2.76/2.760 Multiscale Systems Design & Manufacturing

Fall 2004

Systems Design in Multi-scale

Multi-scale Systems

DNA
~2-1/2 nm diameter

natural

Human heart

Human body (circulatory system)

Diagrams removed for copyright reasons.

manmade

Carbon nanotube
~2 nm diameter

Nanotube transistor

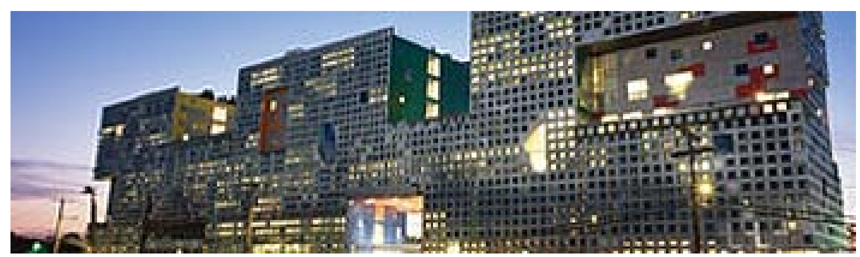
Design for Manufacturing?

MIT Stata Center by Gehry

$300 million, 5years

MIT Simmons Hall

$ 90million, 2 years



Good Design

Does scale matter?

- Lecture Room
- Your Car?
- Boston T ?
- Logan Airport ?
- Government ?

Good designer?

Giorgio Armani

Giugiaro (automobile)

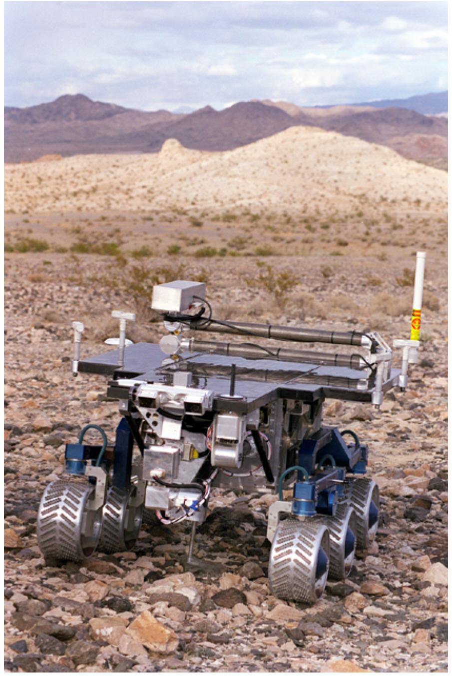
Diagrams removed
for copyright reasons.

Pablo Picasso

Frank O. Gehry

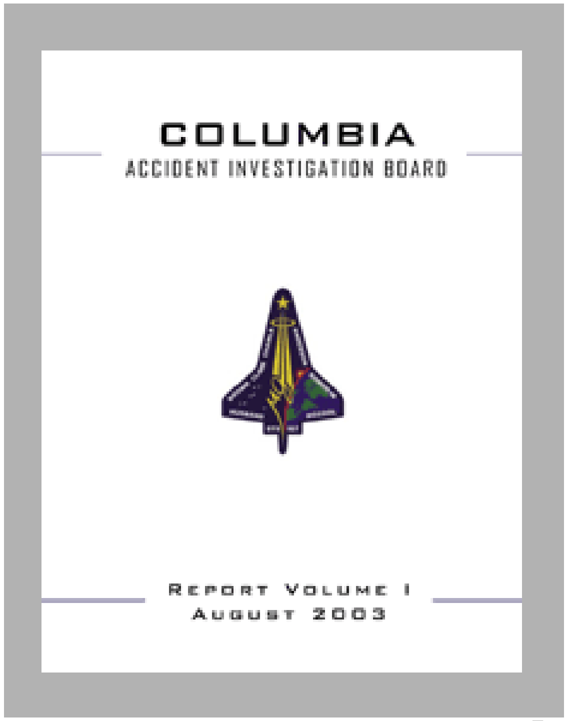
Good designers

Rover



Source: NASA

Fail sometimes,



MRI

Milacron

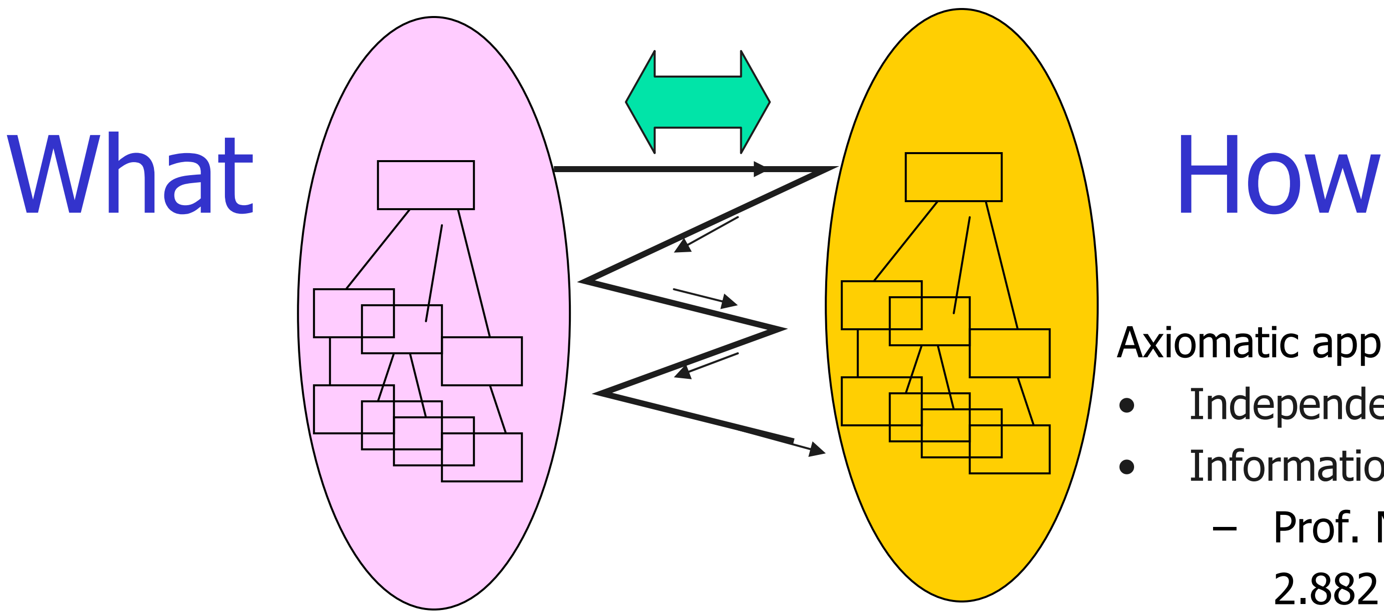
Some say “A good design is made by left, right brain ….

- Uses logic
- Facts rule
- Detail oriented
- Present and past
- Math and science
- Perception
- Reality
- Safe

- Uses feeling
- Imagination rules
- Big picture
- Present and future
- Philosophy and religion
- Spatial perception
- Fantasy based
- Risk taking

Design Domains

"What" to "How", "Top" to "Bottom"



Axiomatic approach

- Independence Axiom
- Information Axiom
  - Prof. Nam Suh @MIT 2.882
  - Evolution to "Complexity Theory for Nano Systems"

No impromptu designs!!

Super bowl 2001, 2003

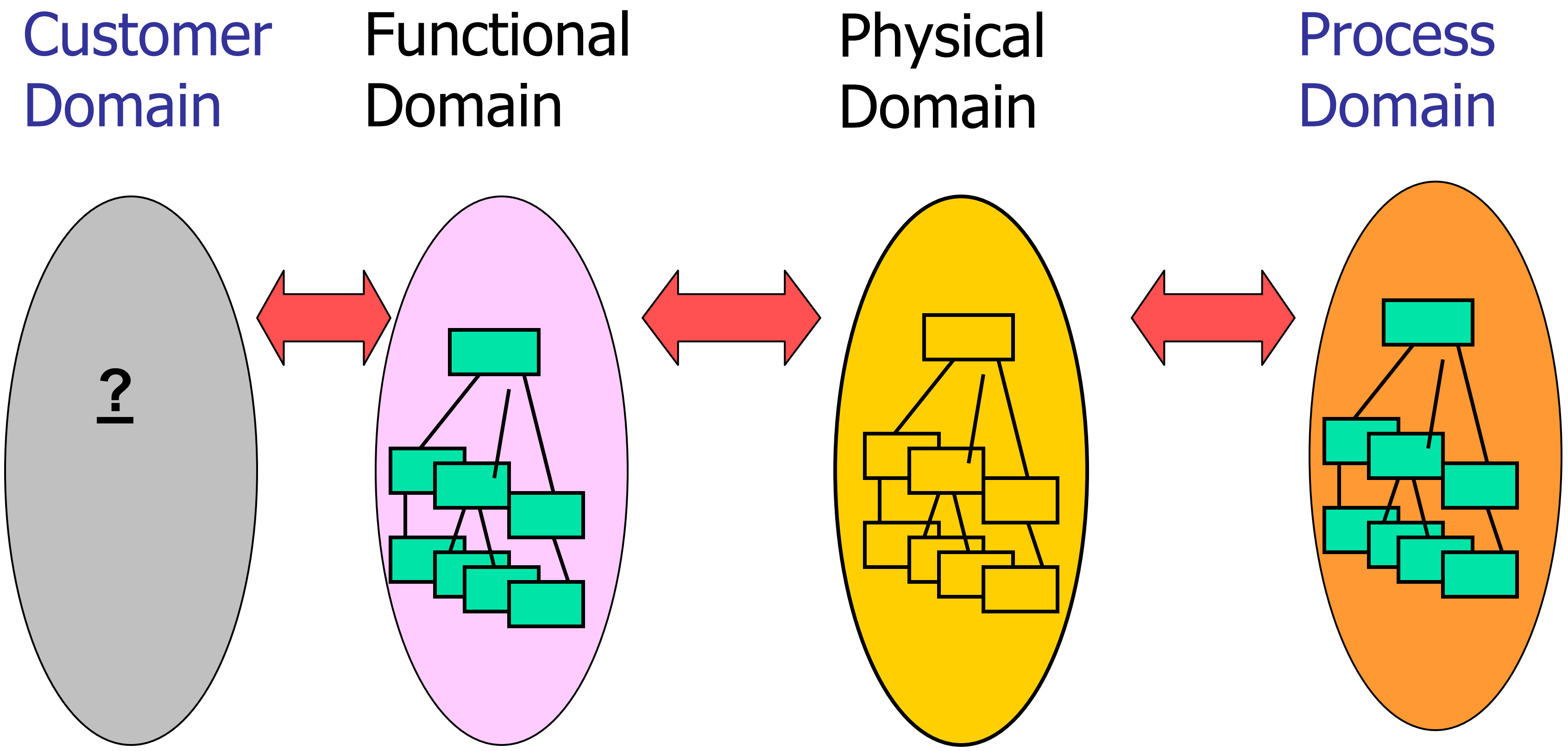
Diagrams of key plays by New England Patriots in Super Bowl victory removed for copyright reasons.

BIG PICTURE

What is "Good"?

- Are Patriots a good team?
- Is MIT a good school?
- Am I a good teacher?

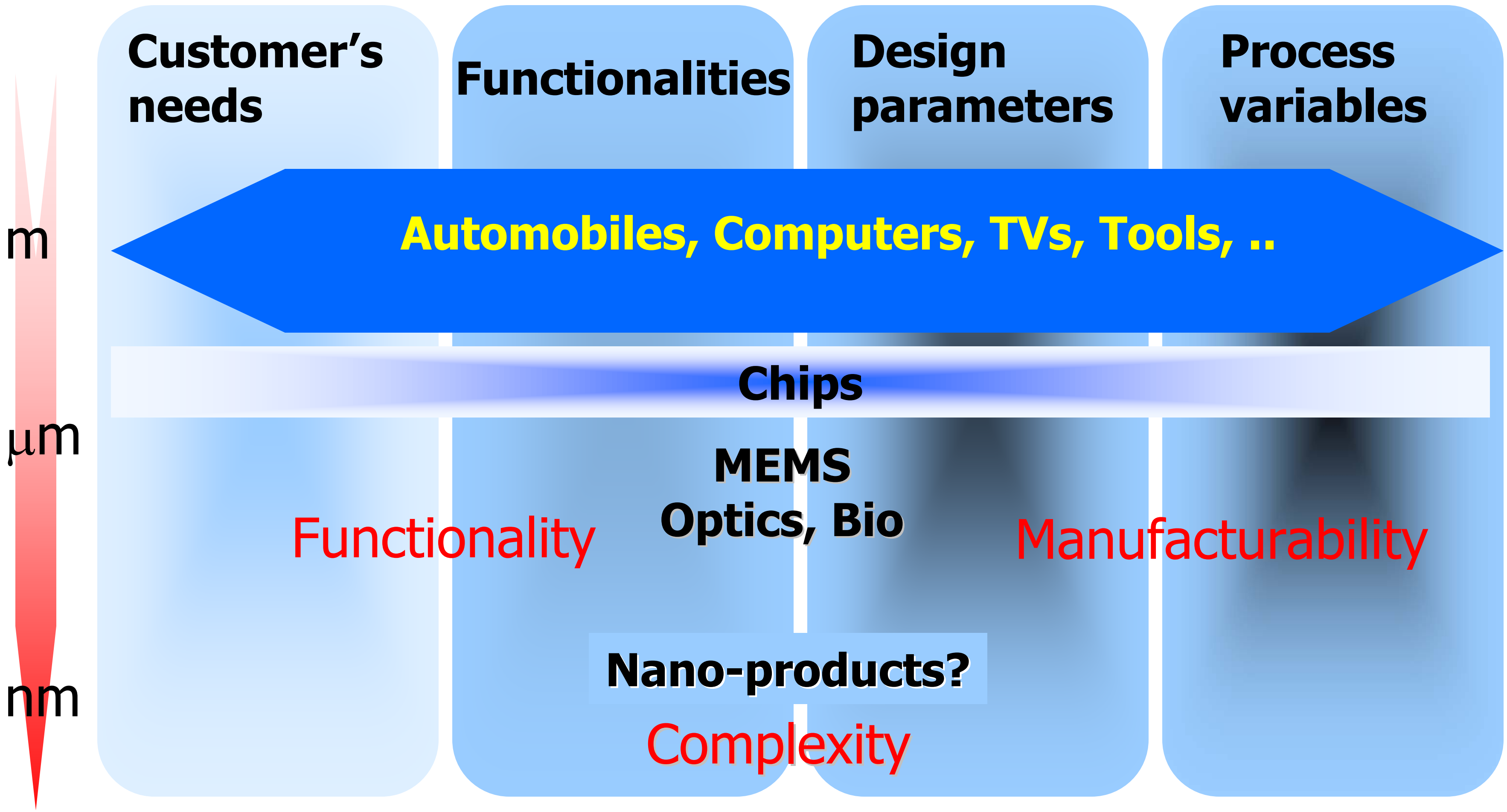
How to do "Systems Design"?
Four Design Domains



Four domains

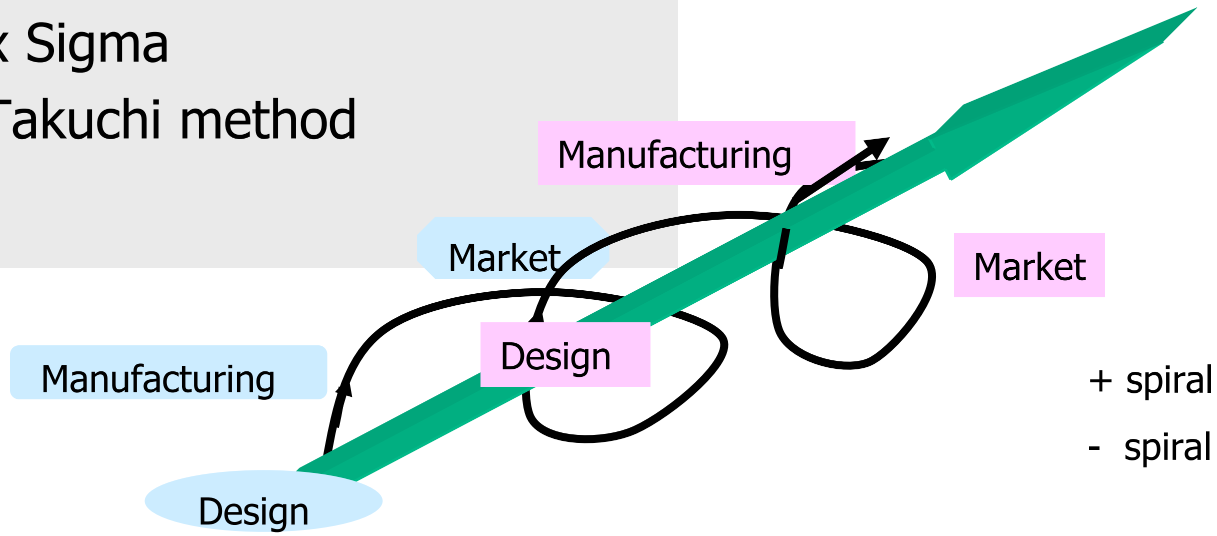
Manufacturing systems	CA	FR	DP	PV
Materials	Performances	Properties	Micro-structure	Processes
Software	Attributes desired	Output of programs	Input variables	Subroutines
Business	ROI	Business goals	Business structure	Resources
Organization	Customer satisfaction	Functions	Programs offices	People resources

A multiscale design should be…



Systems Design

- Customer Satisfaction
- Concurrent Design
- Design for Manufacturing, Assembly and "X"
- Quality Control, Six Sigma
- House of Quality, Takuchi method
- Axiomatic Design



- Any of these efforts in MEMS?
- Nanomanufacturing, Complexity

A Good Design is,

- Concept of Domains, well defined “what”
- Uncoupled (decoupled)
- Minimum information (least complex)

Axiomatic Design, 2.882

1. N.P. Suh, *Principles of Design*, Oxford, 1990
2. N. P. Suh, *Axiomatic Design: Advances and Applications,* Oxford, 2001
3. N. P. Suh, *Complexity: Theory and Applications,* Oxford, 2004

Example: Shower Faucet

Functional Requirements

- Temperature
- Flow rate

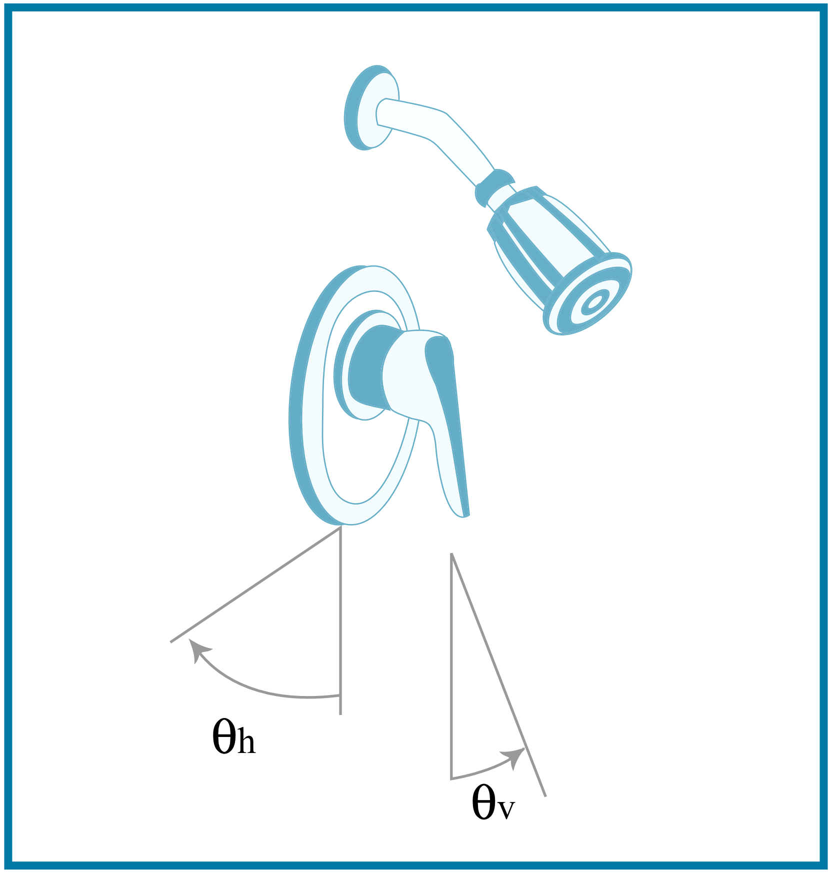


Figure by MIT OCW.

Independence Axiom

- Maintain the independence of FRs.
  - Shower faucet example

FR1= Temperature
FR2= Flow rate

DP1= Hot water
DP2= Cold Water

$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} X & X \\ X & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix}$$

Coupled

FR1= Temperature
FR2= Flow rate

DP1= Horizontal Angle
DP2= Vertical Angle

$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} X & O \\ O & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix}$$

Uncoupled

Design Coupling

- Uncoupled

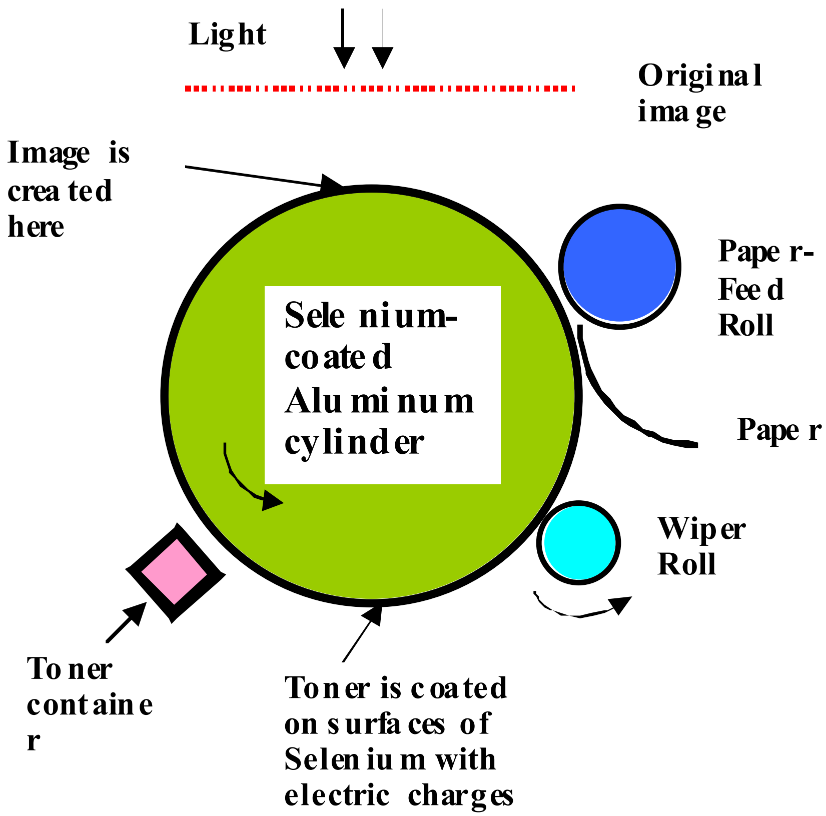
$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} X & O \\ O & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix}$$

- Decoupled

$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} X & O \\ X & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix}$$

- Coupled

Example: Xerography-based Printing Machine



Design Matrix

FR1 = Create electrically charged images.

FR2 = Coat the charged surface with toner

FR3 = Wipe off the excess toner.

FR4 = Make sure that abrasive particles do not cause abrasion.

FR5 = Feed the paper.

FR6 = Transfer the toner to the paper.

FR7 = Control throughput rate.

DP1 = Optical system with light on selenium surface

DP2 = Electrostatic charges of the selenium surface and the toner

DP3 = Wiper roller

DP4 = Filter

DP5 = Paper-feeding mechanism

DP6 = Mechanical pressure

DP7 = Speed of the cylinder

Design Matrix

	DP 1	DP 2	DP 3	DP 4	DP 5	DP 6	DP 7
FR 1	X	0	0	0	0	0	0
FR 2	X	X	0	0	0	0	0
FR 3	0	0	X	0	0	0	0
FR 4	0	0	X	X	X	0	0
FR 5	0	0	0	0	X	0	0
FR 6	0	0	0	0	0	X	0
FR 7	0	0	0	0	X	0	X

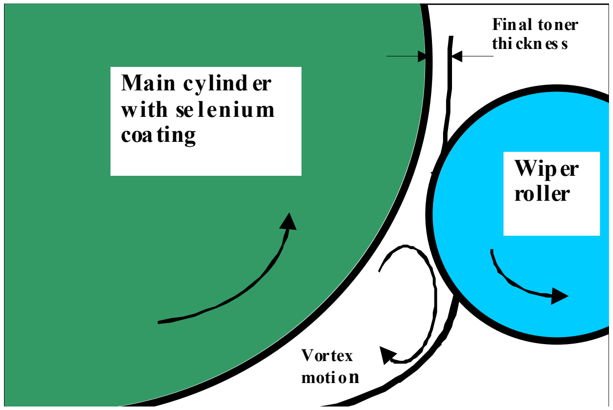
Imaginary Complexity

$$\begin{Bmatrix} FR1 \\ FR2 \\ FR3 \\ \cdots \\ \cdots \\ \cdots \\ FRm \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & \ldots & 0 \\ X & X & 0 & 0 & \ldots & 0 \\ X & X & X & 0 & \ldots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots & 0 \\ X & X & X & X & \ldots & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \\ DP3 \\ \ldots. \\ \ldots. \\ \ldots. \\ DPn \end{Bmatrix}$$

$$P = \frac{1}{n!}$$

Solution

DP41 = The order of rotation of the wiper roller and the main cylinder (wiper roller rotates first)
DP42 = The surface speed of the wiper roller greater than and opposite to the surface speed of the main cylinder



Courtesy of Prof. N. P. Suh. Used with permission.

Case study

TMA(thinfilm micromirror array)

Mirror Array on

Piezoelectric

Actuator Array

Daewoo Electronics

Diagrams removed for copyright reasons.
See S. G. Kim and Kyu-Ho Hwang, "Thin-film Micromirror Array", Information Display (Official Magazine of Society of Information Display, invited), Vol. 15, No. 4/5, pp.30-34, 1999.

Functional Requirements of TMA

1st Generation

FR1= light reflection
FR2= mirror tilting

DP1= cantilever top surface
DP2= PZT sandwich

$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} X & X \\ X & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix}$$

Functional Requirements of TMA

2nd Generation

FR1= light reflection
FR2= mirror tilting

DP1= cantilever top surface
DP2= PZT sandwich

$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} X & O \\ X & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix}$$

Functional Requirements of TMA

3rd Generation

FR1= light reflection
FR2= mirror tilting

DP1= cantilever top surface
DP2= PZT sandwich

$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} X & O \\ O & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix}$$

TMA

XGA
1024 X 768
786,432 pixels

Photos removed
for copyright reasons.

Photos removed
for copyright reasons.

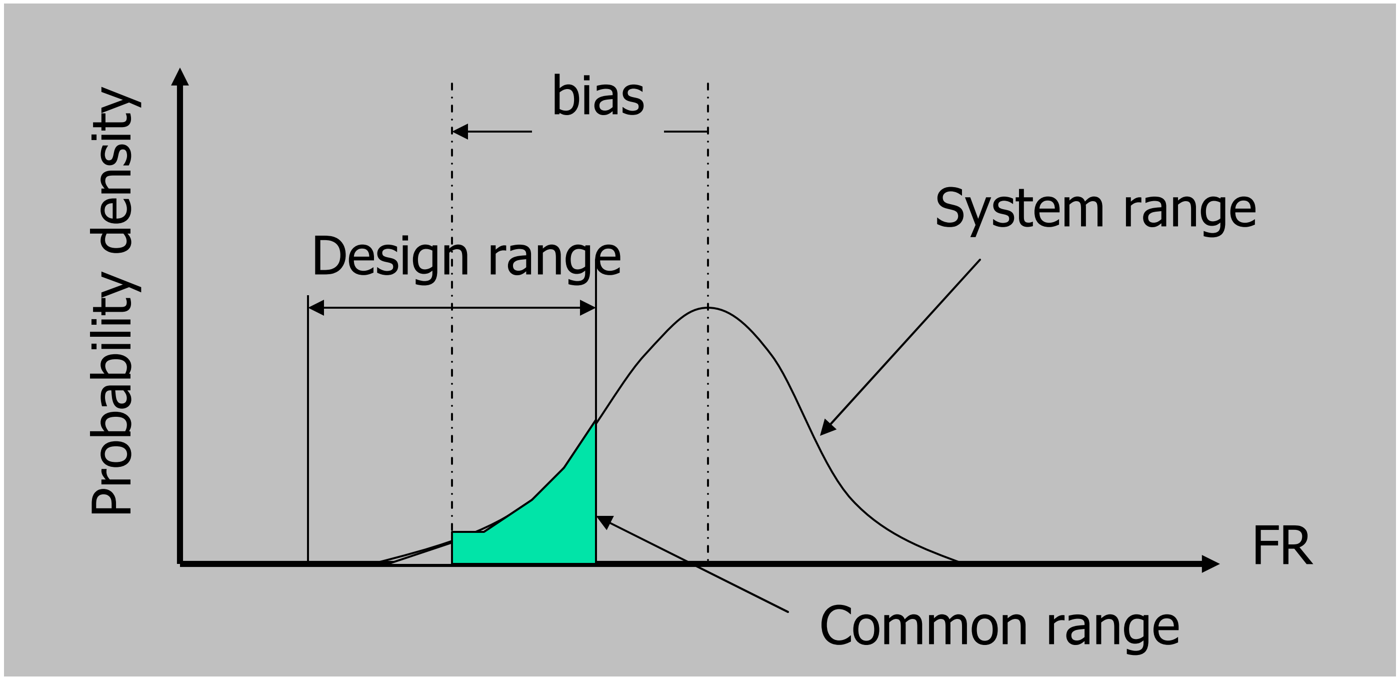
VGA
640 X 480
307,200 pixels

Information Axiom

- Minimize the Information Content

$$I = \log_2 \frac{1}{P} = -\log_2 P$$

P : Probability of success =common range/system range



Multi-scale System Complexity

DNA
~2-1/2 nm diameter

natural

Human heart

Human body (circulatory system)

Diagrams removed for copyright reasons.

manmade

Carbon nanotube
~2 nm diameter

Nanotube transistor

MIT Stata Center by Gehry

$300 million, 5years

MIT Simmons Hall

$ 90million, 2 years

Scale Orders

Scale order, N = $\frac{\text{size of the system}}{\text{smallest characteristic length}}$

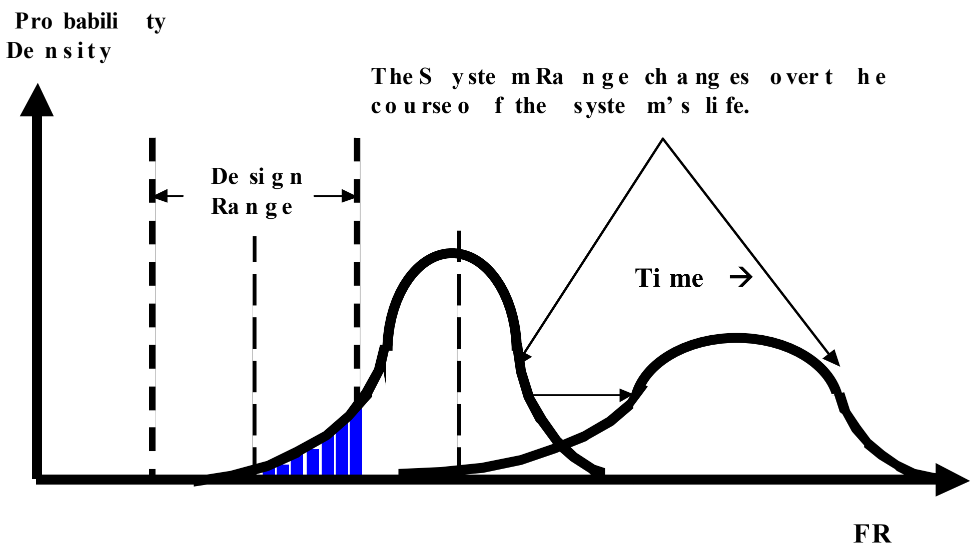
	N
• Cars: 5 m ←→ 500 μ	10^4
• Jig Machines: 5 m ←→ 5 μ	10^6
• Lithography M/C: 30 cm ←→ 30 nm	10^7
• Human Body: 2 m ←→ 2 nm	10^9

- Scale order vs. Complexity?

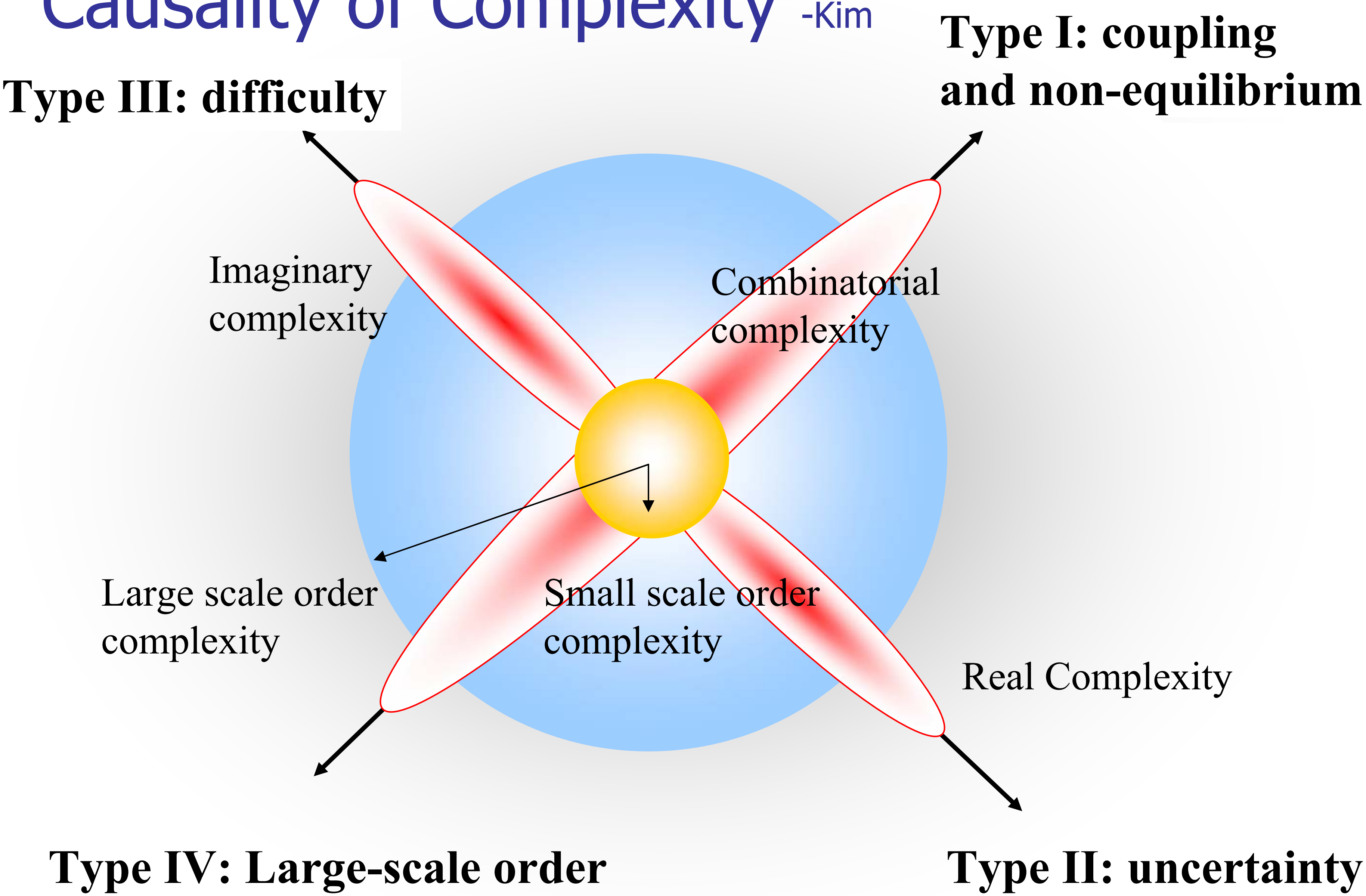
Complexity of social problems

- Uncertainty
- Difficulty
- Complexity

Non-equilibrium systems, long term stability



Causality of Complexity -Kim



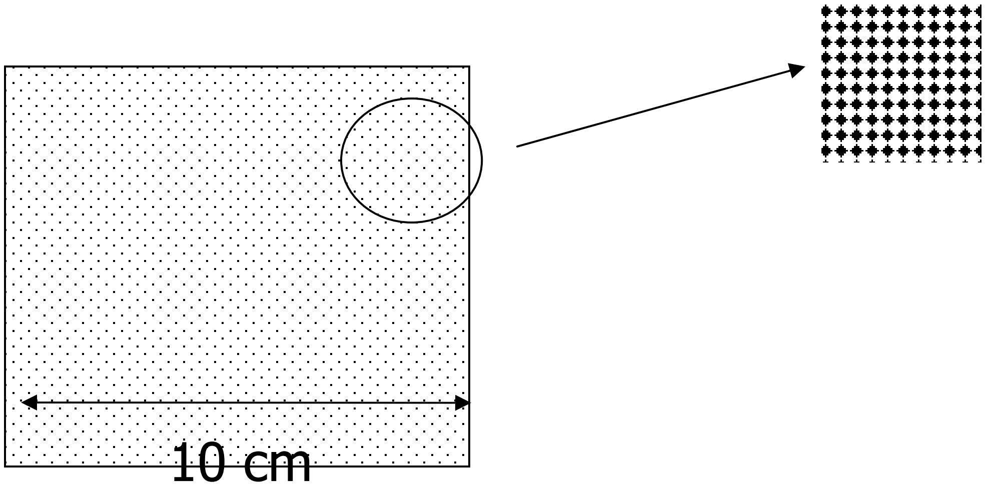
Real Complexity and the Scale Issue

- the ratio (range/tolerance)

$$I = \log\left(\frac{range}{tolerance}\right)$$ Suh

$$I = \log\left(e^{\frac{range}{tolerance}}\right) = \frac{range}{tolerance}$$ Kim

Nano-Scale Assembly

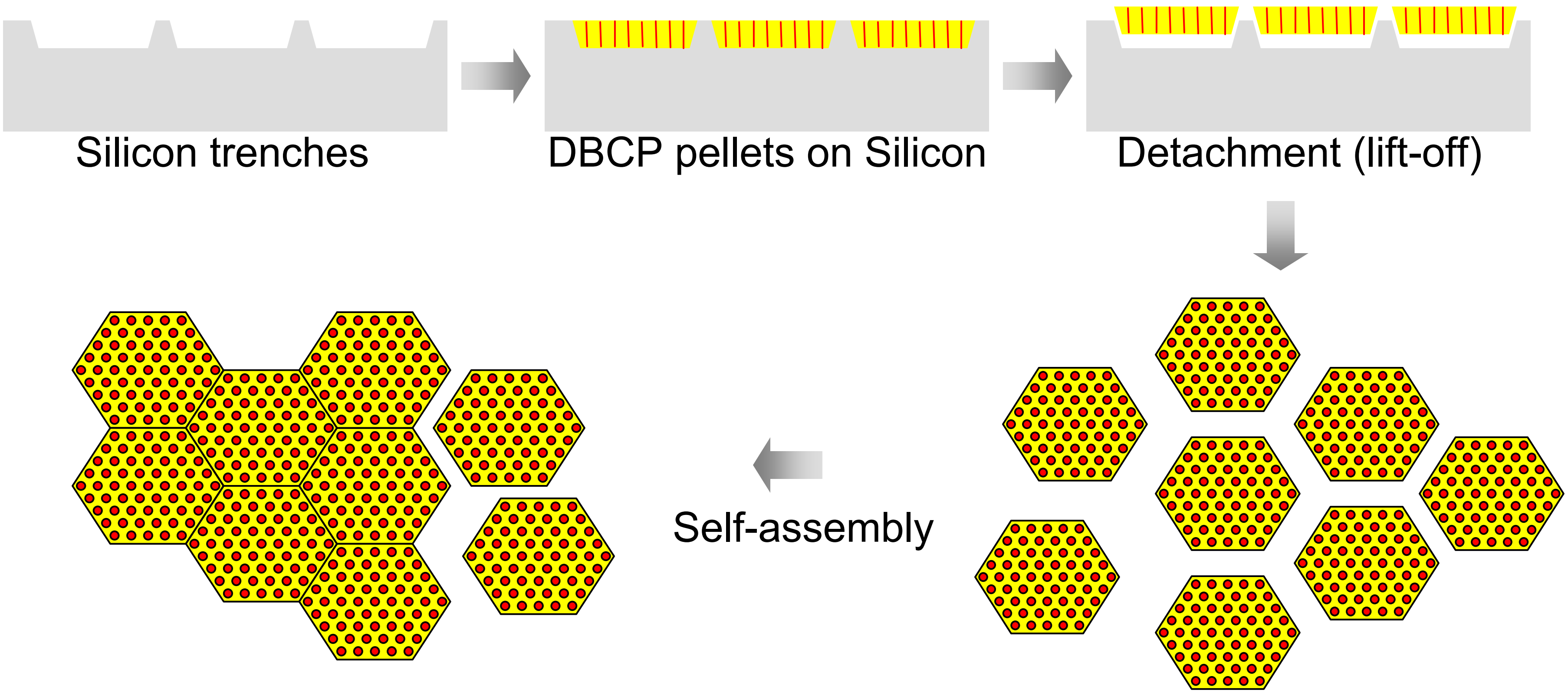


100nm Carbon Nanotube
100nm spacing

Three photos removed for copyright reasons.
Force microscopy tip and two nanotube arrays.

Block Assembly

Nanopelleting Technique*



* US patent pending, S. Kim

Gordon Moore (Intel)

Two graphs of “Moore’s Laws” - removed for copyright reasons.

Moore’s Second Law

- *The cost of building chip fabrication plants will continue to increase (and the return on investment to decrease) until it becomes fiscally untenable to build new plants.*

Lithography Tool Cost

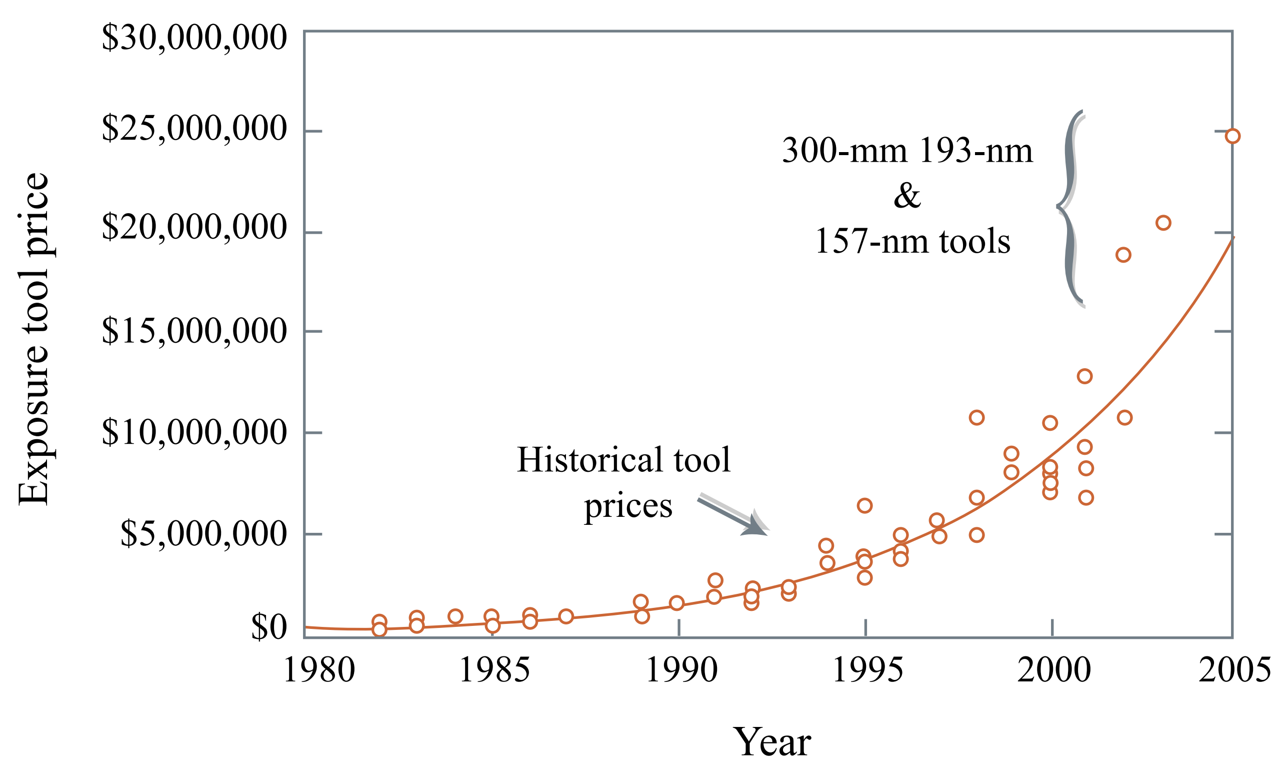
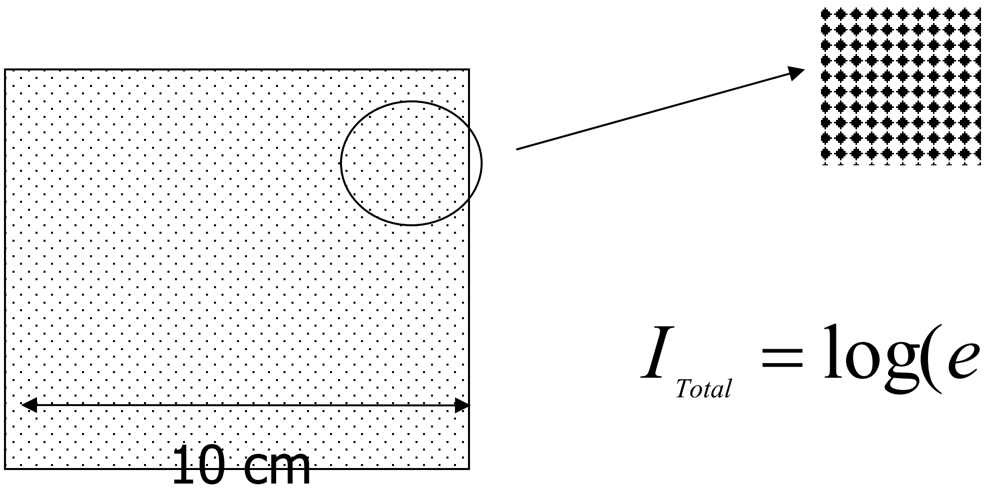


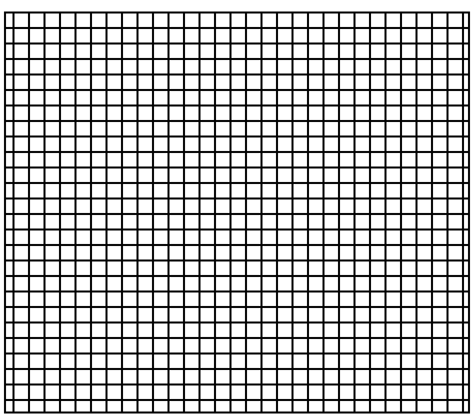
Figure by MIT OCW, after International Sematech.

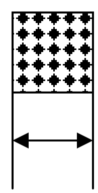
Scale Decomposition and Information Content



100nm Carbon Nanotube
100nm spacing

$$I_{Total} = \log(e^{\frac{range}{tolerance}}) = \frac{range}{tolerance} = 10^6$$





100µm

$$I_{Total} = I_{micro} + I_{nano} = 10^3 + 10^3$$

Block Assembly

Complexity

A system is complex when;

- A design is strongly coupled or path-dependent,
- System ranges vary with time, (non-equilibrium)
- The outcome is uncertain, (low probability of success)
- The scale order is very high.

Complexity can be reduced by;

- Periodic Functions (temporal, spatial, etc.)
- Uncoupled

Functional Periodicity

- Time independent real and imaginary complexity.
- Time dependent combinatorial and periodic complexity.
- Time dependent combinatorial complexity can become periodic complexity by functional periodicity. [Suh, MIT]

  - Temporal
  - Geometrical
  - Biological
  - Manufacturing process
  - Chemical information
  - Circadian
  - etc.

Functional Periodicities

- Temporal periodicity
- Geometric periodicity
- Biological periodicity
- Manufacturing process periodicity
- Chemical periodicity
- Thermal periodicity
- Information process periodicity
- Electrical periodicity
- Circadian periodicity
- Material periodicity

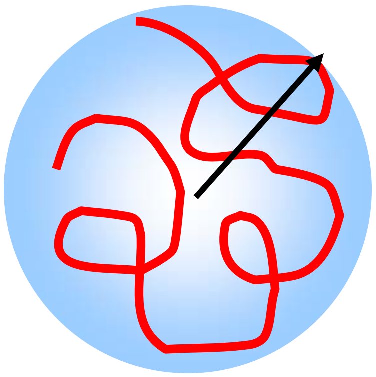
Di-block copolymers

$$\Delta G_m = \Delta H_m - T\Delta S_m$$

$$\frac{\partial^2 \Delta \overline{G}}{\partial X_B^2} < 0$$

Diagrams removed for copyright reasons.
See C.T. Black, et al., Applied Physics Letters 79, 409, 2001.

Micro-phase Separation



Random walk, Gaussian distribution

e-to-e distance, $R = aN^{1/2}$
$R_g = aN^{1/2}/6$
N: number of monomers

Micro-domain periodicity, L

$$L \propto R_g \propto aN^{\frac{1}{2}}$$

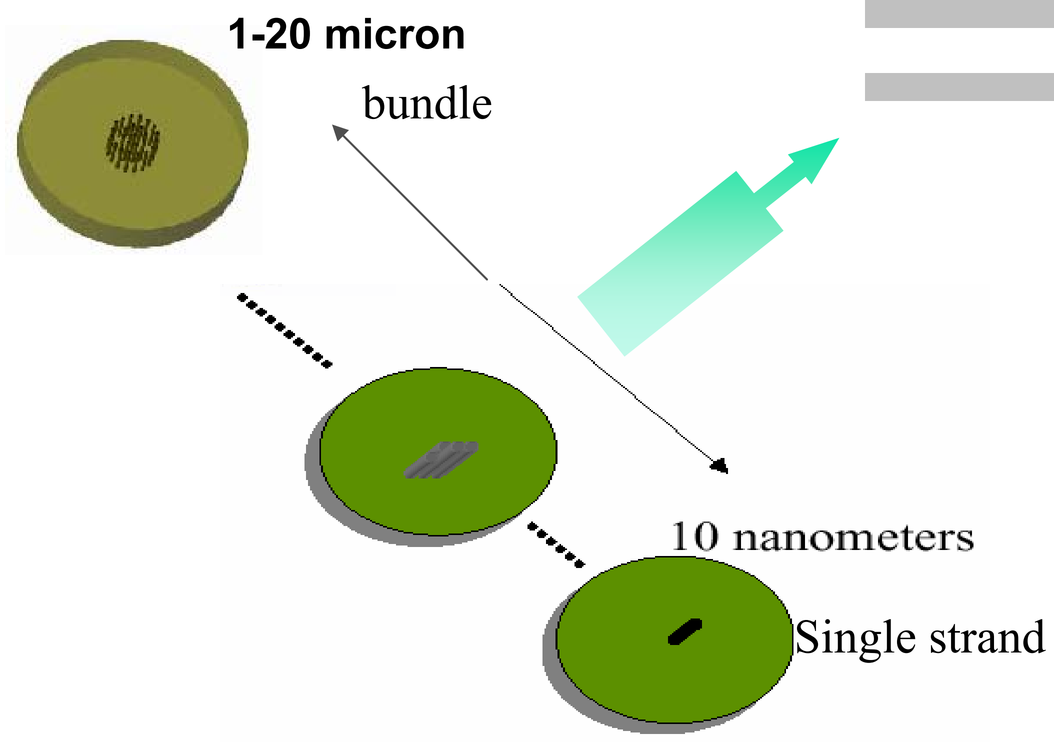
N=1,000
a=5 angstroms
Then, L is around 15 nm.

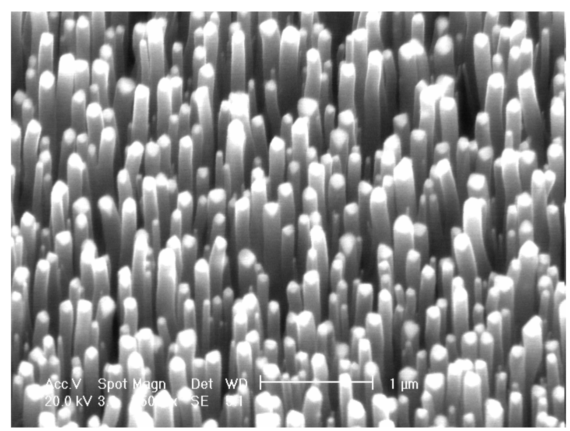
Multi-scale system assembly by periodic building blocks?

- Periodic micro-domains
- Functionally uncoupled domains
- Periodicity, $L \propto R_g \propto aN^{\frac{1}{2}}$
- CNT assembly

MIT Simmons Hall

Inter-layer Nanopellets for Composites[1]





1. Wardle and Kim, US patent pending

Multi-scale Manufacturing at Kim's Group