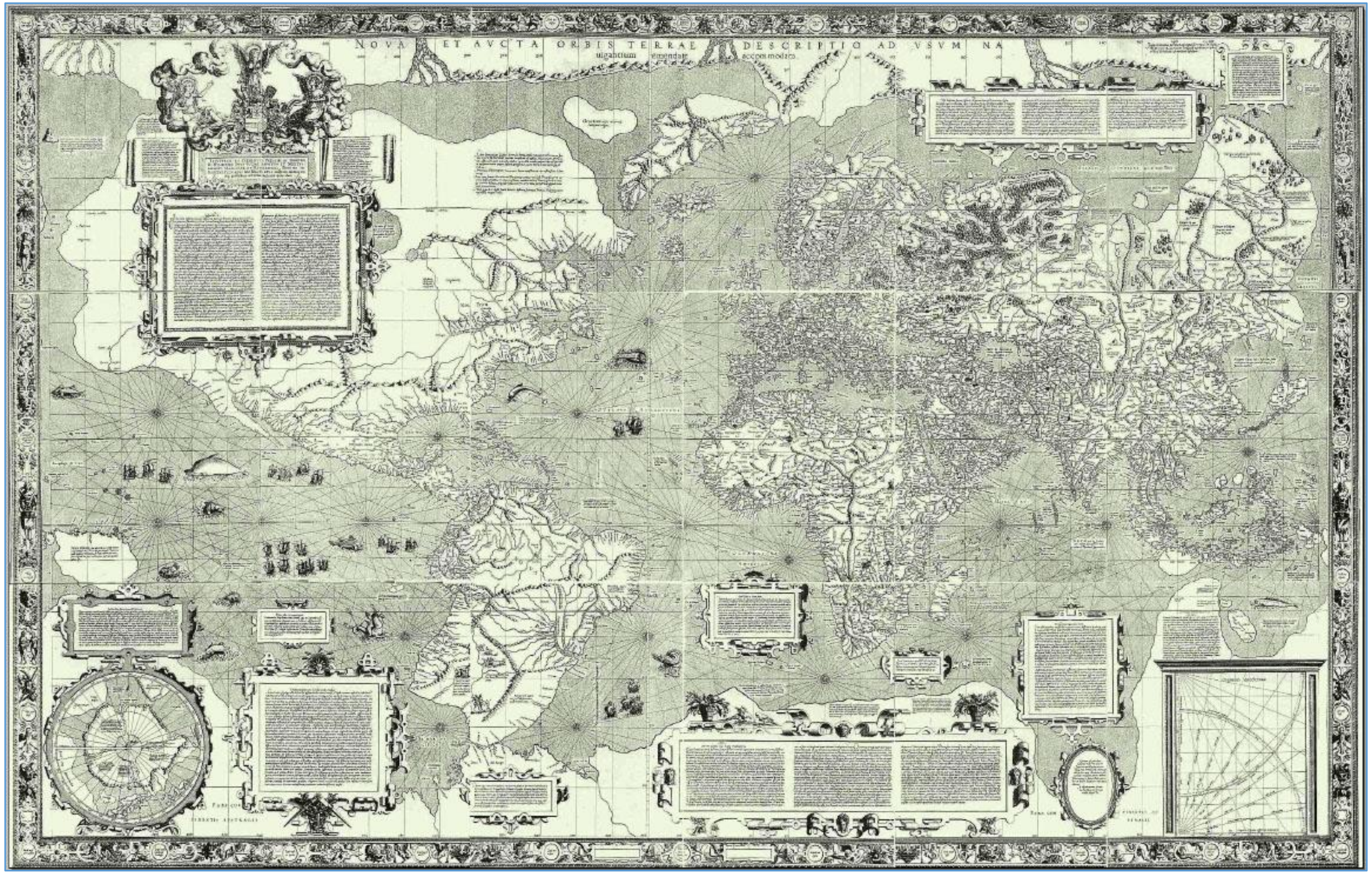
Replica Gutenberg Press at the Featherbed Alley Printshop Museum:

Link; Attribution: Aodhdubh at English Wikipedia

The escalation is evidenced, a generation later,
in Diogo Ribeiro's much-more-detailed World Map as of 1527 . . .

Wiki Commons

And two generations later, in Mercator’s projection-map of 1569 . . .



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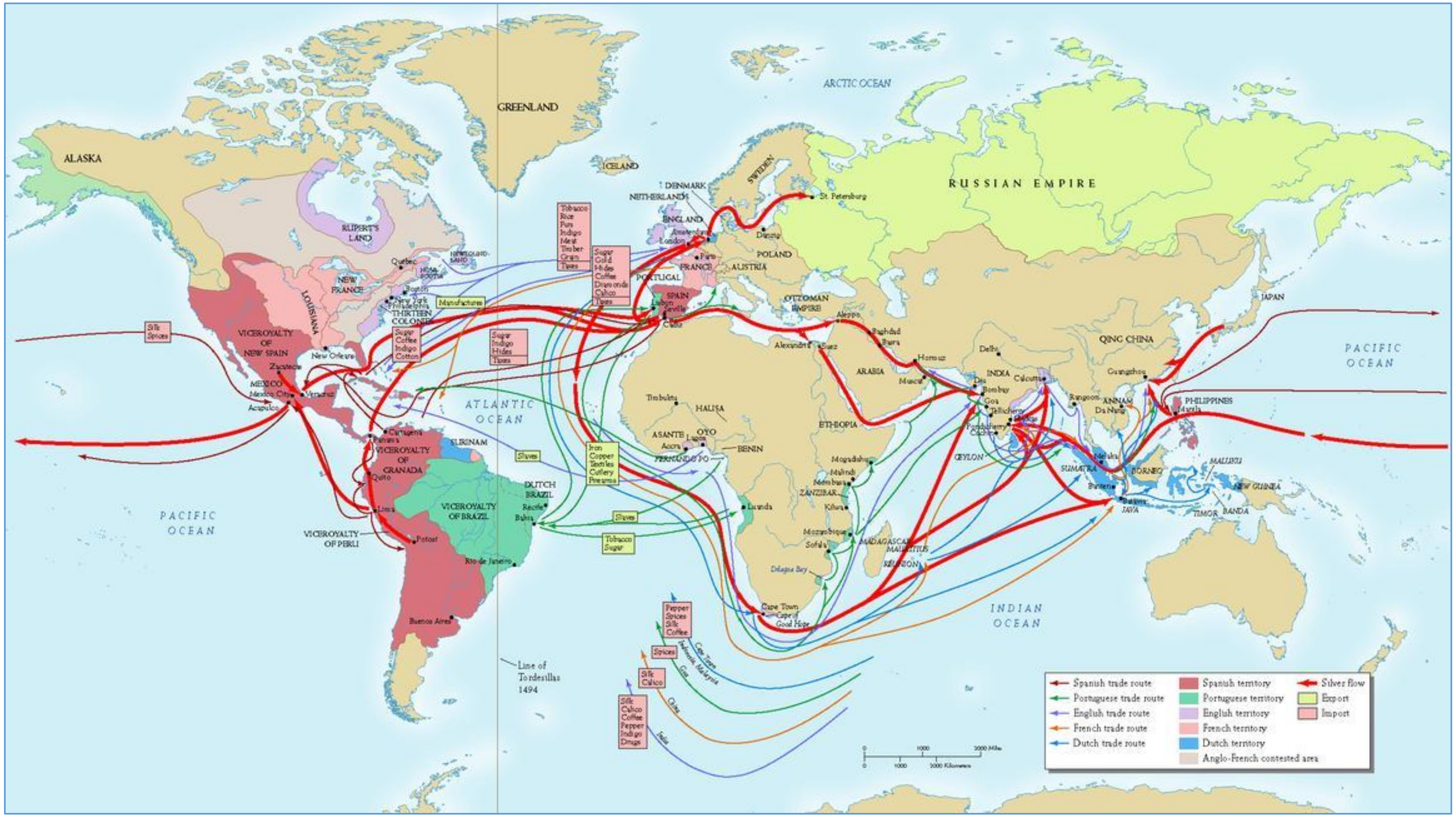
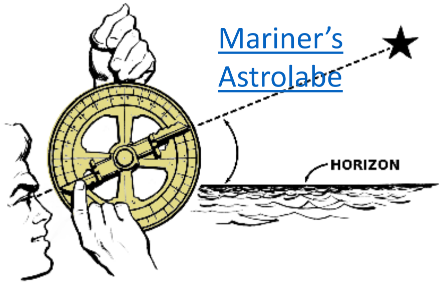
By the early 1700's, exponentiation had generated a massive global trading system . . .



Source

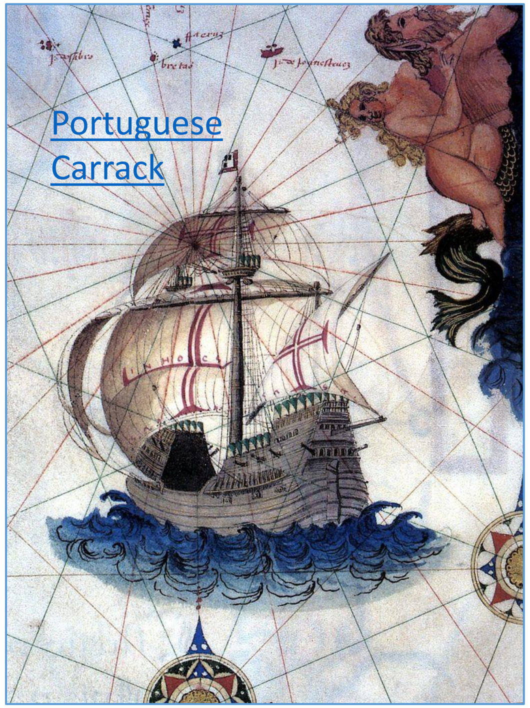
Now, what' happening here?
Just exponentiation of THINGS?
Is that all it is?

Or exponentiation of key clusters of innovative IDEAS in the minds of ever more people?
IDEAS on how to MAKE and USE things . . .



Mariner's Astrolabe


Gimbal Compass


Portuguese Carrack

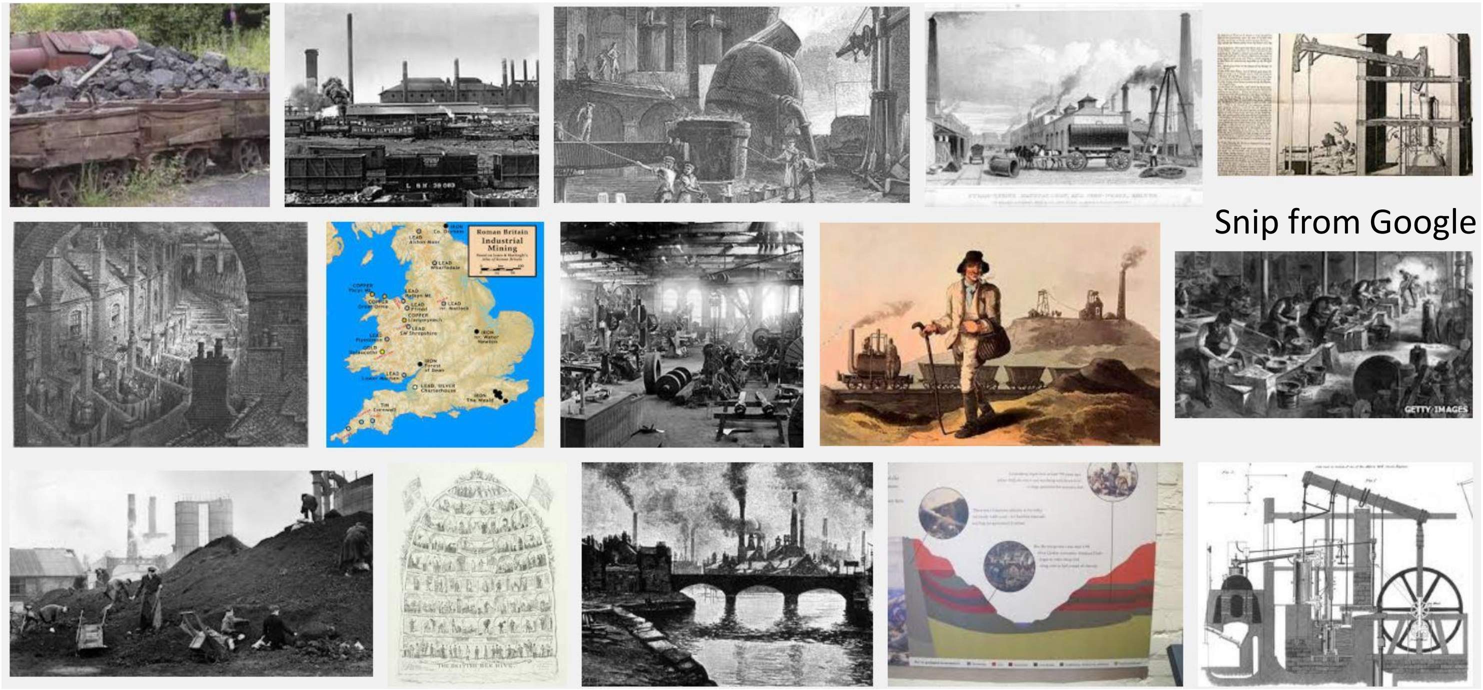

Link
Attribution: Aodhdubh at English Wikipedia


Cantino planisphere (1502)

By the mid-1700’s, the stage was set for a tremendous disruptive wave of technological innovation,
and so began the industrial revolution (~1760-1850) . . .

Link

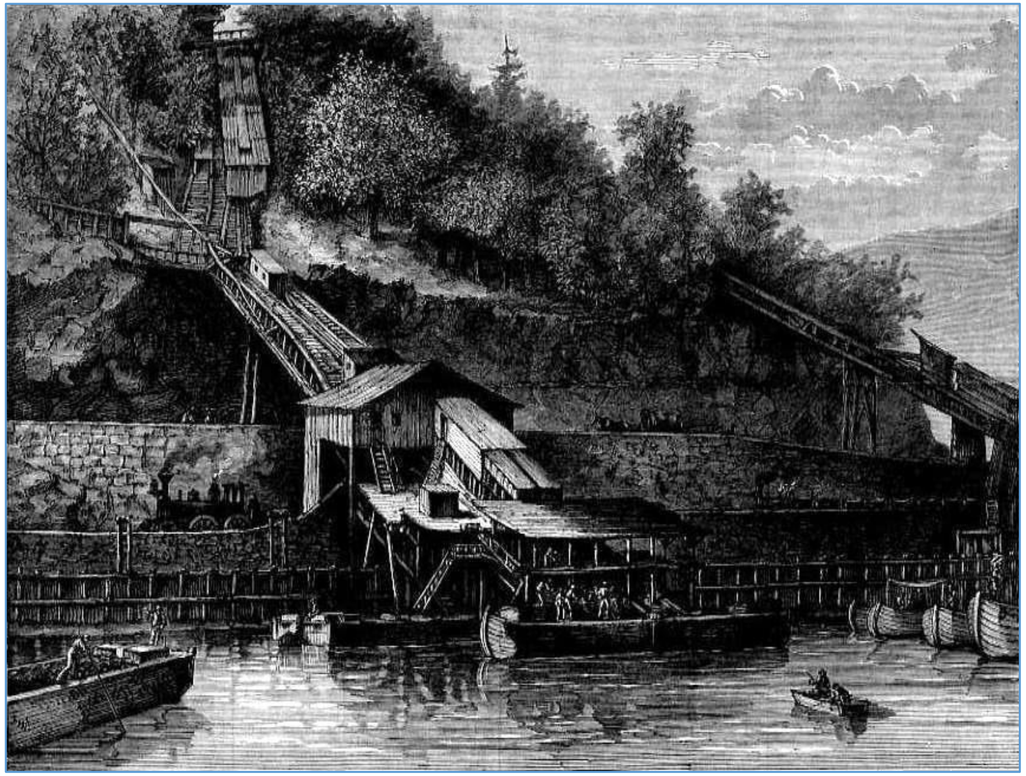
During the Industrial Revolution the mining of
coal and iron-ore was greatly amplified by steam-power . . .



Snip from Google Images

Some of the resulting iron was used to make more steam engines,
and the positive feedback generated an iterative expansion-process . . .

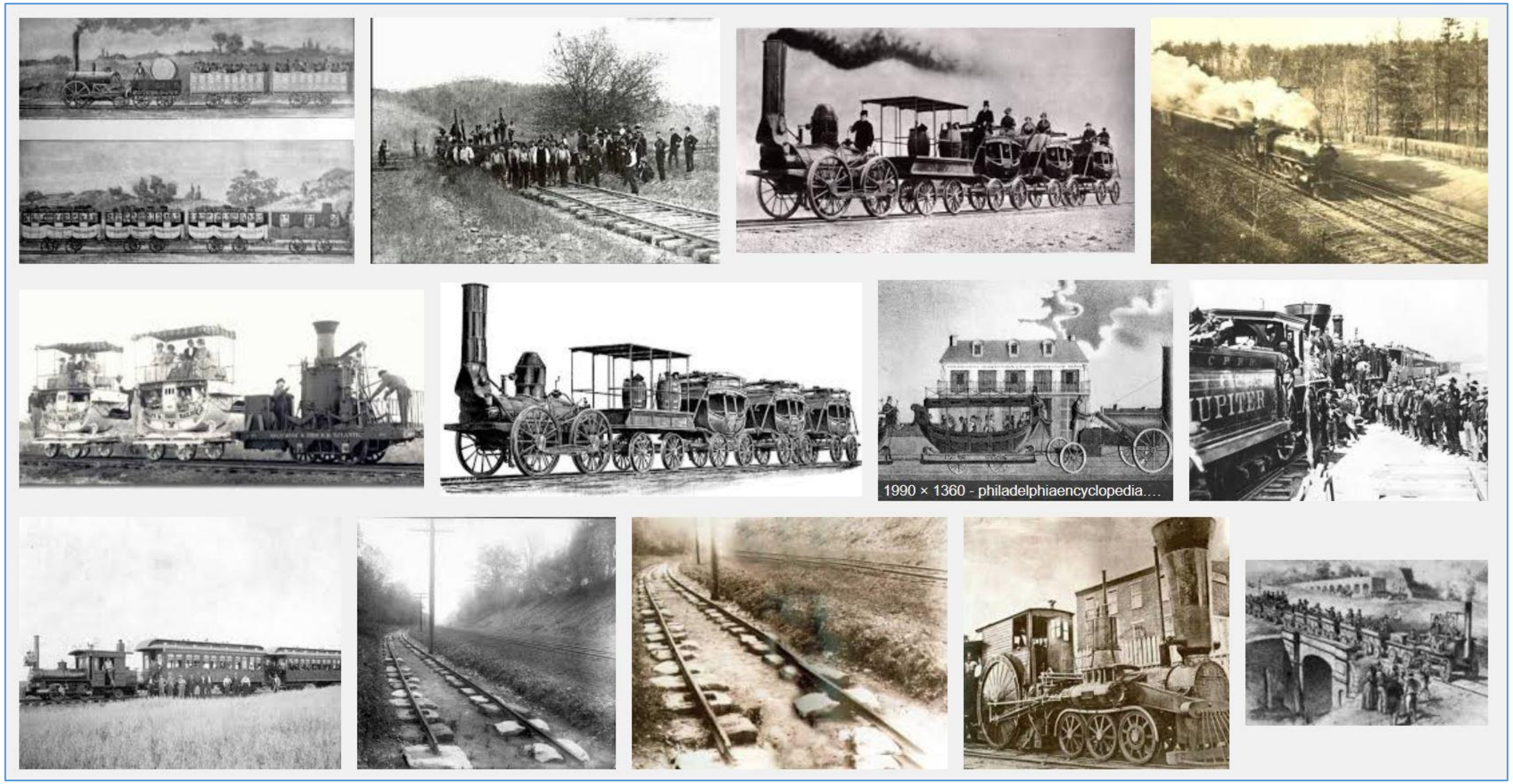
Initially, heavy industrial raw materials and products were transported using the expanding canal system:



Loading coal on the LehighCanal Wiki Commons

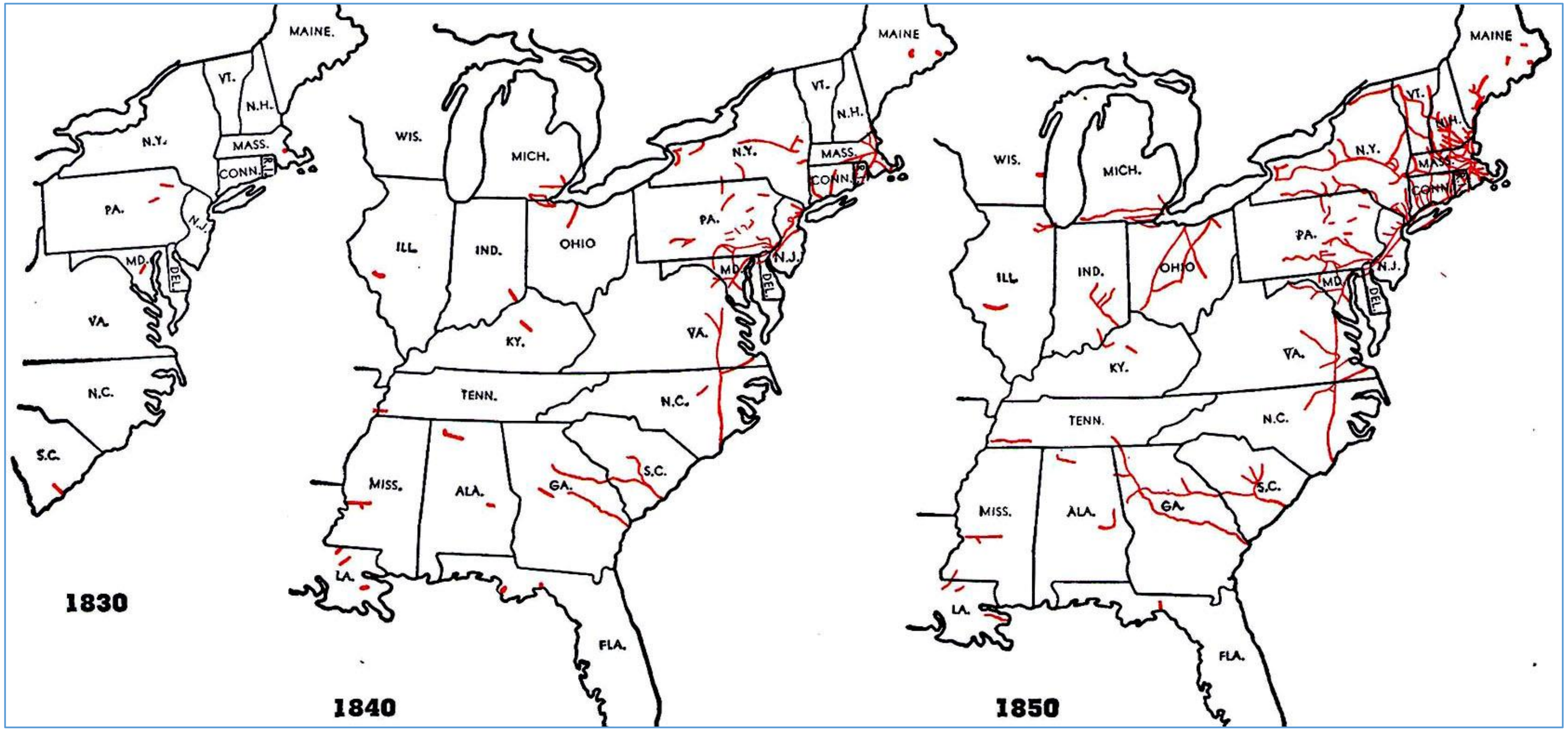
Wiki Commons

By the 1830's, steam-powered railroads began interconnecting mines to iron-works and rail-makers, enabling more-rapid expansion of railroads . . .



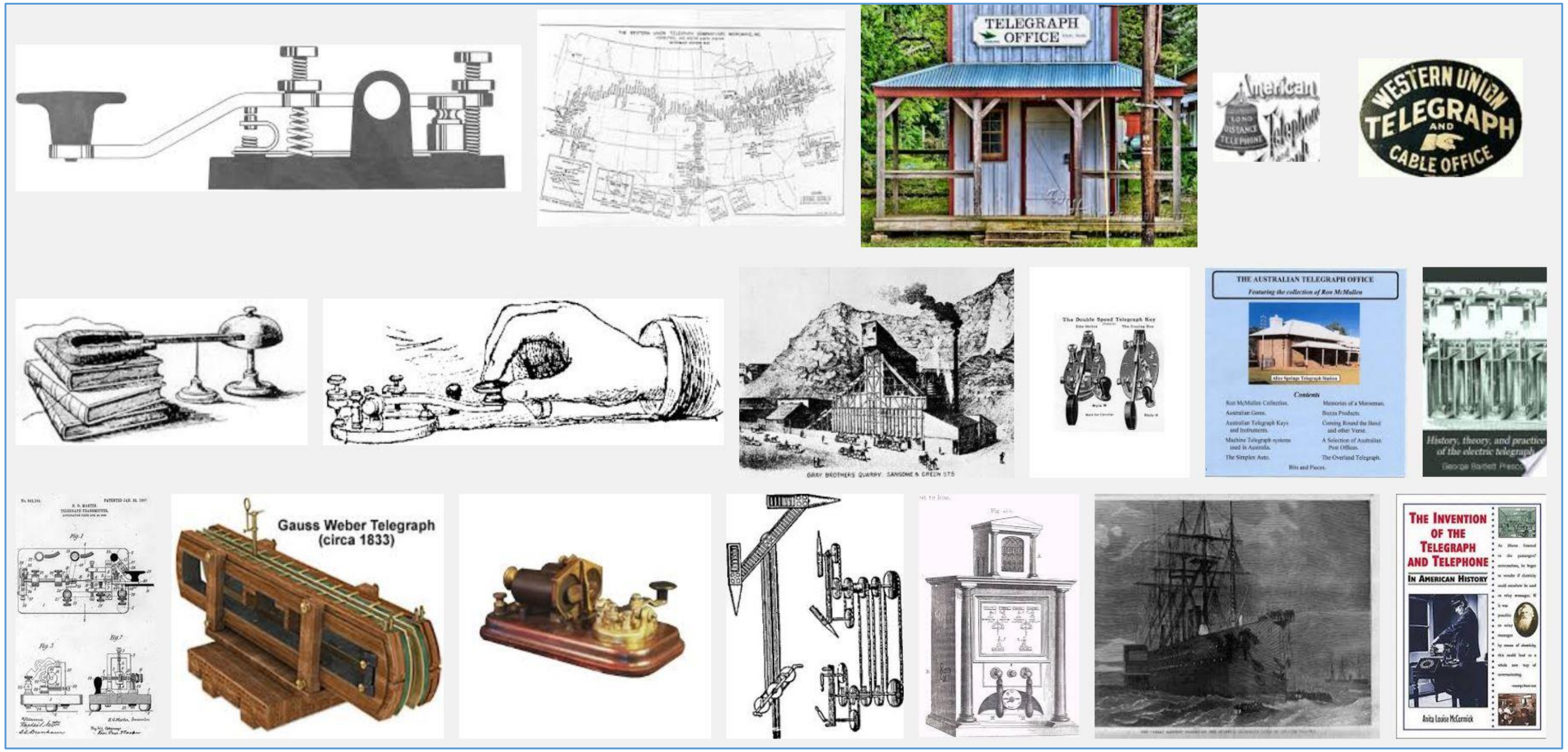
Snip from Google Images

These charts reveal the rapid early spread of railroading in the US . . .



http://www.cprr.org/Museum/RR_Development.html#2

The expansion was accelerated by rapid spread of telegraphy in the 1850s, the effect analogous to that of printing in the age of discovery . . .



(Snip from Google Images)

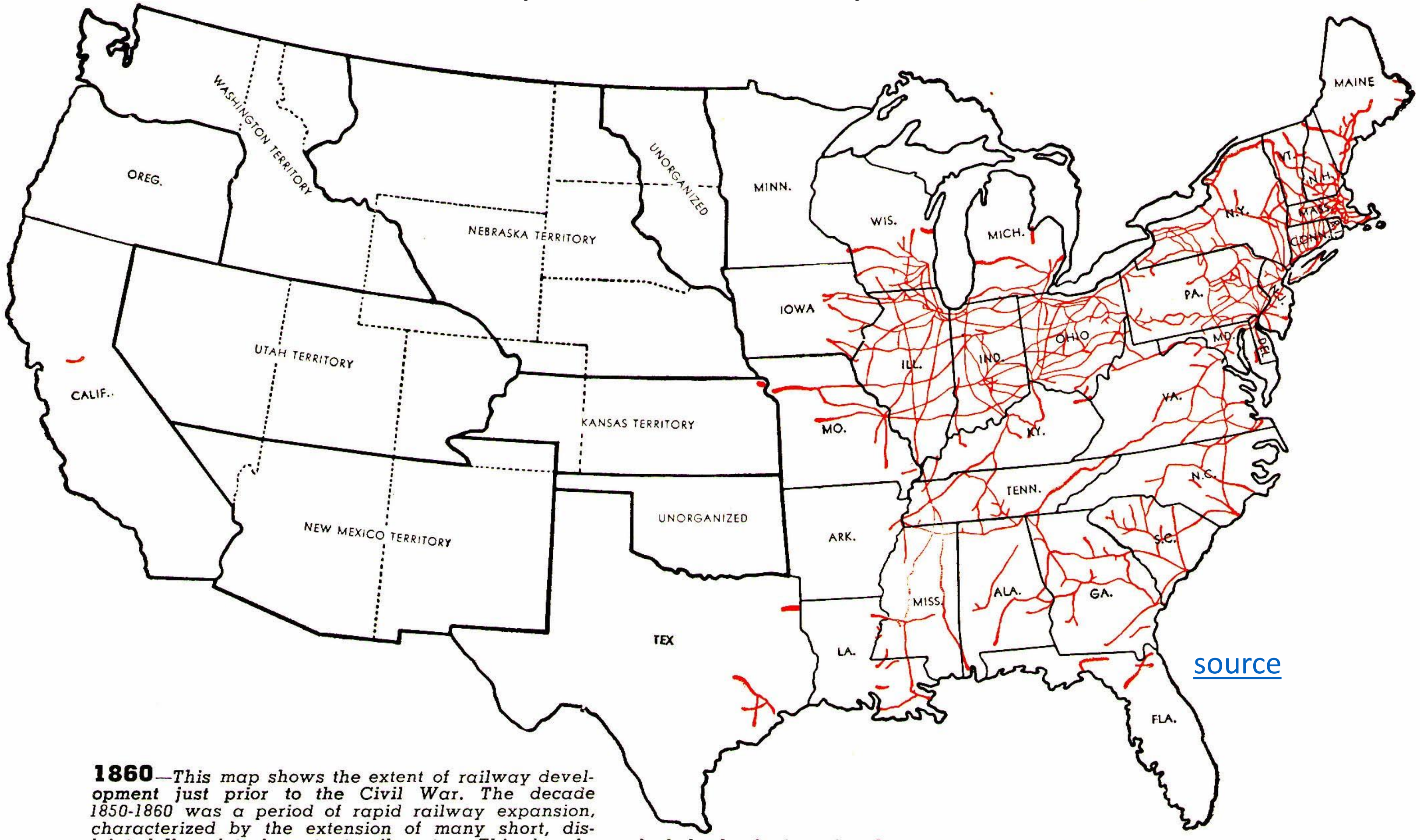
Map of telegraph stations in the United States, Canada and Nova Scotia, 1853

http://www.telegraph-history.org/
http://www.telegraph-history.org/map2.htm

Zooming into the map of telegraph stations in 1853 . . .

http://www.telegraph-history.org/map2.htm

The much expanded railroad system, as of 1860 . . .



source

1860—*This map shows the extent of railway development just prior to the Civil War. The decade 1850-1860 was a period of rapid railway expansion, characterized by the extension of many short, disjointed lines into important rail routes. This decade marked the beginning of railway development in the region west of the Mississippi River. By 1860, the "Iron Horse" had penetrated westward to the Missouri River and was beginning to make itself felt in Iowa, Arkansas, Texas, and California.*

All that set the stage for another disruptive wave of innovation, and the Second Industrial Revolution began in the 1860s/70s . . .

The Second Industrial Revolution* was characterized by

(1) the build out of railroads

(2) large scale iron and steel production

(3) widespread use of machinery in manufacturing

(4) greatly increased use of steam power

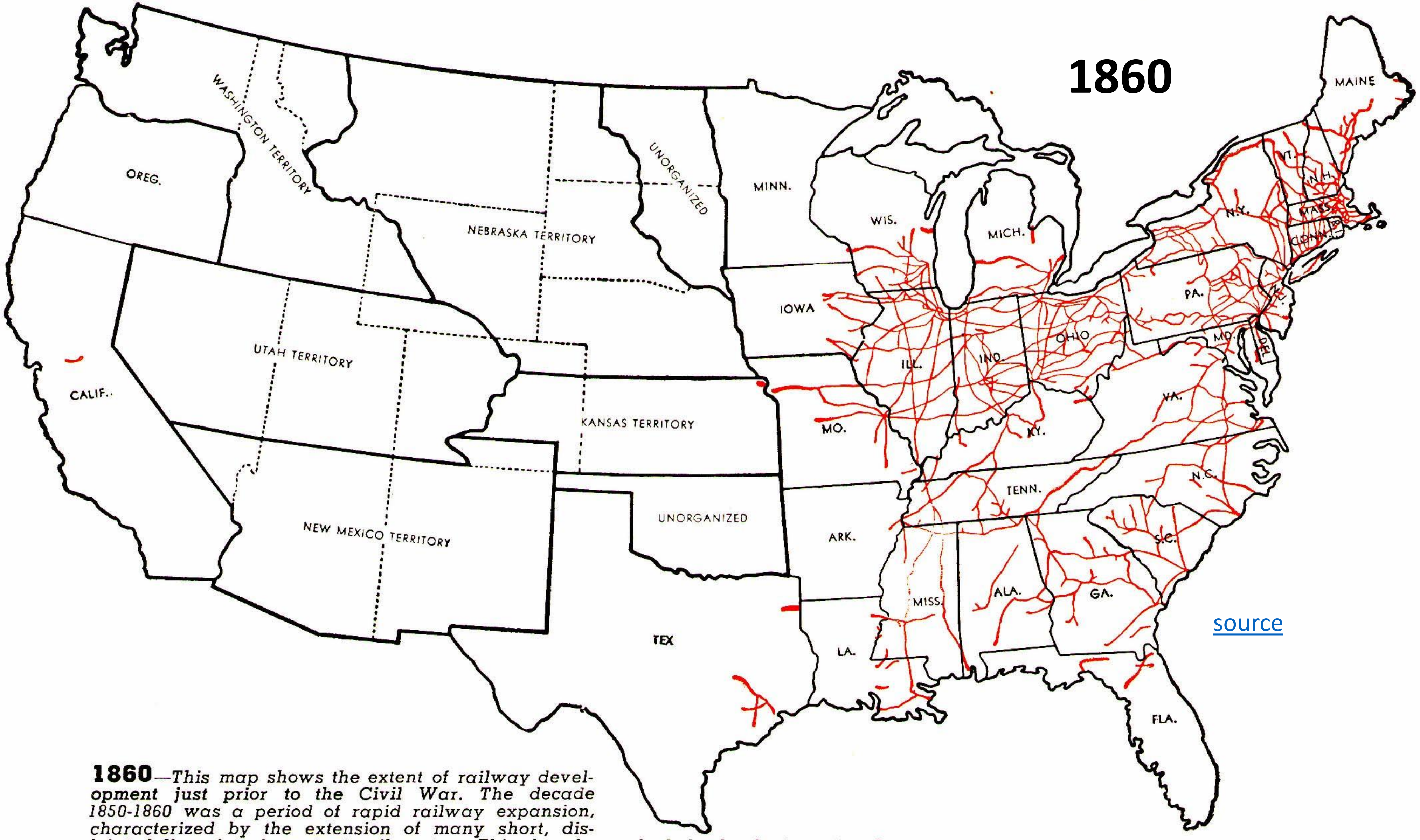
(5) use of oil

(6) beginning of electricity

(7) electrical communications – *Wikipedia*

Let's first zoom-in and follow the progress of the "build out of the railroads" from 1860 – 1890 . . .

1860



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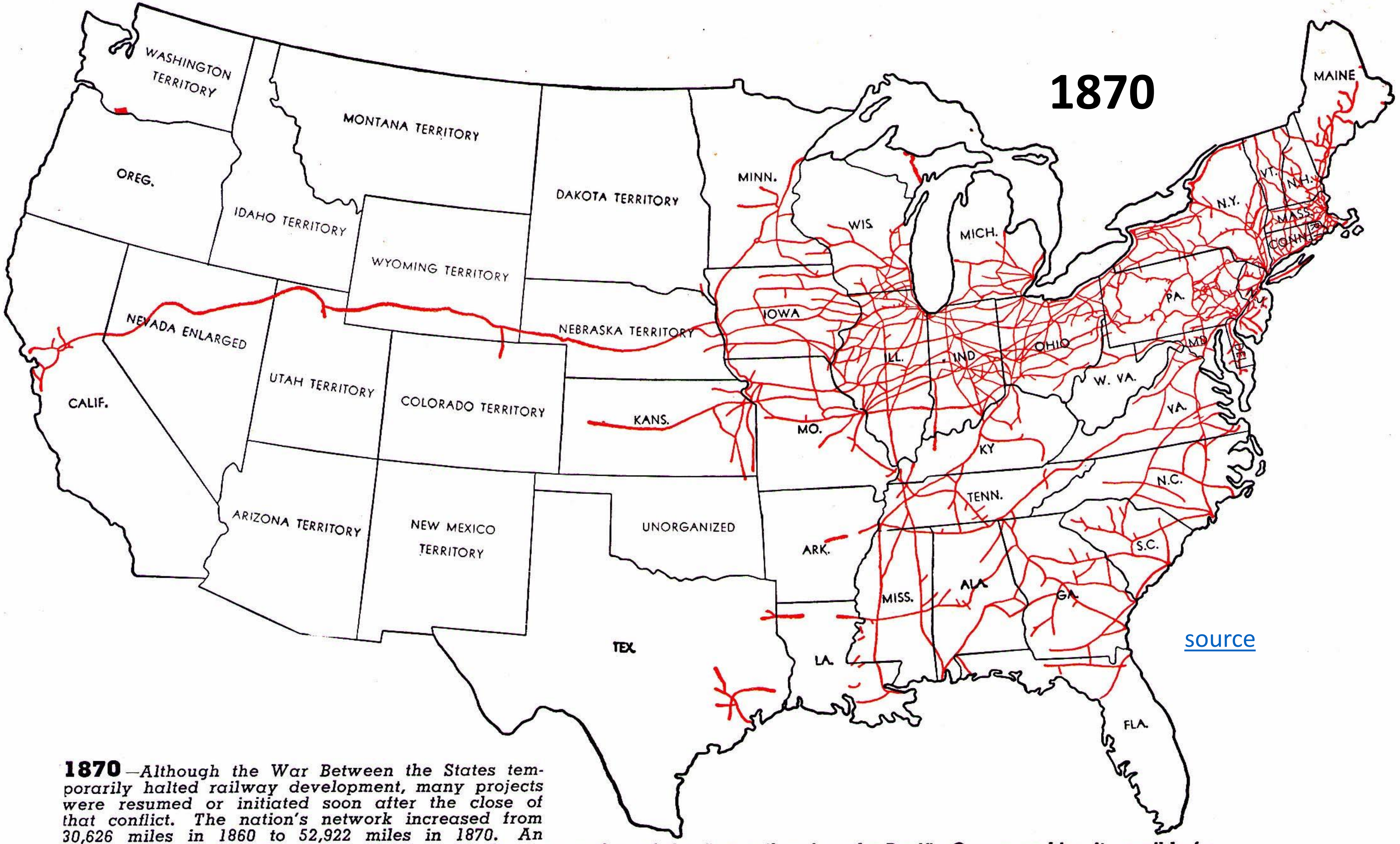
source

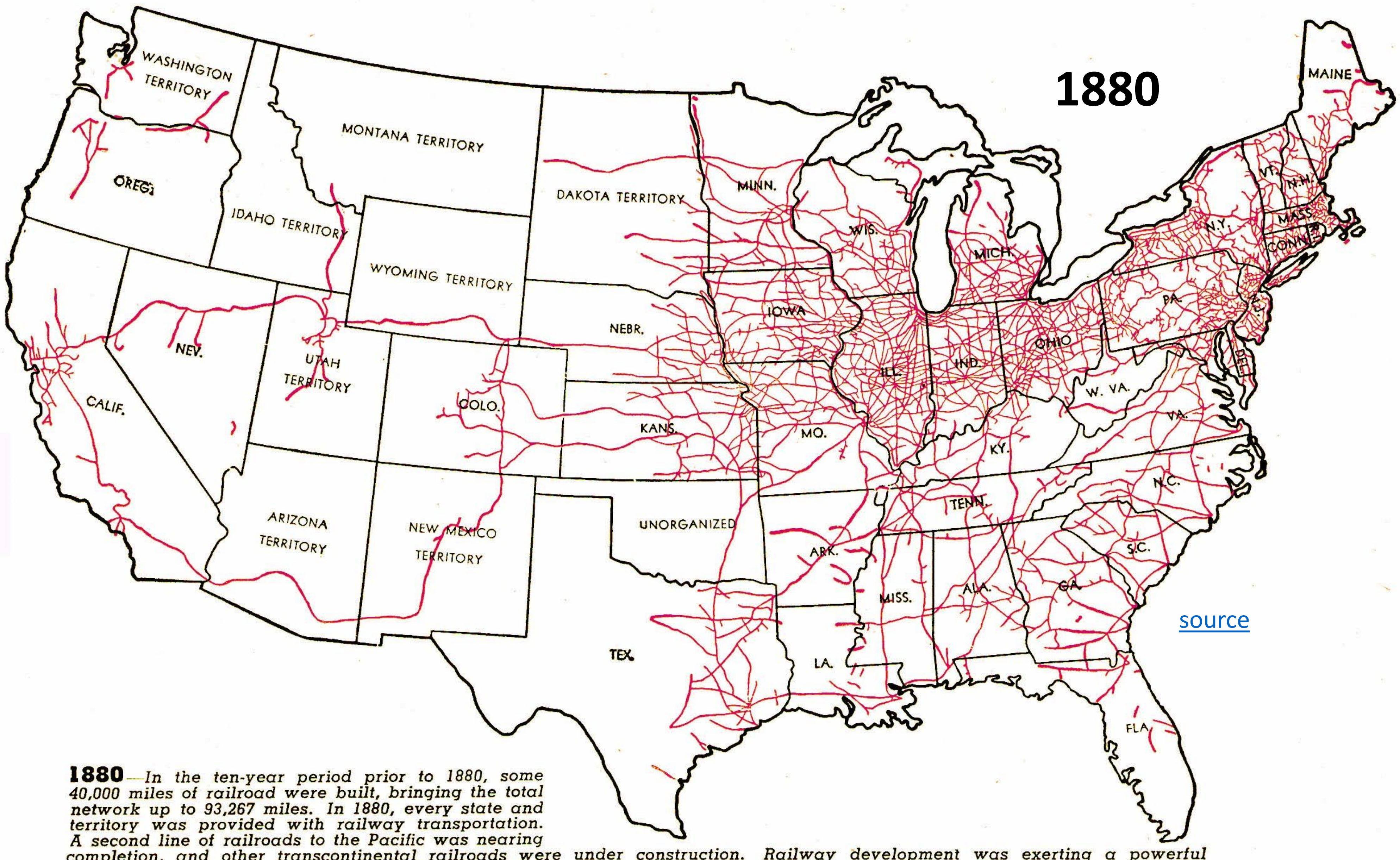
1870



1870—*Although the War Between the States temporarily halted railway development, many projects were resumed or initiated soon after the close of that conflict. The nation's network increased from 30,626 miles in 1860 to 52,922 miles in 1870. An outstanding development of the decade was the construction of the first railroad to the Pacific Ocean, making it possible for the first time to travel all the way across the country by rail. Railway development in the Mississippi and Missouri valleys was especially notable during this period.*

source

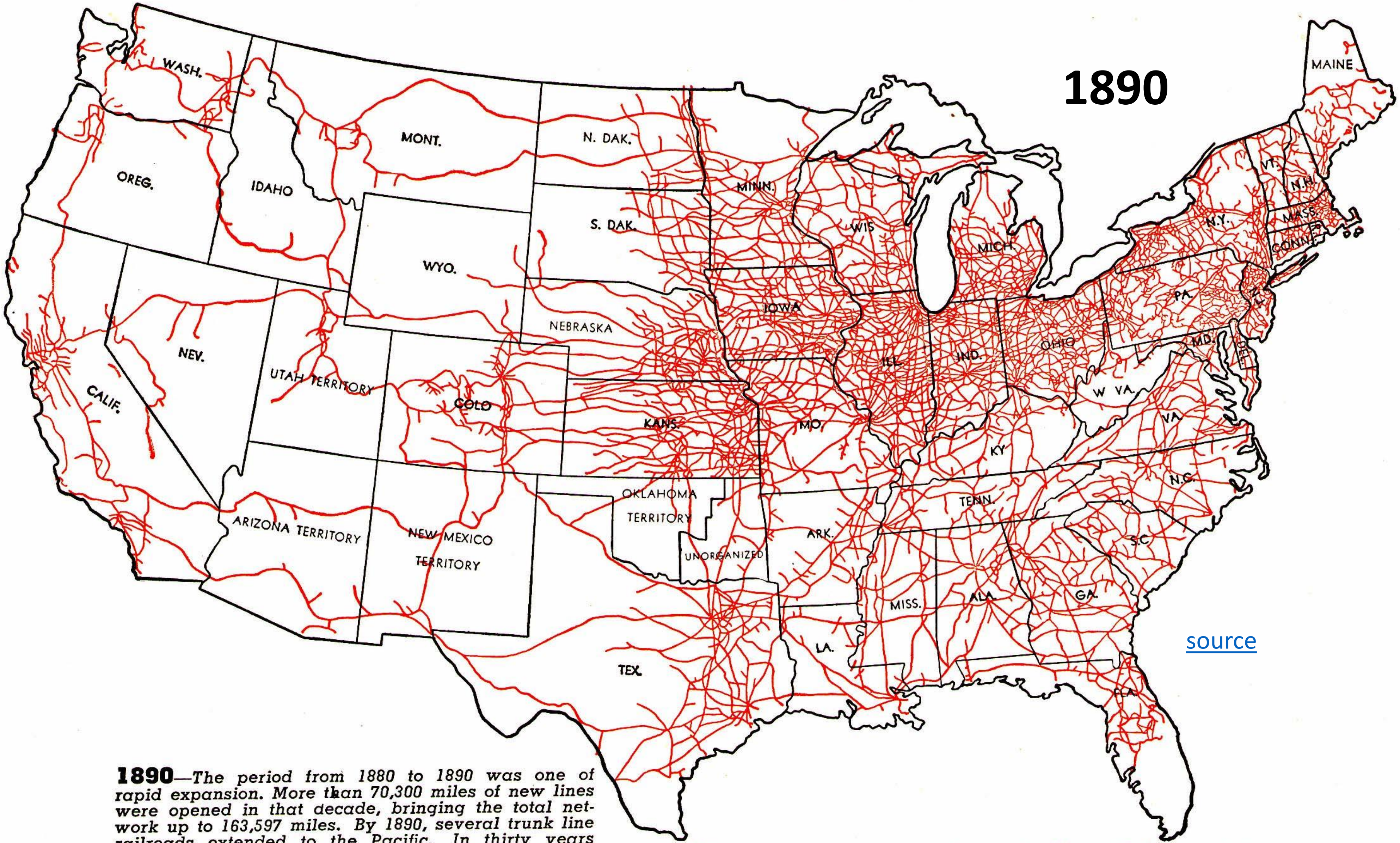
1880



1880—*In the ten-year period prior to 1880, some 40,000 miles of railroad were built, bringing the total network up to 93,267 miles. In 1880, every state and territory was provided with railway transportation. A second line of railroads to the Pacific was nearing completion, and other transcontinental railroads were under construction. Railway development was exerting a powerful influence upon immigration and agricultural and industrial growth throughout the country.*

source

1890

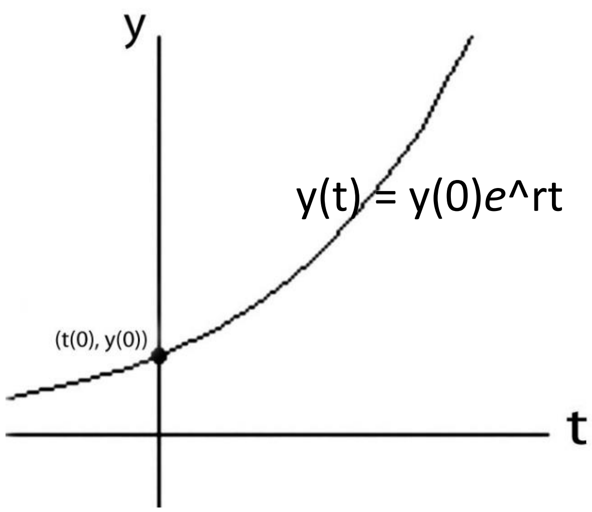


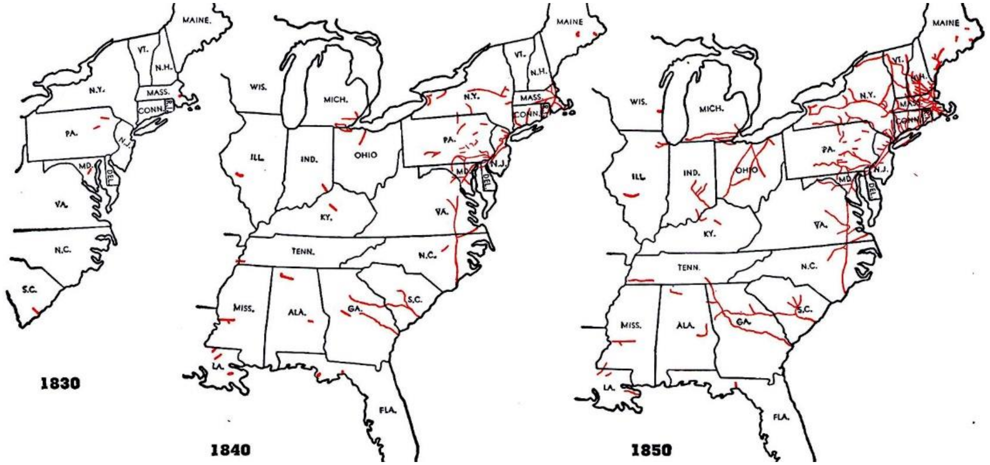
1890—*The period from 1880 to 1890 was one of rapid expansion. More than 70,300 miles of new lines were opened in that decade, bringing the total network up to 163,597 miles. By 1890, several trunk line railroads extended to the Pacific. In thirty years from 1860 to 1890, the total mileage of the region west of the Mississippi River increased from 2,175 to 72,389, and the population of that area increased fourfold.*

source

Like compound interest, the early social-diffusion rate of such clusters of technological ideas is approximately proportional to what's already there at any given point in time . . .

(i.e., exponential function):





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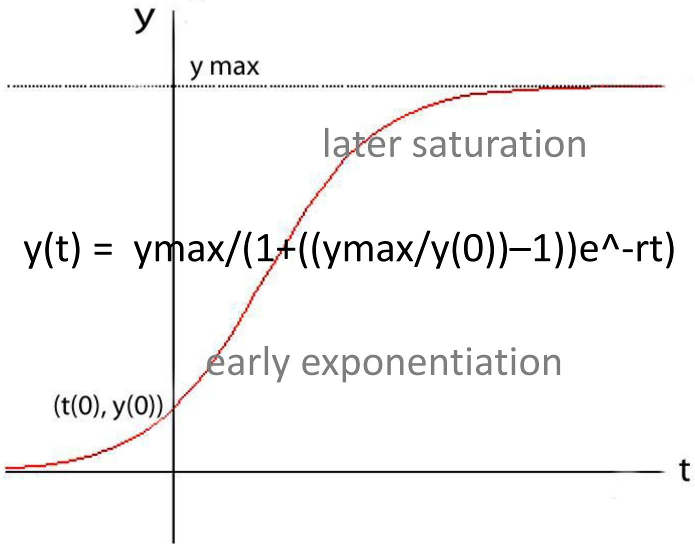
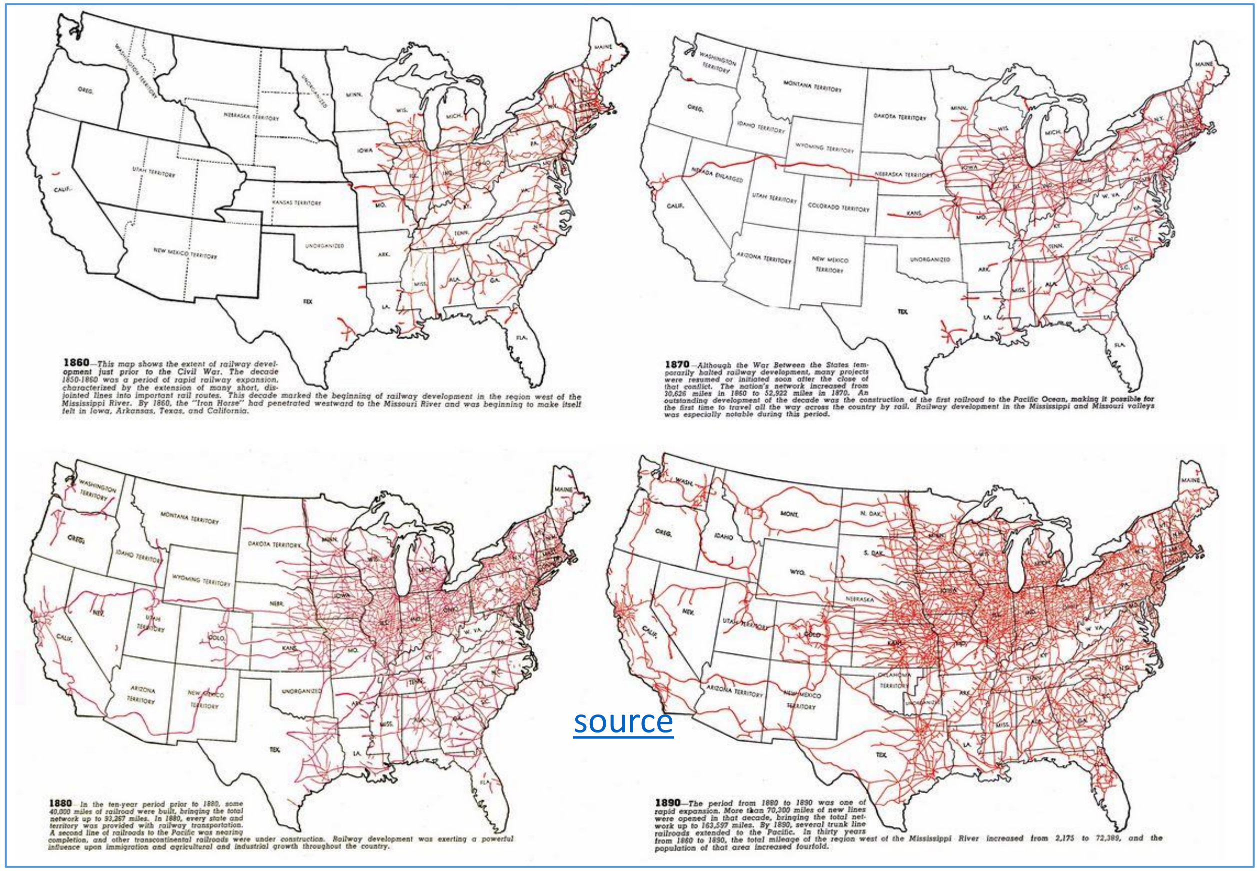
source

But as the opportunity-space fills, the diffusion rate of technological ideas slows as the cluster nears its expansion limits . . .

(i.e., logistic function):



$y(t) = ymax/(1+((ymax/y(0))-1))e^{-rt})$



Let's visualize the harnessing "electricity" by the 1890's:

Electric generators, motors and lights were being embedded in a rapidly-expanding electrically-empowered industrial, commercial and transportation infrastructure.

Names such as Edison, Westinghouse, Tesla, Steinmetz and Sprague were becoming famous for roles in creating the newly-spreading technologies.

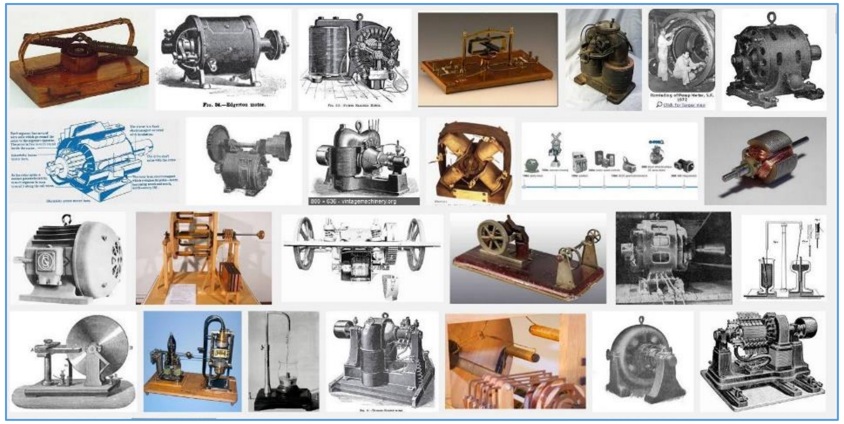
And the alternating vs direct (AC vs DC) "war of the currents" was on . . .

The dramatic story of that era is revealed in detail in the website, displays and resources of the Edison Tech Center here in Schenectady.

Visualizing the spread of electrification, and it's co-evolution with the spread of electric traction subways and interurban light-rail systems . . .

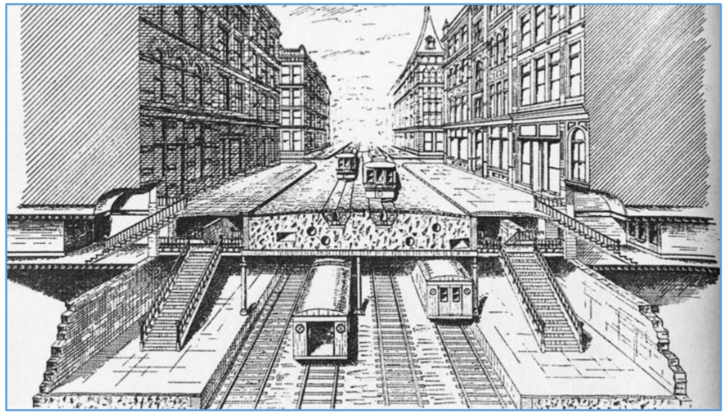
Generators

Motors



Interurban rail

Subways



Planning the IRT, 1891

Now let's zoom-in and look at the special role of Steinmetz in the AC revolution . . .

Encyclopedia Brittanica:

1892:

“Steinmetz’ experiments . . . led to his first important work, the law of hysteresis.

. . . Until that time the power losses in motors, generators, transformers, and other electrically powered machines could be known only after they were built.

Once Steinmetz had found the law . . . engineers could calculate and minimize losses of electric power . . . before starting the construction of such machines . . .

His work was immediately recognized as a classic . . . Steinmetz’ reputation was assured at the age of 27.”

1893:

"His second contribution was . . . a symbolic method of calculating alternating-current phenomena and in so doing simplified an extremely complicated and barely understood field so that the average engineer could work with alternating current.

This accomplishment was largely responsible for the rapid progress made in the commercial introduction of alternating-current apparatus . . .

The problem that Steinmetz faced was that electrical engineers were not taught enough mathematics to understand his new mathematical treatment of problems using complex numbers.

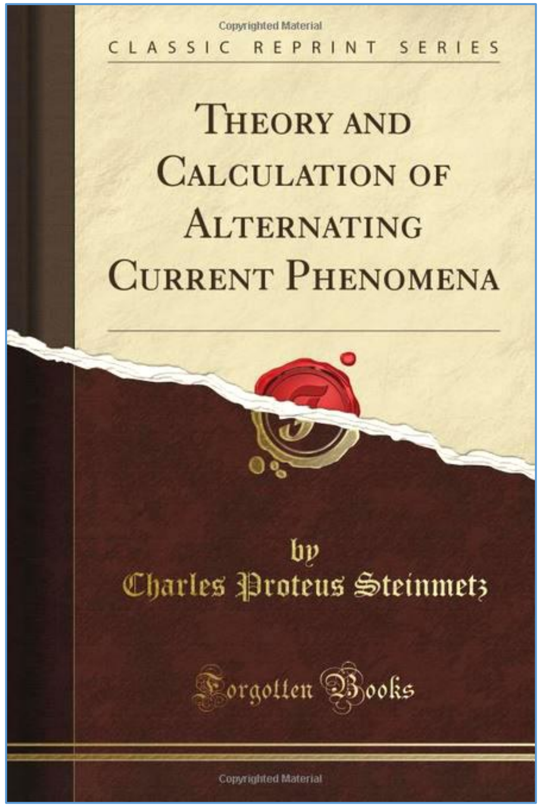
1897-1911:

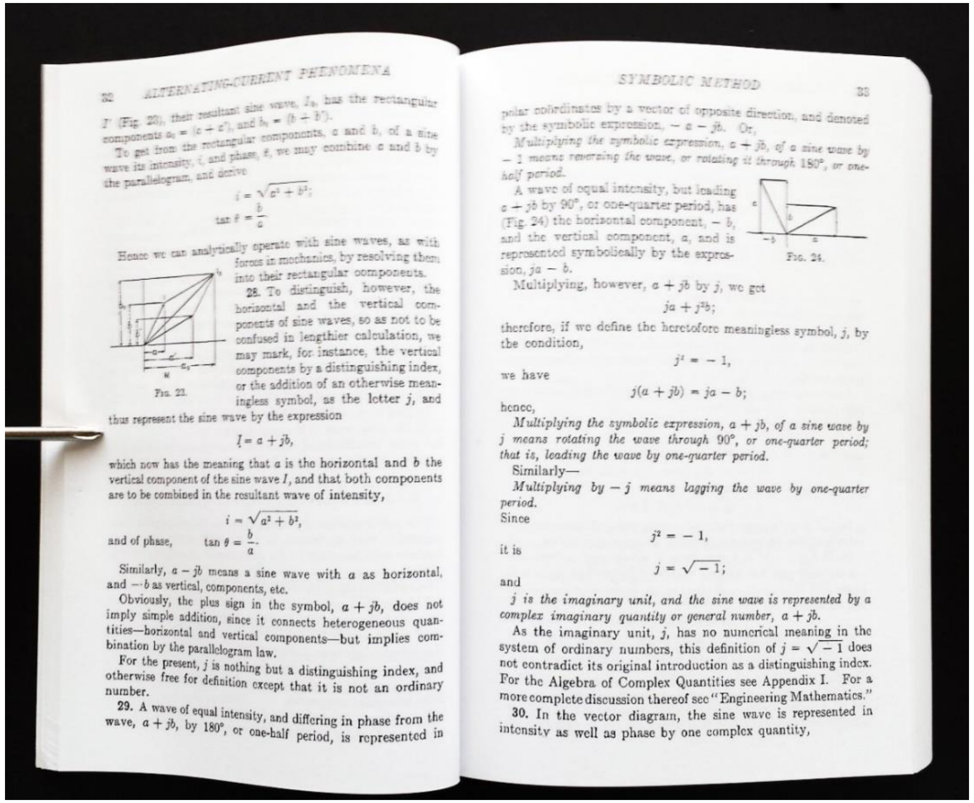
To educate the electrical engineering profession, he published several textbooks . . . through his writing, lecturing, and teaching*, his method of calculation with complex numbers was universally adopted in work with alternating currents."

*at Union College

Encyclopedia Brittanica

Steinmetz's symbolic mathematical methods that enabled large numbers of engineers to easily "navigate" the world of AC electricity:





32 ALTERNATING-CURRENT PHENOMENA

I' (Fig. 23), their resultant sine wave, I_0, has the rectangular components $a_0 = (a + a')$, and $b_0 = (b + b')$.

To get from the rectangular components, a and b, of a sine wave its intensity, i, and phase, θ, we may combine a and b by the parallelogram, and derive

$$i = \sqrt{a^2 + b^2};$$

$$\tan \theta = \frac{b}{a}.$$

Hence we can analytically operate with sine waves, as with forces in mechanics, by resolving them into their rectangular components.

Fig. 23.

28. To distinguish, however, the horizontal and the vertical components of sine waves, so as not to be confused in lengthier calculation, we may mark, for instance, the vertical components by a distinguishing index, or the addition of an otherwise meaningless symbol, as the letter j, and thus represent the sine wave by the expression

$$I = a + jb,$$

which now has the meaning that a is the horizontal and b the vertical component of the sine wave I, and that both components are to be combined in the resultant wave of intensity,

$$i = \sqrt{a^2 + b^2},$$

and of phase, $\tan \theta = \frac{b}{a}$.

Similarly, $a - jb$ means a sine wave with a as horizontal, and $-b$ as vertical, components, etc.

Obviously, the plus sign in the symbol, $a + jb$, does not imply simple addition, since it connects heterogeneous quantities—horizontal and vertical components—but implies combination by the parallelogram law.

For the present, j is nothing but a distinguishing index, and otherwise free for definition except that it is not an ordinary number.

29. A wave of equal intensity, and differing in phase from the wave, $a + jb$, by 180°, or one-half period, is represented in

SYMBOLIC METHOD 33

polar coördinates by a vector of opposite direction, and denoted by the symbolic expression, $-a - jb$. Or,

Multiplying the symbolic expression, $a + jb$, of a sine wave by -1 means reversing the wave, or rotating it through 180°, or one-half period.

A wave of equal intensity, but leading $a + jb$ by 90°, or one-quarter period, has (Fig. 24) the horizontal component, $-b$, and the vertical component, a, and is represented symbolically by the expression, $ja - b$.

Fig. 24.

Multiplying, however, $a + jb$ by j, we get

$$ja + j^2b;$$

therefore, if we define the heretofore meaningless symbol, j, by the condition,

$$j^2 = -1,$$

we have

$$j(a + jb) = ja - b;$$

hence,

Multiplying the symbolic expression, $a + jb$, of a sine wave by j means rotating the wave through 90°, or one-quarter period; that is, leading the wave by one-quarter period.

Similarly—

Multiplying by $-j$ means lagging the wave by one-quarter period.

Since

$$j^2 = -1,$$

it is

$$j = \sqrt{-1};$$

and

j is the imaginary unit, and the sine wave is represented by a complex imaginary quantity or general number, $a + jb$.

As the imaginary unit, j, has no numerical meaning in the system of ordinary numbers, this definition of $j = \sqrt{-1}$ does not contradict its original introduction as a distinguishing index. For the Algebra of Complex Quantities see Appendix I. For a more complete discussion thereof see "Engineering Mathematics."

30. In the vector diagram, the sine wave is represented in intensity as well as phase by one complex quantity,

In doing this work, Steinmetz also pioneered in the emergence of 20th century methods in engineering science and engineering education . . .

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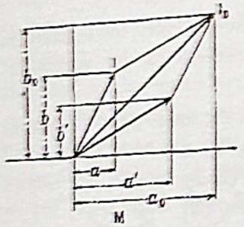
Hence we can analytically operate with sine waves, as with forces in mechanics, by resolving them into their rectangular components.



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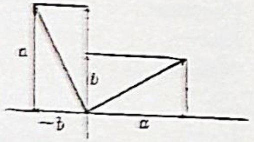

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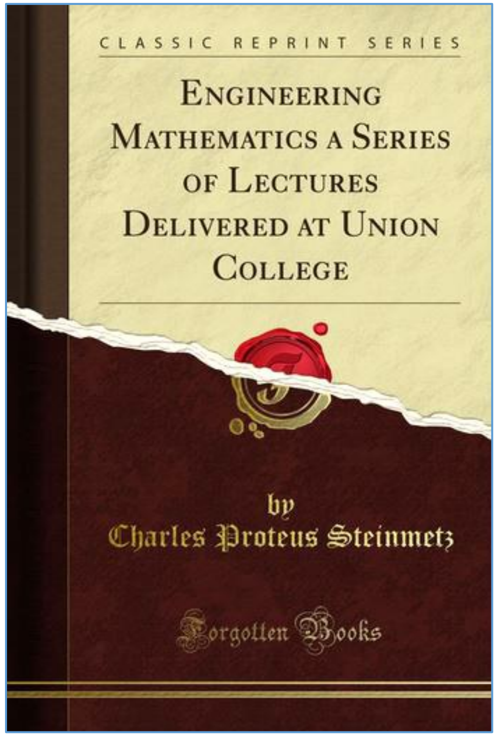
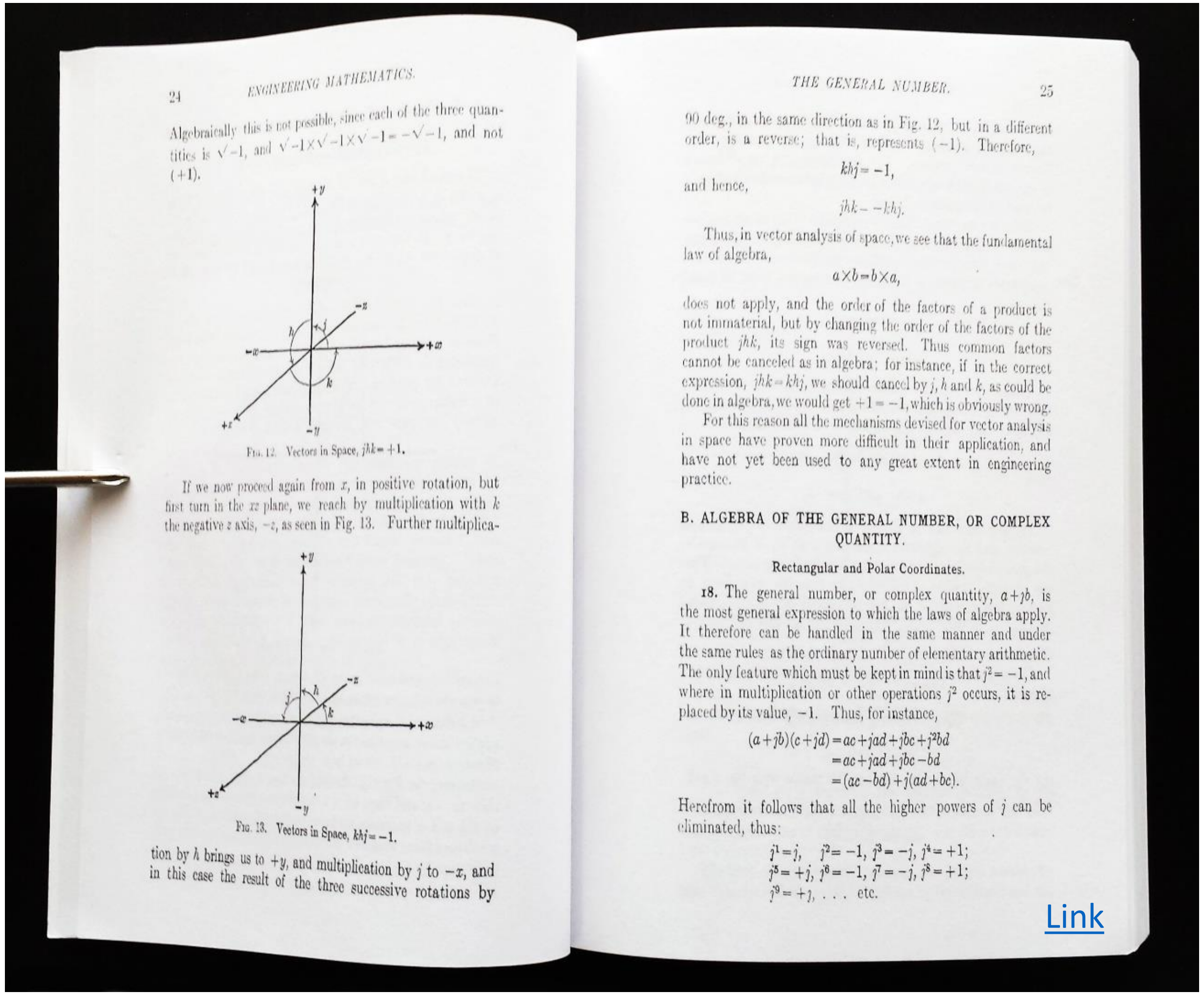
He also masterfully unfolded the abstract mathematics behind his symbolic methods . . .





Link

Algebraically this is not possible, since each of the three quantities is $\sqrt{-1}$, and $\sqrt{-1}\times\sqrt{-1}\times\sqrt{-1}=-\sqrt{-1}$, and not (+1).

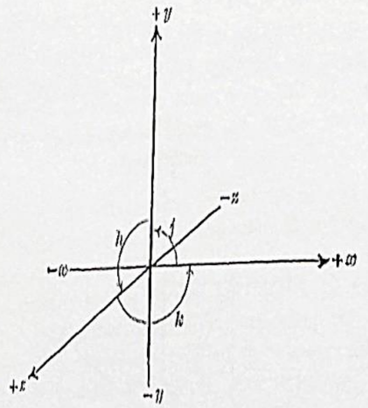


FIG. 12. Vectors in Space, $jhk=+1$.

If we now proceed again from x, in positive rotation, but first turn in the xz plane, we reach by multiplication with k the negative z axis, $-z$, as seen in Fig. 13. Further multiplica-

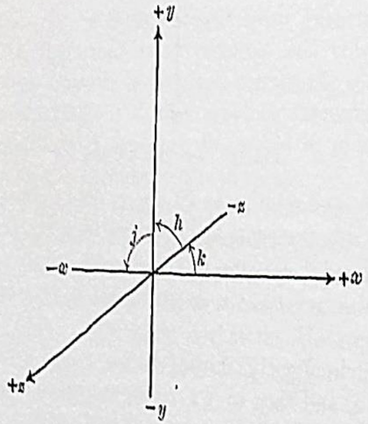


FIG. 13. Vectors in Space, $khj=-1$.

tion by h brings us to $+y$, and multiplication by j to $-x$, and in this case the result of the three successive rotations by

90 deg., in the same direction as in Fig. 12, but in a different order, is a reverse; that is, represents (-1). Therefore,

$$khj=-1,$$

and hence,

$$jhk=-khj.$$

Thus, in vector analysis of space, we see that the fundamental law of algebra,

$$a\times b=b\times a,$$

does not apply, and the order of the factors of a product is not immaterial, but by changing the order of the factors of the product jhk, its sign was reversed. Thus common factors cannot be canceled as in algebra; for instance, if in the correct expression, $jhk=khj$, we should cancel by j, h and k, as could be done in algebra, we would get $+1=-1$, which is obviously wrong.

For this reason all the mechanisms devised for vector analysis in space have proven more difficult in their application, and have not yet been used to any great extent in engineering practice.

B. ALGEBRA OF THE GENERAL NUMBER, OR COMPLEX QUANTITY.

Rectangular and Polar Coordinates.

18. The general number, or complex quantity, $a+jb$, is the most general expression to which the laws of algebra apply. It therefore can be handled in the same manner and under the same rules as the ordinary number of elementary arithmetic. The only feature which must be kept in mind is that $j^2=-1$, and where in multiplication or other operations j^2 occurs, it is replaced by its value, -1. Thus, for instance,

$$\begin{aligned}(a+jb)(c+jd)&=ac+jad+jbc+j^2bd\\&=ac+jad+jbc-bd\\&=(ac-bd)+j(ad+bc).\end{aligned}$$

Herefrom it follows that all the higher powers of j can be eliminated, thus:

$$\begin{aligned}&j^1=j,\quad j^2=-1,\quad j^3=-j,\quad j^4=+1;\\&j^5=+j,\quad j^6=-1,\quad j^7=-j,\quad j^8=+1;\\&j^9=+j,\quad \ldots \text{ etc.}\end{aligned}$$

If we now proceed again from x, in positive rotation, but first turn in the xz plane, we reach by multiplication with k the negative z axis, $-z$, as seen in Fig. 13. Further multiplication by h brings us to $+y$, and multiplication by j to $-x$, and in this case the result of the three successive rotations by

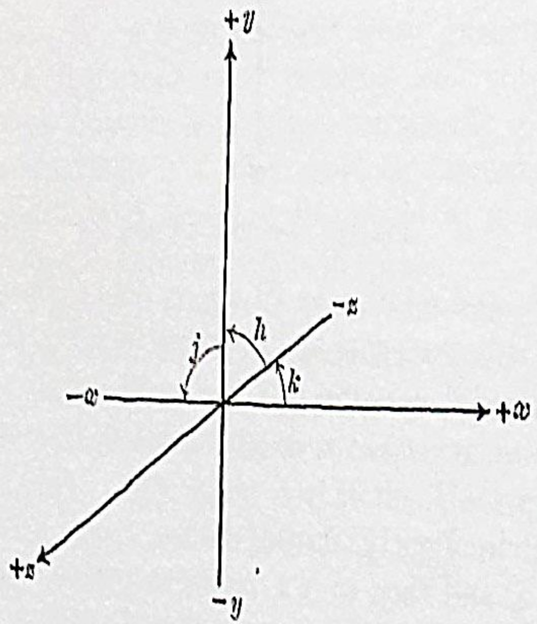


FIG. 13. Vectors in Space, $khj=-1$.

practice.

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Rectangular and Polar Coordinates.

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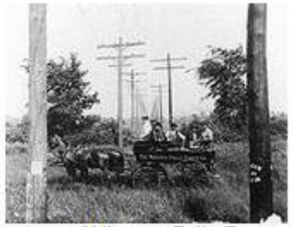
With the result that newly-educated electrical engineers could mechanize the resulting mathematical calculations using instruments such as this K&E 4053-3 Slide Rule, c.1910 . . .

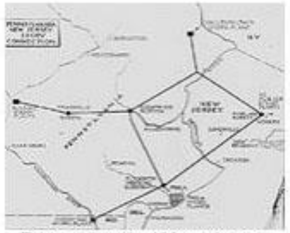
Source

Leading to a rapid build-out of AC generation and transmission infrastructure from 1900's onwards . . .

Transmission lines near intersection of Niagara Junction 1906
Image 792148
Electricity & Modern Physics Collection
National Museum of American History
Smithsonian Institution



Line crew of Niagara Falls Power Co. c.1895
Image 79-2142
Electricity & Modern Physics Collection
National Museum of American History
Smithsonian Institution



Pennsylvania / New Jersey Interconnection, 220kv
Image 80-16516
Electricity & Modern Physics Collection
National Museum of American History
Smithsonian Institution

1902 Westinghouse Flywheel Generators, c.1940
Image #21.029 Science Service
Historical Image Collection
National Museum of American History
Smithsonian Institution

Westinghouse Turbine Rotor, 1925
Image #21.035 Science Service
Historical Image Collection
National Museum of American History
Smithsonian Institution

Potomac Electric Power Co. power station near Washington DC, 1939
Image #33.011 Science Service
Historical Image Collection
National Museum of American History
Smithsonian Institution

Smithsonian

45,000 Kilovolt-ampere waterwheel for Tennessee Valley Authority (foreground), c.1938
Image #21.038 Science Service
Historical Image Collection
National Museum of American History
Smithsonian Institution

Westinghouse worker assembles 2,500-kilowatt Generator 1942
Image #10.035 Science Service
Historical Image Collection
National Museum of American History
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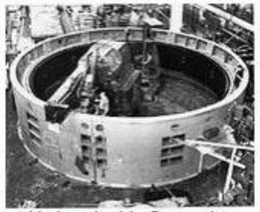
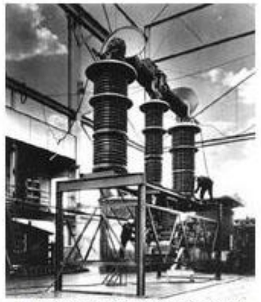
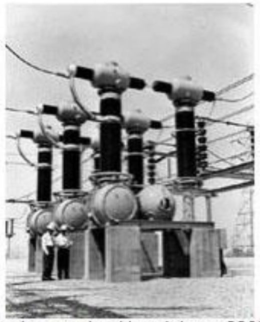


Hydro-electric Generator for Russia's Dnieprostroi Dam 1945
Image #21.009 Science Service
Historical Image Collection
National Museum of American History
Smithsonian Institution

Cold Weather Testing of an Oil Circuit Breaker 1936
Image #15.009 Science Service
Historical Image Collection
National Museum of American History
Smithsonian Institution



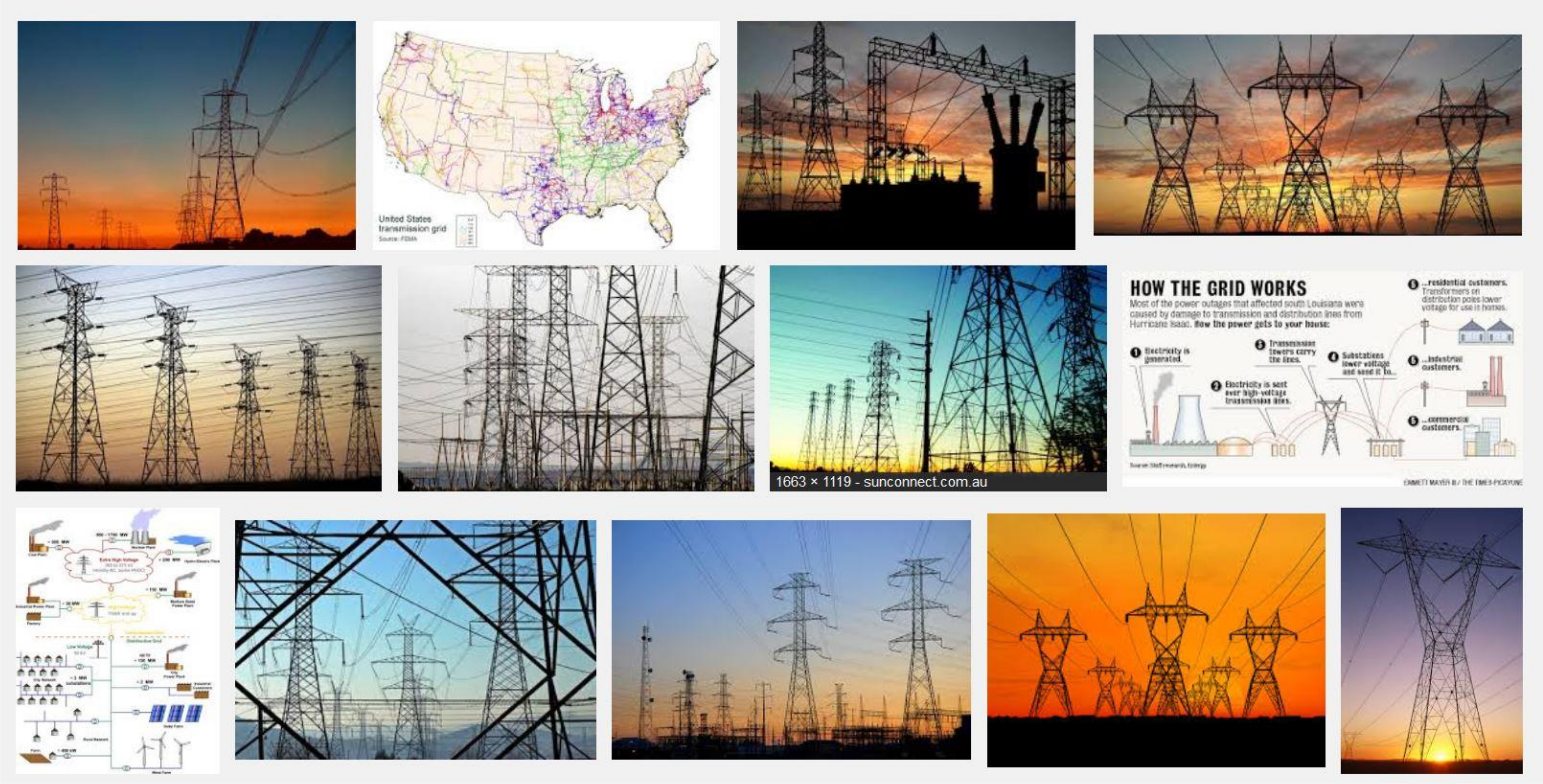
2,500,000-kv-a Impulse Oil Circuit Breaker, 1934
Image #15.011 Science Service
Historical Image Collection
National Museum of American History
Smithsonian Institution



Engineers checking data on 230kv air-blast circuit breaker 1960
Image #15.021 Science Service
Historical Image Collection
National Museum of American History
Smithsonian Institution

Smithsonian

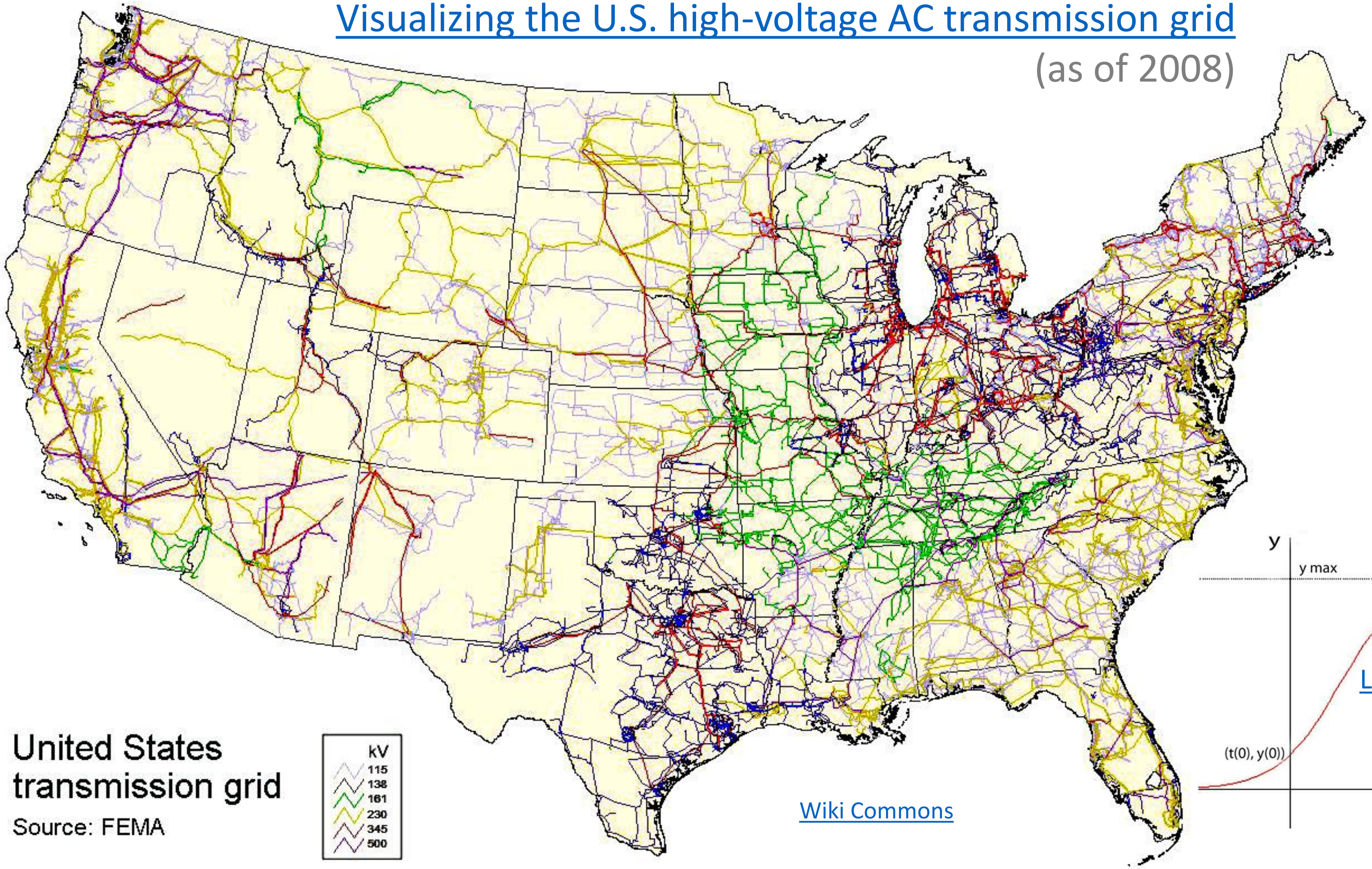
Expanding into the vast infrastructure now used for efficiently generating and transmitting AC electric power from energy-sources to end-users . . .



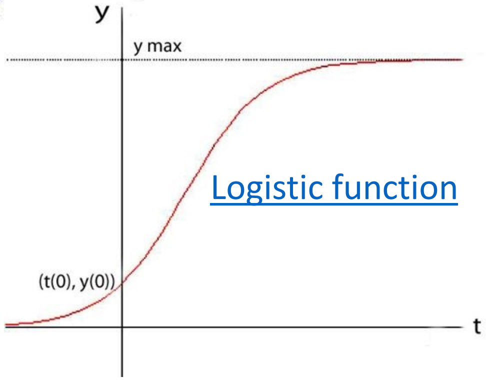
Snip from Goggle images

[Visualizing the U.S. high-voltage AC transmission grid](#)

(as of 2008)



Wiki Commons



Logistic function

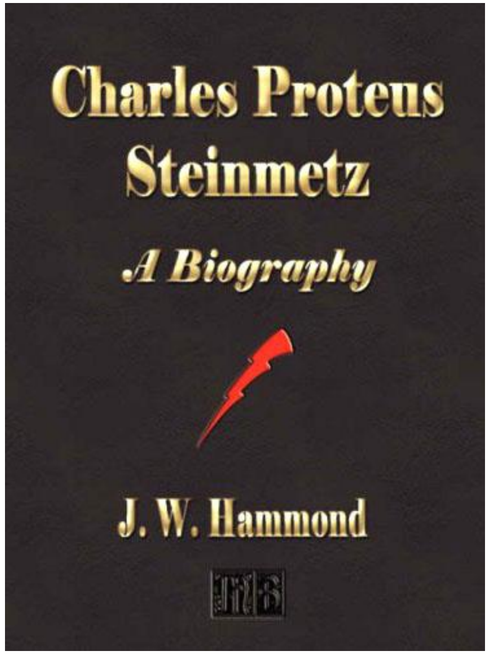
To envision its dramatic scale, look at the US at night, as seen from space . . .

NASA

Think how many minds Steinmetz's ideas passed thru to make this happen . . .

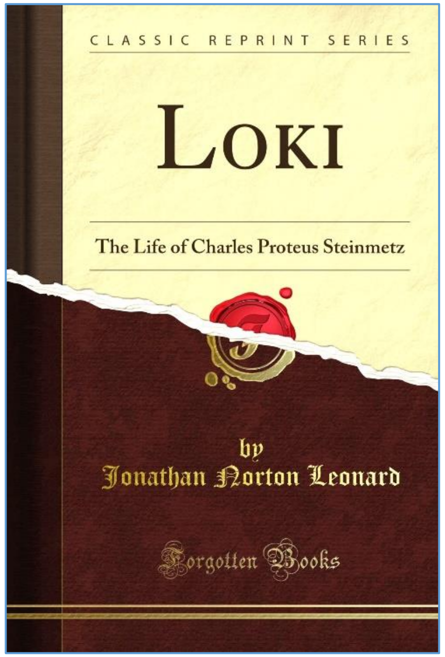
Readings where you can learn more about Steinmetz's amazing life . . .

1924



Link

1929



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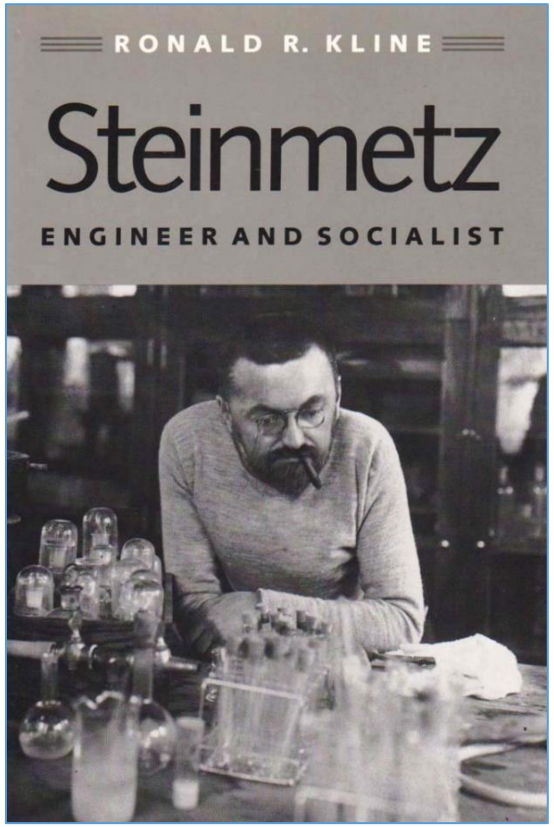
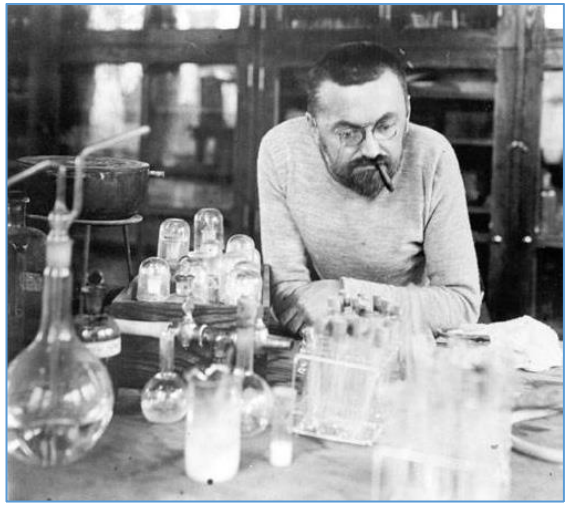
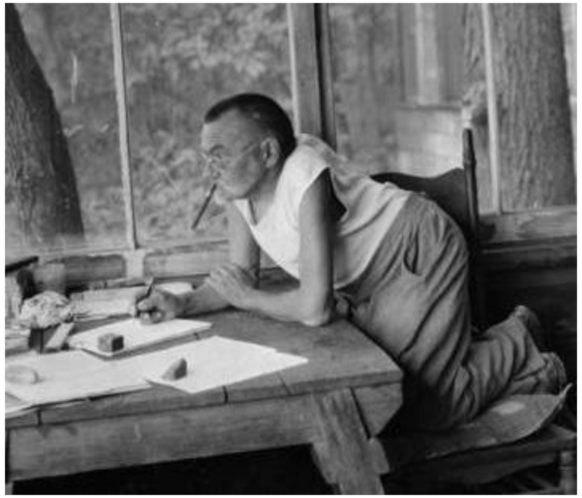
1992



Link

Working in his home laboratories . . and at Camp Mohawk . . enjoying life with his adopted family



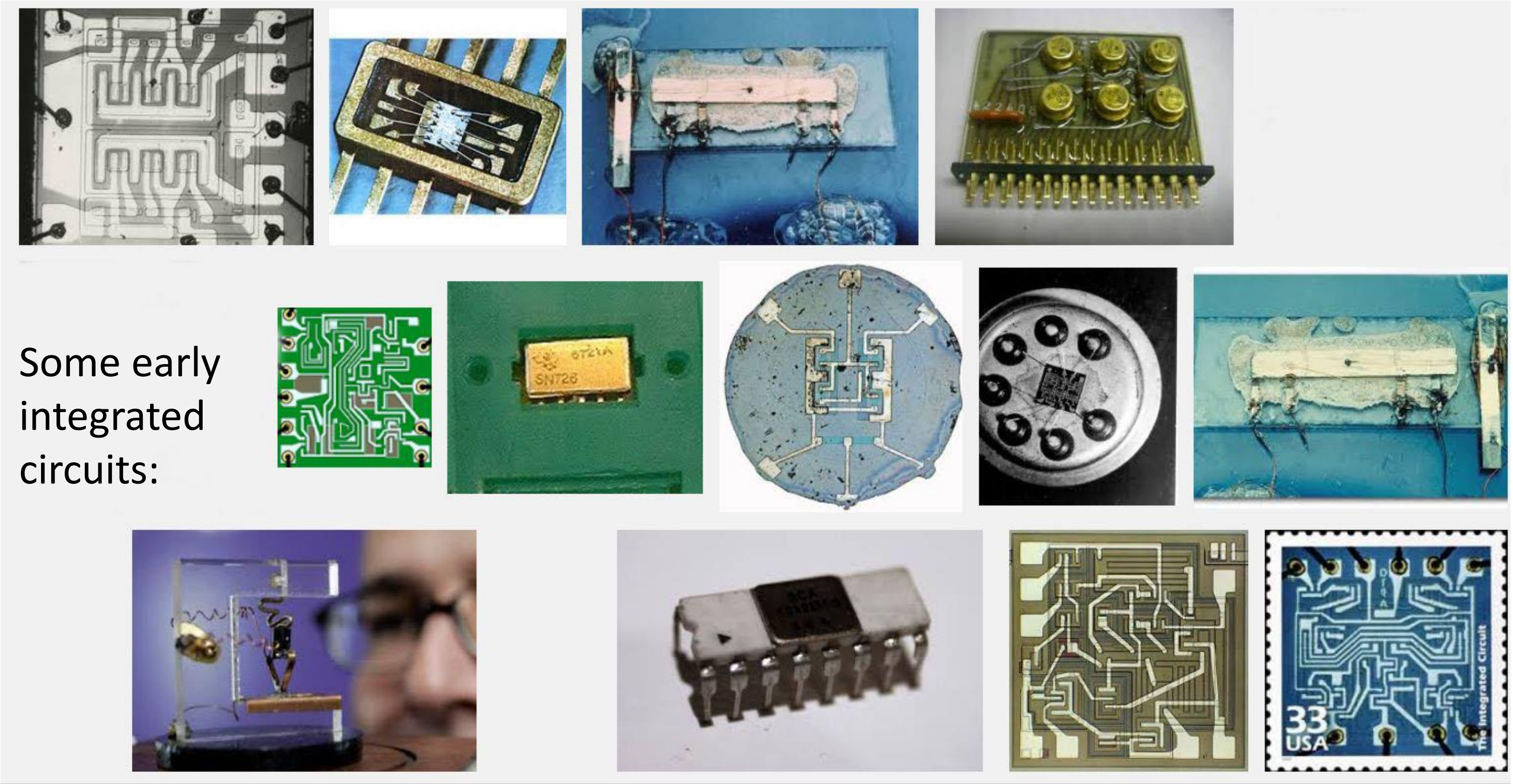


Steinmetz Digital Collection of Schenectady

Let’s go ‘Back to the Future’ again, and zoom-in on a later disruptive wave of innovation in electronics and computing . . .

One I participated in: the revolution in Very Large Scale Integrated (VLSI) microchip design, beginning in 1976 . . .

The stage was set by **emergence of** integrated circuit **technology** in the 1960's, enabling numbers of transistors and their wiring to be 'printed' onto chips of silicon . . .



Snip from Goggle images

And by the early 70s revolution in computer design (using MSI integrated circuits):

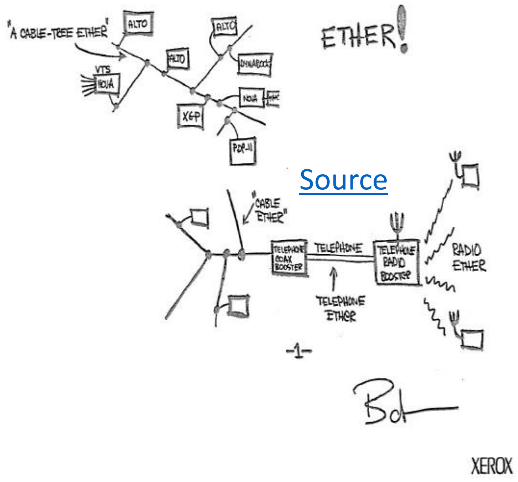
Innovation of the interactive-display, mouse-controlled “personal computer”,
the “Ethernet” local-area network, and the “laser printer” (at Xerox PARC) . . .

And the Dept. of Defense’s “Arpanet” (the early internet, at DARPA) . . .

Xerox Alto, 1973

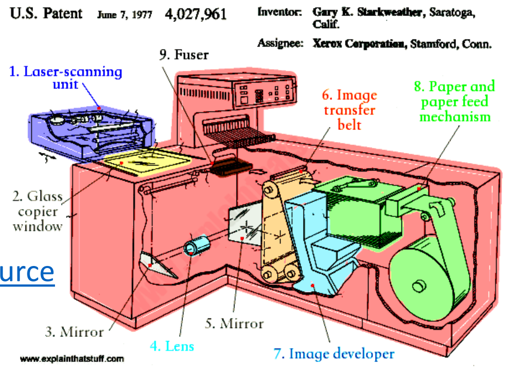
Wiki commons

Metcalfe’s original Ethernet sketch, 1973



Source

Laser printer, 1971



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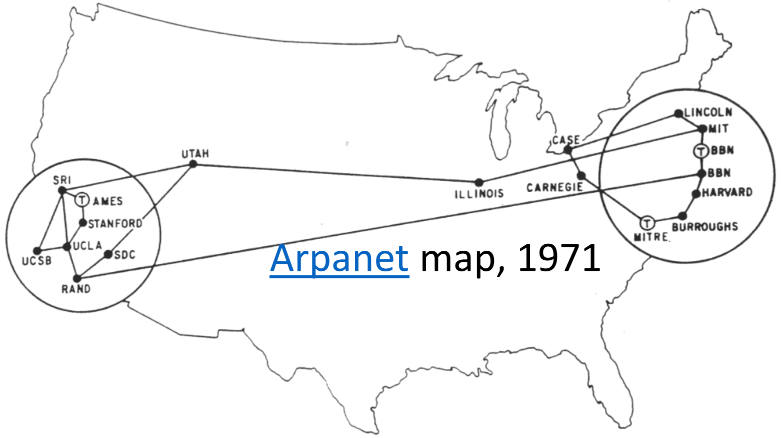
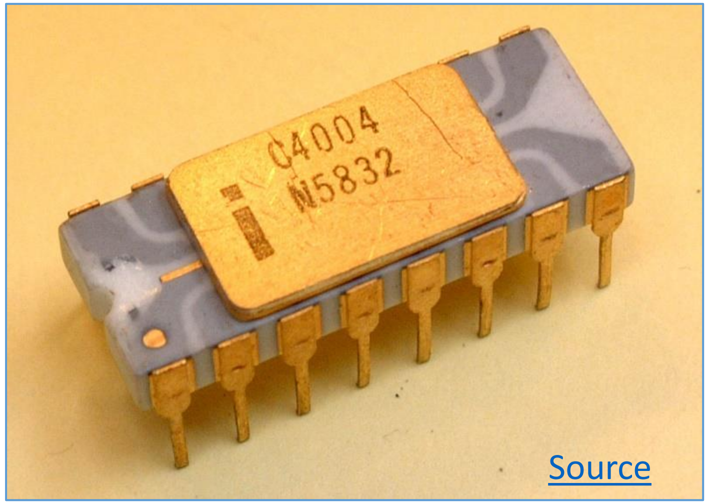


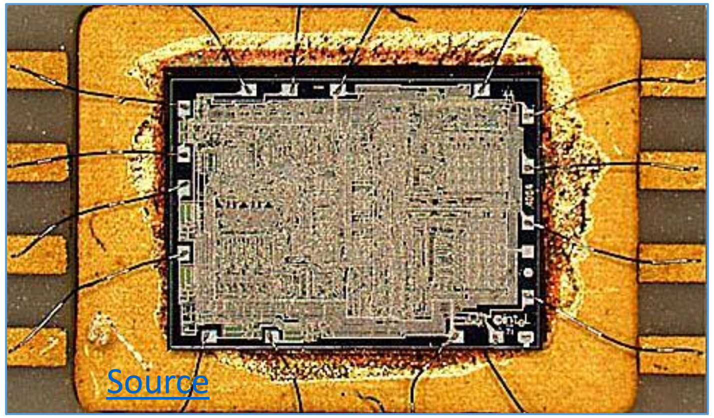
Arpanet map, 1971

Ongoing advances in lithography enabled ever-finer features to be printed, rapidly increasing the number of transistors printable on single chips.

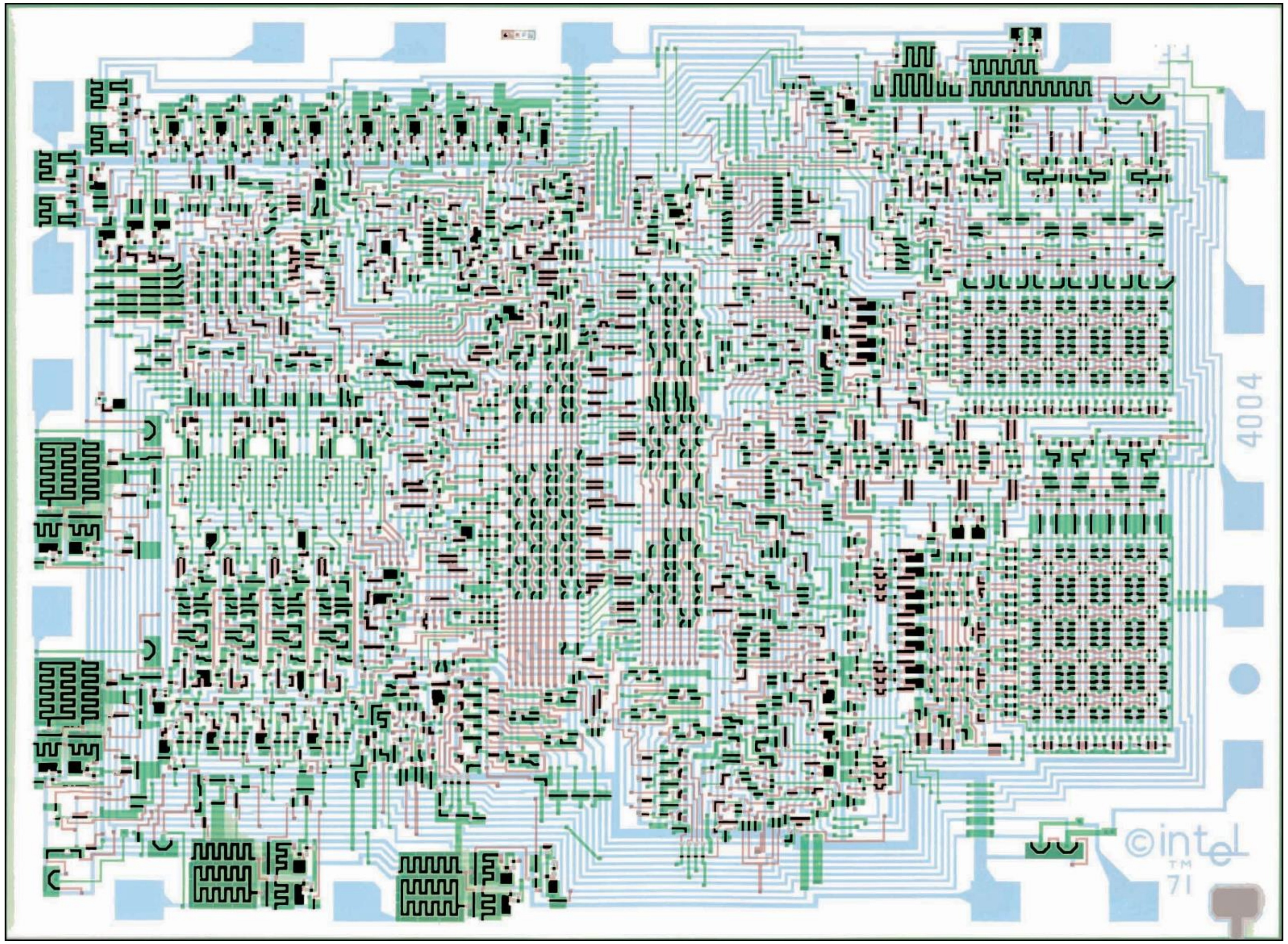
And by 1971, a watershed was crossed with the introduction of the Intel 4004, the first single-chip "microprocessor": a "computer processor on a chip" . . .

It contained 2300 transistors . . .





Here's a 4004's mask set (overlain like a stack of photo negatives), showing patterns "printed" in each layer of the chip that together will create the 2300 transistors and their interconnections.



This "at-the-time" complex design had to be manually drafted, without aid of computers.

Each mask layer was crafted by hand-cutting its drafted pattern into a large sheet of 'rubylith'.

Sheets were then overlain to check for interlayer design-rule violations.

Then each photo-reduced to make the 4004's mask set.

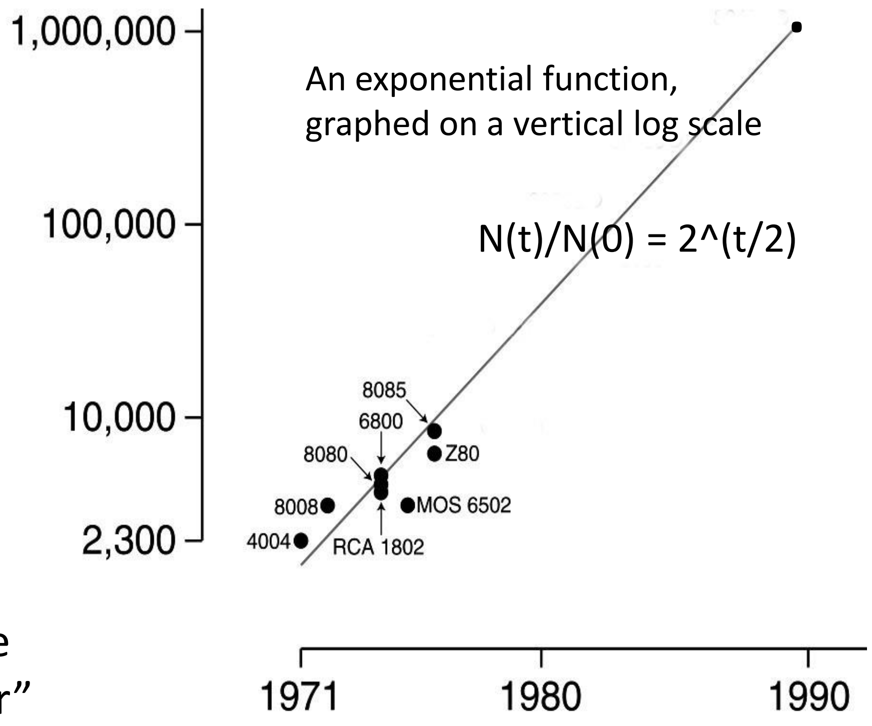
Gordon Moore at Intel observed that the number of transistors reliably printed on chips was roughly doubling every two years . . .

Carver Mead named this "Moore's Law" and determined that there were no physical limits to increasing the density up to ~ 1 million transistors.

In 1976 this set-off a push at Xerox PARC and Caltech to figure out how to enable such complex things to be designed.

After all, looking ahead it appeared conceivable by ~1990 an entire superscalar "supercomputer" could be printed on a single chip. . .

Moore's Law (as of 1976)

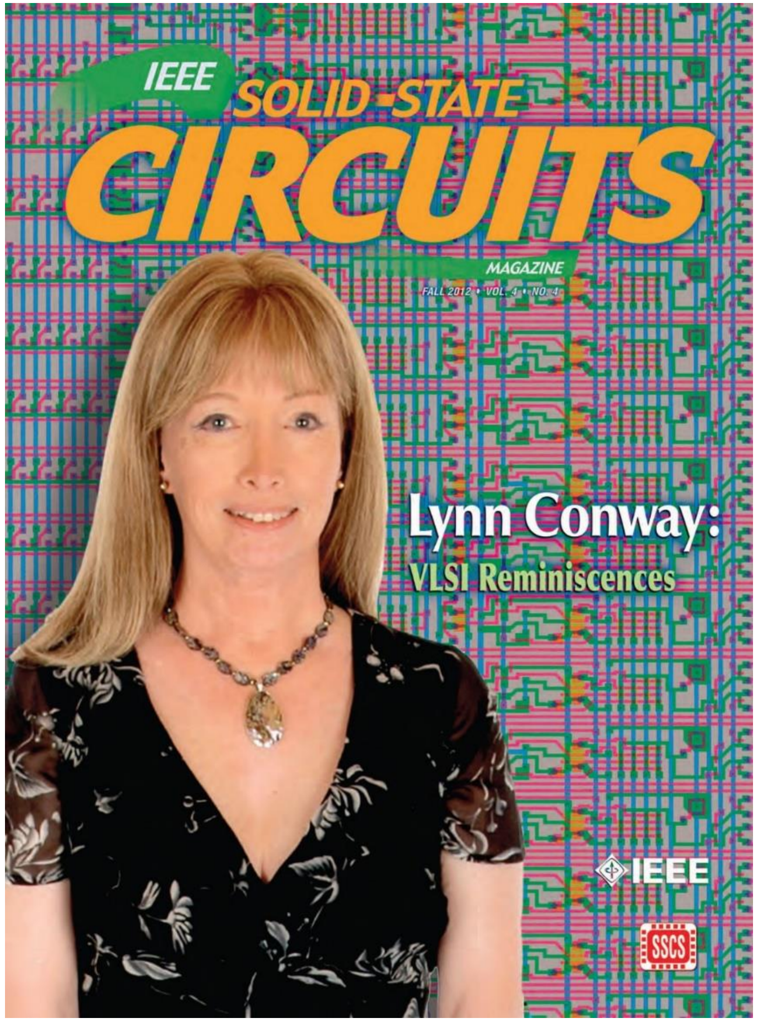


The story of what unfolded over the following three/four years is quite a saga . . .

For more insight into that, you can browse my "Reminiscences of the VLSI Revolution" in the Fall 2012 IEEE *Solid State Circuits Magazine*.

That was the first time I'd come forward to tell the whole story . . .

Tonight we'll just hit the highlights, including how Steinmetz's story influenced the outcome ...



The breakout was triggered by a cluster of abstract innovations at Xerox PARC and Caltech . . .

Included were a set of scalable VLSI chip-layout design rules, in the form of ratioed (dimensionless) inequality equations (Conway, Xerox PARC) . . .

These enabled abstract chip designs to be digitally shrunk down (and reused) as Moore's law rapidly advanced . . .

They also enabled accruing chip subsystem designs to be widely shared . . .

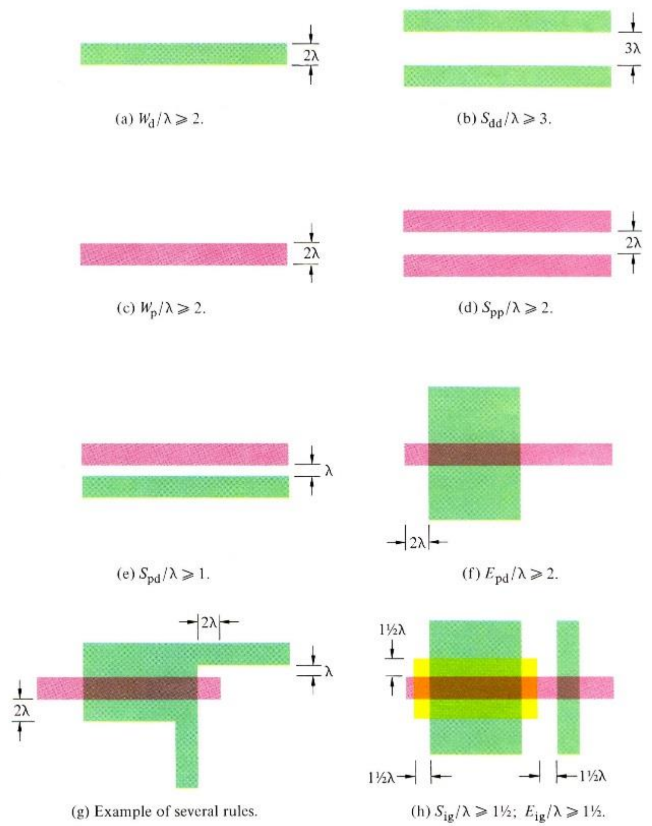


PLATE 2 *n*MOS design rules

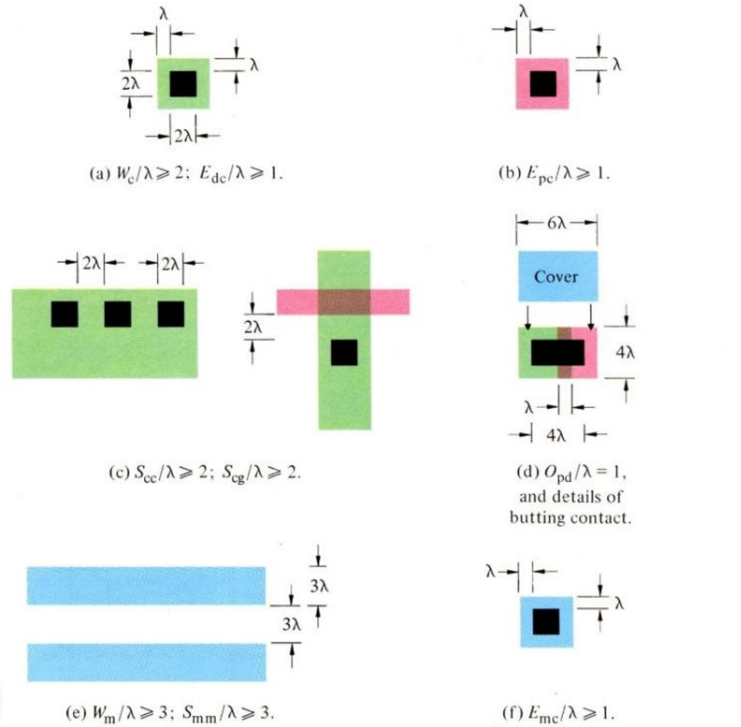


PLATE 3 *n*MOS design rules (continued)

Link

The driving idea:

Assuming that chip lithography scales-down year by year according to Moore's Law,
And ever-more ever-faster transistors can be printed on single chips as time goes by, do:

Step (i): Use a computer and the new methods to design the layout patterns for a processor of more a powerful computer, to be "printed" in the next denser process.

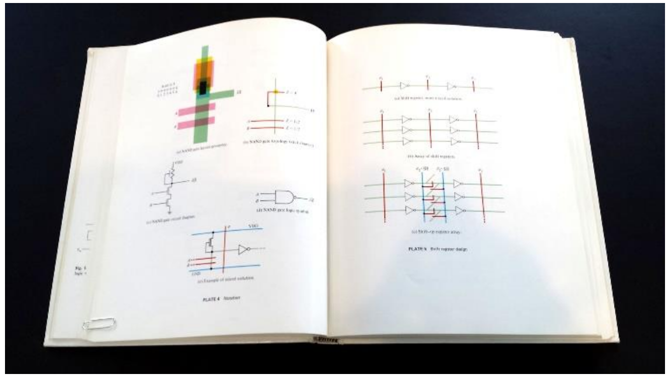
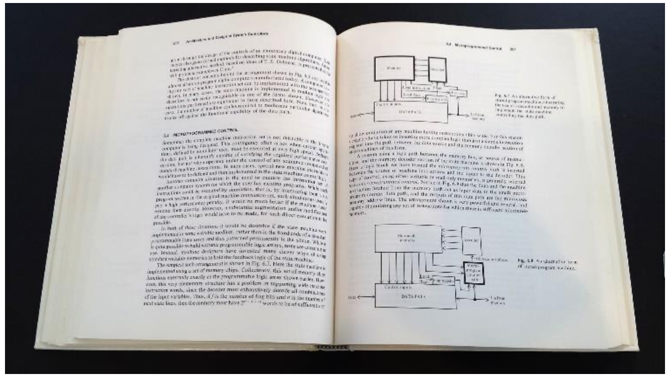
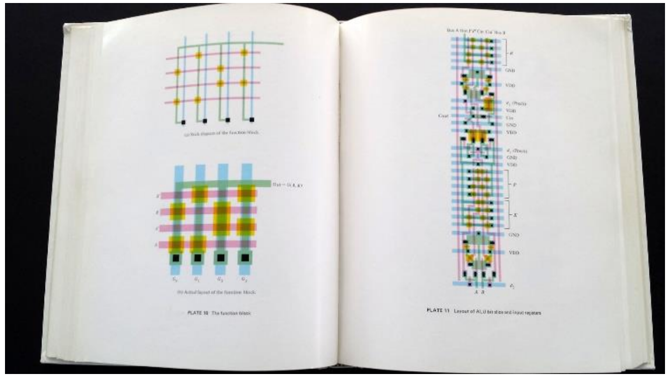
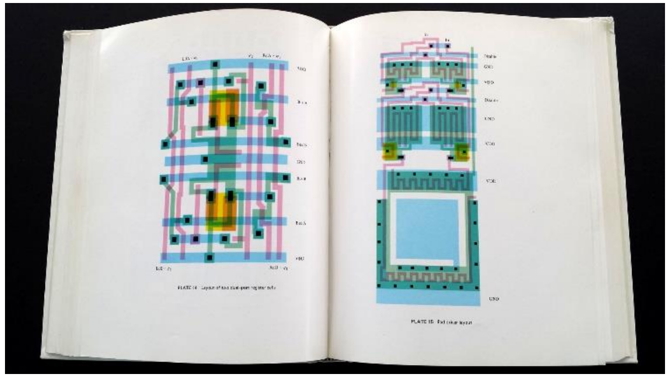
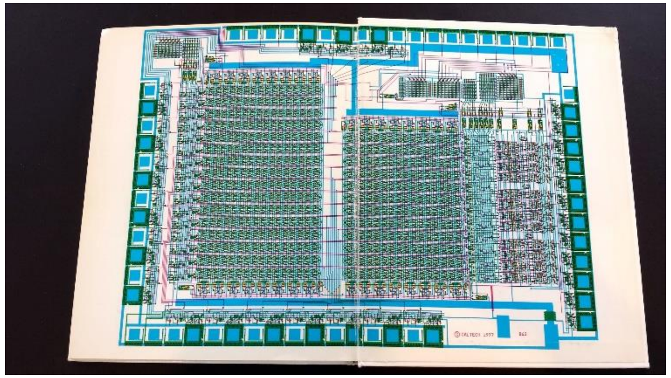
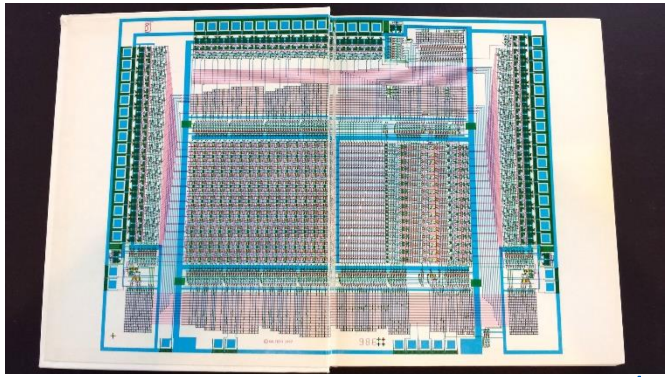
Step(i+1): Use the new chips and new software chip-design tools to create more powerful "computer-design" computers, then repeat step (i).

If ever more engineers and programmers could do this, and on an expanding number of increasingly powerful computers, then the iterative expanding-process could explosively generate ever-more and ever-more-powerful digital systems . . . (i.e., exponentiate!).

The big problem:

Where are all the engineers and programmers going to come from, and how are they going to learn how to do this? **Aha! Recall how Steinmetz coped with this problem . . .**

So, we first documented the 'Mead-Conway' system of simplified, restructured, design-level abstractions and chip design methods in an evolving computer-edited book . . .

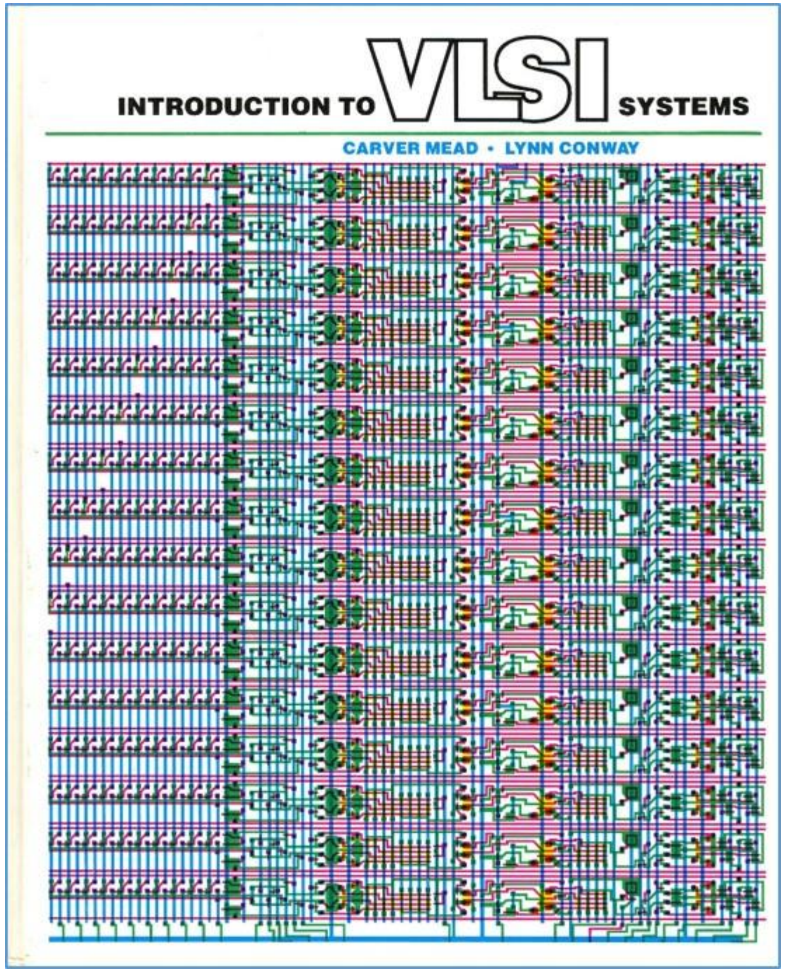







Link

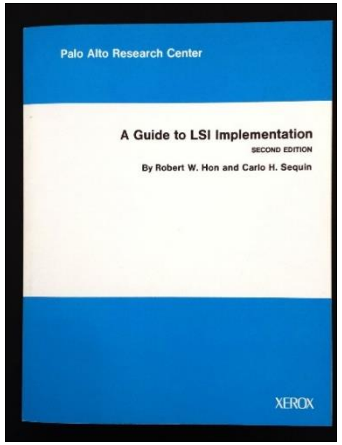
Thus we used our Alto computers to mechanize not only our computations, and our generation of chip-design layouts, but also the evolution of the book itself . . .

That computer-edited evolving book, printed using the laser printers at PARC, became the draft of the famous textbook:

Introduction to VLSI Systems by Mead and Conway, published in 1980 . . .



We also used our Altos to generate (at Xerox PARC) many open-source cell-layout-designs for key digital-subsystems, easily disseminated to students and colleagues via the Arpanet …



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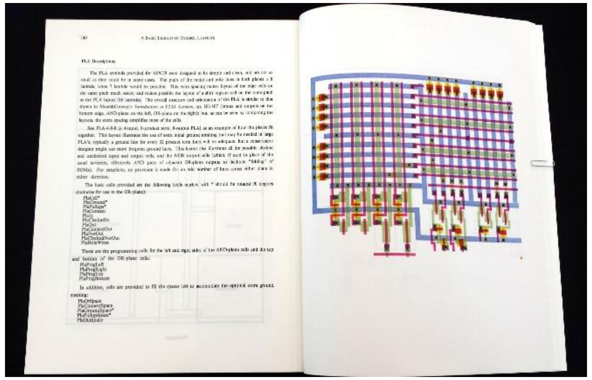
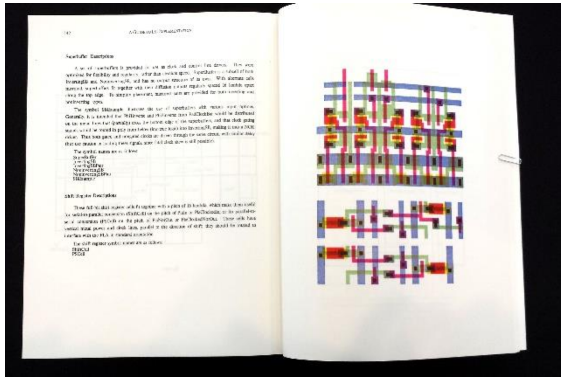
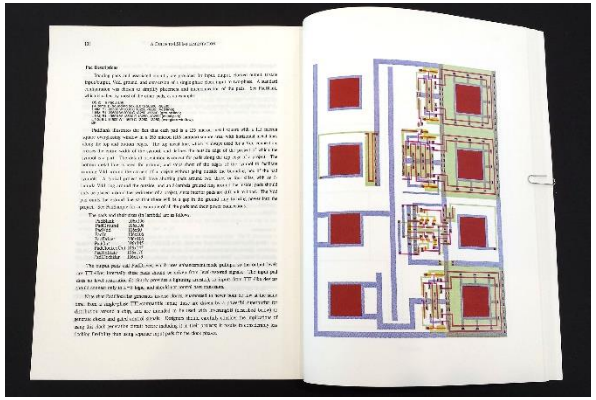


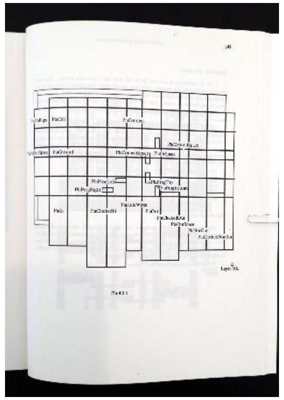
PLA cells



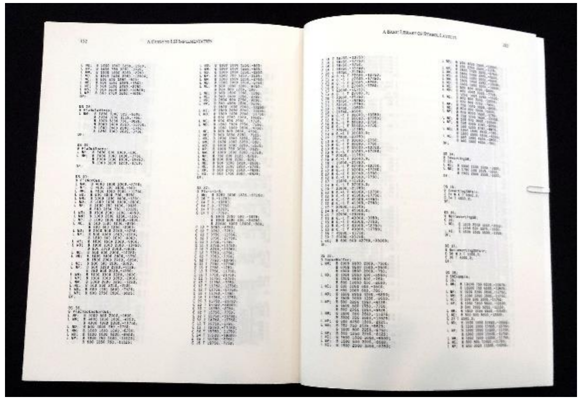
Clock drivers



I/O Pads



Cell locations



CIF 2.0 Cell-Library code

And, following the "script" Steinmetz used to propagate his revolutionary AC methods at Union College, I introduced the new methods in a special VLSI design course at MIT in 1978.

THE M.I.T. 1978 VLSI SYSTEM DESIGN COURSE

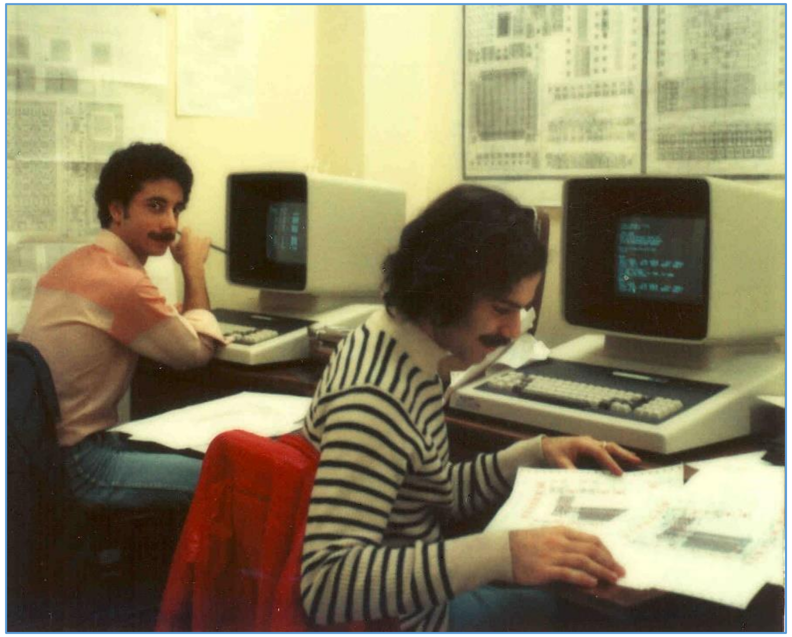
by Lynn Conway

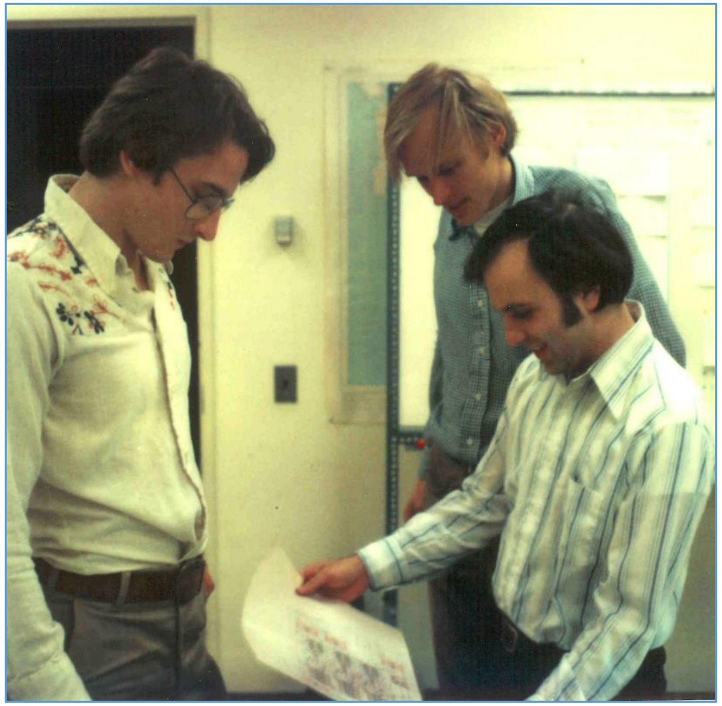
[Update: 11-14-07]

This course was an important milestone in the development, demonstration and evaluation of the Mead-Conway structured VLSI design methods. Lynn Conway conceptualized and planned the course during the late spring and summer of '78, and taught the course while serving as Visiting Associate Professor of EECS at MIT in the fall of '78 and early '79.

Link
Link
Link

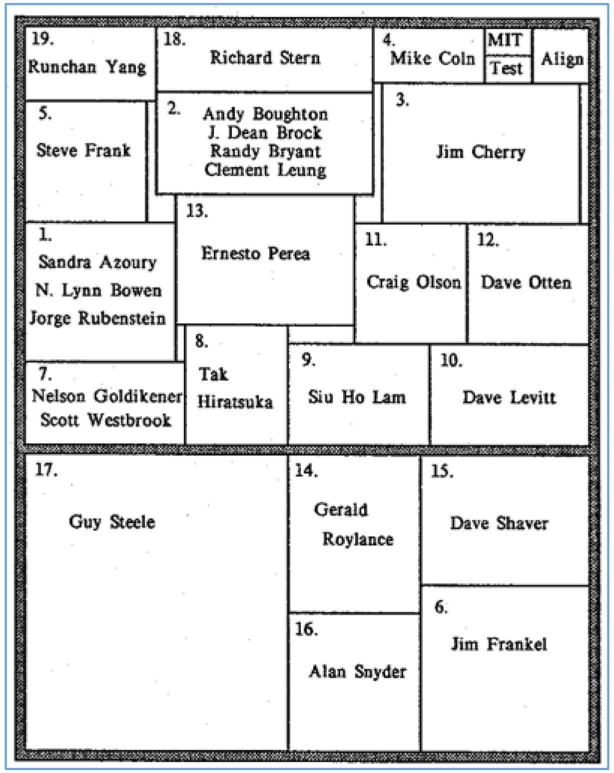
The students learned to design chips in the 1st half of the course, then did project-chip designs in the 2nd half. They were fabricated in Pat Castro's lab at HP shortly after the course.

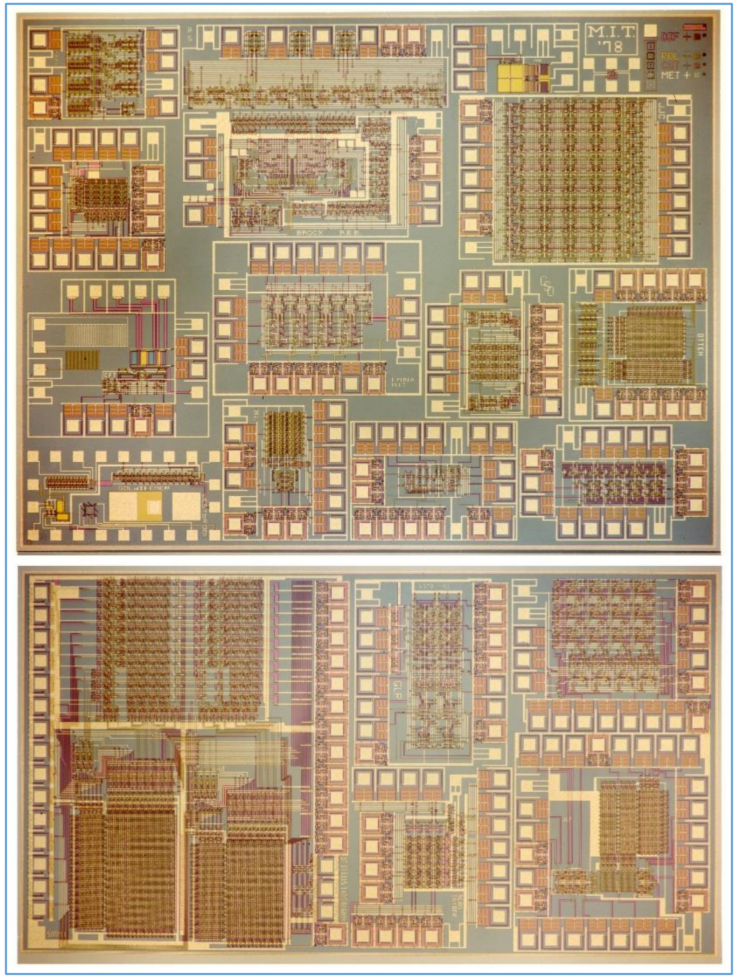




There were many amazing results including a complete Lisp microprocessor design by Guy Steele . . .

[Map and photomicrograph](#) of the 19 student projects on the MIT'78 'MultiProject' Chip





For more about the MIT'78 course, see Lynn's "MIT Reminiscences"

The MIT'78 course stunned top folks in Silicon Valley . . . Chip design till then had been a mystery, only grasped by a few computer architects working for chip manufacturers . . who thus had access to the "printing plants" . . .

Many other top research universities wanted to offer such a course. But how?

After intensive pondering, I came up with the answer: Rerun the MIT'78 course at a dozen research universities, using my MIT lecture notes to keep everything in sync.

But how to "print" the student project chips?

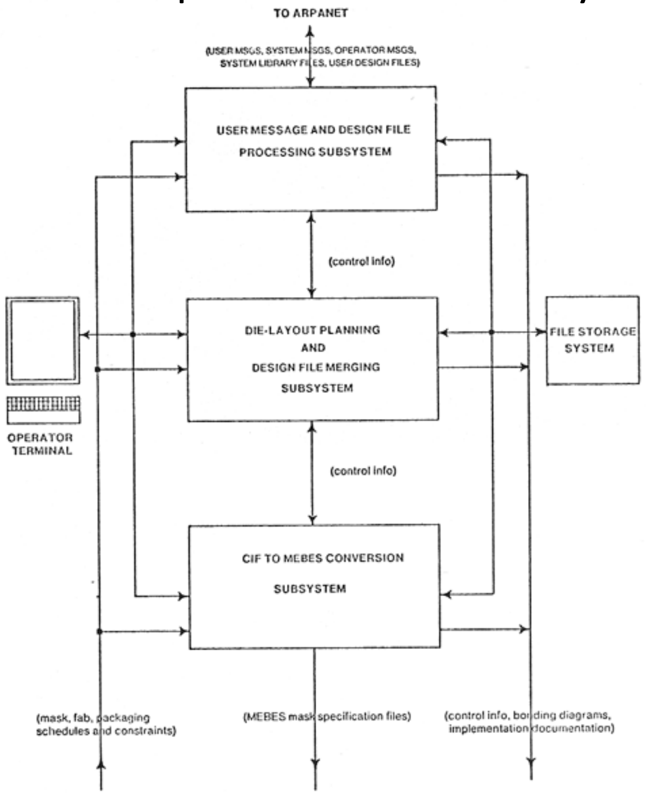
I suddenly envisioned a new form of "E-commerce" system, enabling student design files to be remotely submitted via the Arpanet to a "server" at PARC . . .

The server would run logistics-software to pack the designs into multi-project chip files (like composing the print-files for a magazine, using remotely-submitted articles) . . .

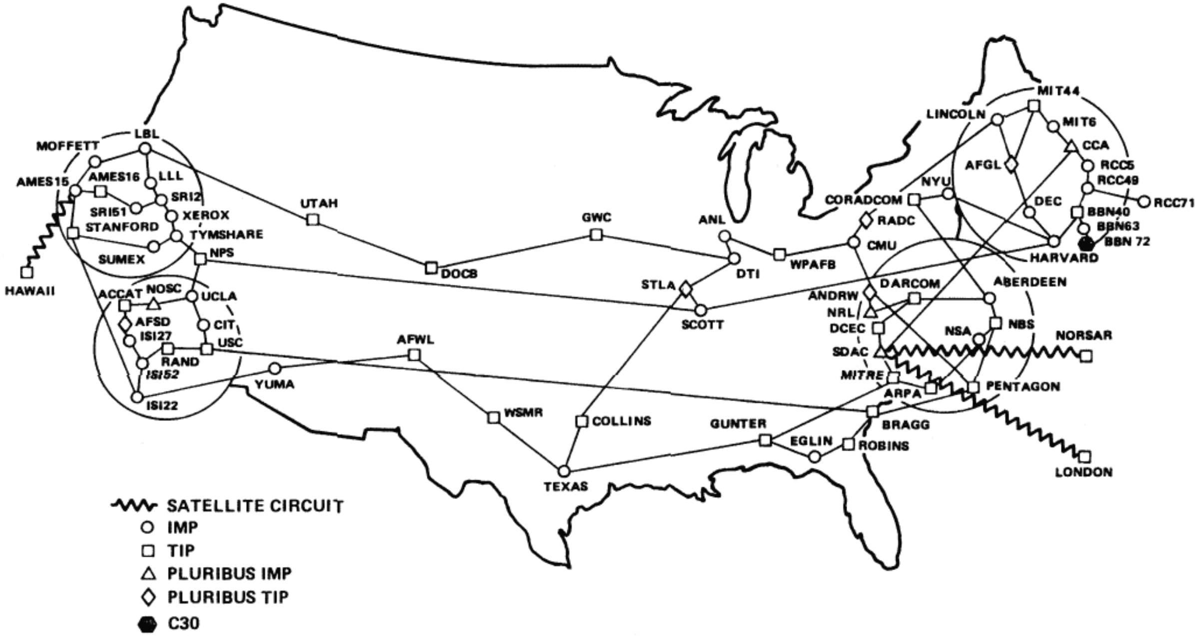
We'd then make masks, "print" MPC's at HP Labs (where my collaborator Pat Castro had prototyped the first "silicon foundry"), and quickly return the chips to students.

In the fall of 1979, we orchestrated a huge “happening” (MPC79*) . . . It involved 129 budding VLSI designers taking Mead-Conway courses at 12 research universities…

MPC79 Arpanet E-commerce system:



ARPANET GEOGRAPHIC MAP, OCTOBER 1980



*The MPC Adventures, L. Conway, Xerox PARC, 1981

MPC79 not only provided a large-scale “demonstration-operation-validation” of the design methods, design courses, design tools and e-commerce digital-prototyping technology … it also triggered ‘cyclic gain’ in, and exponentiation of, the budding VLSI-design-ecosystem…

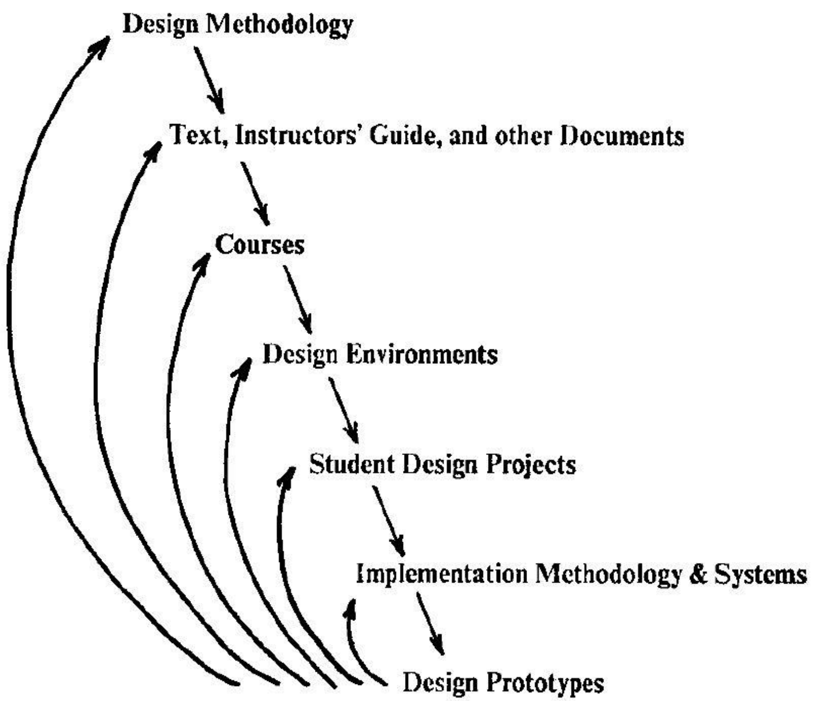
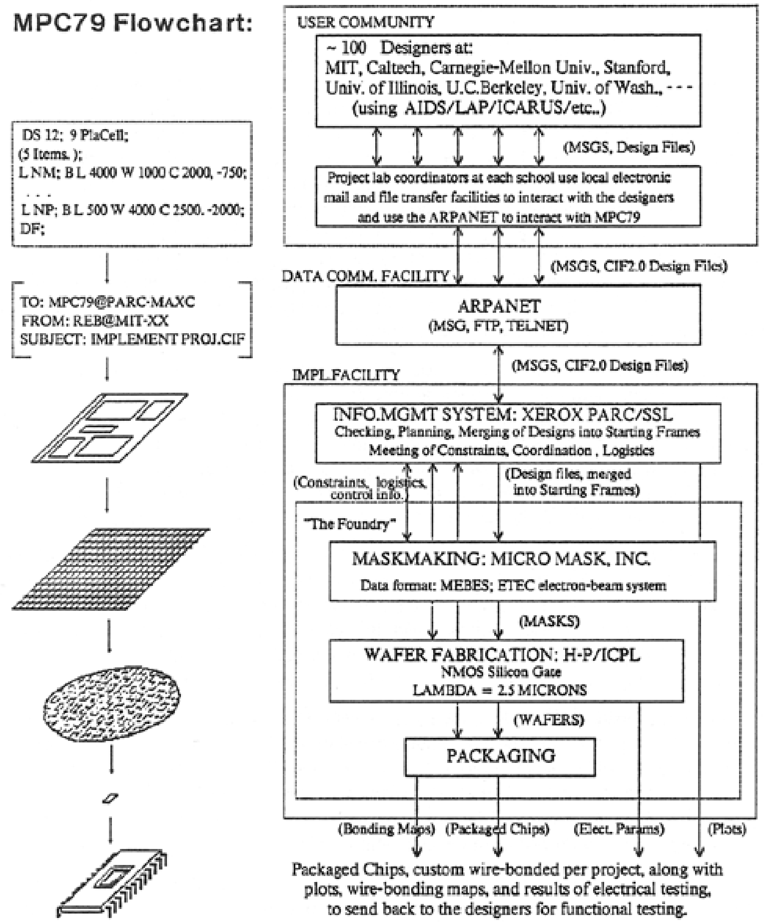


Figure 8. The Joint Evolution of the Multi-Level Cluster of Systems



The MPC Adventures, L.ynn Conway, Xerox PARC 1981.

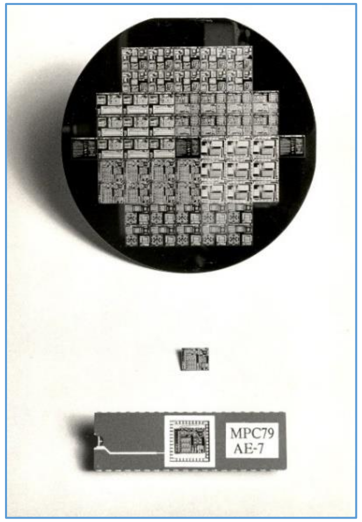
Thus breaking the "VLSI complexity barrier", spawning the MOSIS* national chip-prototyping service, and bootstrapping the "fabless-design + silicon foundry" paradigm of chip-making …

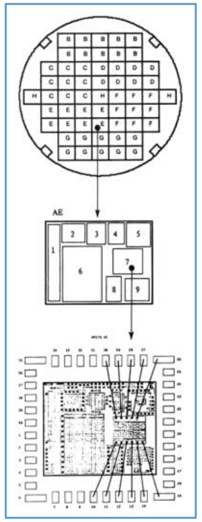
MPC79:

Wafer . . . . .

Chip . . . .

Packaged Chip . .

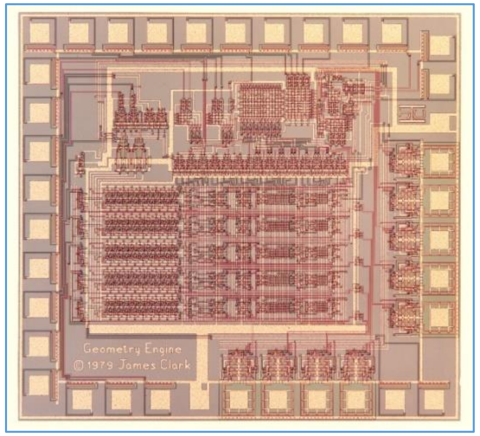


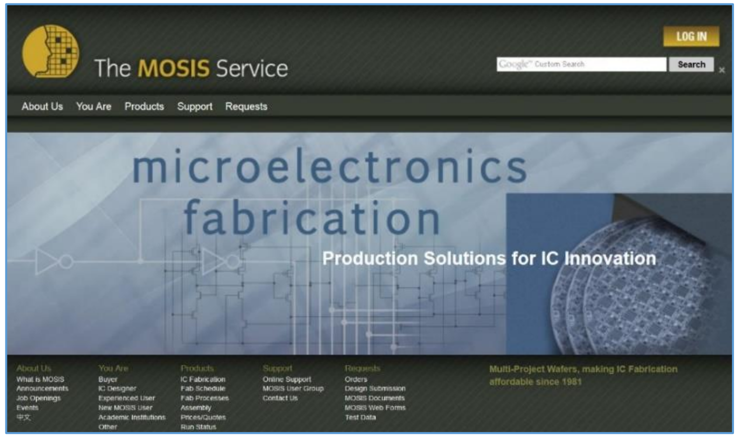


Lynn and her team prepare packaged chips to send to designers, Jan 4, 1980

Example:

Jim Clark's **"Geometry Engine"**





*By transfer of MPC79 technology from Xerox PARC to USC-ISI

Visualizing how techno-social dynamics triggered an exponentiation in the spread of the innovative VLSI design ideas via the emerging internet communication technology . . .

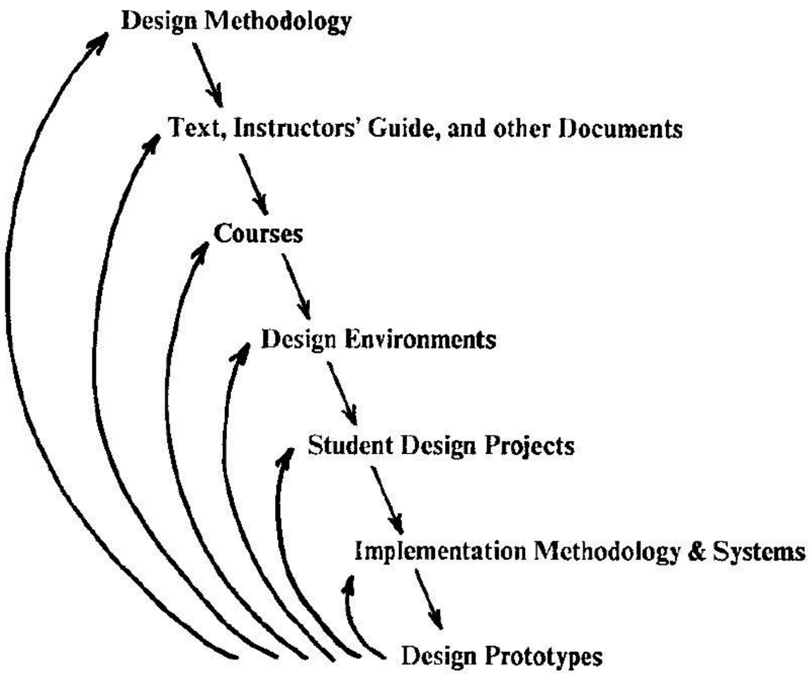
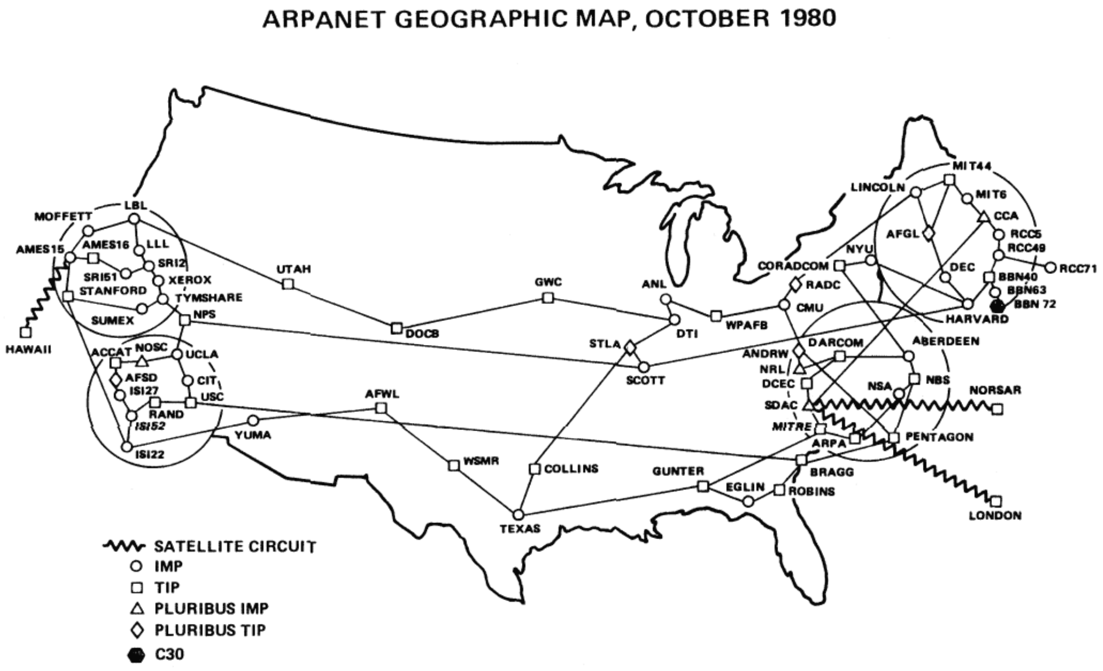


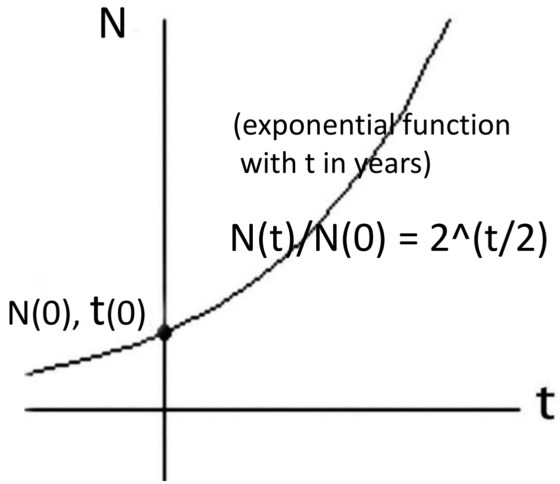
Figure 8. The Joint Evolution of the Multi-Level Cluster of Systems

The MPC Adventures (p. 16)

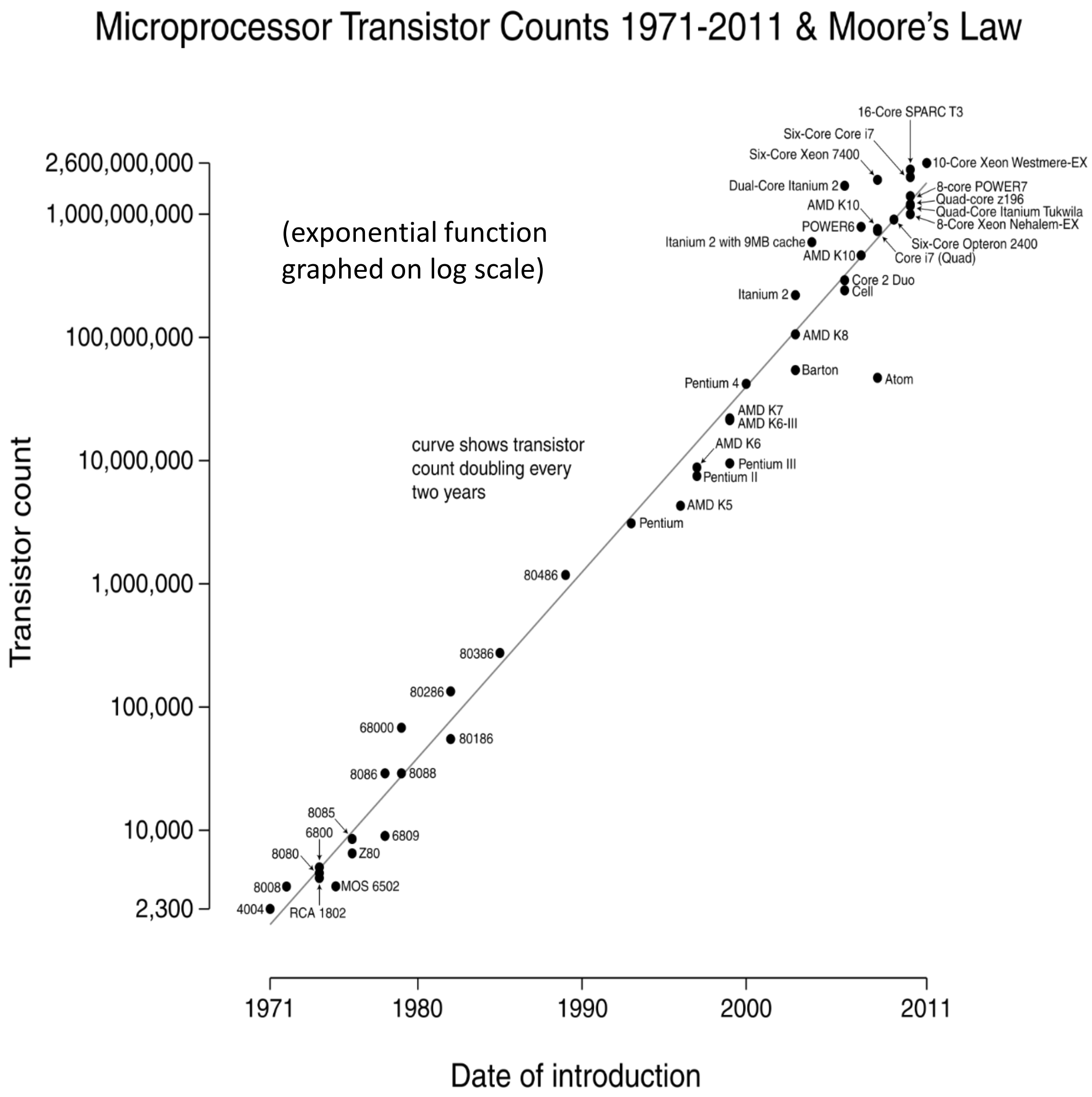


By 1982-83, Mead-Conway VLSI design courses were being offered at 113 universities all around the world

In parallel with all that, over the past 40 years or so, we've see [Moore's Law] stay on track all the way!

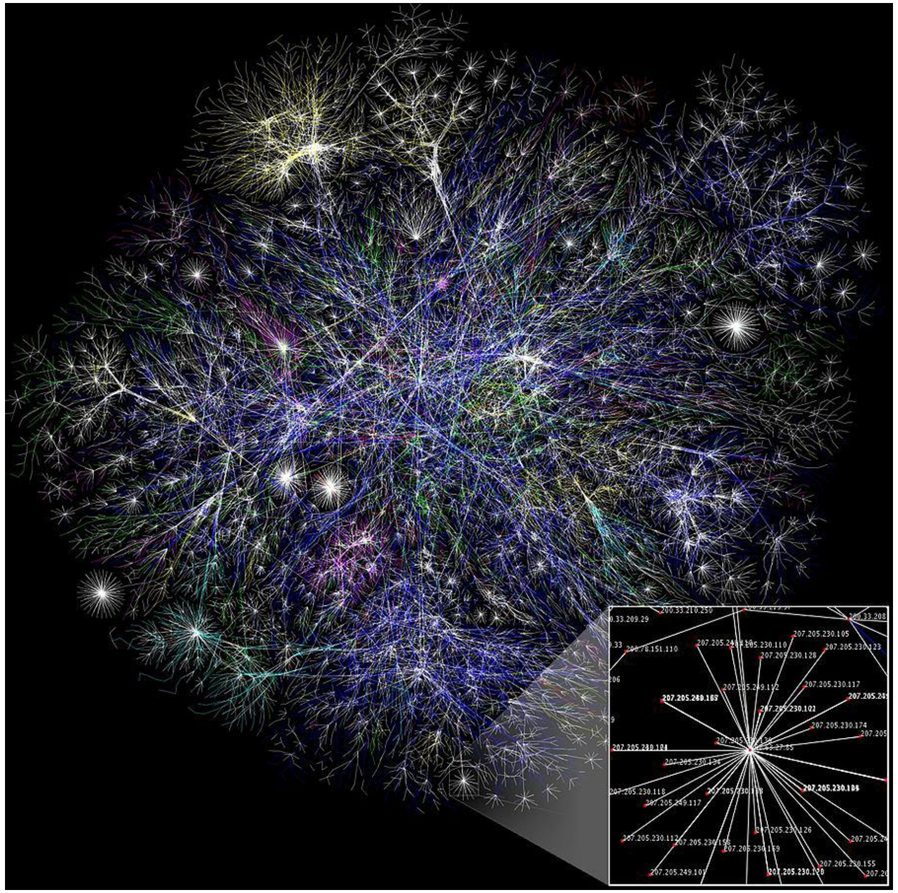


Starting with [several thousand] in 1971, by 2011 the number of transistors on a chip had passed [several billion]!

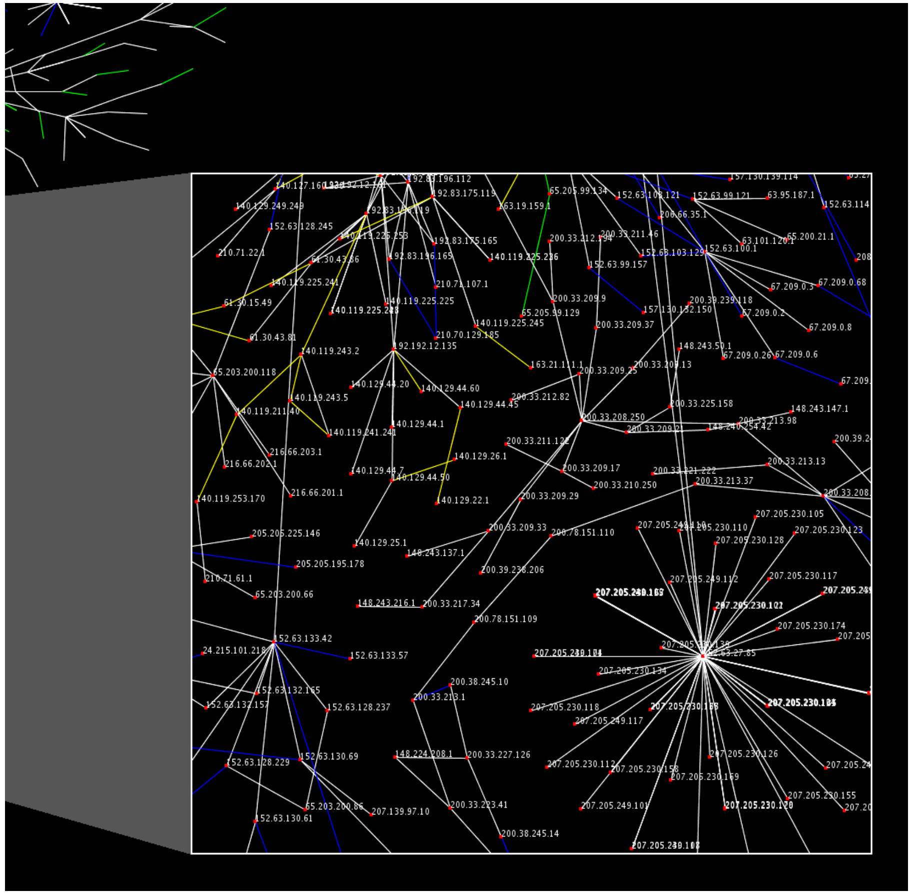


Visualizing the Internet's expansion by 2010 . . .

Here's a partial map of the Internet . . .



Zooming in to see IP Addresses . . .



Wiki Commons

And Under Construction, June 26, 2014!

Global Foundries VLSI silicon-chip fabrication plant, Malta, NY . . .

A giant "printing plant" for patterning complex microsystems onto vast numbers of silicon chips . . .

Panoramio, Google Maps

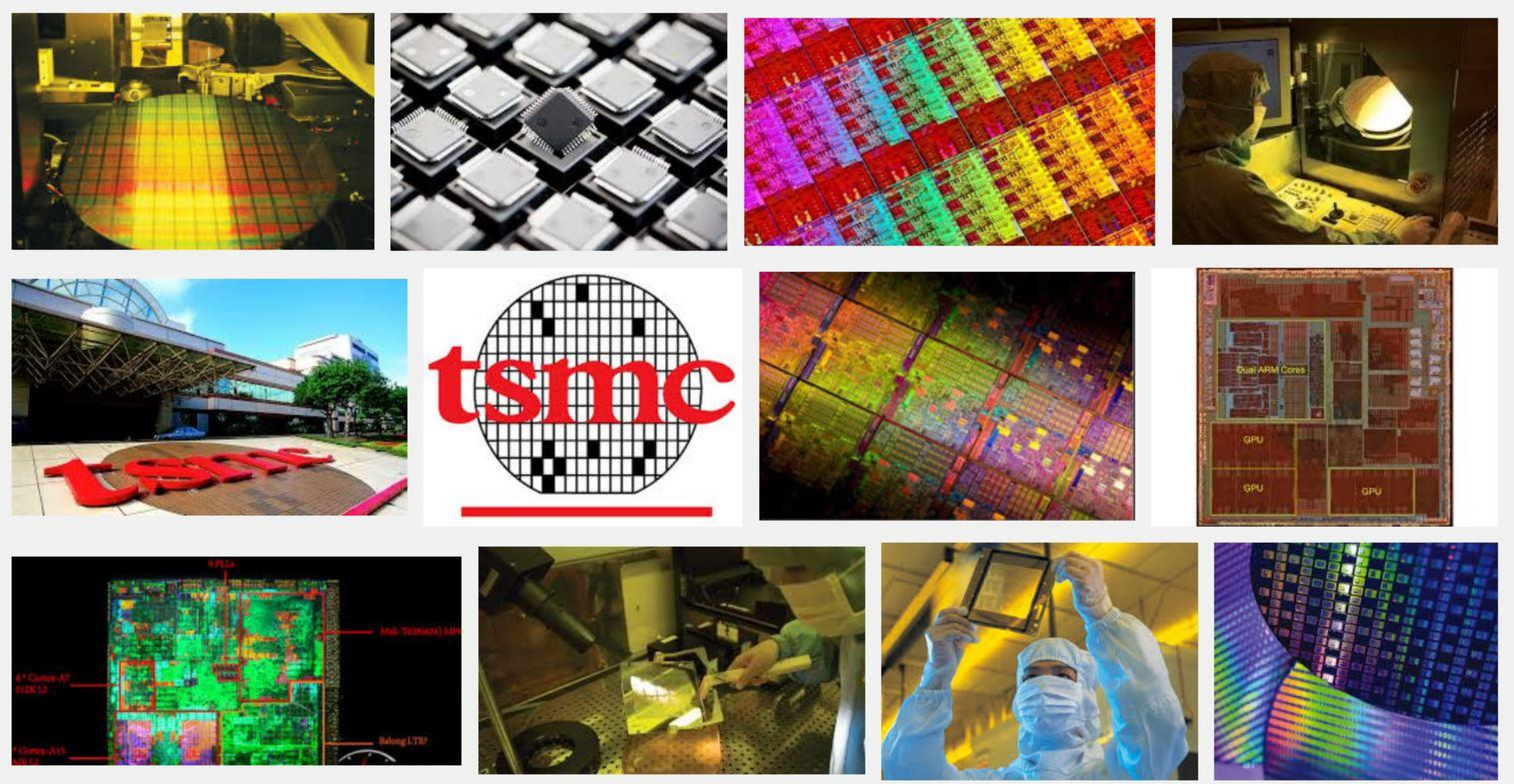
And here are the top "Silicon Foundries," as of 2013:

These are where many of the world's VLSI silicon microchips are "printed" . . .

2013 Rank	2012 Rank	Company	Foundry Type	Country of origin	Revenue (million $USD)
1	1	TSMC	Pure-play	Taiwan	19,850
2	2	Globalfoundries	Pure-play	United States	4,261
3	3	UMC	Pure-play	Taiwan	3,959
4	4	Samsung Semiconductor	IDM	South Korea	3,950
5	5	SMIC	Pure-play	China	1,973
6	8	PowerChip	Pure-play	Taiwan	1,175

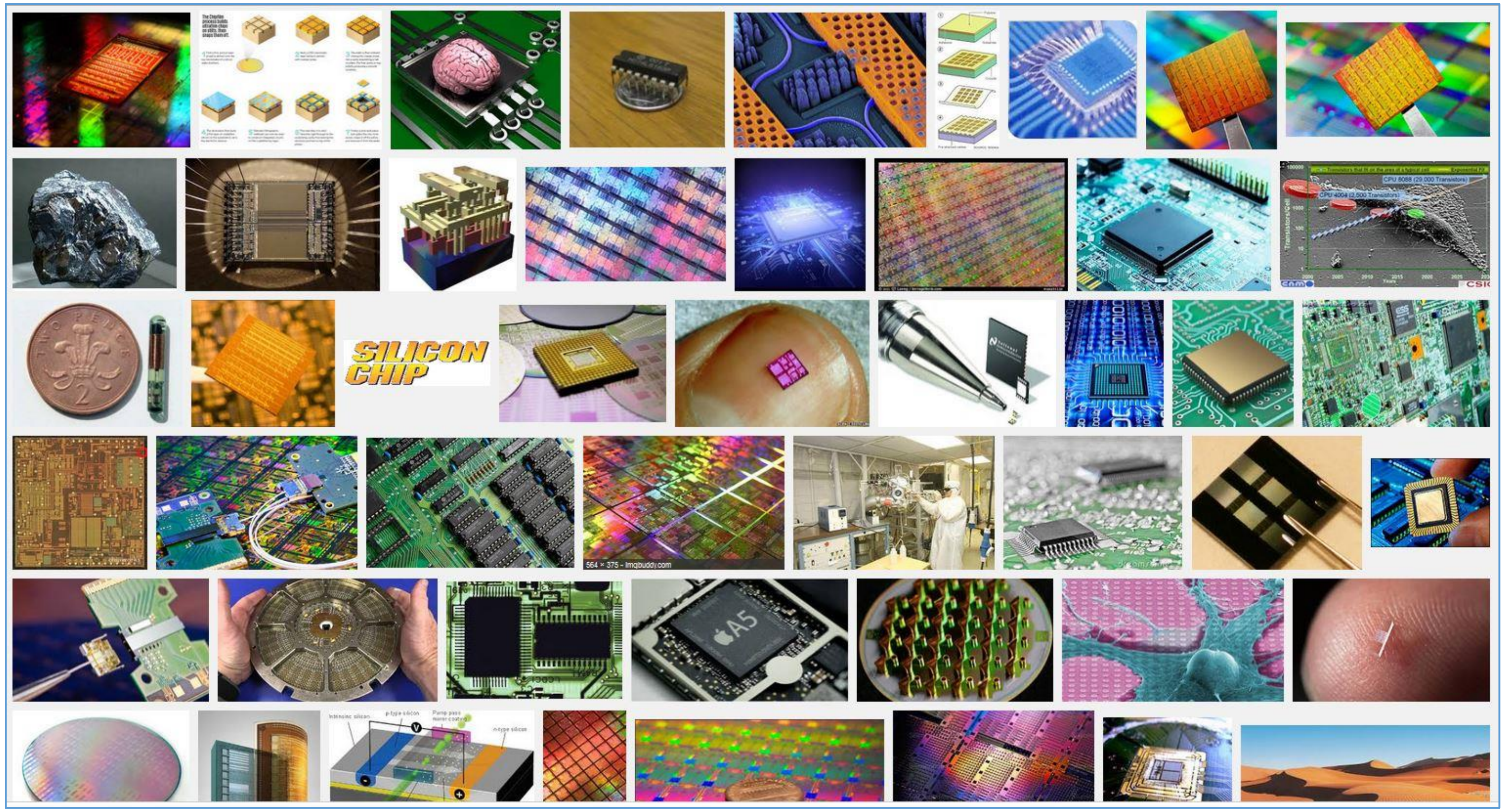
Wikipedia

Taking a glimpse inside the huge TSMC foundry in Taiwan . . .



Google Images

The microchip designs are being created by engineers in companies all around the world, then sent via the internet to such “foundries” for “printing” . . .



In effect, turning “Sand” (which is mostly SiO2) **into “Gold”. . . !**

The resulting VLSI chips are then used by design engineers to functionally empower and control all sorts of things . . . things that they're deeply embedded into . . .

Smartphones

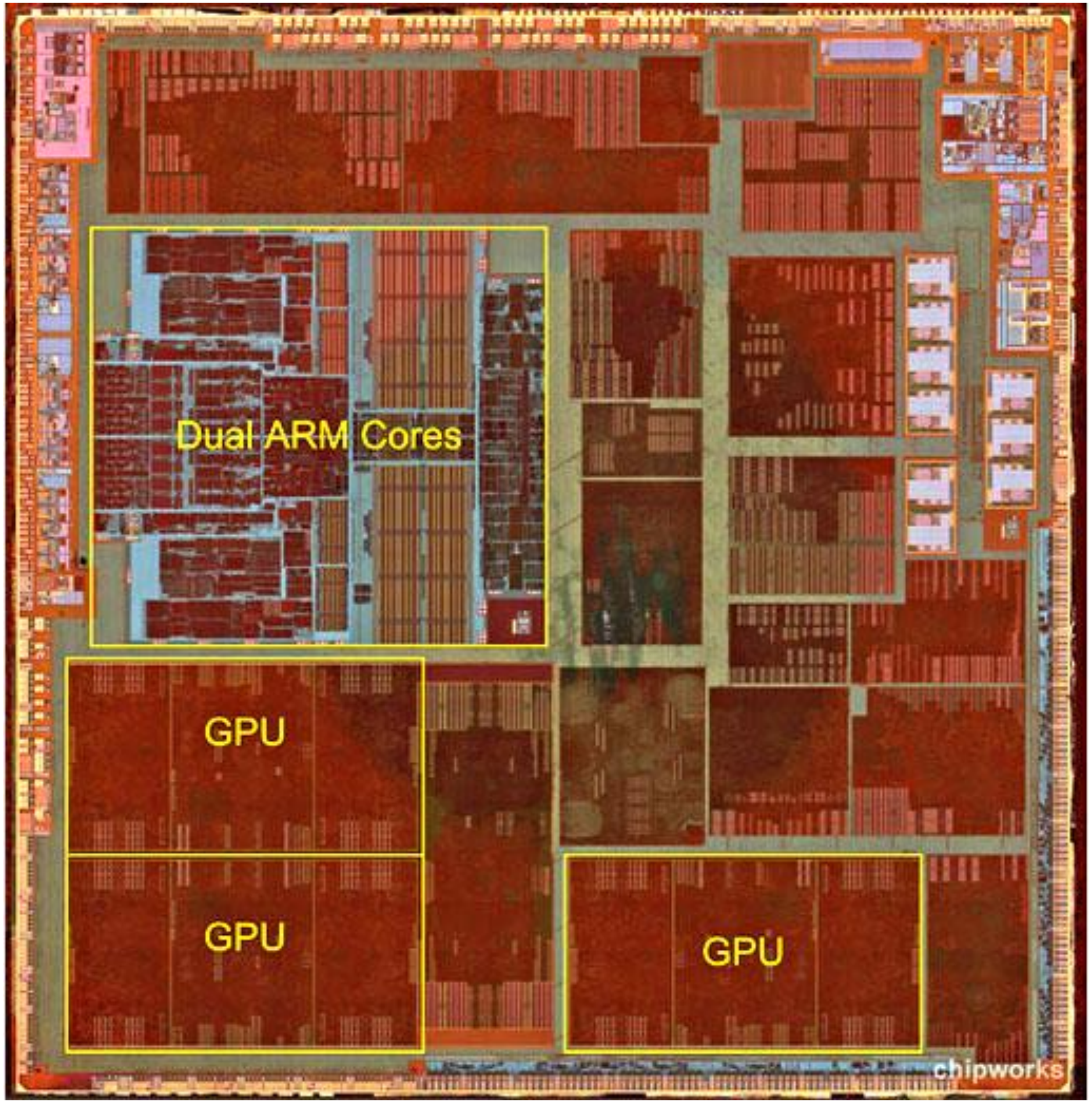
Wearables

Autos

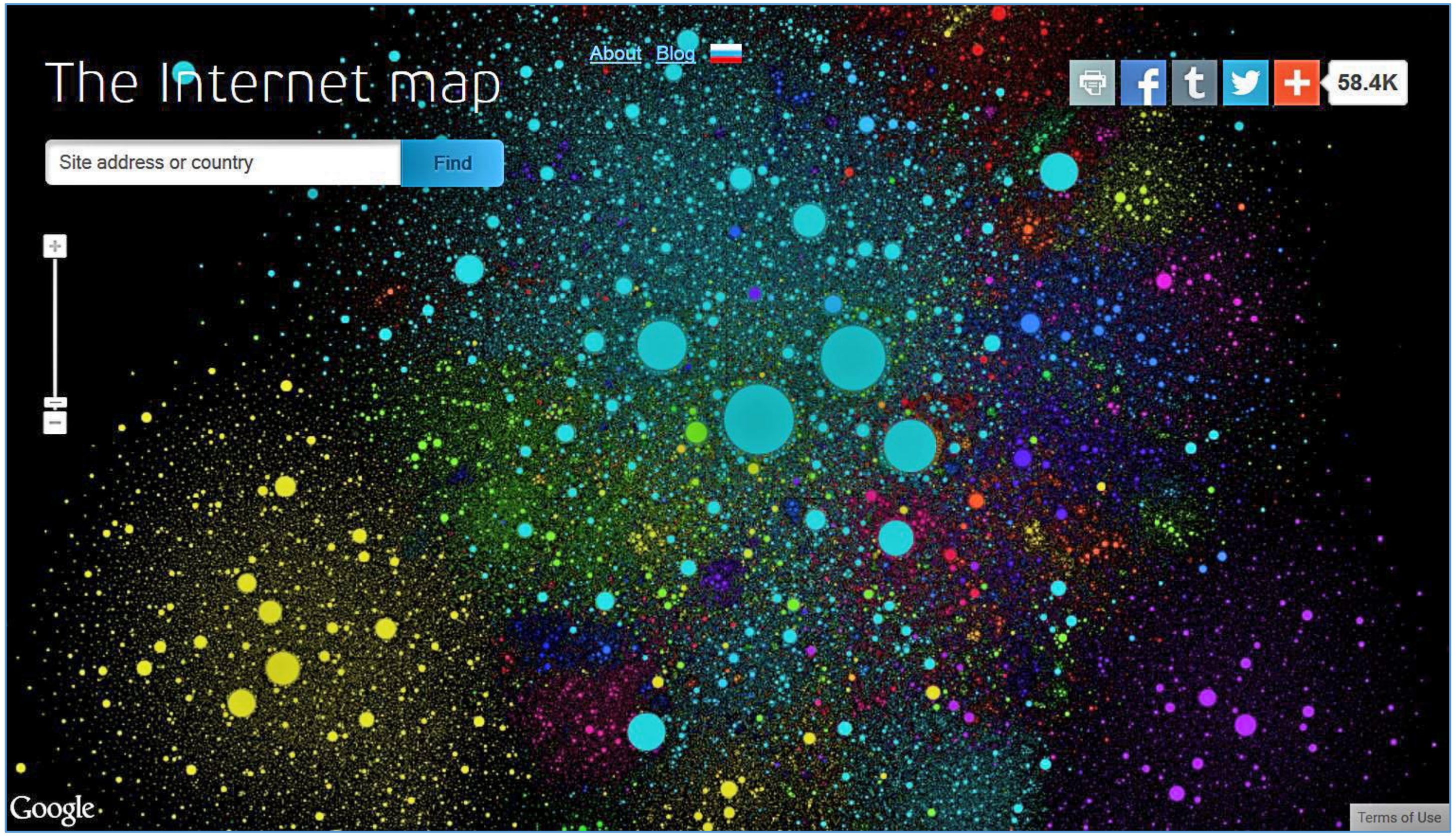
Drones

Snips from Google Images

Zooming in on one example, here we see an [iPhone 5 chip] with Dual ARM Cores and multiple GPUs

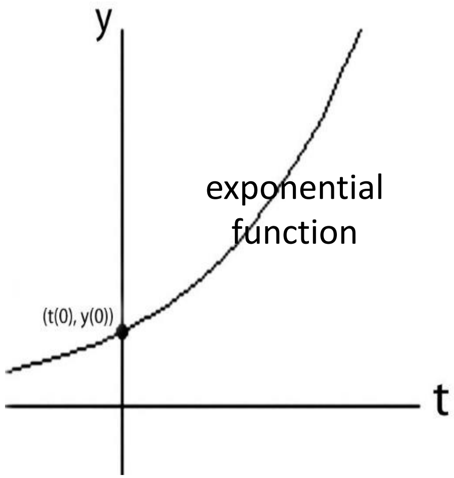


This also includes chips that empower the internet . . . which continues to expand exponentially . . .

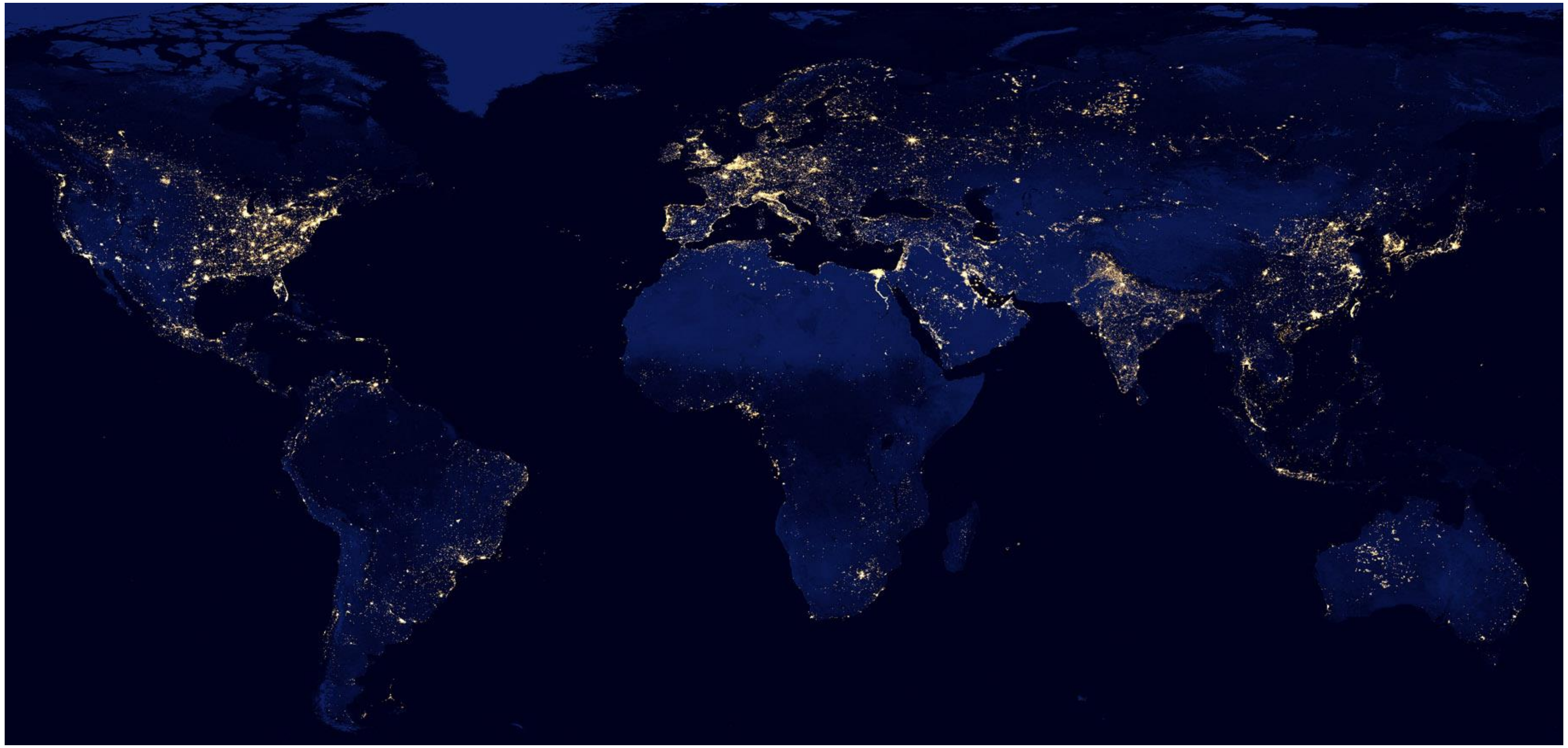


Link

Interactive Zoom-in Internet Map, 2015



With the internet connecting ever-more-people and chip-empowered-things, just imagine what's going on out there, right now, all around the world!

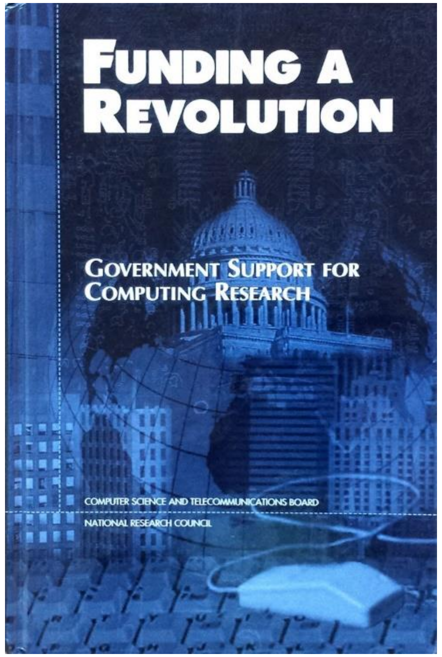


NASA: Earth from space at night

Thus setting the stage for what's coming next . . . !

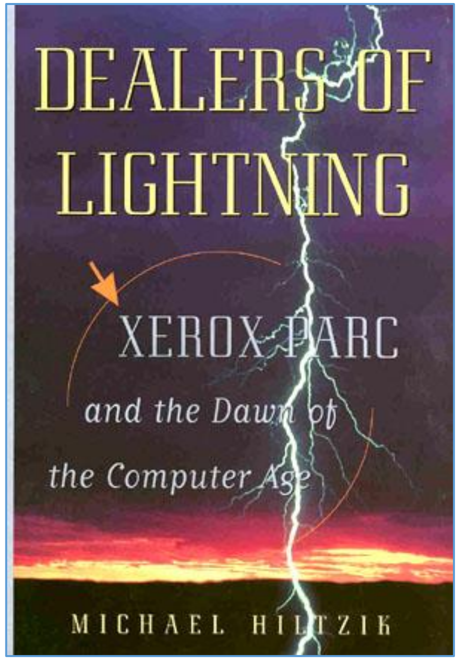
To learn more about the social, technological and human drama surrounding the remarkable birth of personal computing and the internet, see these books:

1999



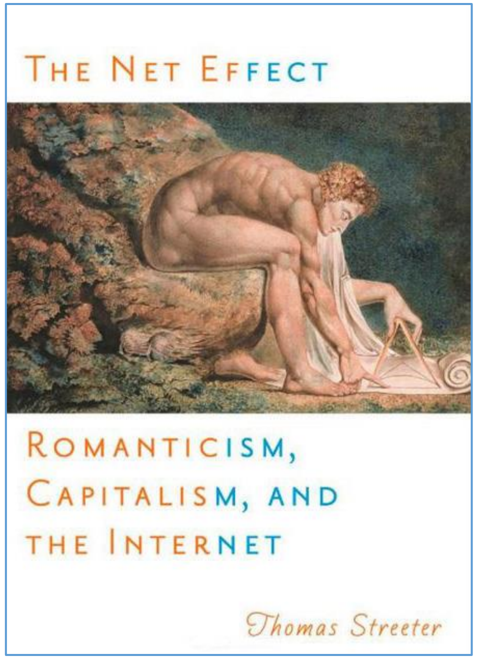
Link

1999



Link

2010



Link

"[What's past is prologue]" – William Shakespeare

It's now time to look forward, into the future . . . !

As we turn 180º and look ahead . . . we can visualize a huge incoming wave of innovation out there, now just beyond the social-time-horizon . . .

One thing for sure: This one is the "Big One"! . . .

Link

But why is it starting now? . . . Let’s set the stage:

Up until now microsystems have been deeply embedded **out-of-sight and out-of-mind** inside of “things” like . . .

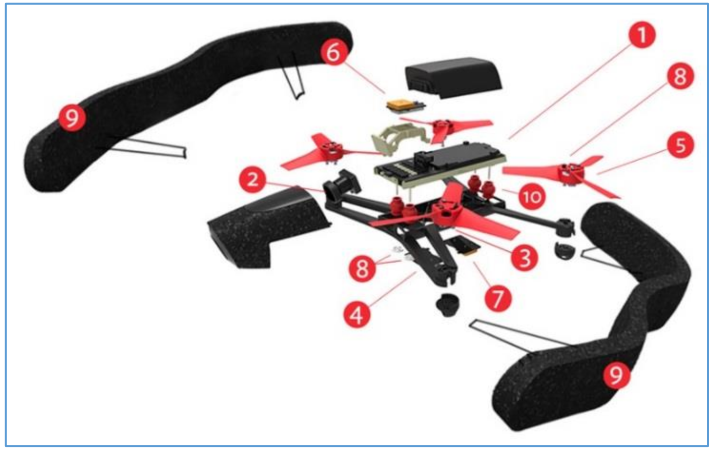
Smartphones

Wearables

Autos

Drones

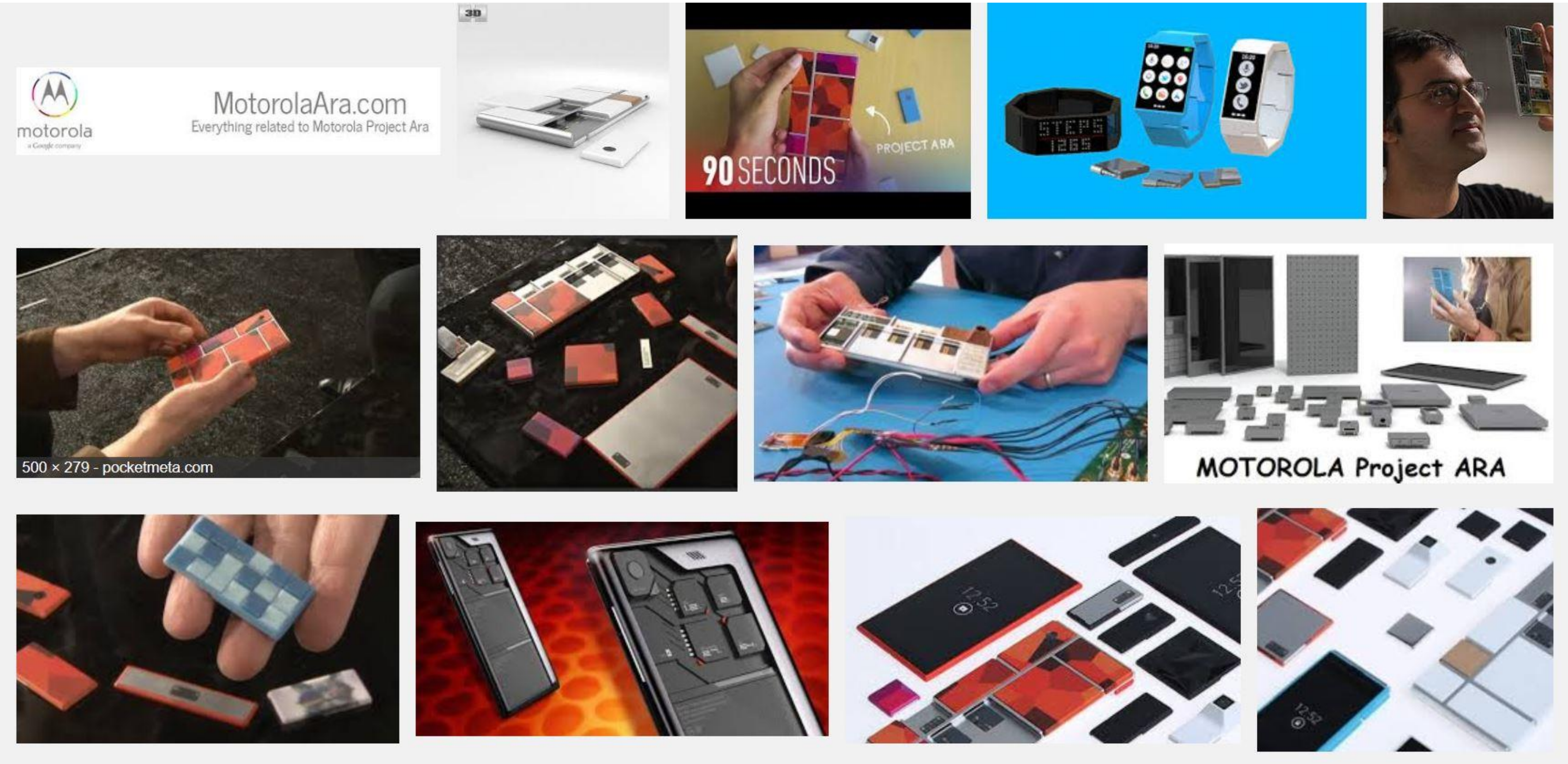
Thus few folks visualize the “many ideas in motion” that generate the astonishing ‘out-of-body’ experiences when flying a Parrot Bebop with an Oculus Rift. . .



www.youtube.com/watch?v=6ZdSMAG90Rs

www.youtube.com/watch?v=Io6V0NR7DN0

That’s all about to change due to technological milestones such as Motorola's "Project Ara" to create modular smartphones . . .



Ara's 'Phonebloks' will popularize the concept of micro 'Hardware Apps'

Many far-tinier than current-day 'big things" like cameras, GPS units, servos, bluetooth links, microphones . . .

Such microsystems now in our smartphones (but out of sight and out of mind) will suddenly become more visible.

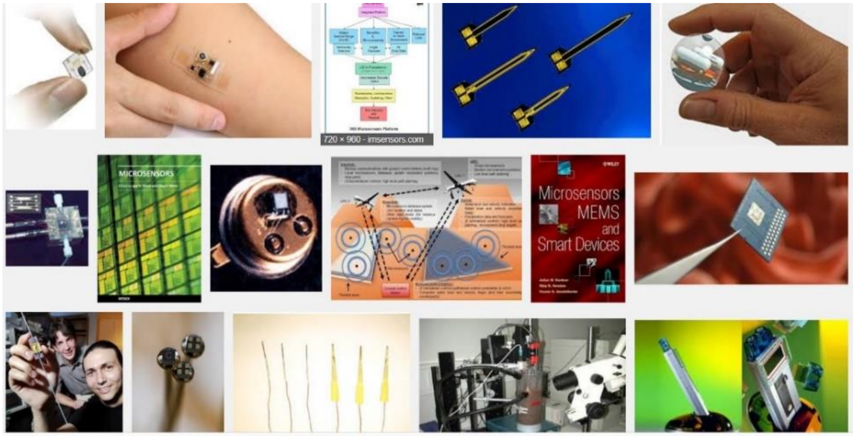
And they're not just processor chips, they're also **Micro Electro Mechanical (MEMS) Chips**, tiny micro-mechanisms also printed lithographically in "foundries". . .

MEMS, such as inertial measurement units (IMUs), microsensors, microcams and micro-transducers . . . and their microcontrollers and micro-interconnects . . .

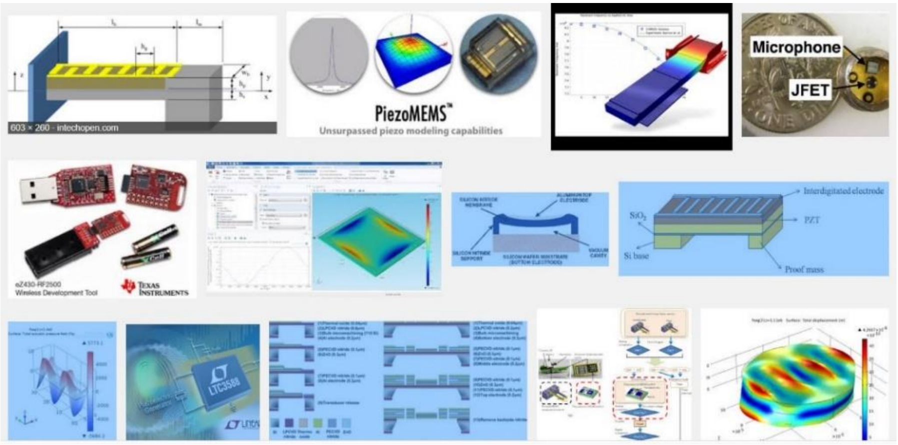
IMUs

Microcameras

Sensors



Interconnects

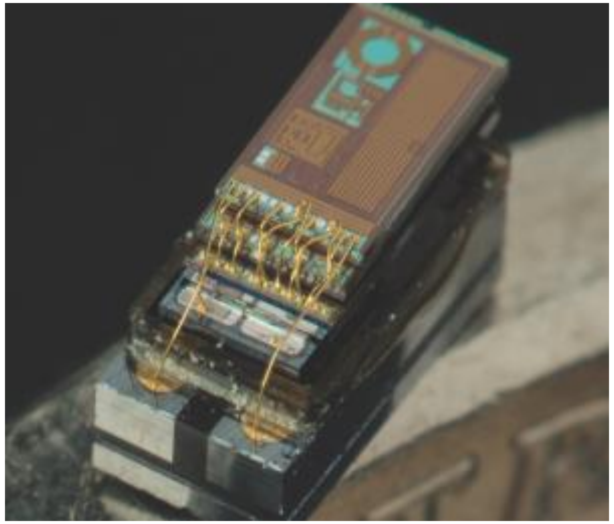


And they're all getting a LOT tinier!

See for example: The Michigan Micro Mote:

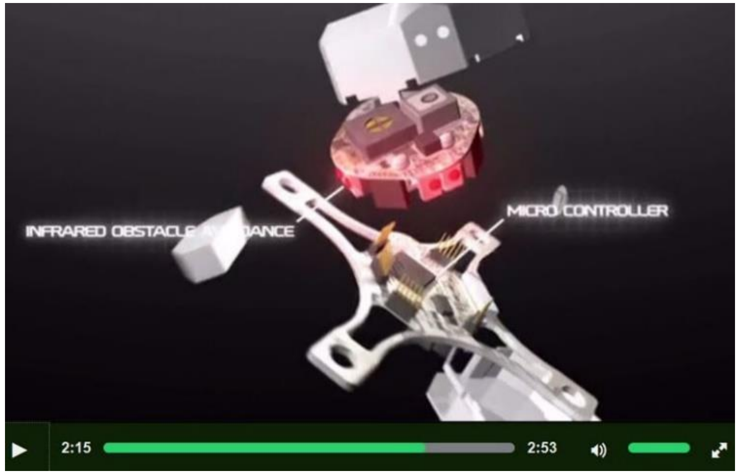
" . . . researchers at the University of Michigan under the direction of Professors David Blaauw, Dennis Sylvester, David Wentzlof and Prabal Dutta have recently announced the . . . "Michigan Micro Mote."

. . . a multi-layered integrated circuit with built-in solar cells, battery, microprocessor, sensors, radio and memory . . . come(s) in three types, measuring temperature, pressure or images"



Computer History Museum

To glimpse where this is heading, check out the **Zano drone**,
a recently launched "animated system" …



Source

Extremely tiny, it includes an HD cam, IMU, GPS, MCU, IR obstacle avoidance, gesture control, auto following, swarming and more…

There are so many dimensions to its capabilities, it's hard to even say where the "system" begins and where it ends . . . check out this amazing VIDEO!

https://www.youtube.com/watch?v=hgkbhjXTbOE

These aren’t just frivolous recreational play-things, but instead have vast potential for human empowerment . . .

Consider the story of a heart-patient confined by an lengthy hospital stay

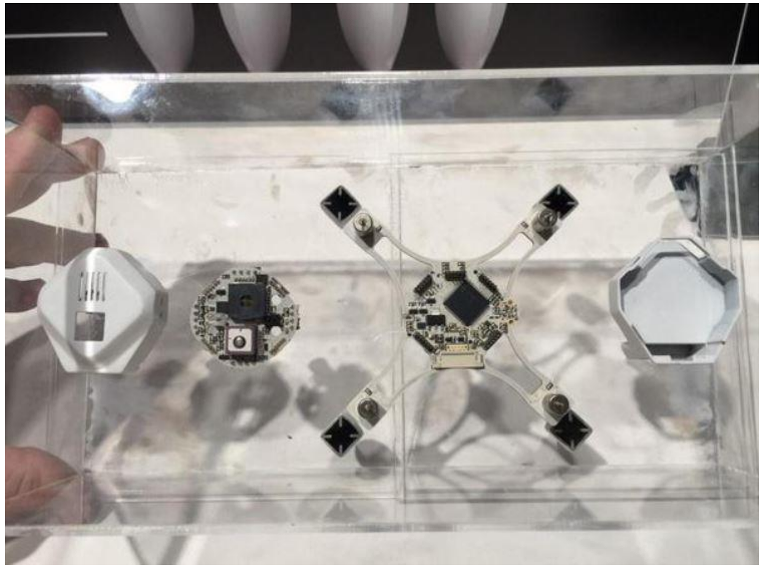
He can now enjoy exploring the beautiful world outside his window, a laptop controlling his drone, providing stunning views of what’s out there

It won’t be long before we can join friends on group “drone-tours” of remote places around the world, right from own individual homes . . .

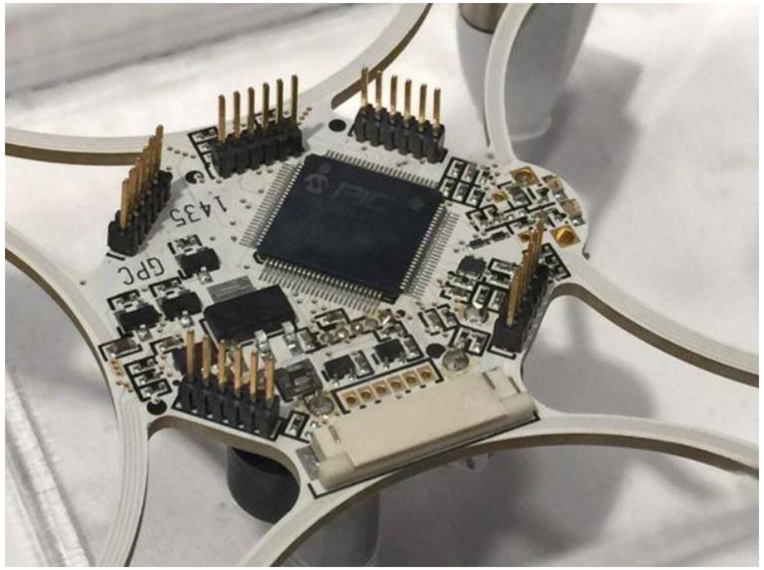
With each our drones “carrying our eyes” remotely in the form of fisheye lenses and microcams (as in the Bebop)

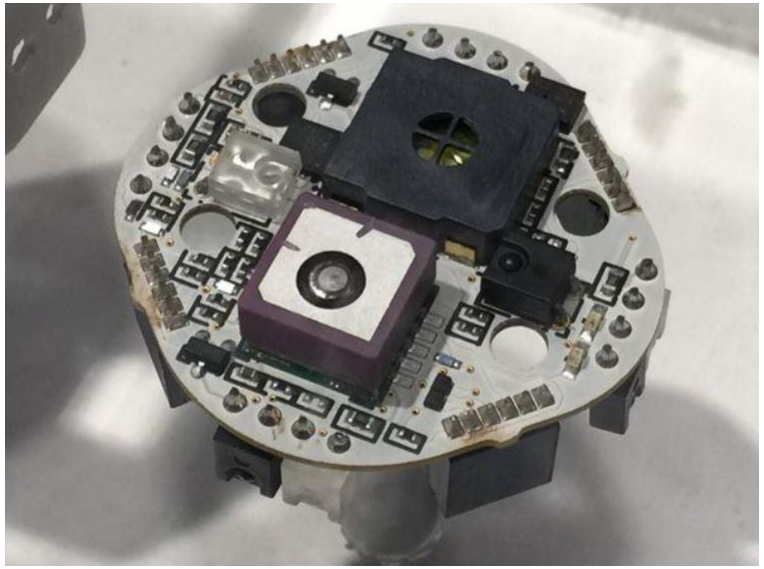
Which we see through by using our Oculus Rifts over the internet!

Imagine the impact as today's kids start peeking at the insides of Zano nanodrones!



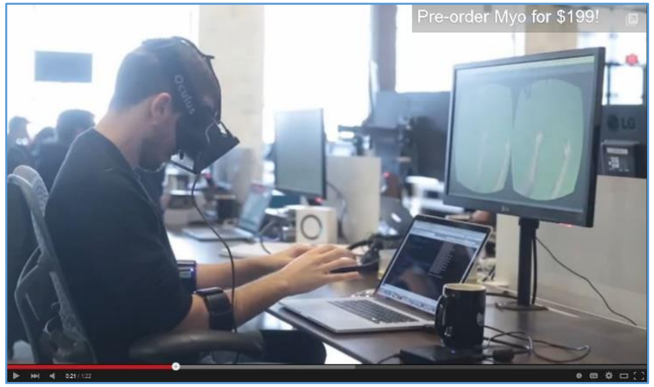
Think of the possibilities of what they might do next!





URL

Some ideas/things in the coming wave of innovations are hinted-at by the new Myo gesture control armbands from the mechatronics engineers at Thalmic Labs:



VIDEO VIDEO VIDEO VIDEO!

So, what’s happening here?

Instead of just printing a billion transistors onto single “large” smartphone chips.

We can also print a million transistors onto 1000 very tiny but very powerful chips.

I.e., you can actually do a lot with a million transistors!

So we can now embed lots and lots of tiny micro-processors and MEMS micro-mechanisms into almost everything.

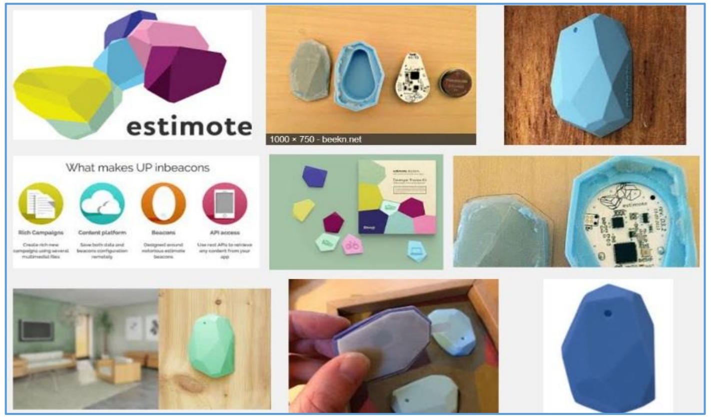
Placing them were they can get local physical data such as position, acceleration, temperature, pressure, etc.

Thus enabling smart-distributed-clusters of tiny chips to animate and interactively control many macro-scale systems such as robots, drones, autos . . .

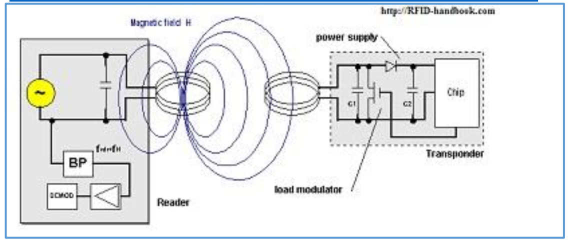
Such chips can be selected and embedded in macro-scale systems
By exploiting innovations in selection methods, and innovations in woven, printed, near-field and wireless interconnections . . .

Micro Chiplets (XeroxPARC)

Low-energy Bluetooth beacons



Near-field communications

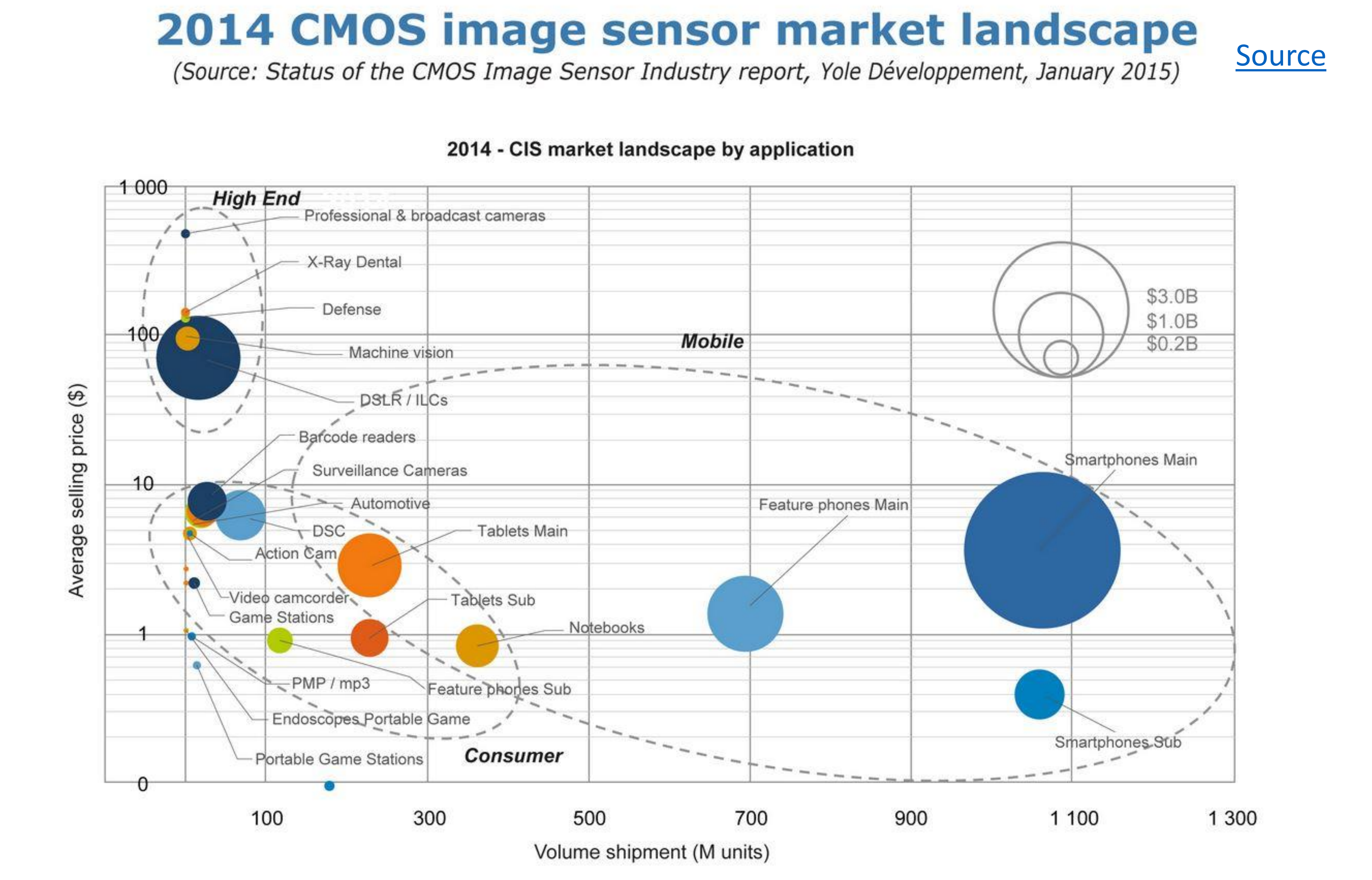


Smart textiles (PASTA)

Video

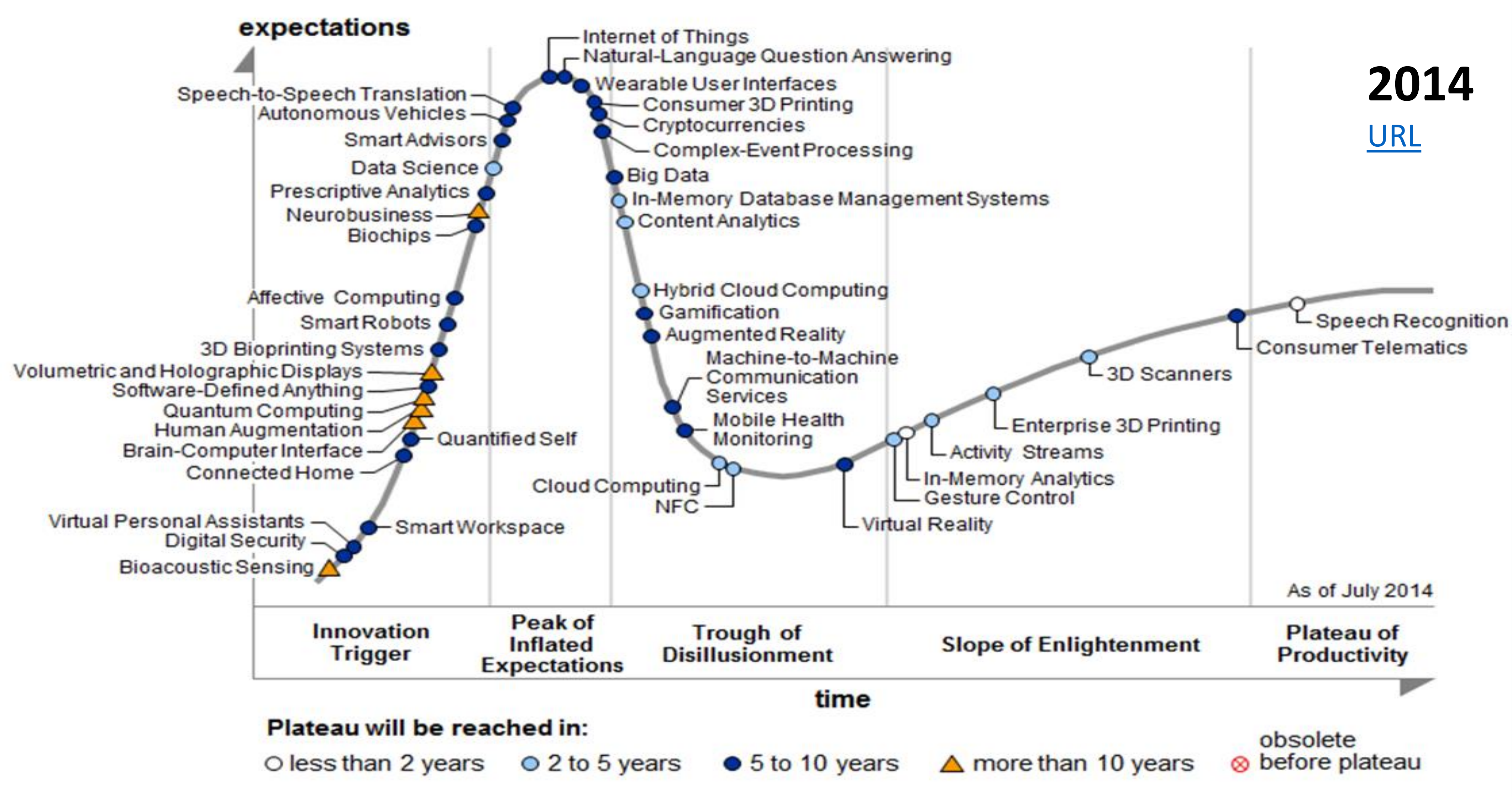
This embedded-microsystems revolution is getting up a big head of steam in emerging “Silicon Valleys”, “Cambridges” and “Maker Valley’s” all around the world …

We can zoom-in and watch it unfold in mappings of many specific areas of micro-system technology, such as the image sensors for "microcameras" . . .



Source

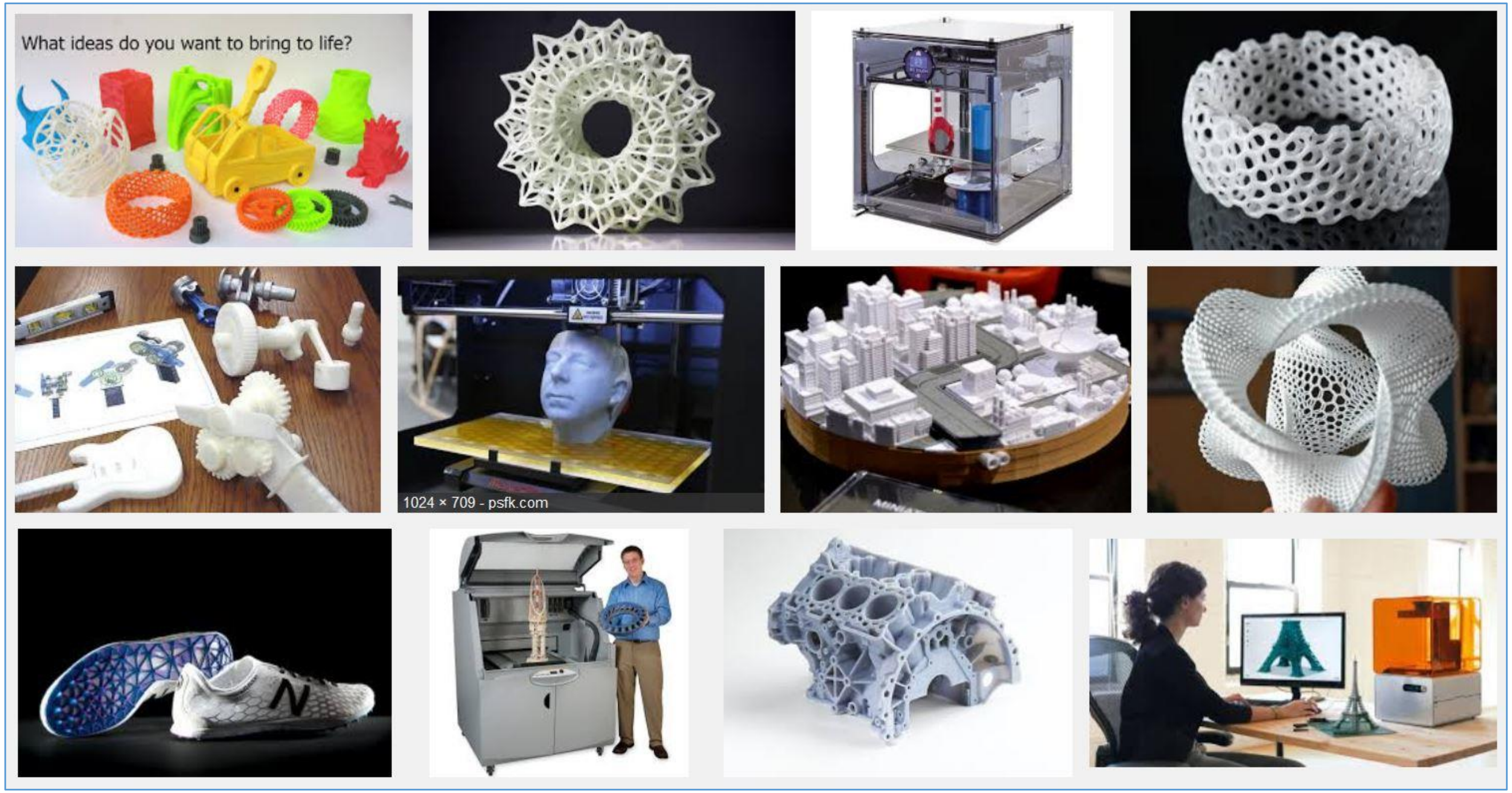
And in the movement of "application-idea-clusters" along Gartner's "Hype Cycle"



2014

URL

One key cluster of innovations on that wave is "3D Printing". . .
Enabling macro-scale 3D "things" to be quickly made from digital-specs created by designers using personal computers . . .



3D printers enable making prototype macrostructures such as robots, drones, medical devices, and more . . . into which microsystems can be embedded . . .

Once prototypes are perfected, design-files can be shared or marketed to other 3D printer users anywhere . . .

When those “things” become obsolete, their polymer macro-structures can be ‘melted-down’ and reused to make new “things” . . .

Innovative *new micro-hardware apps* can also be inserted into such additive manufacturing systems . . . enabling a 3D printer that print 3D printers* to prototype *a yet more powerful 3-D printer!*

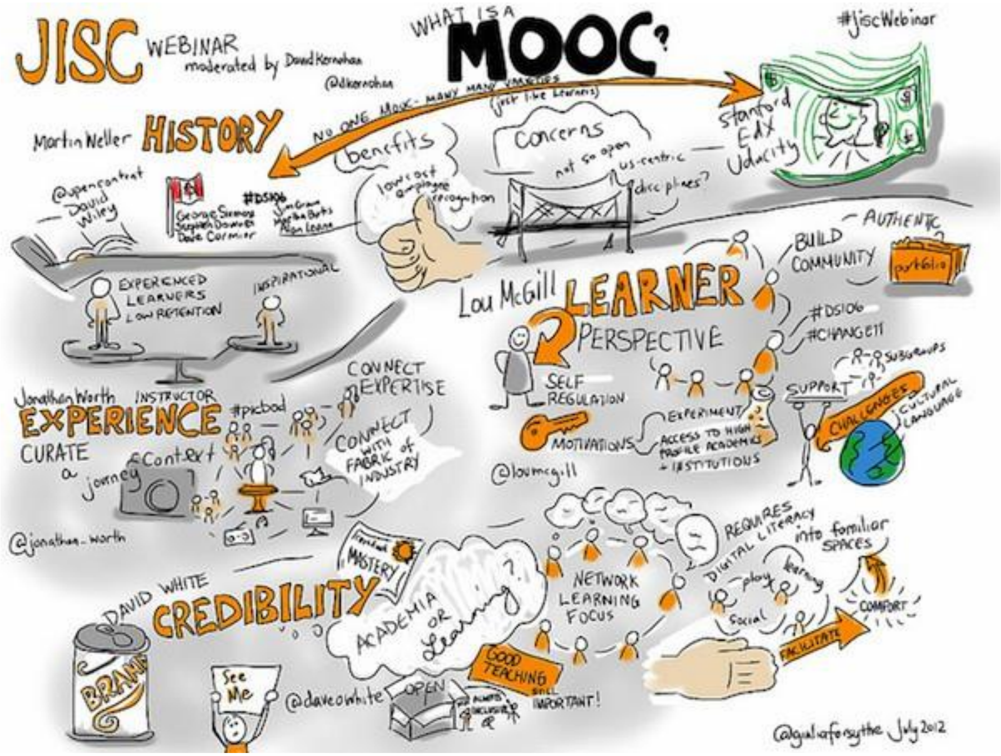
*"Printers for Pearce: An Interview with 3D Printers for Peace's Dr. Joshua Pearce", Michael Molitch-Hou, *3D Printing Industry*, 10/18/13 See also: http://www.youtube.com/watch?v=C8Wv3LCJcUE and http://www.youtube.com/watch?v=yiJDx9dCfEQ

Just as when some of the iron was fed-back to make more steam engines to further empower the industrial revolution . . .

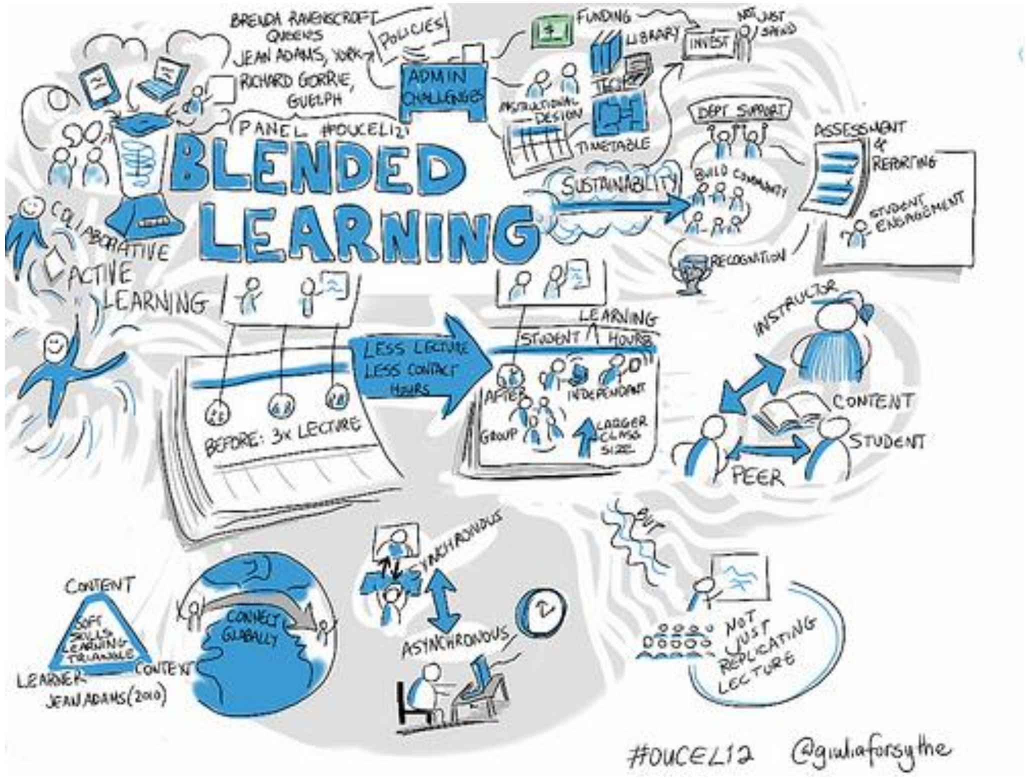
Innovating such iterative feedback loops yields "gain" in the technological exploration system . . .

But (recalling Steinmetz's dilemma) **how will all the young innovators learn to grasp the new wave of concepts propelling this revolution?**

Fortunately, a wave of exploratory change is sweeping engineering education, just in time . . .

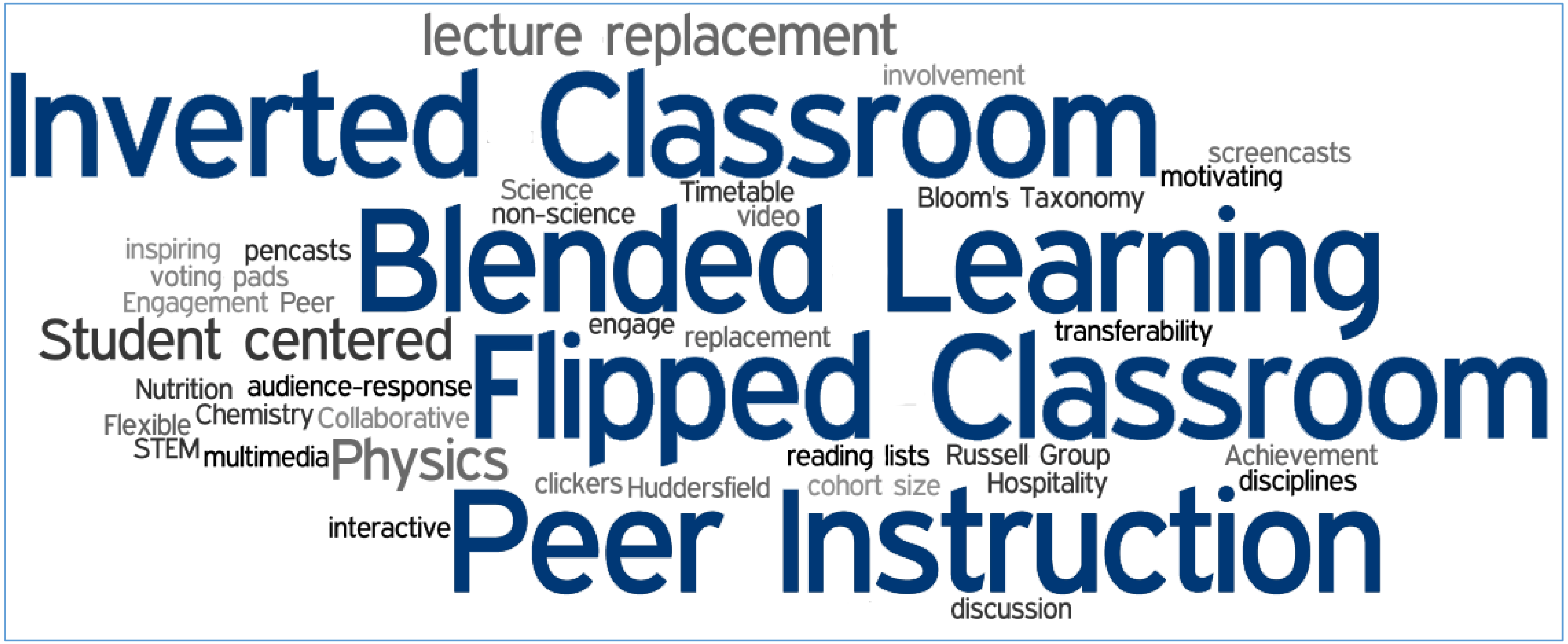


[‘What is a MOOC?’ by giulia.forsythe, Flickr]



[‘Blended Learning’ by giulia.forsythe, Flickr]

And more . . .



Source

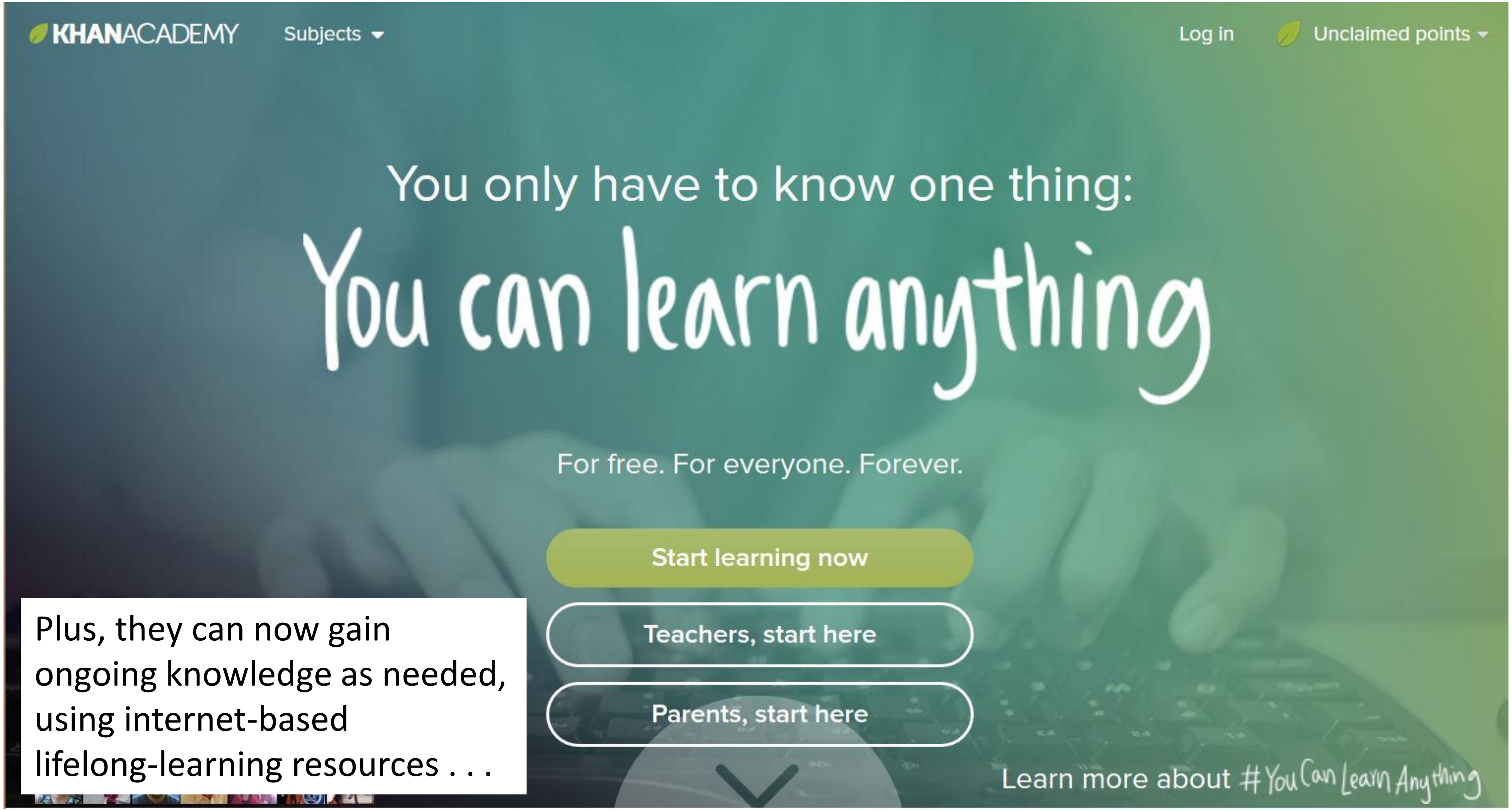
Many young incoming engineering students have also gained deep-experiences at. . .

LEGO Camps

Maker Faires

FAB Labs

Robot Competitions

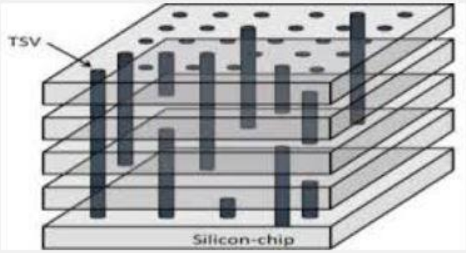


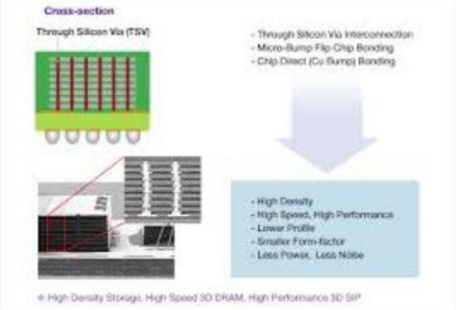
Plus, they can now gain ongoing knowledge as needed, using internet-based lifelong-learning resources . . .

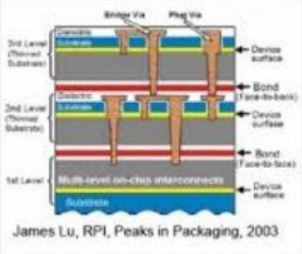
Some (the “microsystems designers”) will go on to exploit rapidly-evolving **electronic design automation (EDA)** and **“multi-physics” design tools** to create new micro-hardware apps . . .

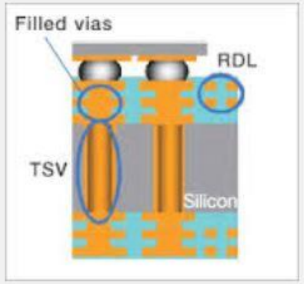
Snip from Google Images

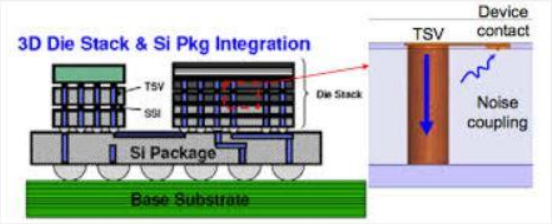
Exploiting innovations such as [3D chip-stacking]and [through-silicon vias (TSVs)]
to compose ever-tiner chip-modules and “hardware Apps” (like the ‘Micro Mote’) . . .

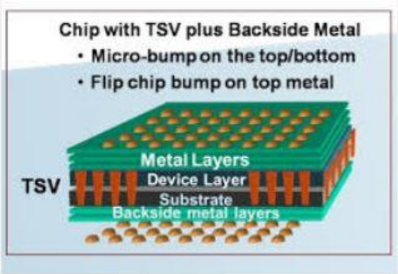


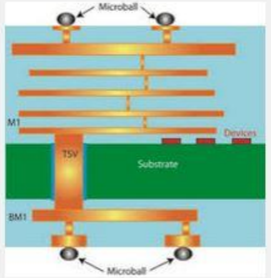


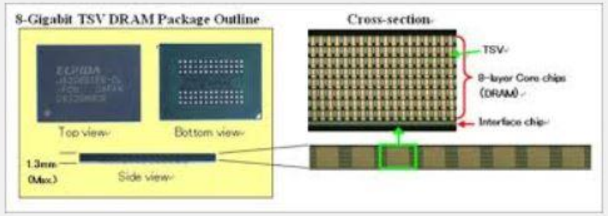


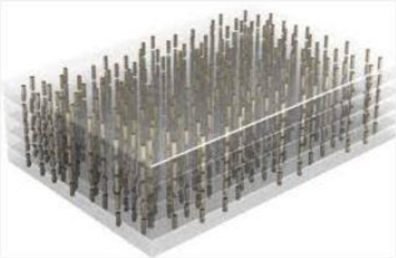


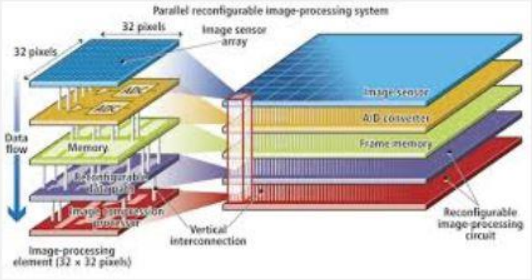


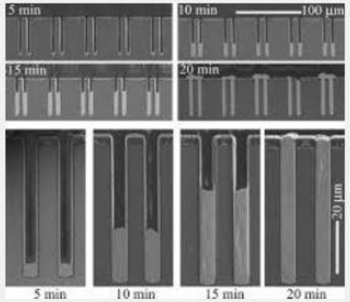


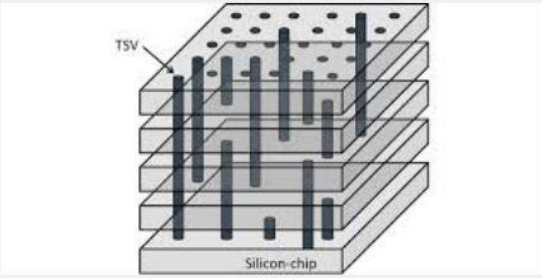






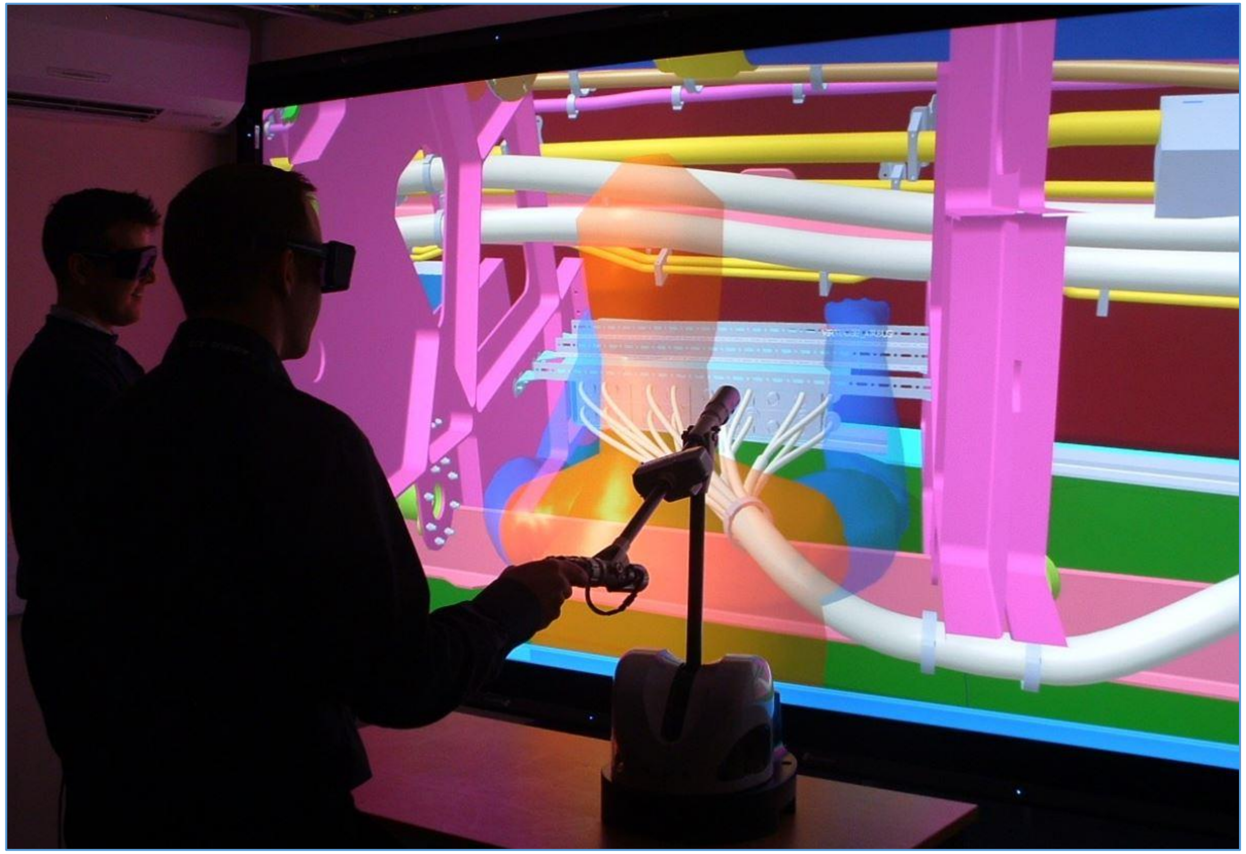






Many others (the "mechatronics designers") will use collaborative macro-scale design tools such as Dessault Systems' '3D Experience Platform'

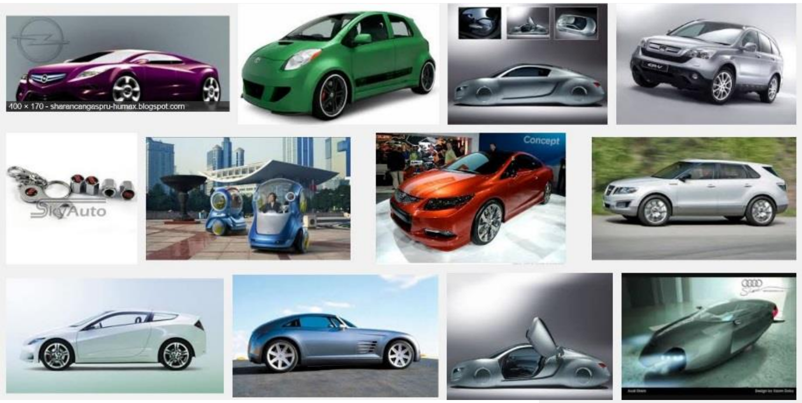
to innovatively embed smart modular hardware-apps to dramatically animate a new wave of human-scale systems . . .



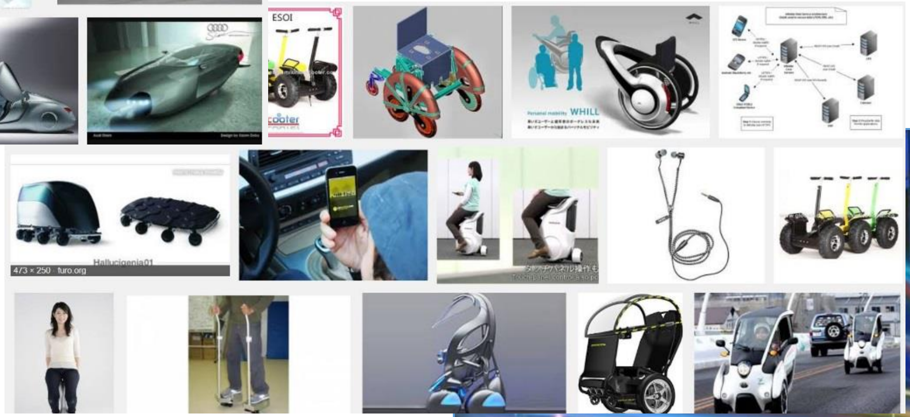
https://www.youtube.com/watch?v=IPu28vUcZzI

World-wide automotive technology will be a huge driver of the rapid embedding of micro-hardware Apps into human-scale systems. . .

Starting within cars



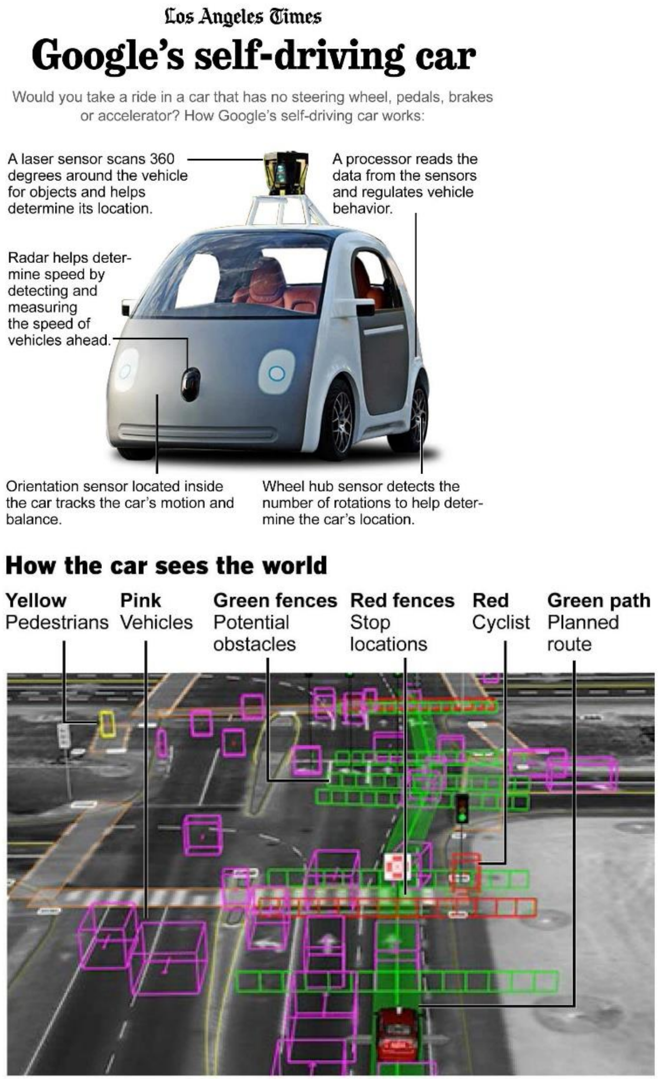
and on into Mobility technology

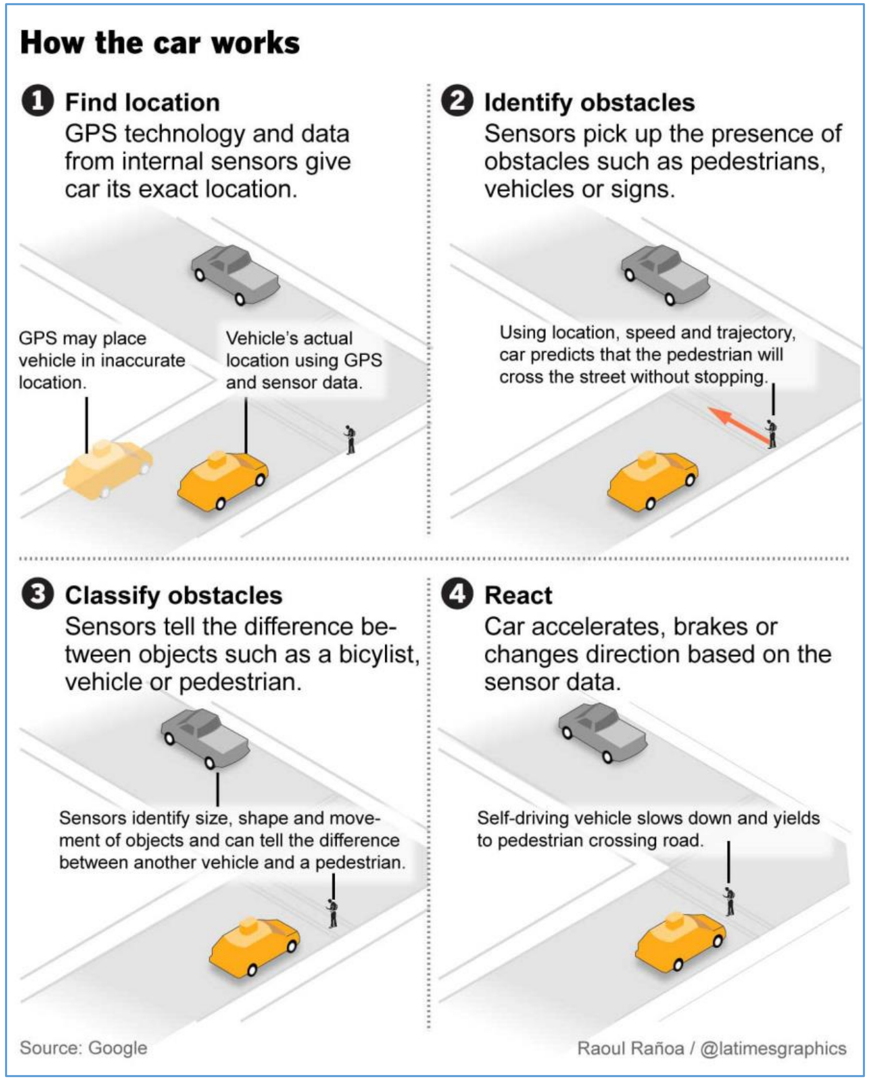


and into Smart_Roadways

LA Times Infographic:

Now we've all heard about Self-driving cars . . .





But what about exploiting "Augmented Reality" (as in "Parrot Bebop + Oculus Rift") in conjunction with mobility technology . . .

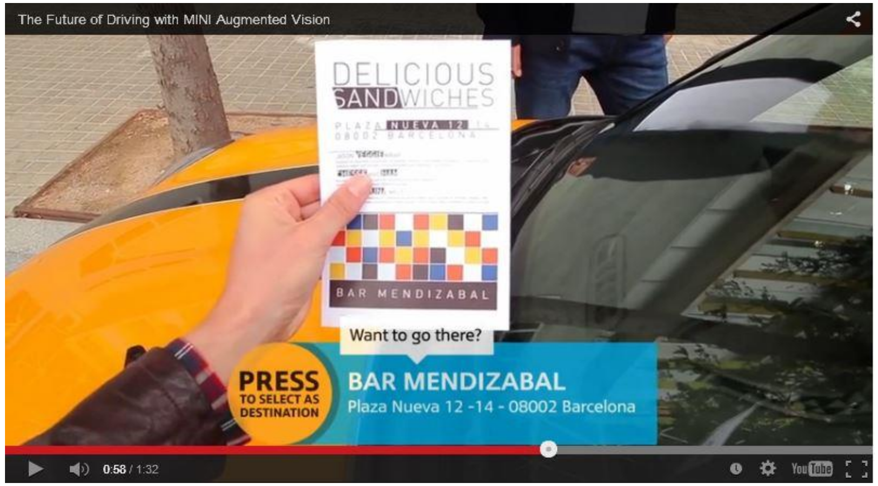
For example, just this week at the Shanghai Motor Show (April 20-29, 2015) Mini is showcasing their new augmented-reality glasses concept . . .

http://traffictechnologytoday.com/news.php?NewsID=68125

To visualize the many possibilities of this concept, watch this remarkable VIDEO

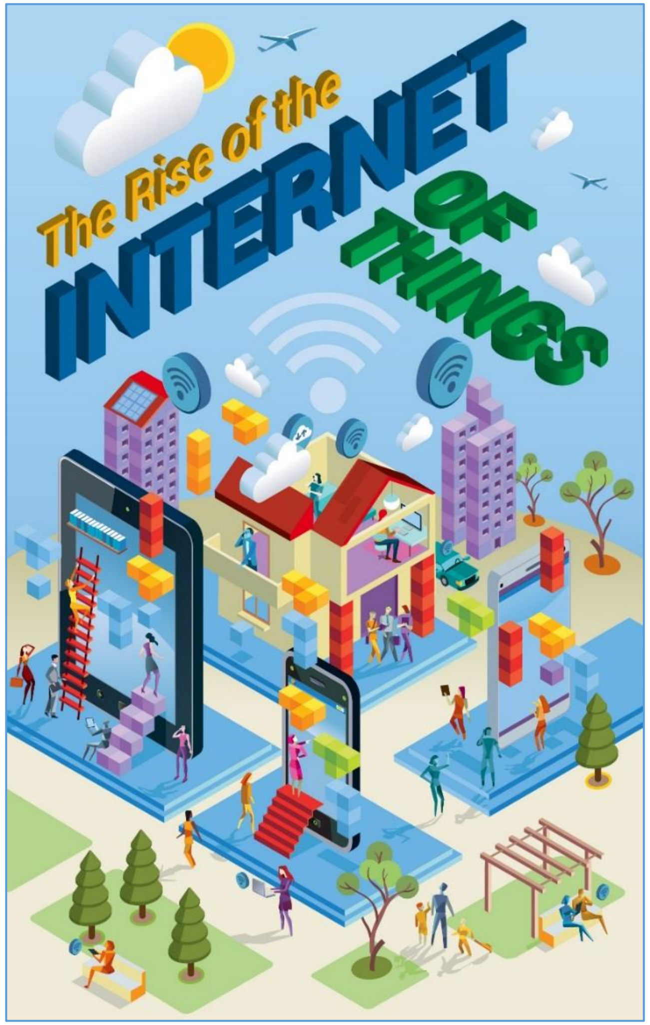
VIDEO: Approaching the Mini . . .
Seeing real wheel when parking . . .

Seeing through the side-doors . . .
Deciding where to go next . . .



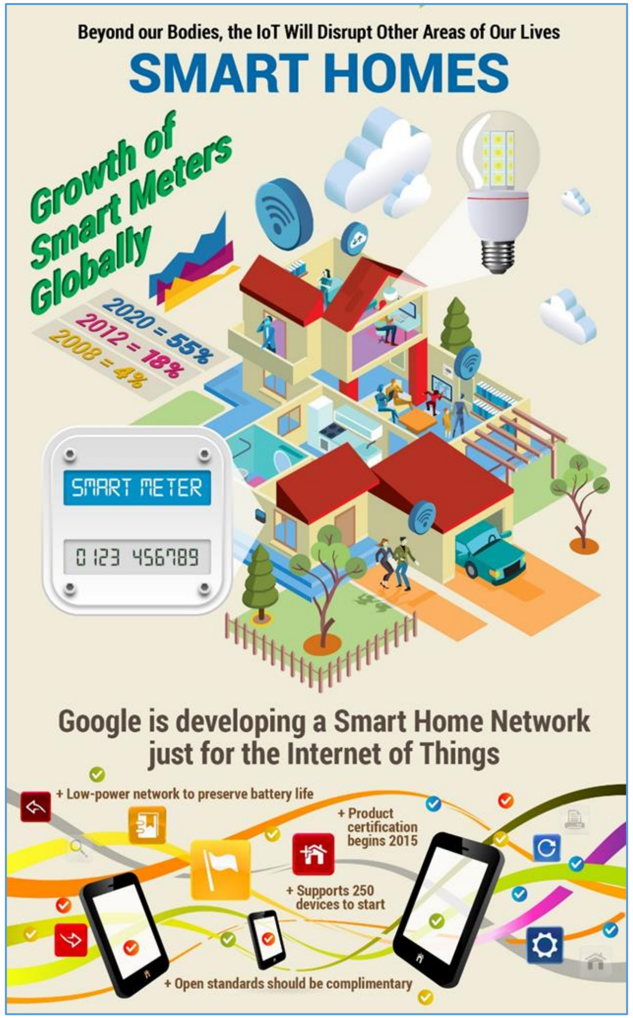
https://www.youtube.com/watch?v=QARt89_6Jrs#t=19

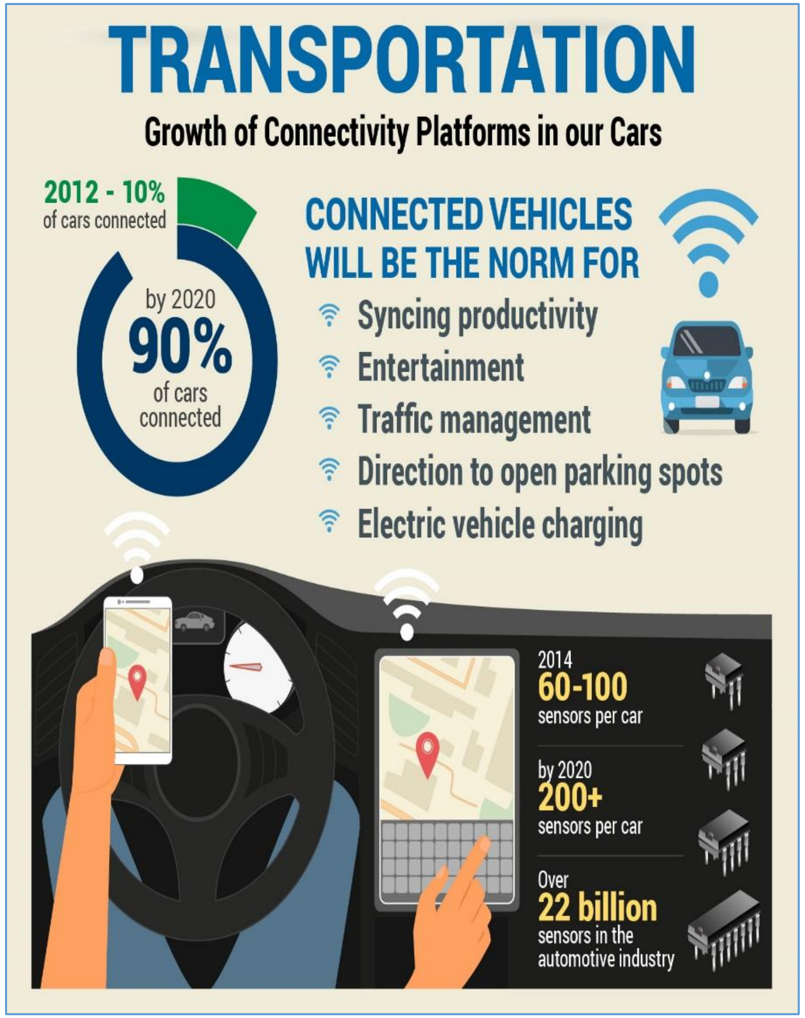
The innovative embedding of ever-tiner micro-hardware apps will quickly spread . . .



http://blogs.jabil.com/2014/08/13/internet-of-things-infographic/

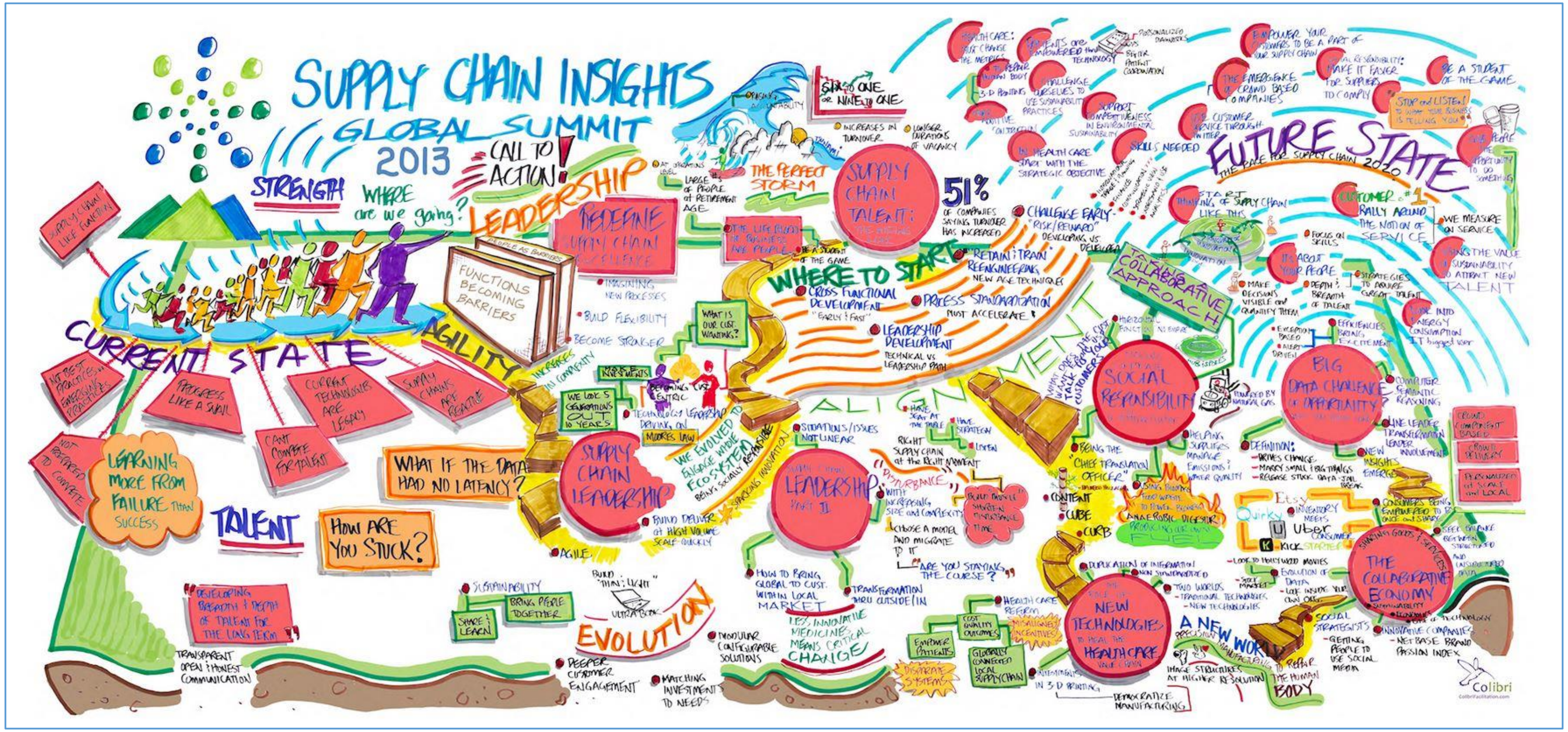
And begin to functionally enhance just about everything . . .





http://blogs.jabil.com/2014/08/13/internet-of-things-infographic/

Along the way, the microsystem supply-chains into the electronics, automotive, medical, clothing, home-appliance and building industries will cross-couple and commingle and enhancements gained in each will quickly cross-fertilize others . . .



Source

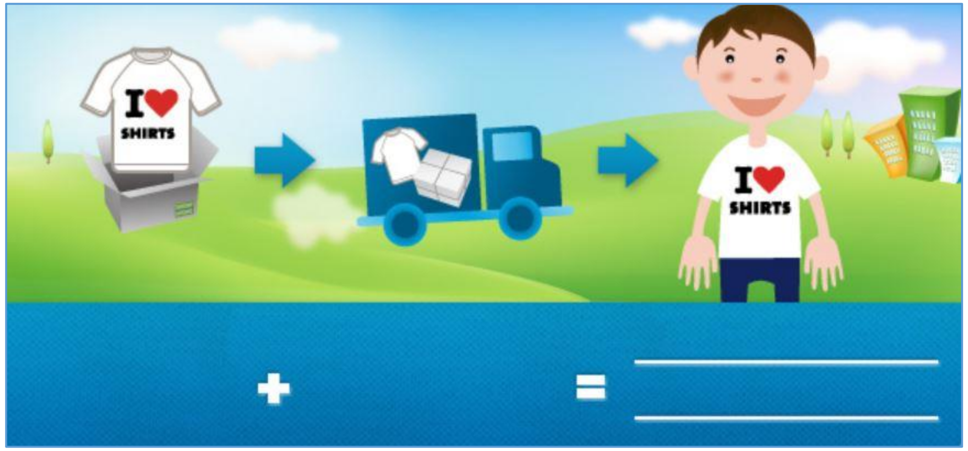
There will be many disruptive changes in current business models such as . . .

Reshorings will reduce clustered turnaround times . . .

Source

Logistics systems will take center stage . . .

Order-to-Delivery times pace rates of exploration . . .



Source

But how will we cope with the 'complexity' of the emerging techno-social ecosystem?

[From: The Age of Opportunity: Harnessing Complexity To Solve Big World Problems by Frank Spencer, kedgefutures.com]

By exploiting things like
collaborative learning, crowdsourcing, crowdfunding, IP brokering, agile methods, rapid-digital-prototyping, and more . . .

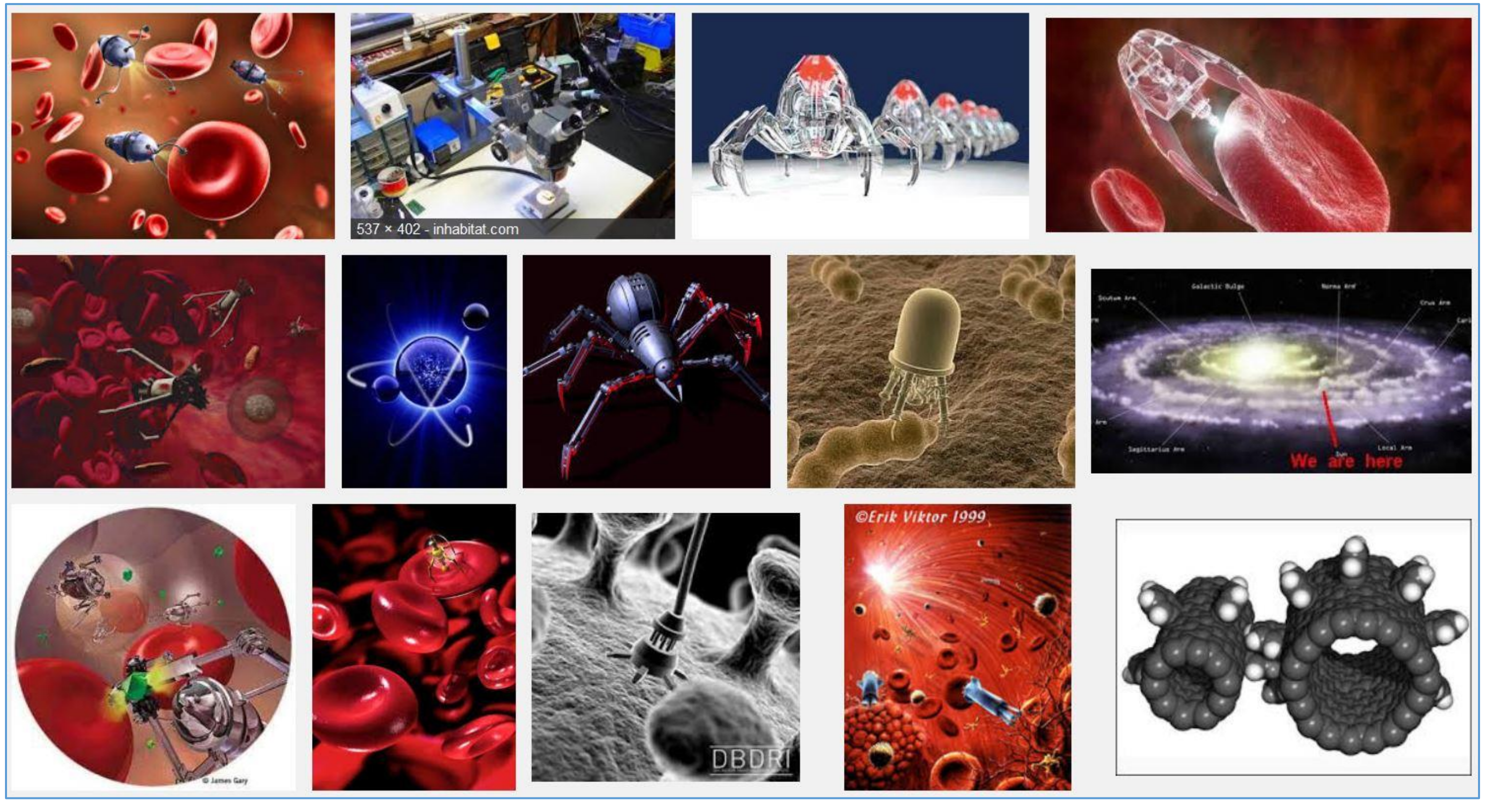
Everyone, from
engaged-users to makers,
will be able to scale up their participation and impact.

Only now, instead of just exploring how to make ever bigger things that go ever further and ever faster, such as when reaching for “outer space”. . .

NASA

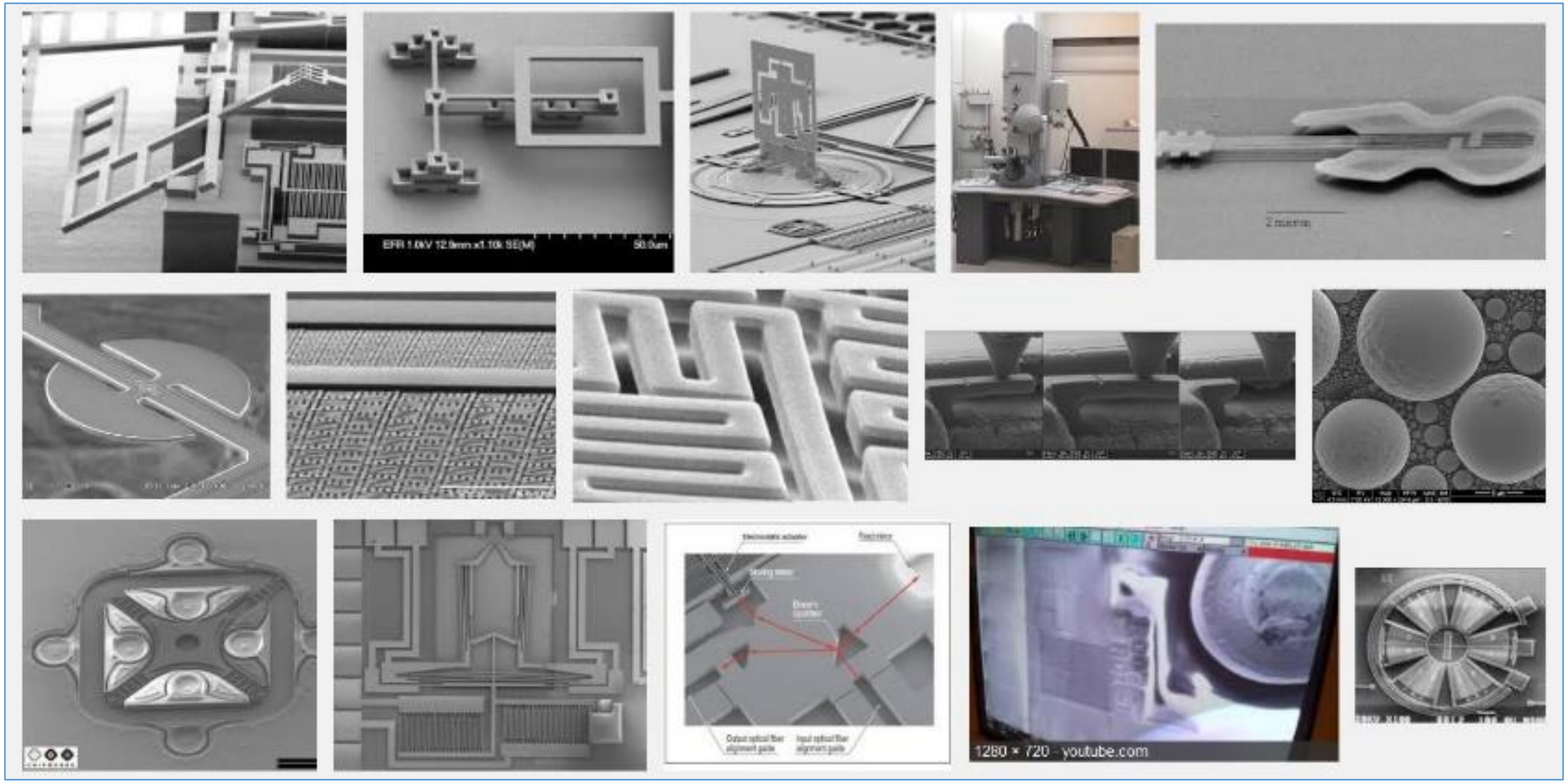
We've inverted our perspective 180^{0}, reaching down into the "deep inner spaces" of the micro/nano/pico world . . .

And are exploring how to make and exploit vast-quantities of ever-tinier, ever-more-empowering "micro/nano things" . . .

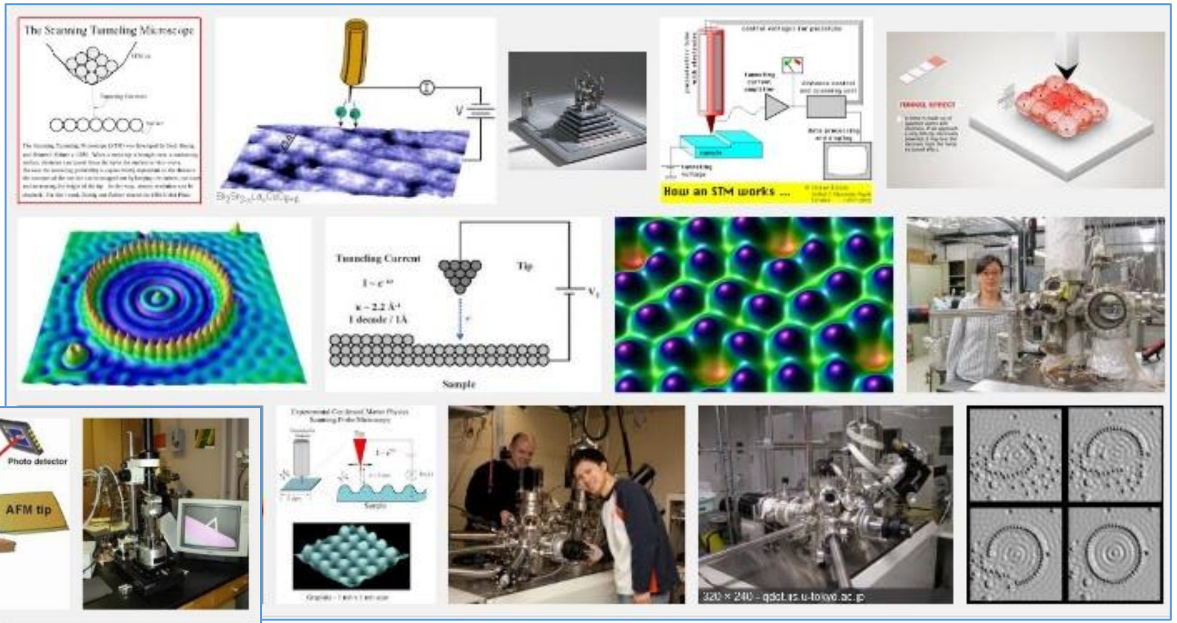


Google Images

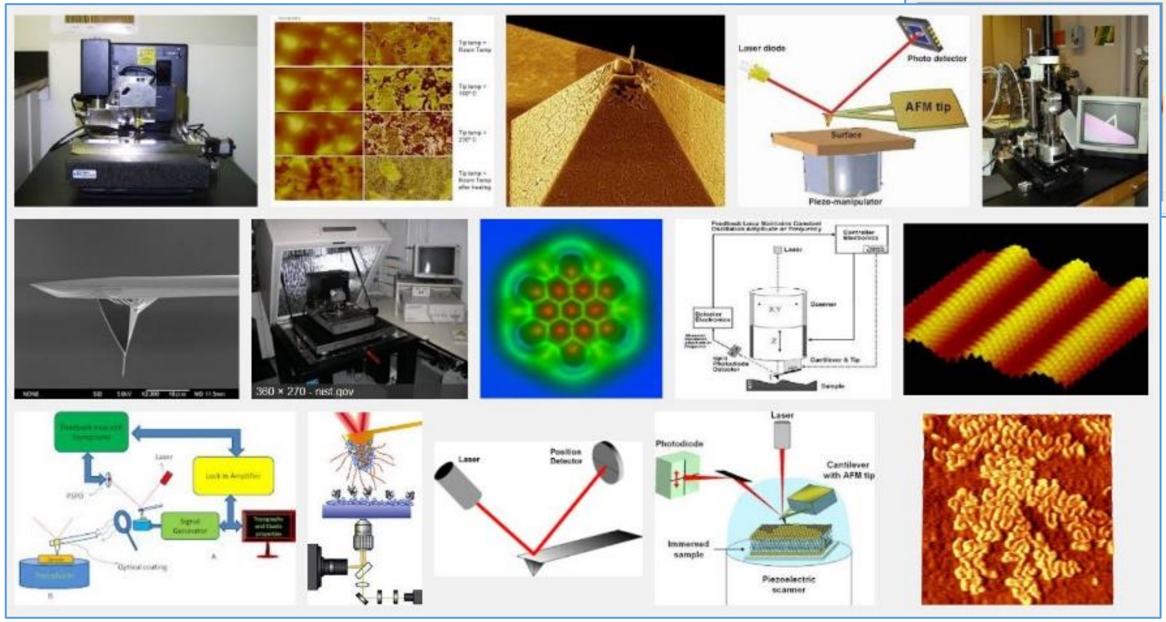
For example, using Scanning Electron Microscopy (SEM) to study the details of the tiny micro-machinery printed on MEMS chips . . .



And zooming-in even further to measure and maps things down at the molecular and atomic levels . . .



Scanning Tunneling Microscopy (STM)



Atomic Force Microscopy (AFM)

So as to guide adventurers on explorations at places and in fields such as . . .

Augmented Reality

Social Media

Harvard Wyss Institute

Model-Based Design

Biologically Inspired Engineering

Draper Lab

MIT Nano

Collaboration Technology

Multiengineering

Machine Vision

Social Physics

DARPA Microsystems

Machine Hearing

Research Universities

Meta^2Mathematics

Augmented Kinesthetics

Social Dynamics

Google ATAP

Synthetic Biology

MetaArchitecture

UPS

Social Machines

Microsoft Research

Genetic Algorithms

Self Assembling Systems

Social Learning

Facebook

Exploration Infrastructure

Amazon

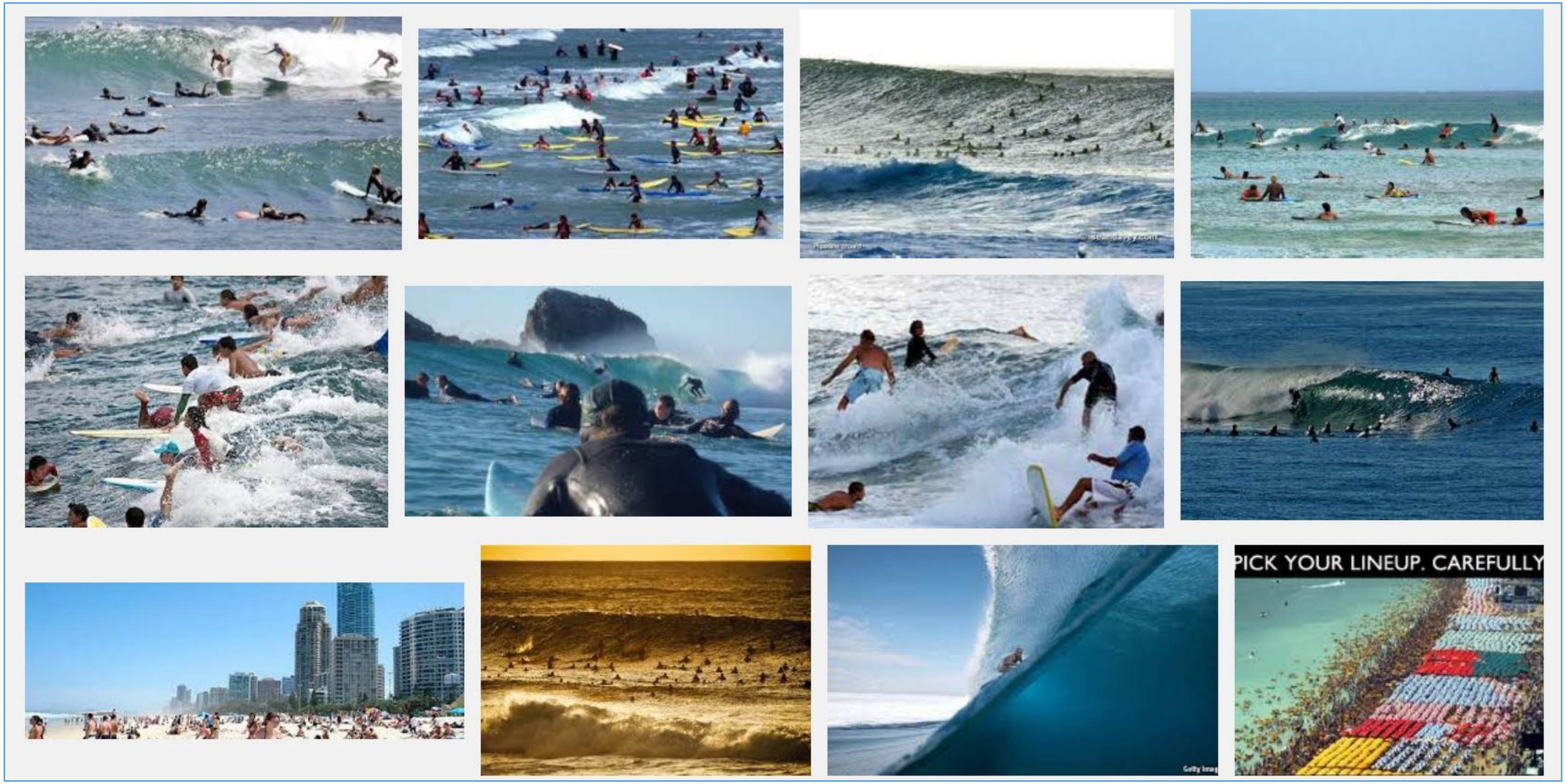
STEM + ARTS = STEAM

Thus it begins, all around the world . . .

And it’s on its way . . . !

Link

Before long, adventurers around the world will be “surfing” somewhere on this wave . . .!



Ah, but the escalating rates of techno-social-change will challenge existing cultural patterns, because of massive social accumulations of past habits:

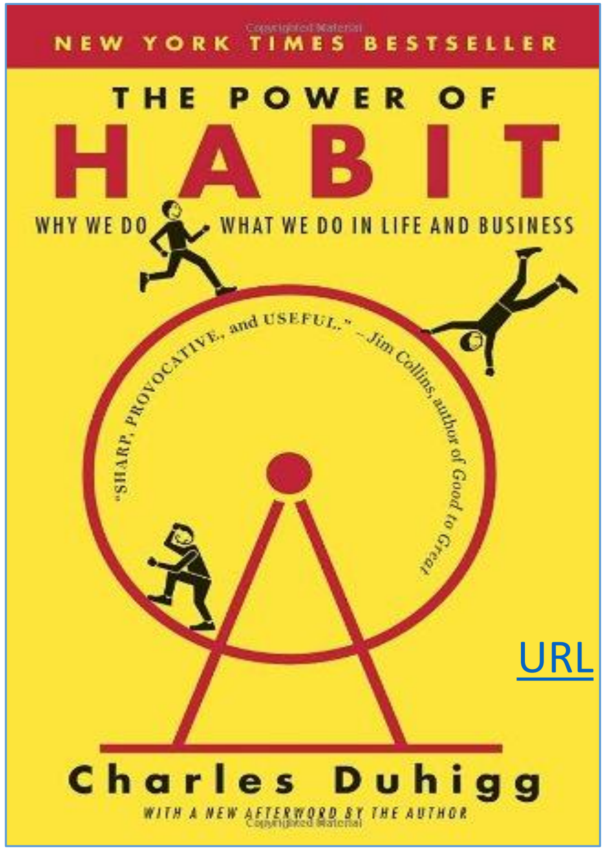
What’s the new game this time?

Who gets to play?

What rules do we play by?

Where can we turn for guidance?

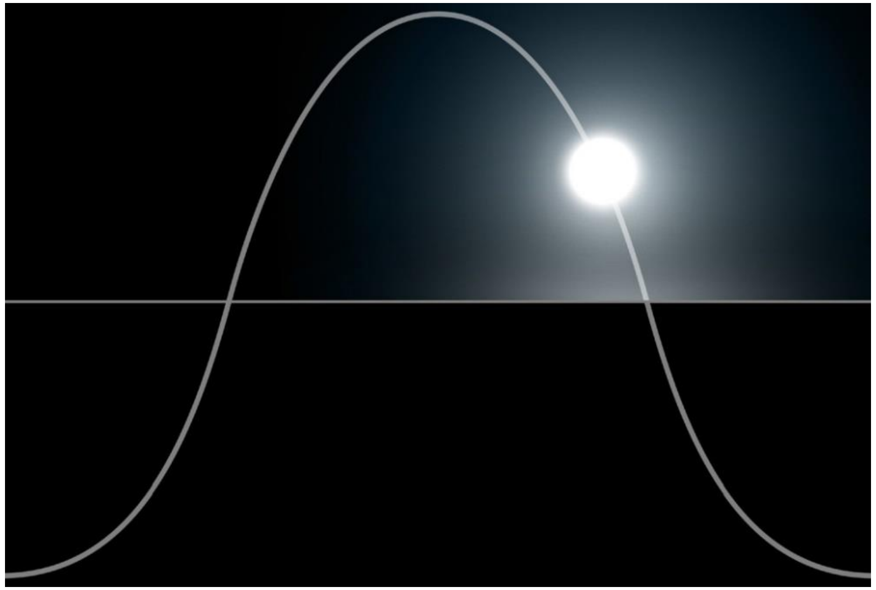
And how do we drop old habits? . . .



URL

For insight into what's about to happen, reflect on this news:

['Apple Watch designers on easing the smartphone tyranny they created']



http://www.wired.com/2015/04/the-apple-watch/

It will help you to *"Remember, this bold step into the future is NOT about "the things", it's about the creative "IDEAS and VISION embodied in the things“.* – Lynn Conway

But you say, “how can we ever keep up?”
Hasn’t the train already left the station, for many of us?

Some words to remember:
"In a world of change, the learners shall inherit the earth, while the learned shall find themselves perfectly suited for a world that no longer exists" – Eric Hoffer

And it’s ever-easier to engage in fun-filled, lifelong learning . . .

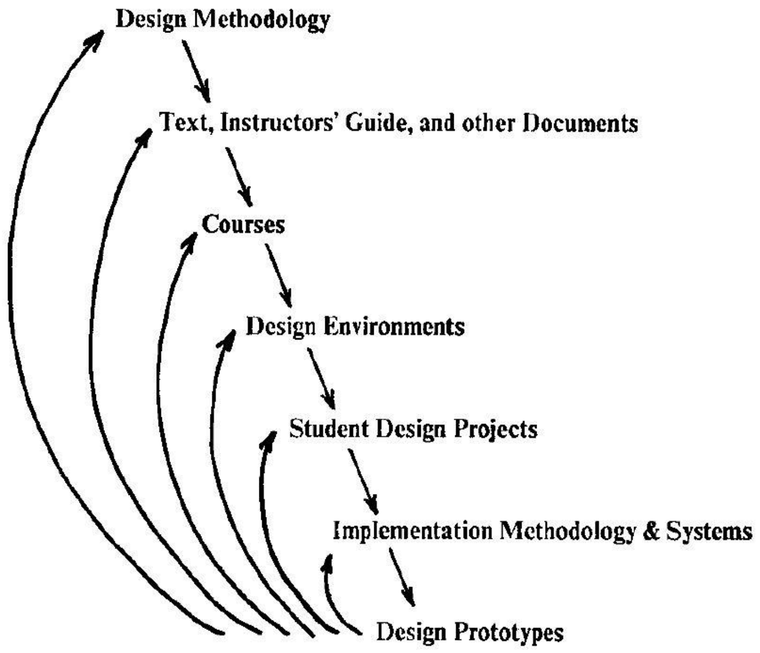
Besides,

“As the rate of techno-social change increases, we’ll all live far further into the unfolding future than we ever dared dream“ – Lynn Conway

When visualizing these swirling masses of ideas in motion reflect back on the rapid-evolutionary-process-diagram from the VLSI revolution . . .

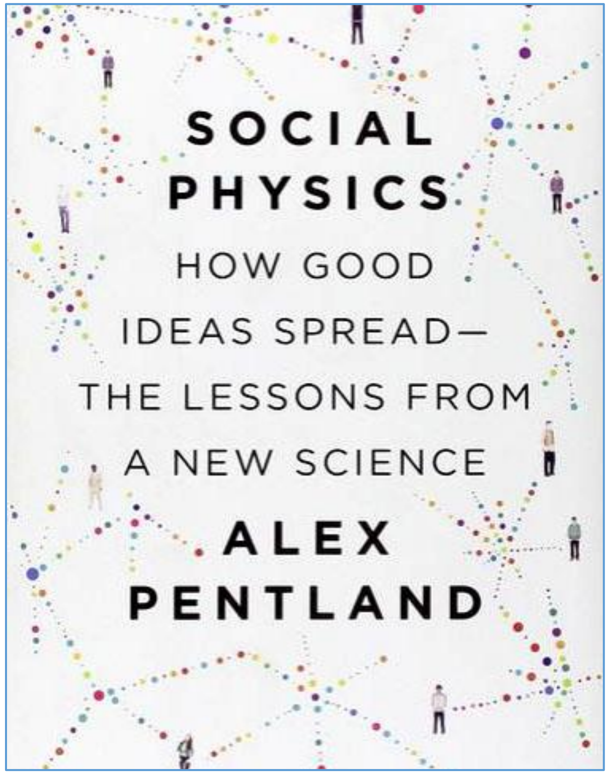
Only now, vastly more such processes run in parallel and cross-fertilize . . .

While a new science explores, maps and describes what's happening . . .



The MPC Adventures (p. 16) Xerox PARC 1981.

Figure 8. The Joint Evolution of the Multi-Level Cluster of Systems



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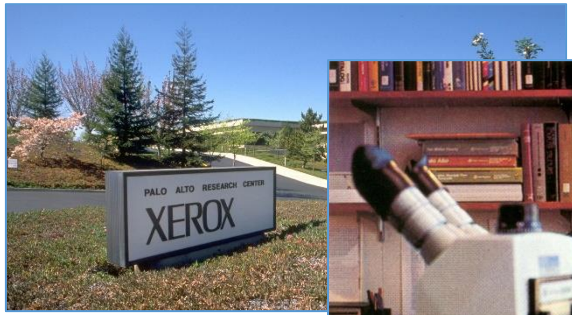
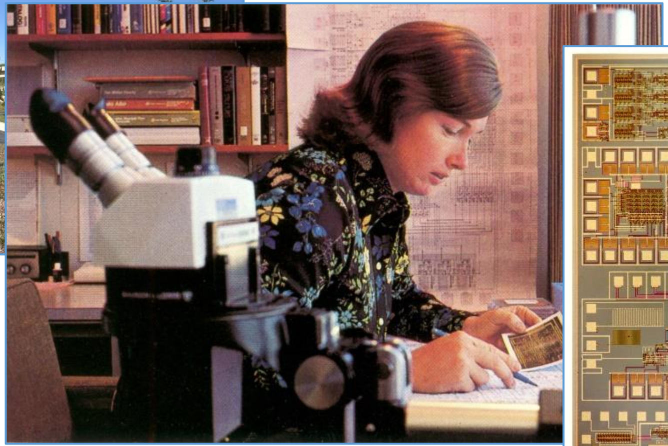
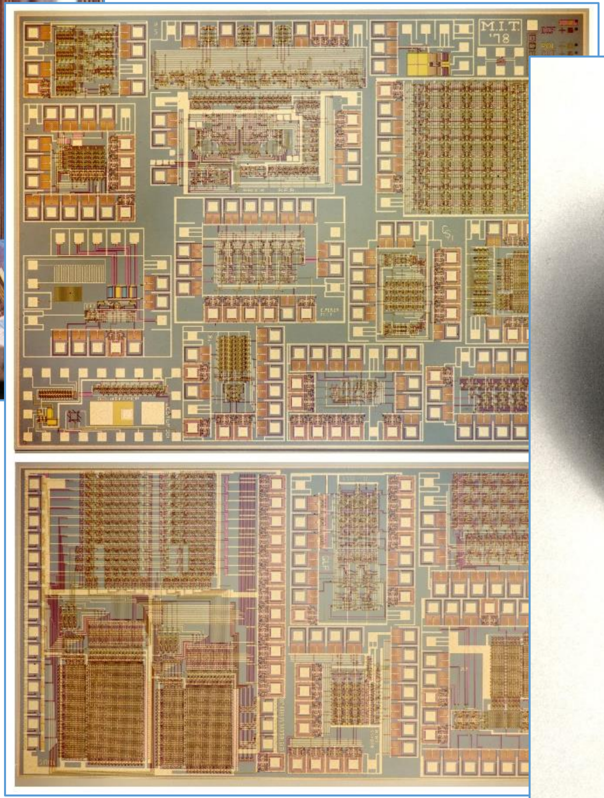
1976



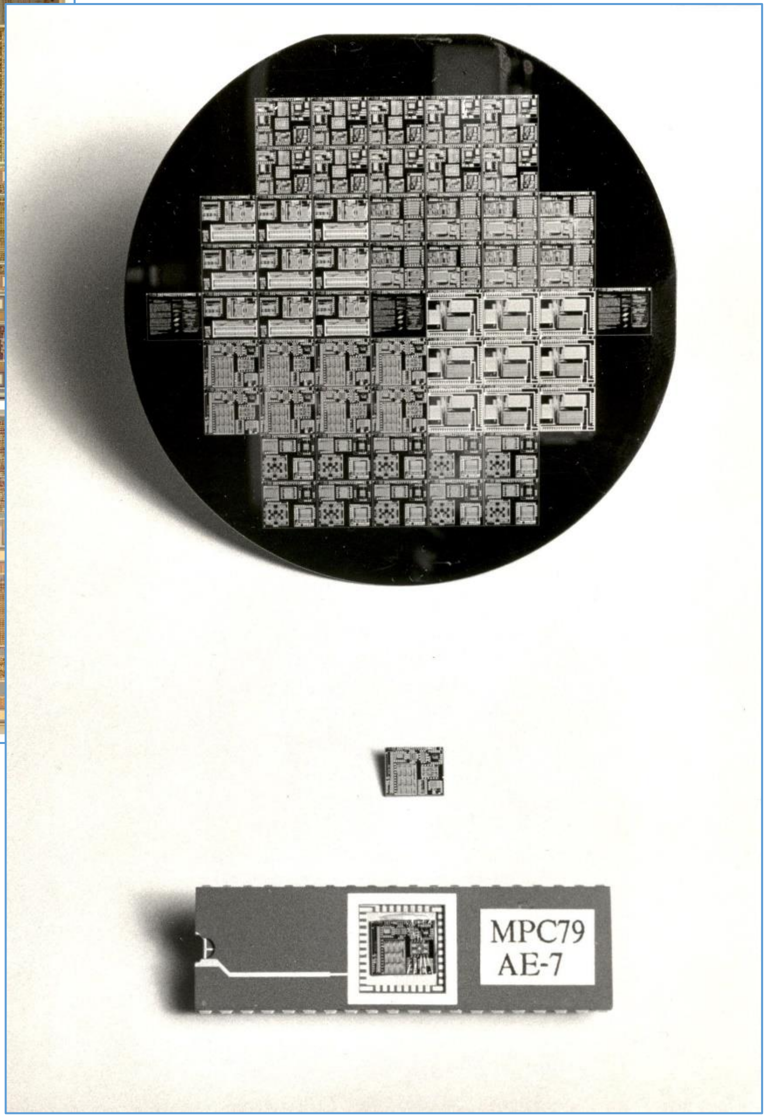
1977



1978



1979



Visualizing the exponentiating wave of VLSI innovation . . .

’76: How to cope with VLSI complexity?

’77: Inventing scalable VLSI design rules.

’78: Launching the VLSI methods at MIT!

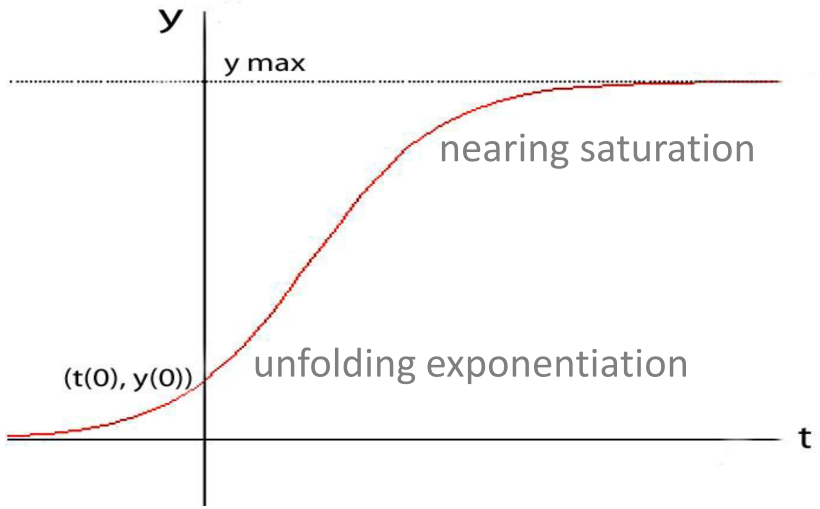
’79: Launching the VLSI courses via MPC79!!

Some questions to ponder as we begin surfing such waves:

How do we gear-up and learn the basic moves?

Who do we team-up with and where do we go exploring?

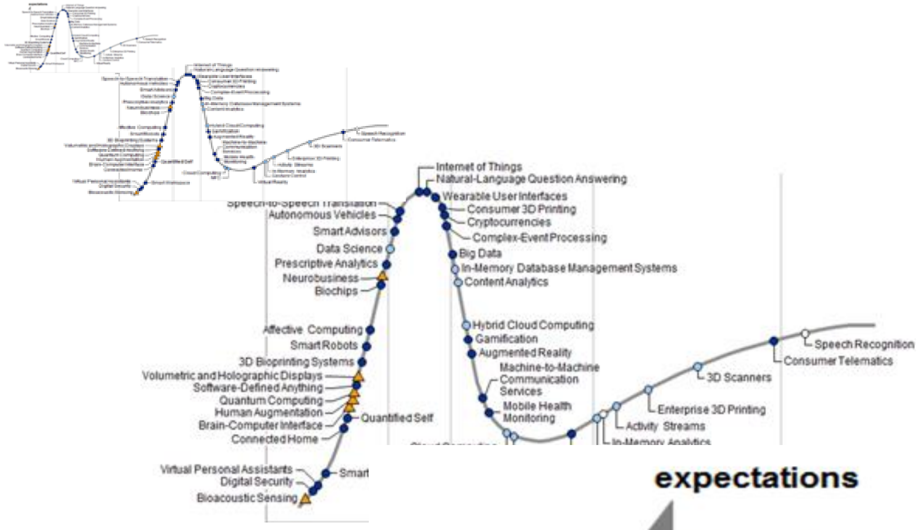
Where is this thing headed and what's our mission?



Of course such 2D views miss lots of what's happening . . .

Let's play with visualizing waves in 4D to gain a better perspective . . .

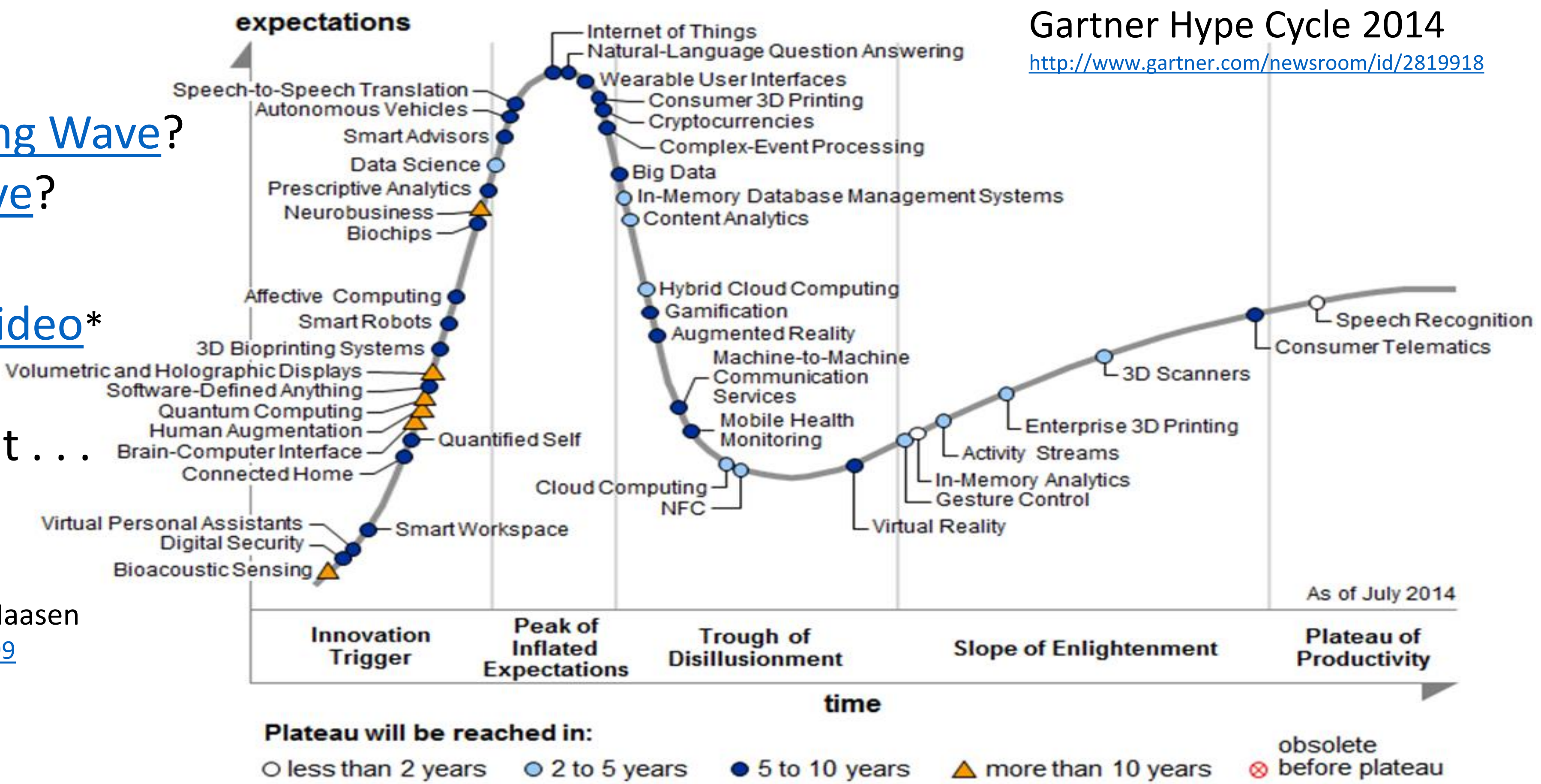
Lets playfully visualize the incoming wave of innovation as a time series of "GHC profiles"
(2D slices thru the 3D wave at increments in time) . . .



Gartner Hype Cycle 2014
http://www.gartner.com/newsroom/id/2819918

Is this a [Traveling Wave]?
A [Standing Wave]?
[Or What]?

[This stunning video]*
hints at ways
to think about it . . .



*"Water," by Morgan Maasen
http://vimeo.com/90429499

Finally, some conjectures about possible futures:

By cooperatively learning and sharing ideas on how to do more-and-more with less-and-less, the incoming wave of innovations has the stunning potential of:

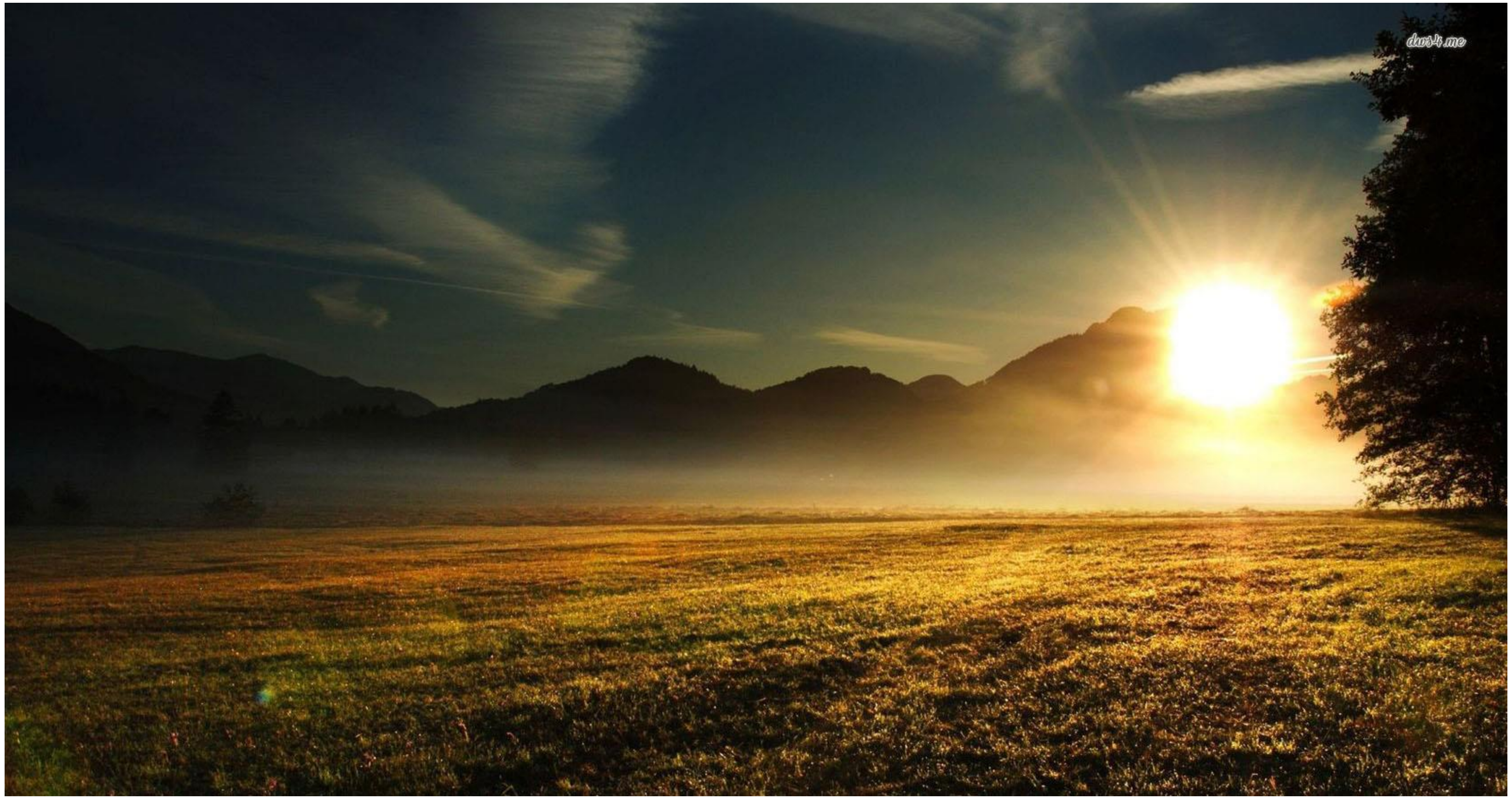
(1) Sustainably providing **ever-increasing** infrastructural functionality and life empowerment per person,

(2) While consuming **ever-decreasing** energy and material resources per person

(3) Thus beginning the **reigning-in** of our unsustainable over-use of planet earth

(4) While simultaneously **opening** an unprecedented collaborative/competitive exploration of the greatest of frontiers, the frontier of "What it's possible to do"!

. . . and a personal perspective on “Our Travels Through Time”. . .



Source

“If you want to change the future, start living as if you’re already there!”

– Lynn Conway

END

[*Link to Epilogue, References, Notes & Afterwords*]

http://ai.eecs.umich.edu/people/conway/Memoirs/Talks/Union_IEEE/2015_Steinmetz_Memorial_Lecture_Epilogue.html