



# **SCIENCE OF POLYMERS : QUO VADIS**

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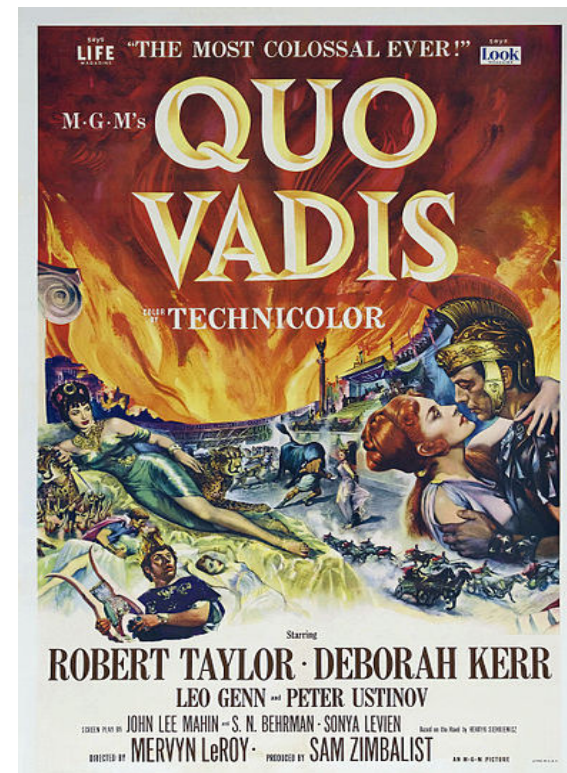
# Quo Vadis ?

Peter asks Jesus "*Quo vadis?*" (pronounced [\[kwo: wadi:s\]](#)), to which he replies, "*Romam vado iterum crucifigi*" ("I am going to Rome to be crucified again"). Peter thereby gains the courage to continue his ministry and returns to the city, to eventually be martyred by crucifying upside down

[http://en.wikipedia.org/wiki/Quo\\_vadis%3F](http://en.wikipedia.org/wiki/Quo_vadis%3F)



***A 1951 movie which won eight Academy Awards; considered a classic***





## ***OUTLINE***

- Nature of scientific research (or why do we perform research) ?
- Scientific frontiers and technology fronts
- Polymer Science : From the visible to the invisible
- What can we learn about the future from the past?
- What does the future beckon?

## ***ANSWERS MUST BE SUBJECTIVE !***

***We are all like the blindfolded men who were asked  
to describe an elephant***



***And so these men of  
Hindoostan  
Disputed loud and long  
Each in his own opinion  
Exceeding stiff and  
strong  
Though each one was  
partly in right  
But all were in the  
wrong***

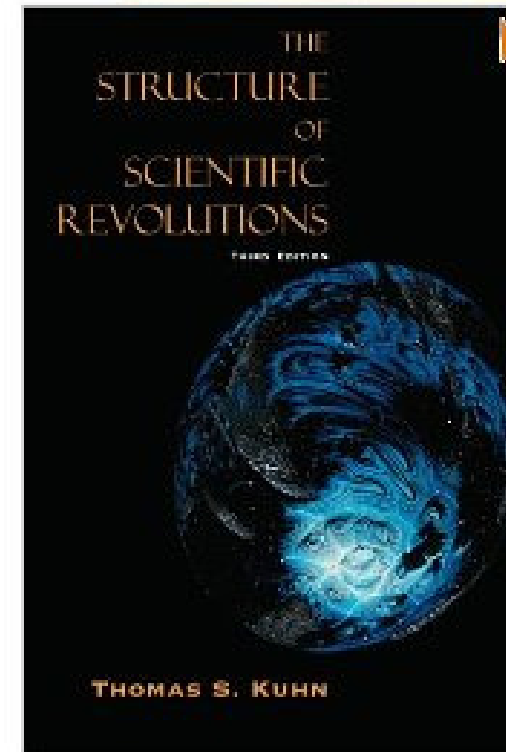
***John Saxe (1872)***

# THE NORMAL, DISCOVERY AND USE INSPIRED SCIENCE



- **Normal Science** : Develops existing and accepted ideas or scientific paradigms; solution of puzzles; answer is not important, but elegance of solution is more important
- **Discovery Science**: Fundamental change in thought; solutions to problems; answer is important
- **Use inspired science** : It means using basic science for a purpose and practical problems as stimulus to curiosity driven research (G. W. Whitesides and J, Deutch, Nature 460, 21 (2011); D. E. Stokes, Pasteur's Quadrant, Brookings Institution, 1996 )

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***The Structure of Scientific Revolution,  
T.S. Kuhn , University of Chicago  
Press, 1962***

*Sheltering and justifying curiosity driven discovery research ?*



## **SCIENTIFIC FRONTIERS AND TECHNOLOGY FRONTS**

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<b>SCIENTIFIC FRONTIERS</b>	:	<b>Frontiers, is a thought or knowledge not explored; difficult to predict frontiers; new science emerges rather unexpectedly</b>
<b>TECHNOLOGY FRONTS</b>	:	<b>Front, is a position directly ahead and can be forecast with some accuracy; it is often an extrapolation of the present</b>

***New science can lead to technology; similarly emergence of technology can stimulate science***

***It is a two way street; science leads technology and technology leads science***



## ***HOLY GRAILS IN SCIENCE***

- Artificial photosynthesis
- Reforming carbon dioxide to methane
- Functionalisation and homologation of methane, e.g methane to methanol or methane to polyethylene
- Ammonia from nitrogen and hydrogen under mild conditions
- Room temperature superconductivity
- Building molecular complexity and diversity in the scale which nature does ; Nature takes ~20 amino acids and creates 10 billion molecular assemblies; polymer scientists take ~20 monomers and can make only 100 polymers !

How many of us will risk our career and reputation in science in pursuit of holy grails ?



## ***IS SCIENCE DRIVEN BY IDEAS OR TOOLS?***

- Early Science, in the first half of 20<sup>th</sup> century was driven by ideas, largely abstract; quantum chemistry, theoretical physics, existence of large molecules, etc. Tools were primitive
- The latter half of the 20<sup>th</sup> century belonged to tools; tools defined new frontiers of science
- At the threshold of 21<sup>st</sup> century, both ideas and tools will compete in the world of science.

Freeman Dyson, Science, 338, 1426, 14 December 2012

# SCIENCE ENABLED BY TOOLS

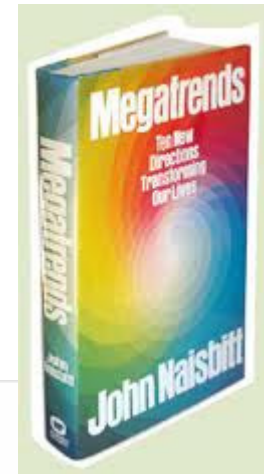


Tools	Science
NMR	Organic Synthesis
Laser	Spectroscopy
XRD	Protein structure
XPS/SIMS/EXFAS	Surface science
PCR	Genomics
Mass spectroscopy	Proteomics
Photolithography	Microelectronics
Ink jet printing	Flexible electronics
Hand held devices and connectivity	Sensors/actuators/diagnostics
3D printing	Advanced manufacturing
Computers/information technology	Big data / Fifth Paradigm



# THE NEW BUZZWORD

# MEGATRENDS !



**Security**

- Hacking is free

**Religion**

- Expanding Impact

**Business**

- New competitors
- Cooption everywhere
- Peak everything

**Health**

- Longer life\*
- Healthier life\*
- Chronic is normal

**Work**

- Automation of "normal"
- Skills gap and need for reskilling
- Technology-enhanced employees

**Law**

- Relative stability

**Government & Society**

- Flattening world
- Pockets of instability

**Demographics**

- Older consumer

**Science & Technology**

- Bandwidth is distance
- Context is king

**Energy**

- Oil important, not king

**Economy**

- Water as currency

**Transportation**

- Security challenged
- Infrastructure impacted
- Tight economics

**Environment**

- Business measure
- Need to Know

**Education**

- Better educated\*
- Distance learning

**Food & Agriculture**

- Stable currently but linked to environment

# MEGATRENDS

\* Not all the world may participate

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## SIX GLOBAL MEGA-TRENDS AND HOW TO MAKE THEM WORK FOR YOU

THIERRY MALLERET

kindle edition

1. Virtual assistants  
2. Biomimicry  
3. Clean coal  
4. Comfort eating  
5. Contextual deficit  
6. Diminishing use of email  
7. Decline of voice communication  
8. Electrification of transport  
9. Facial recognition on mobile phones  
10. Gene hacking  
11. Holographic telepresence  
12. Increasing complexity  
13. Local living  
14. Mobile money  
15. Peak water  
16. Peer-to-peer lending/giving  
17. Quantum computing  
18. Reverse migration  
19. Self-tracking  
20. Smart infrastructure  
21. Slow education  
22. Shift from products to experiences  
23. Ultra-efficient solar  
24. Value redefinition  
25. Voluntary simplicity

**SOURCES & FURTHER READING**

*The Future: 50 Ideas You Really Need to Know* by Richard Watson

See [www.futuretrendsbook.com](http://www.futuretrendsbook.com) and [www.nowandnext.com](http://www.nowandnext.com)

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High resolution digital files for this table and ready printed copies can be obtained from: [richard@nowandnext.com](mailto:richard@nowandnext.com)

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KEY		MEGATRENDS														
Society	Technology	Energy	Environment	Gd	Um	Cs	P	Lr								
Global risk Low probability	Global risk High probability	Global risk High probability	Uncategorised	Globalisation	Urbanisation & migration	Climate change & sustainability	Population & demographic growth	Localism & re-regulation								
<b>H</b> Hyper connectivity	<b>Eg</b> Equipment	<b>Sr</b> Scarcity of resources	<b>Ir</b> Ideological resurgence	<b>Er</b> Erosion of trust	<b>V</b> Volatility	<b>Xe</b> Xenophobia	<b>Fr</b> Fusion engine & demateriality	<b>W</b> Workforce ageing	<b>Ex</b> Extreme weather events	<b>Po</b> Population growth	<b>Mc</b> Emergence of global middle class	<b>B</b> Loss of biodiversity	<b>A</b> Rise of Africa	<b>Sv</b> Shared value creation	<b>I</b> Focus on the self	<b>Pm</b> Purpose & meaning
<b>Na</b> Nano materials	<b>Rb</b> Robotics & smart objects	<b>No</b> Socialism	<b>He</b> Helium	<b>Cf</b> Clean fuels	<b>Mg</b> Micro-grids & micro-generation	<b>Ne</b> Non conventional reserves	<b>Rn</b> Reverse rationalism	<b>O</b> Obesity	<b>Uub</b> Ultra-ubiquitous sensor & tracking	<b>Db</b> Desert based solar	<b>Tc</b> Technology convergence	<b>Ga</b> Generational	<b>Fe</b> Fertility decline	<b>Ac</b> Clean acidification	<b>C</b> Carbon pricing	<b>Sc</b> State capitalism
<b>Sb</b> Synthetic biology	<b>Md</b> Medical	<b>Pd</b> Personalised medicine	<b>Ca</b> Contact aware computing	<b>Sw</b> Semantic web	<b>As</b> Autonomous systems & devices	<b>Pg</b> Personal clouds	<b>He</b> Culture of immediacy	<b>N</b> Normalisation of obesity	<b>Ai</b> Artificially intelligent devices	<b>Uu</b> Ubiquitous sensor & tracking	<b>Os</b> Open-source economy & invention	<b>Li</b> Urban living	<b>F</b> Changing family unit	<b>Ar</b> Aquifer depletion	<b>Es</b> Ethical shifts	<b>Ag</b> Precision agriculture
<b>Hg</b> Holographic & 3D web	<b>It</b> Internet of things	<b>Ra</b> Real-time data & analytics	<b>Ti</b> Total information transparency	<b>Au</b> Augmented & virtual worlds	<b>At</b> Automation	<b>Ge</b> Geothermal	<b>Mo</b> Mobility & portability	<b>Bh</b> Bio-hacking of outsourcing	<b>Nfc</b> Near-field communication	<b>Ha</b> Haptic technology	<b>Ds</b> 3D printing	<b>Os</b> Open-source economy & invention	<b>Li</b> Urban living	<b>F</b> Changing family unit	<b>Ar</b> Aquifer depletion	<b>Es</b> Ethical shifts
<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>Ge</b> Geothermal	<b>Bq</b> Battery life and energy storage	<b>S</b> Sharing	<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>At</b> Automation	<b>Ge</b> Geothermal	<b>Mo</b> Mobility & portability	<b>In</b> Interfacing competition	<b>Ha</b> Haptic technology	<b>Ds</b> 3D printing	<b>Os</b> Open-source economy & invention	<b>Li</b> Urban living	<b>F</b> Changing family unit	<b>Ar</b> Aquifer depletion	<b>Es</b> Ethical shifts	<b>Ag</b> Precision agriculture
<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>Ge</b> Geothermal	<b>Bq</b> Battery life and energy storage	<b>S</b> Sharing	<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>At</b> Automation	<b>Ge</b> Geothermal	<b>Mo</b> Mobility & portability	<b>Ic</b> Industry concentration	<b>Ha</b> Haptic technology	<b>Ds</b> 3D printing	<b>Os</b> Open-source economy & invention	<b>Li</b> Urban living	<b>F</b> Changing family unit	<b>Ar</b> Aquifer depletion	<b>Es</b> Ethical shifts	<b>Ag</b> Precision agriculture
<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>Ge</b> Geothermal	<b>Bq</b> Battery life and energy storage	<b>S</b> Sharing	<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>At</b> Automation	<b>Ge</b> Geothermal	<b>Mo</b> Mobility & portability	<b>Atm</b> Atomisation	<b>Ha</b> Haptic technology	<b>Ds</b> 3D printing	<b>Os</b> Open-source economy & invention	<b>Li</b> Urban living	<b>F</b> Changing family unit	<b>Ar</b> Aquifer depletion	<b>Es</b> Ethical shifts	<b>Ag</b> Precision agriculture
<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>Ge</b> Geothermal	<b>Bq</b> Battery life and energy storage	<b>S</b> Sharing	<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>At</b> Automation	<b>Ge</b> Geothermal	<b>Mo</b> Mobility & portability	<b>Re</b> Regulatory change	<b>Ha</b> Haptic technology	<b>Ds</b> 3D printing	<b>Os</b> Open-source economy & invention	<b>Li</b> Urban living	<b>F</b> Changing family unit	<b>Ar</b> Aquifer depletion	<b>Es</b> Ethical shifts	<b>Ag</b> Precision agriculture
<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>Ge</b> Geothermal	<b>Bq</b> Battery life and energy storage	<b>S</b> Sharing	<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>At</b> Automation	<b>Ge</b> Geothermal	<b>Mo</b> Mobility & portability	<b>Bt</b> Biological terrorism	<b>Ha</b> Haptic technology	<b>Ds</b> 3D printing	<b>Os</b> Open-source economy & invention	<b>Li</b> Urban living	<b>F</b> Changing family unit	<b>Ar</b> Aquifer depletion	<b>Es</b> Ethical shifts	<b>Ag</b> Precision agriculture
<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>Ge</b> Geothermal	<b>Bq</b> Battery life and energy storage	<b>S</b> Sharing	<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>At</b> Automation	<b>Ge</b> Geothermal	<b>Mo</b> Mobility & portability	<b>Eu</b> European reorientation	<b>Ha</b> Haptic technology	<b>Ds</b> 3D printing	<b>Os</b> Open-source economy & invention	<b>Li</b> Urban living	<b>F</b> Changing family unit	<b>Ar</b> Aquifer depletion	<b>Es</b> Ethical shifts	<b>Ag</b> Precision agriculture
<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>Ge</b> Geothermal	<b>Bq</b> Battery life and energy storage	<b>S</b> Sharing	<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>At</b> Automation	<b>Ge</b> Geothermal	<b>Mo</b> Mobility & portability	<b>Op</b> Oil price spikes	<b>Ha</b> Haptic technology	<b>Ds</b> 3D printing	<b>Os</b> Open-source economy & invention	<b>Li</b> Urban living	<b>F</b> Changing family unit	<b>Ar</b> Aquifer depletion	<b>Es</b> Ethical shifts	<b>Ag</b> Precision agriculture
<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>Ge</b> Geothermal	<b>Bq</b> Battery life and energy storage	<b>S</b> Sharing	<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>At</b> Automation	<b>Ge</b> Geothermal	<b>Mo</b> Mobility & portability	<b>Np</b> Nationism & protectionism	<b>Ha</b> Haptic technology	<b>Ds</b> 3D printing	<b>Os</b> Open-source economy & invention	<b>Li</b> Urban living	<b>F</b> Changing family unit	<b>Ar</b> Aquifer depletion	<b>Es</b> Ethical shifts	<b>Ag</b> Precision agriculture
<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>Ge</b> Geothermal	<b>Bq</b> Battery life and energy storage	<b>S</b> Sharing	<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>At</b> Automation	<b>Ge</b> Geothermal	<b>Mo</b> Mobility & portability	<b>Sws</b> Skilled worker shortages	<b>Ha</b> Haptic technology	<b>Ds</b> 3D printing	<b>Os</b> Open-source economy & invention	<b>Li</b> Urban living	<b>F</b> Changing family unit	<b>Ar</b> Aquifer depletion	<b>Es</b> Ethical shifts	<b>Ag</b> Precision agriculture
<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>Ge</b> Geothermal	<b>Bq</b> Battery life and energy storage	<b>S</b> Sharing	<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>At</b> Automation	<b>Ge</b> Geothermal	<b>Mo</b> Mobility & portability	<b>Fp</b> Food price volatility	<b>Ha</b> Haptic technology	<b>Ds</b> 3D printing	<b>Os</b> Open-source economy & invention	<b>Li</b> Urban living	<b>F</b> Changing family unit	<b>Ar</b> Aquifer depletion	<b>Es</b> Ethical shifts	<b>Ag</b> Precision agriculture
<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>Ge</b> Geothermal	<b>Bq</b> Battery life and energy storage	<b>S</b> Sharing	<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>At</b> Automation	<b>Ge</b> Geothermal	<b>Mo</b> Mobility & portability	<b>Fi</b> Fiscal imbalances	<b>Ha</b> Haptic technology	<b>Ds</b> 3D printing	<b>Os</b> Open-source economy & invention	<b>Li</b> Urban living	<b>F</b> Changing family unit	<b>Ar</b> Aquifer depletion	<b>Es</b> Ethical shifts	<b>Ag</b> Precision agriculture
<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>Ge</b> Geothermal	<b>Bq</b> Battery life and energy storage	<b>S</b> Sharing	<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>At</b> Automation	<b>Ge</b> Geothermal	<b>Mo</b> Mobility & portability	<b>Gp</b> Global pandemic	<b>Ha</b> Haptic technology	<b>Ds</b> 3D printing	<b>Os</b> Open-source economy & invention	<b>Li</b> Urban living	<b>F</b> Changing family unit	<b>Ar</b> Aquifer depletion	<b>Es</b> Ethical shifts	<b>Ag</b> Precision agriculture
<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>Ge</b> Geothermal	<b>Bq</b> Battery life and energy storage	<b>S</b> Sharing	<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>At</b> Automation	<b>Ge</b> Geothermal	<b>Mo</b> Mobility & portability	<b>Cw</b> Cyber viruses and data theft	<b>Ha</b> Haptic technology	<b>Ds</b> 3D printing	<b>Os</b> Open-source economy & invention	<b>Li</b> Urban living	<b>F</b> Changing family unit	<b>Ar</b> Aquifer depletion	<b>Es</b> Ethical shifts	<b>Ag</b> Precision agriculture
<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>Ge</b> Geothermal	<b>Bq</b> Battery life and energy storage	<b>S</b> Sharing	<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>At</b> Automation	<b>Ge</b> Geothermal	<b>Mo</b> Mobility & portability	<b>Ua</b> Unusual access to food & water	<b>Ha</b> Haptic technology	<b>Ds</b> 3D printing	<b>Os</b> Open-source economy & invention	<b>Li</b> Urban living	<b>F</b> Changing family unit	<b>Ar</b> Aquifer depletion	<b>Es</b> Ethical shifts	<b>Ag</b> Precision agriculture
<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>Ge</b> Geothermal	<b>Bq</b> Battery life and energy storage	<b>S</b> Sharing	<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>At</b> Automation	<b>Ge</b> Geothermal	<b>Mo</b> Mobility & portability	<b>Si</b> Severe income inequality	<b>Ha</b> Haptic technology	<b>Ds</b> 3D printing	<b>Os</b> Open-source economy & invention	<b>Li</b> Urban living	<b>F</b> Changing family unit	<b>Ar</b> Aquifer depletion	<b>Es</b> Ethical shifts	<b>Ag</b> Precision agriculture
<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>Ge</b> Geothermal	<b>Bq</b> Battery life and energy storage	<b>S</b> Sharing	<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>At</b> Automation	<b>Ge</b> Geothermal	<b>Mo</b> Mobility & portability	<b>Rc</b> Rogue employee	<b>Ha</b> Haptic technology	<b>Ds</b> 3D printing	<b>Os</b> Open-source economy & invention	<b>Li</b> Urban living	<b>F</b> Changing family unit	<b>Ar</b> Aquifer depletion	<b>Es</b> Ethical shifts	<b>Ag</b> Precision agriculture
<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>Ge</b> Geothermal	<b>Bq</b> Battery life and energy storage	<b>S</b> Sharing	<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>At</b> Automation	<b>Ge</b> Geothermal	<b>Mo</b> Mobility & portability	<b>Mq</b> Mega-quake	<b>Ha</b> Haptic technology	<b>Ds</b> 3D printing	<b>Os</b> Open-source economy & invention	<b>Li</b> Urban living	<b>F</b> Changing family unit	<b>Ar</b> Aquifer depletion	<b>Es</b> Ethical shifts	<b>Ag</b> Precision agriculture
<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>Ge</b> Geothermal	<b>Bq</b> Battery life and energy storage	<b>S</b> Sharing	<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>At</b> Automation	<b>Ge</b> Geothermal	<b>Mo</b> Mobility & portability	<b>Cc</b> Collapse of China	<b>Ha</b> Haptic technology	<b>Ds</b> 3D printing	<b>Os</b> Open-source economy & invention	<b>Li</b> Urban living	<b>F</b> Changing family unit	<b>Ar</b> Aquifer depletion	<b>Es</b> Ethical shifts	<b>Ag</b> Precision agriculture
<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>Ge</b> Geothermal	<b>Bq</b> Battery life and energy storage	<b>S</b> Sharing	<b>Uu</b> Ultra-ubiquitous sensor & tracking	<b>At</b> Automation	<b>Ge</b> Geothermal	<b>Mo</b> Mobility & portability	<b>Vol</b> Volcanic eruption	<b>Ha</b> Haptic technology	<b>Ds</b> 3D printing	<b>Os</b> Open-source economy & invention	<b>Li</b> Urban living	<b>F</b> Changing family unit	<b>Ar</b> Aquifer depletion	<b>Es</b> Ethical shifts	<b>Ag</b> Precision agriculture

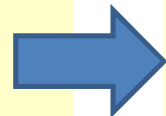
High probability  
Low probability

Chart maker: Richard Watson

# MEGATRENDS USEFUL FOR PREDICTING THE FUTURE OF TECHNOLOGY



- Consumer habits & demands
- Demographics
- Population
- Climate Change
- Economic growth
- Disposable income
- Infrastructure
- Urbanization
- Constrained natural resources



- Food, nutrition & hygiene
- Energy
- Water
- Health
- Transportation
- Environment
- Sustainability
- Housing
- Education
- Job creation
- Safety and protection



## S&T Solutions

- Precision agriculture
- Plant biotechnology
- Fortified food
- Renewable energy
- Green Chemistry and catalysis
- Light weight materials
- Lower water foot print
- Lower carbon footprint
- Materials based on renewable resources
- Affordable drugs and health care, etc.



## **SCIENCE AND TECHNOLOGY**

**Technology: predictable (somewhat)**  
**Science : unpredictable (totally)**

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To succeed in technology : pick robust science

To succeed in science : pick fragile assumptions

*G. W. Whitesides, Assumptions: Taking Chemistry in New Directions, Angew. Chem., 43,3632 (2004)*



## ***TEMPTATIONS OF PREDICTING THE FUTURE: WHY DO IT?***

- Choice of research area
- Curiosity
- Philosophy
- Expectations from Society
- To ask if there is research that should not be done.



## ***PERILS OF PREDICTION***

Those who have knowledge do not predict; Those who predict do not have knowledge

Lao Tzu

When a distinguished but elderly scientist states that something is possible, he is almost certainly right. When he states that something is impossible, he is very probably wrong

Arthur C. Clarke

**Fools predict the future; smart people create it**



## ***POLYMER SCIENCE : HISTORY***

- Polymers were the product of post war renaissance in chemical industry driven by the promise of inexpensive petroleum derived feed-stocks
- The fifties and sixties saw the introduction of many polymers that changed the face of human civilization
- From early curiosities polymers became an indispensable part of our daily living and so ubiquitous that we no longer realize how addicted we are to polymer materials !

# POLYMERS FULFILLING MATERIAL NEEDS OF SOCIETY...



## Precursor 19<sup>th</sup> Century → Semi Synthetics

1839 : Natural Rubber  
1843 : Gutta Percha  
1856 : Shellac / Bois Durci  
1862 : Parkesine  
1863 : Celluloid  
1894 : Viscose Rayon

### Natural Polymers



### Semi Synthetics



## 1900 – 1950 → Thermoplastics

1908 : Cellophane  
1909 : Bakelite  
1926 : Vinyl or PVC  
1927 : Cellulose Acetate  
1933 : Polyvinylidene chloride  
1935 : Low density polyethylene  
1936 : Polymethyl Methacrylate  
1937 : Polyurethane  
1938 : Polystyrene  
1938 : Teflon  
1939 : Nylon and Neoprene  
1941 : PET  
1942 : LDPE  
1942 : Unsaturated Polyester

## 1950 onwards → Growth Phase

1951 : HDPE  
1951 : PP  
1954 : Styrofoam  
1960 : PC, PPO  
1964 : Polyamide  
1970 : Thermoplastic Polyester  
1978 : LLDPE  
1985 : Liquid Crystal Polymers

### Plastics in Packaging



### Hi Tech Plastics



## ***NEW POLYMER INTRODUCTION : ENTRY BARRIERS***



- No new polymers has entered the market since the early nineties. The last ones were poly(propylene terephthalate) by DuPont (PTT) , poly(ethylene naphthalate) by Teijin (PEN) and Nature Works poly (Lactic Acid)s by Cargill.
- Several new polymers developed in the last fifteen years have been abandoned after market introductions. Example, Carilon by Shell, Questra (syndiotactic polystyrene), PCHE (hydrogenated polystyrene), Index (ethylene –styrene copolymers) by Dow, COC by Ticona, Syndiotactic PP etc
- The rate of growth of markets of the new polymers introduced after the nineties have been painfully slow.



## ***POLYMER SCIENCE: FROM A VISIBLE TO AN INVISIBLE SCIENCE***

- In the early years, advances in polymer science led to objects that you could see, touch and feel
- However, increasingly polymer science is becoming invisible.
  - Energy harvesting, conversion and storage devices
  - Micro-electronics
  - Medicine / therapeutics / diagnostics
  - Information technology
  - Clean air and water
  - Formulated products( adhesives, coatings, lubricants, cosmetics, personal care products, construction chemicals etc )



## ***IS POLYMER SCIENCE LOSING ITS FOCUS?***

- Are we repackaging a discipline ?
  - Nanomaterials
  - Supramolecular chemistry
  - Self assembly
  - Soft matter / complex fluids
  - Advanced materials, etc.
- Motivation: Fashion, Funding and Factors (I, H etc.)

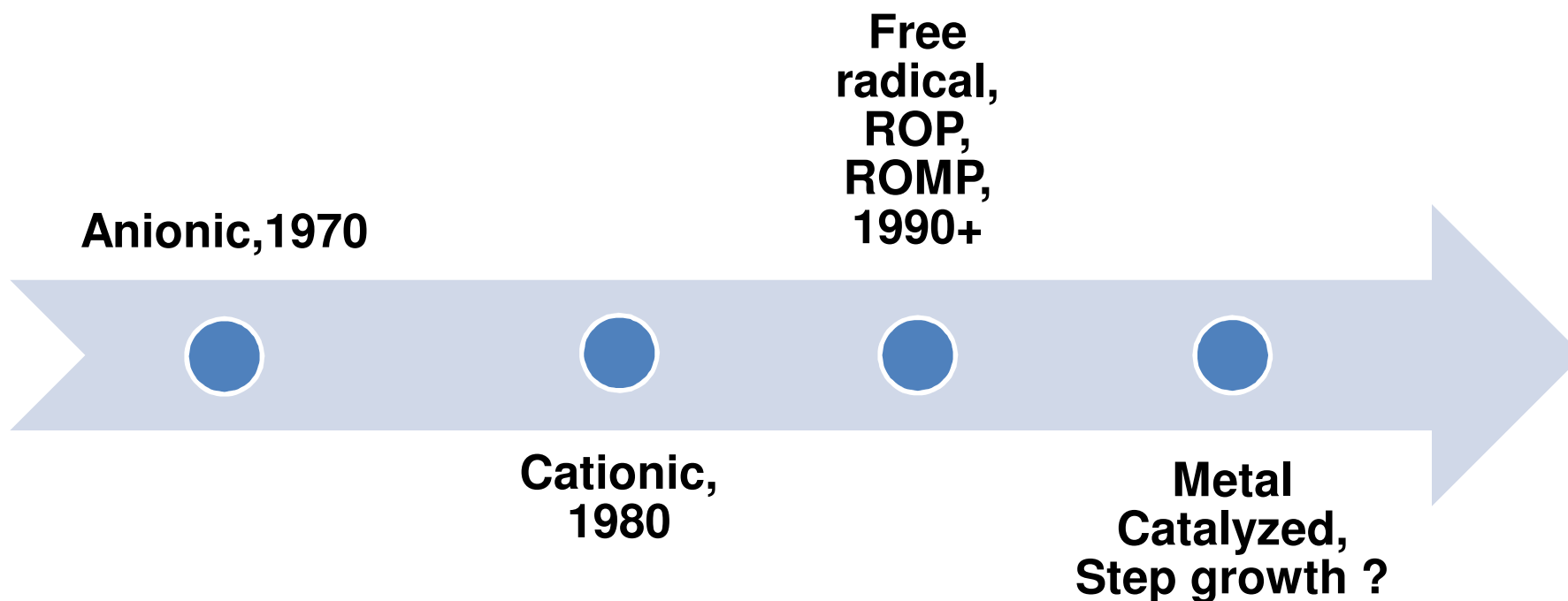
# ***EVOLUTION OF RESEARCH TOPIC IN POLYMER SCIENCE, 1990-2013***

January 1990	January 2000	November 12, 2013
Radical Solution polymerization Cyclo-polymerization Radiation polymerization Poly-esterification	Metal catalyzed polymerization ROP ROMP Living Cationic and controlled free radical polymerization	Catalyst transfer polycondensation RAFT ROP Functional Polymers Metal catalyzed polymerization
High resolution 13-C ESR Fluorescence FT IR ESCA	11-Boron and 13-C NMR Solid state NMR	STEM XPS SAXS Real time spectroscopy

# ***EVOLUTION OF RESEARCH TOPIC IN POLYMER SCIENCE, 1990-2013***

January 1990	January 2000	November 12, 2013
<p>Mean square radius of gyration and hydrodynamic radii Theta temperature Phase separation, thermodynamics and diffusivity in miscible blends</p>	<p>Second virial coefficient in miktoarm star polymers Order disorder transitions in diblock copolymers Morphology of stereoblock PP</p>	<p>Thermal, mechanical, solvent, photo-responsive soft matter Transport, thermal, phase and solution properties of brush, ring, networks and entangled polymers</p>
<p>Chiral polymers Conformation in glasses and gels Light induced phase transitions</p>	<p>Band gap modifications in polymers</p>	<p>Molecular dynamics, DFT and simulations Nano-templating and patterning Polymer thin films Polymer electrolytes</p>

# ***ARE THERE STILL OPPORTUNITIES IN POLYMER SYNTHESIS ?***

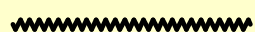


Perfect control of polymerization is only possible in anionic polymerization  
Catalytic controlled polymerization is still not a general technique in metal catalyzed polymerization  
Step growth polymerization under equilibrium conditions has problems of control

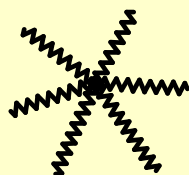
# STRUCTURES ACCESSIBLE VIA TECHNIQUES OF CONTROLLED POLYMER SYNTHESIS



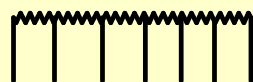
## Topology



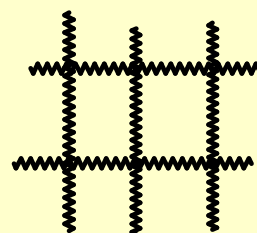
Linear



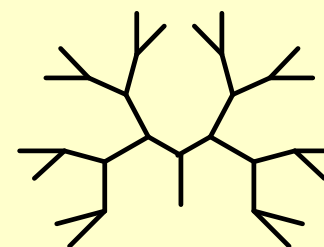
Star /  
Multi-Armed



Comb Polymers



Networks



(Hyper) Branched

## Composition



HomoPolymers



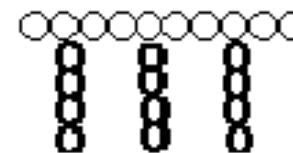
Block  
Copolymers



Statistical  
Copolymers

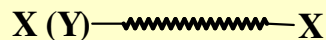


Tapered / Gradient  
Copolymers

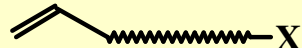


Graft

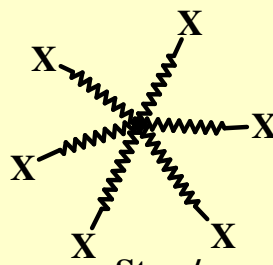
## Functionality



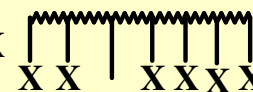
Homo / Hetero  
Telechelic



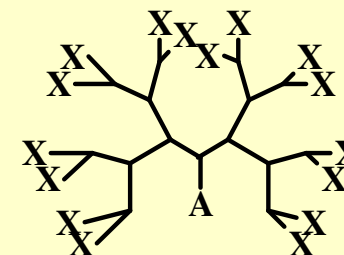
Macromonomers



Star /  
Multi-Armed



Side Functional  
Groups



Hyperbranched /  
Multifunctional



## ***CHAIN LENGTH***

*Determines .....*

- Mechanical strength
- Thermal behavior
- Processability
- Adsorption at interfaces

*Control of chain length*

- Still difficult and is determined largely by statistics

***Challenge.....***

- **Synthesis of polymers with absolutely uniform length for a wide range of polymers**



## ***CHAIN SEQUENCE***

*Determines .....*

- Thermal behavior
- Crystalline properties

*Copolymer sequence*

- Random
- Alternating
- Block
- Graft

***Challenge.....***

- **Synthesis of macromolecules with precisely defined comonomer sequences**



## **CHAIN ISOMERISM**

*Determines .....*

- Thermal behavior
- Morphology
- Crystallization

*Polymer stereochemistry*

- Geometrical isomerism
- Regio-isomerism
- Stereo-isomerism
- Tacticity

***Challenge.....***

- **Control polymer stereochemistry through rational design of catalysts**



## **CHAIN TOPOLOGY**

Determines .....

- Crystalline properties, solubility and rheological behavior

Diversity of polymer architectures

- Linear, Branched, Hyper-branched
- Stars, Dendrimers
- Catenanes , Rotaxanes
- Ribbons , Wires, etc

***Challenge.....***

- ***To provide control of both topology and molecular geometry over large length scales in real space***

# COMPLEX POLYMER SYSTEMS

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Organic –inorganic hybrids, stimuli responsive polymers, polymer networks with defined functions and control, block and hetero-copolymers, polymers that self assemble into large supramolecular forms with hierarchical order and polymer materials capable of interacting with other materials, especially biological material

## ***Key fundamental scientific challenges***

- Directing structures via controlled kinetic and thermodynamic pathways
- Complex structure via chain architecture
- Entropy driven assembly in multicomponent hybrid systems
- Template assisted synthesis of complex systems

The beginning of the concept of *Emergent Properties* : when *whole becomes larger than the sum of the parts*



## ***POLYMER SYNTHESIS: IS THERE ANYTHING LEFT TO DO?***

- Increased synthetic precision
- Sequence controlled polymerization
- Orthogonal chemistries
- Iterative synthesis of mono-disperse step growth polymers
- Living , controlled chain growth  $\pi$ - conjugated polymers
- Synthesis of two dimensional polymers



## ***SOME UNSOLVED PROBLEMS : THE CHALLENGE OF THE OPPOSITE***

- High molecular weight polymers without chain entanglement
- High glass transition temperature with high ductility
- High impact with high modulus
- Chain stiffening through conventional processing
- High optical clarity with electrical conductivity
- High thermal conductivity in virgin polymers through chain alignment
- Conducting or semiconducting polymers with inherent flexibility



## ***SOME UNSOLVED PROBLEMS : ENDOW POLYMERS WITH NEW PROPERTIES***

- Metamaterials : polymers with negative index of refraction or negative coefficient of expansion
- Self replenishing and self healing surfaces
- Photonic and piezoelectric properties in polymer nanocrystals
- Polymers with  $T_g$  in between PMMA and Polycarbonate
- Creation of co-ordinated multiple responses to one stimulus in sensing and actuating materials
- Polymers with reversible crosslinking
- Attaining theoretical limits of E modulus in synthetic fibers, e.g defect free (free of voids, entanglement, chain ends, metal residues) ordered fibers



# **FROM STRUCTURAL TO FUNCTIONAL MATERIALS**

**STRUCTURAL MATERIALS**

**FUNCTIONAL MATERIALS**

## **MACROCOMPOSITES**

- Shear
- wetting
- Orientation

## **BIOCOMPOSITES**

- Molecular self assembly
- Hydrogen bonding
- Hydrophobic interaction

## **NANOCOMPOSITES**

- Intercalation and exfoliation
- In-situ polymerization
- Polymerization in constrained spaces
- Nanofibers and nanotubes

# **FUTURE OF POLYMER SCIENCE**

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- Systems, not molecules
- Functions, not molecular structure

***No longer “What is it?” but “What does it do?”***

*Is the focus on “molecules” obsolete ? G. M. Whitesides, Annu. Rev. Anal. Chem., 6, 1 (2013)*



## ***POLYMER SCIENCE : NEW PARADIGMS***

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- Research in polymer science began about sixty years ago as a discipline borne out of disciplines of chemistry , physics and engineering
- For over half a century the discipline flourished as an independent discipline – in education and research
- Explosive developments in the emergence of new polymers and the birth and growth of the polymer industry paralleled the growth of polymer science as a discipline
- Polymer science as a stand alone discipline has probably now attained maturity. Most of the major challenges facing this discipline today are at the interface of polymer science with material science, biology, medicine or physics
- The next frontiers that await polymer scientist will need deep collaboration with multiple disciplines

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***THANK YOU***

