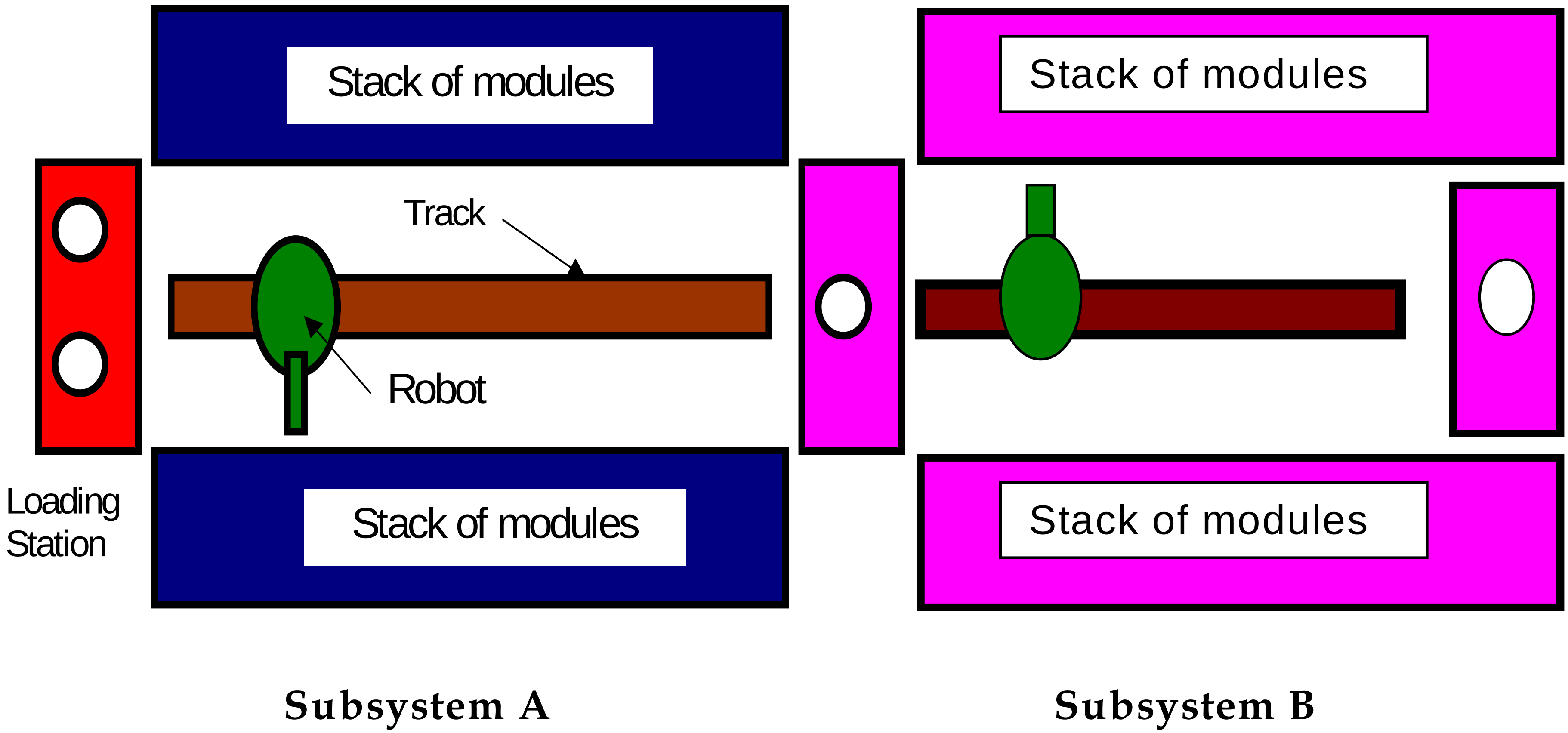
Complexity - II

Consider the creation of a manufacturing system by combining two sub-systems serially.

A Manufacturing System Composed of Two Sub-Systems



A Cluster of two machines that are physically coupled to manufacture a part.

Each subsystem consists of many processing steps and a robot that transports the part.

After the part is finished in Subsystem A, the part is further processed in Subsystem B.

We want to maximize the production rate.

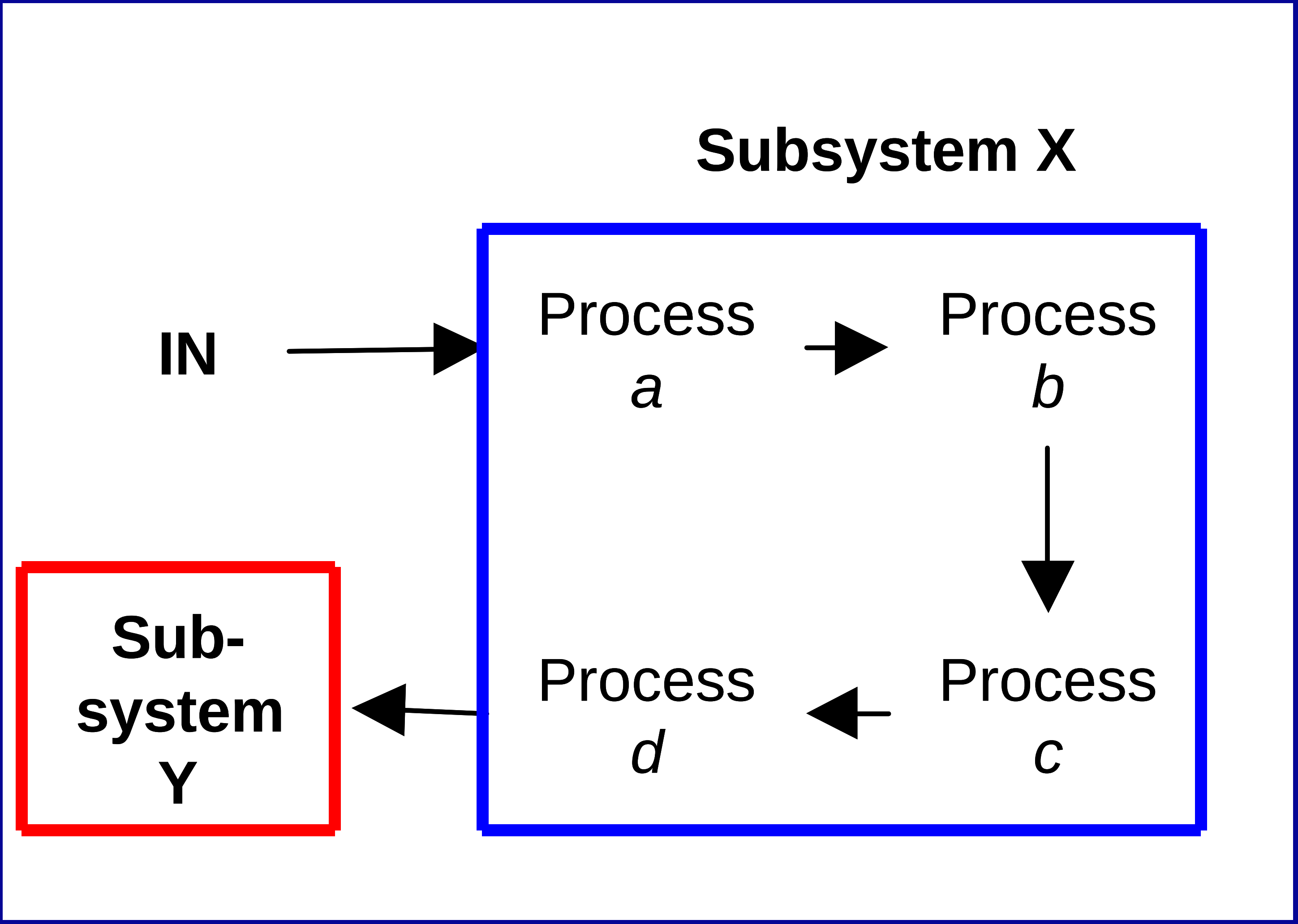
If the throughput rates are the following:

Subsystem A -- 100 parts/hr and

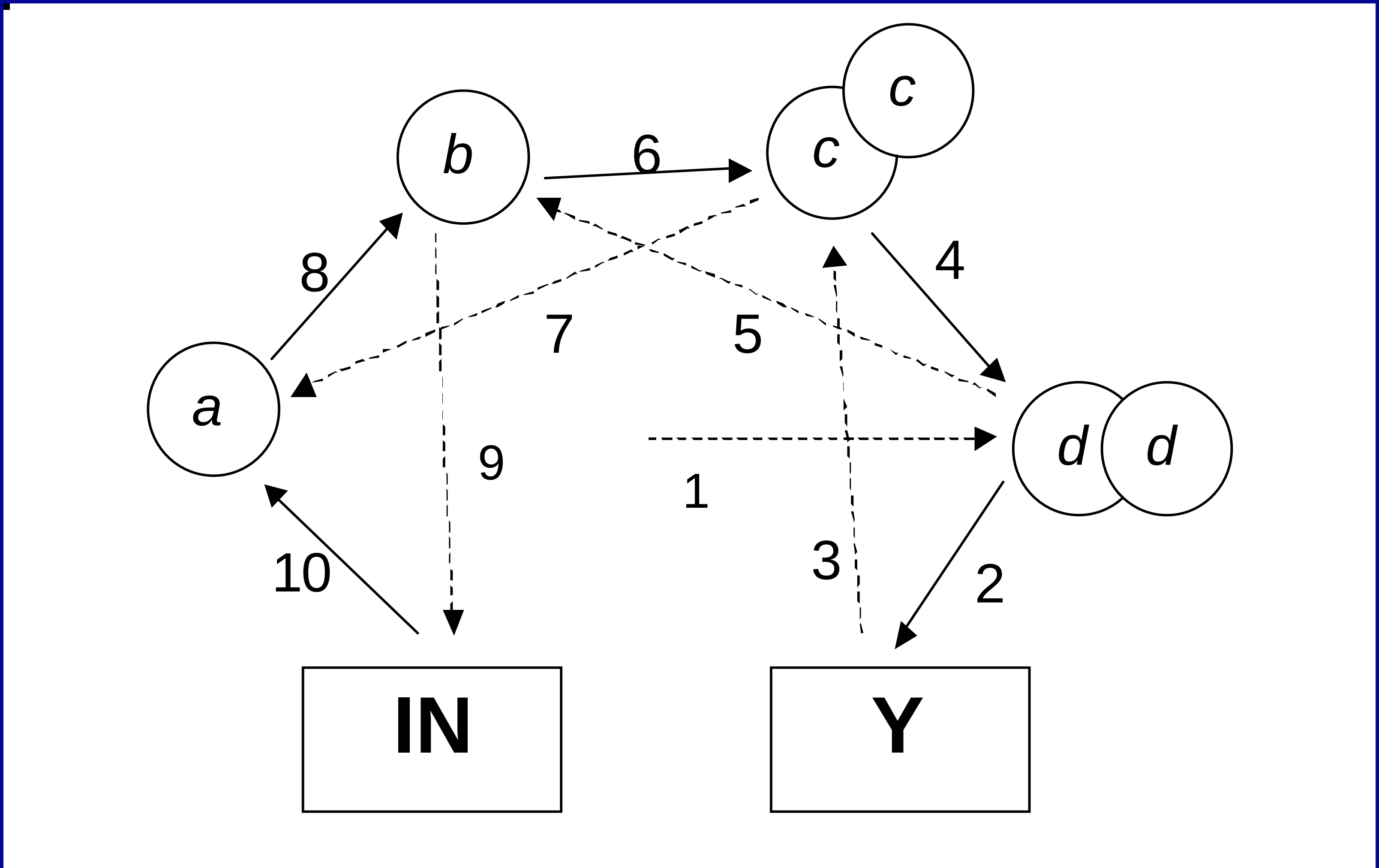
Subsystem B -- 60 parts/hr,

what should be the throughput rate of the manufacturing system that consists of Subsystem A and Subsystem B?

Example: Subsystem X feeds parts to Subsystem Y



Example: Physical Configuration



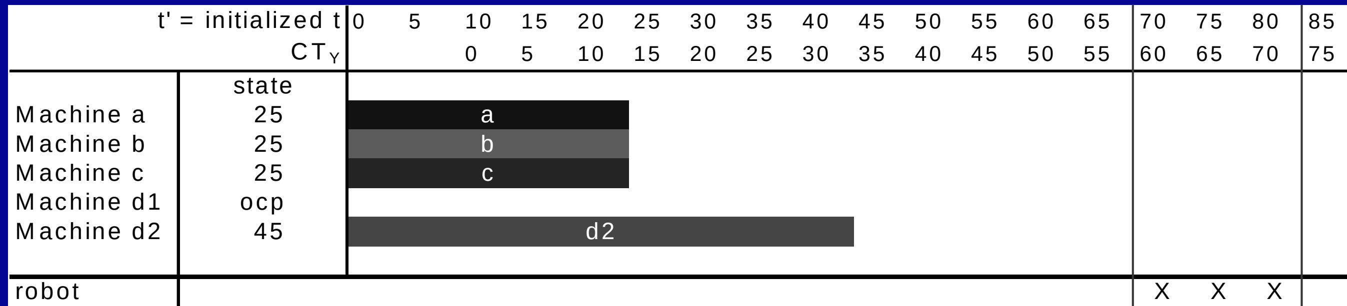


Figure 13. Information at the instant of initialization

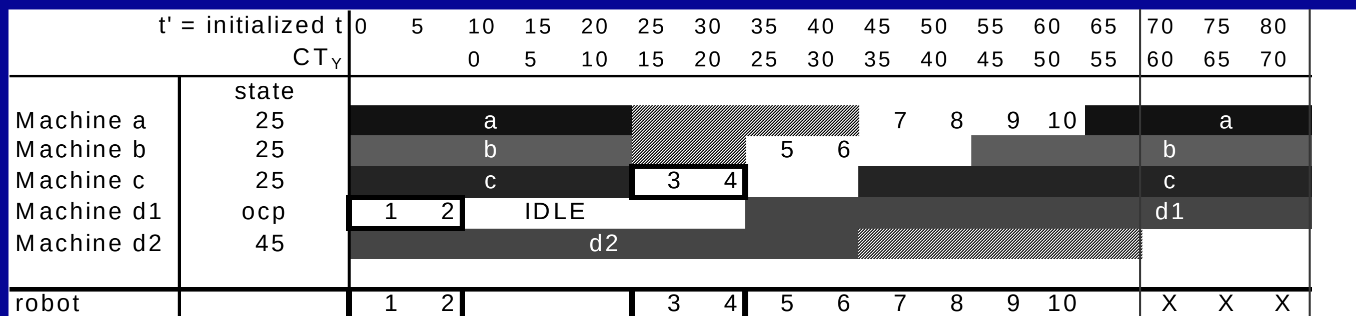


Figure 14. Result of scheduling for a period

The same approach as in case 2, with the no-transport-time adjusted, applies to case 3.

Functional Periodicity

- The functional periodicity are the following types:

(1) Temporal periodicity

(2) Geometric periodicity

(3) Biological periodicity

(4) Manufacturing process periodicity

(5) Chemical periodicity

(6) Thermal periodicity

(7) Information process periodicity

(8) Electrical periodicity

(9) Circadian periodicity

(10) Material periodicity

Example: Design of Low Friction Sliding Surfaces

Consider the following task:

Reduce friction between two sliding surfaces under load

Friction Space

Design of Low Friction Sliding Surfaces without Lubricants

Design of Low Friction Sliding Surfaces without Lubricants

- What are the FRs?

- What are the constraints?

Design of Low Friction Sliding Surfaces without Lubricants

FR_1 = Support the normal load

FR_2 = Prevent particle generation

FR_3 = Prevent particle agglomeration

FR_4 = Remove wear particles from the interface

- Constraint: No lubricant

Design of Low Friction Sliding Surfaces without Lubricants

DP_1 = Total contact area of the pad, A

DP_2 = Roughness of the planar surface of pads, R

DP_3 = Length of the pad in the sliding direction, λ

DP_4 = Volume and depth of the pocket for wear particles, V

Design of Low Friction Sliding Surfaces without Lubricants

The design equation:

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & x & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & x & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} A \\ R \\ \lambda \\ V \end{Bmatrix}$$

Design of Low Friction Sliding Surfaces without Lubricants

Test Results:

Drive sprockets, idlers, rollers, Grouser shoes

Pin-Joint Design

Figures removed for copyright reasons.
See Figure 7.25 and 7.26 in [Complexity].

Electrical Connectors

(Courtesy of Teradyne, Inc.)

Photo removed for copyright reasons.
See Figure 7.29 in [Complexity].

Conventional Electrical Connectors

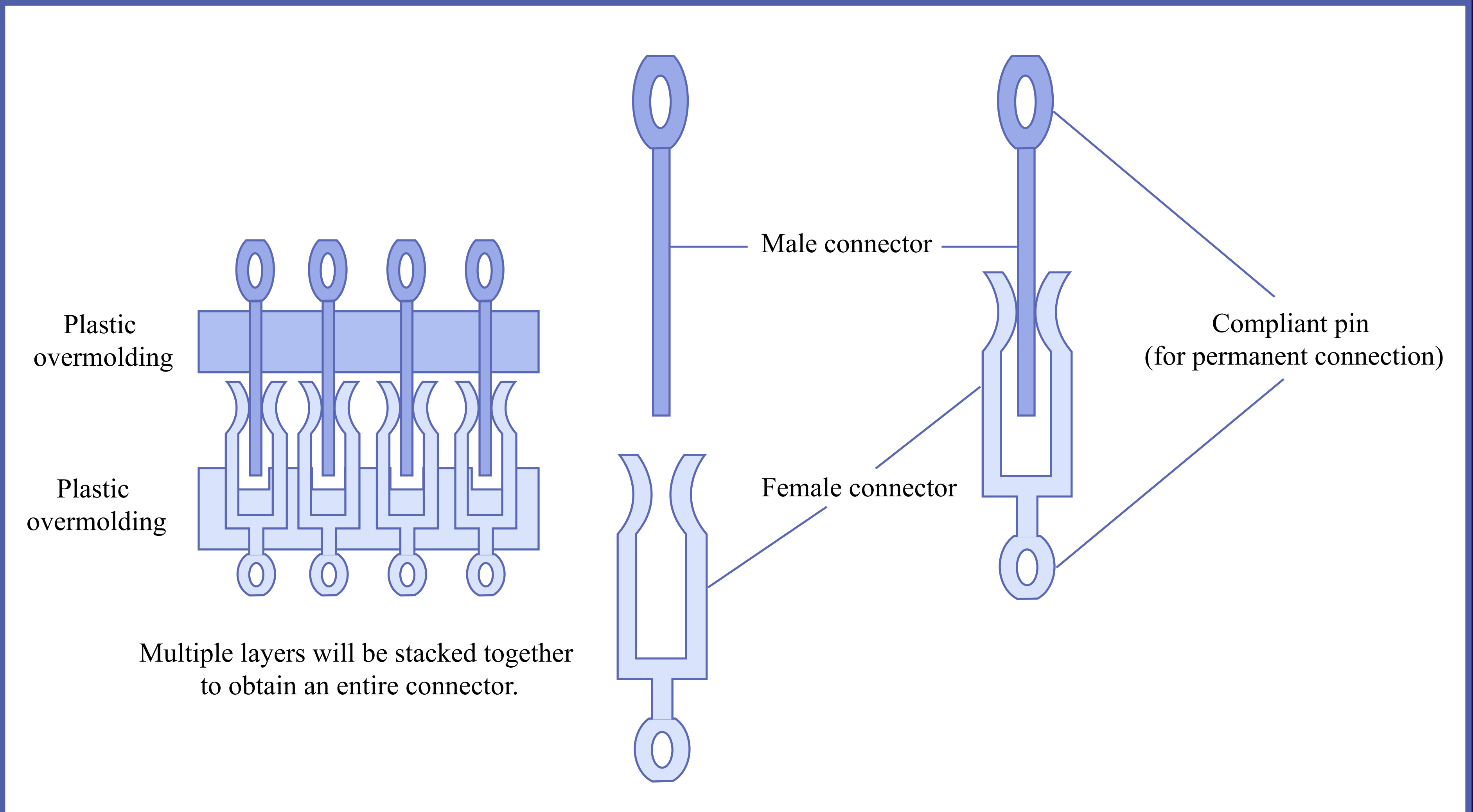


Figure by MIT OCW.

FRs of a Data Electrical Connector

FR1 = Mechanically connect and disconnect electrical terminals

FR2 = Control contact resistance (should be less than 20mΩ)

FR3 = Prevent the cross-talk (i.e., interference) between the connections

Subject to the following constraints (Cs):

C1 = Low cost

C2 = Ease of use

C3 = Long life (> million cycles)

C4 = Maximum temperature rise of 30 ^{o}C

C5 = Low insertion force

FRs of a Power Electrical Connector

FR1 = Mechanically connect and disconnect electrical terminals

FR2 = Control contact resistance (should be less than 20mΩ)

FR3 = Maximize power density

Subject to the following constraints (Cs):

C1 = Low cost

C2 = Ease of use

C3 = Long life (> million cycles)

C4 = Maximum temperature rise of 30 ^{o}C

C5 = Low insertion force

DPs of a Data Electrical Connector

DP1 = Cylindrical assembly of the woven tube and the pin

DP2 = Locally compliant electric contact

DP3 = Number of conducting wires

Decomposition of FR1 (Mechanically connect and disconnect electrical terminals) and DP1 (Cylindrical assembly of the woven tube and the pin)

FR11 = Align the rod axially inside the tube

FR12 = Locate the axial position of the rod in the tube

FR13 = Guide the pin

DP11 = Long aspect ratio of the rod and the tube

DP12 = Snap fit

DP13 = Tapered tip of the pin

Decomposition of FR2 (Control contact resistance to be less than 20mΩ) and DP2 (Locally compliant electric contact)

FR21 = Prevent oxidation of the conductor

FR22 = Remove wear particles

FR23 = Control line tension/deflection of the non-conducting fiber

DP21 = Gold plated metal surface

DP22 = Space created in the crevices between fibers

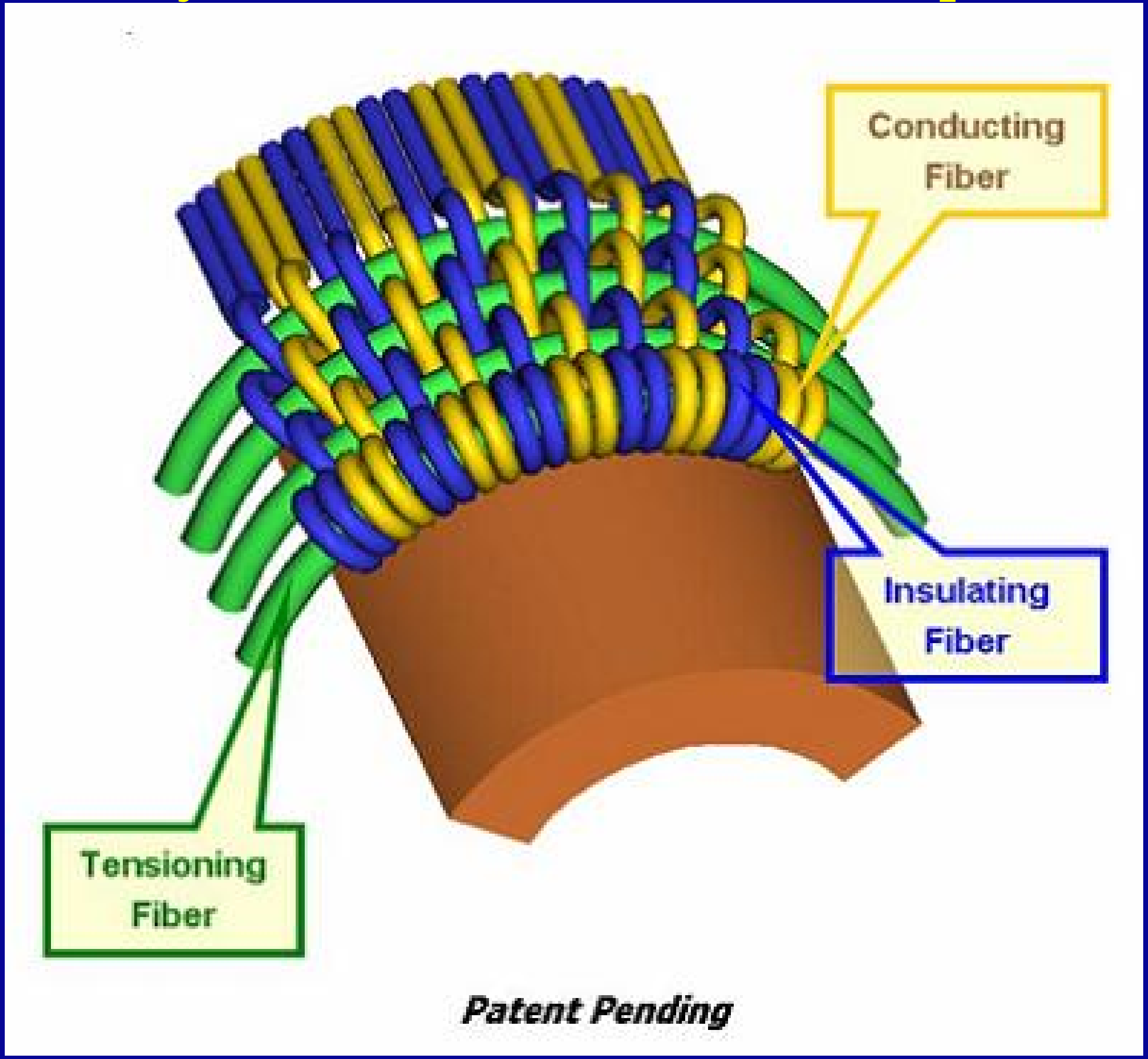
DP23 = Spring

Design Matrix

$$\begin{Bmatrix} FR1 \\ FR2 \\ FR3 \end{Bmatrix} = \begin{bmatrix} X00 \\ XX0 \\ 0XX \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \\ DP3 \end{Bmatrix}$$

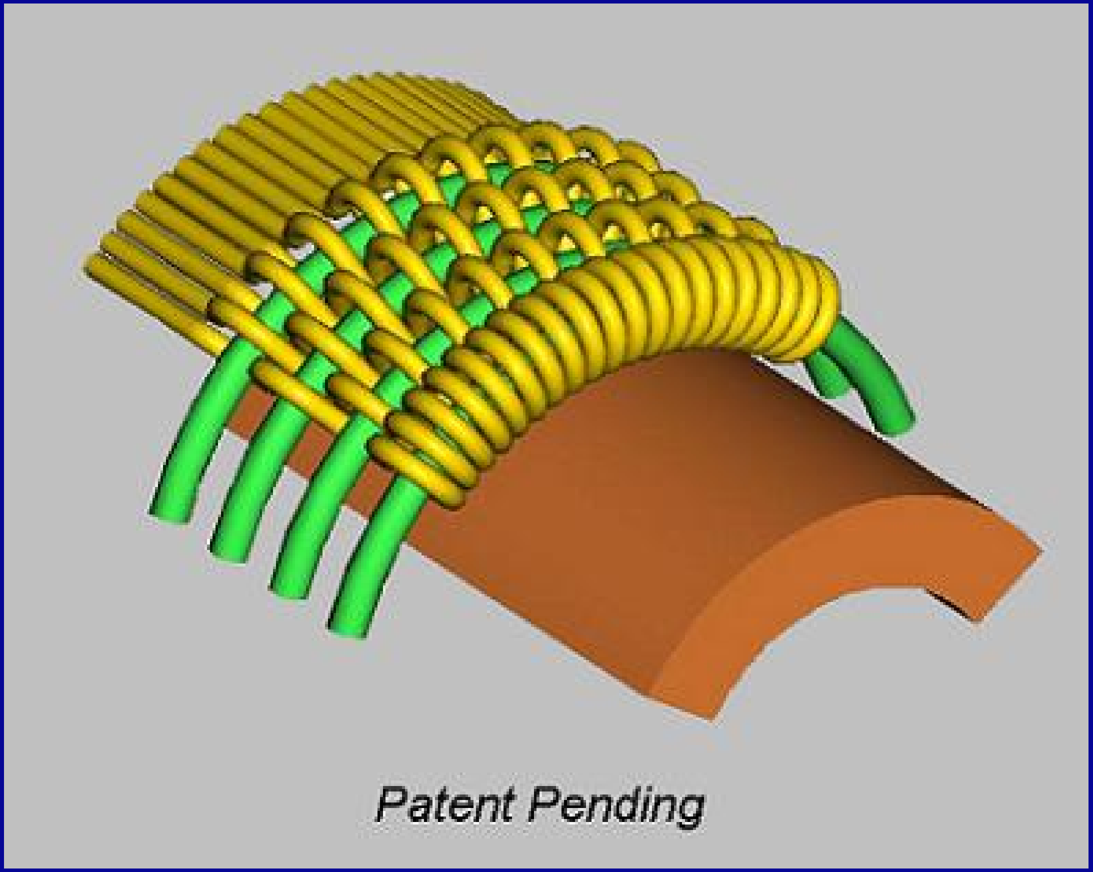
Tribotek Electrical Connectors

(Courtesy of Tribotek, Inc. Used with permission.)



Tribotek Electrical Connectors

(Courtesy of Tribotek, Inc. Used with permission.)



Performance of “Woven” Power Connectors

- Power density => 200% of conventional connectors
- Insertion force => less than 5% of conventional connectors
- Electric contact resistance = 5 m ohms
- Manufacturing cost
- Capital Investment

Functional Periodicity

- The functional periodicity are the following types:

(1) Temporal periodicity
(2) Geometric periodicity
(3) Biological periodicity
(4) Manufacturing process periodicity
(5) Chemical periodicity
(6) Thermal periodicity
(7) Information process periodicity
(8) Electrical periodicity
(9) Circadian periodicity
(10) **Material periodicity**

Material Functional Periodicity

Unstable Crack growth

Figure removed for copyright reasons.
See Figure 8.1 in [Complexity].

Material Functional Periodicity

Stress intensity factor at the crack tip

$$k_1 = \sigma_{22\infty}\sqrt{c}$$

Material Functional Periodicity

Crack Growth under cyclic loading

Figure removed for copyright reasons.
See Figure 8.2 in [Complexity].

Material Functional Periodicity

Crack Growth rate per cycle under cyclic loading

$$\frac{dc}{dN} = A\left(\frac{\Delta k_1}{\sigma_Y}\right)^n$$

Material Functional Periodicity

- 1-D functional periodicity
  - Rope
  - Fibers and yarns
- 2-D functional periodicity
  - Fabric
- 3-D functional periodicity
  - Fiber reinforced composites

Material Functional Periodicity

Figure removed for copyright reasons.
See Figure 8.3 in [Complexity].

Functional Periodicity to Control Material Properties

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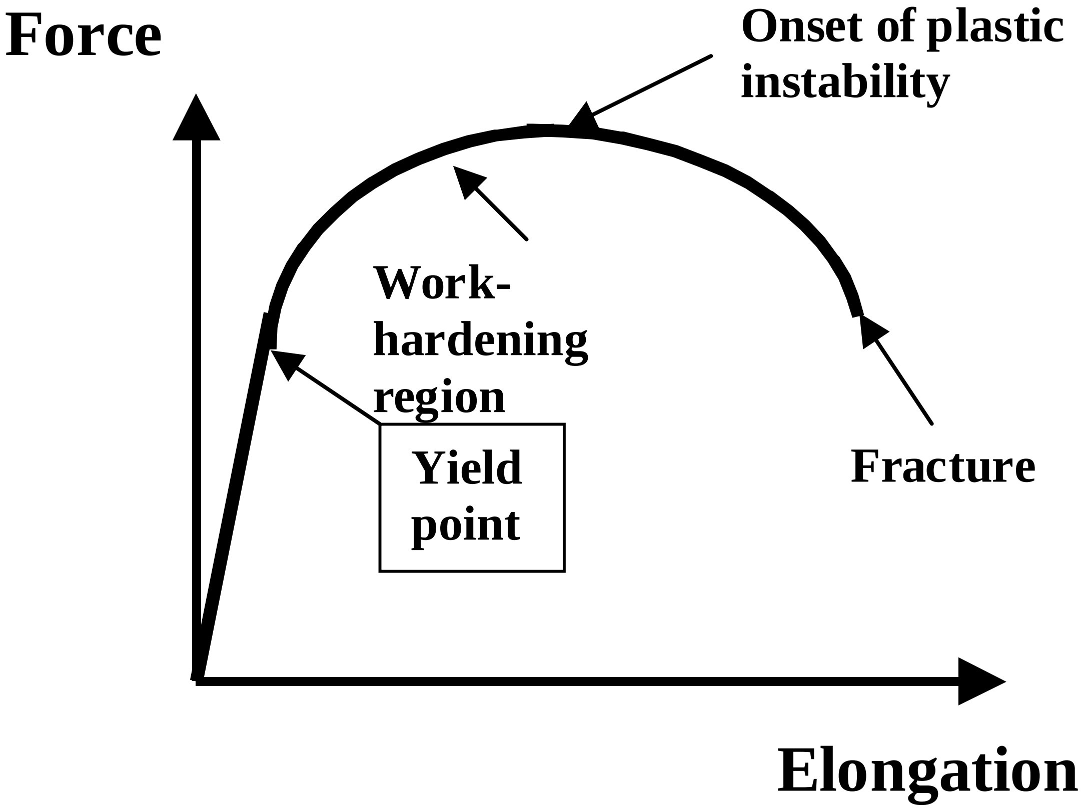
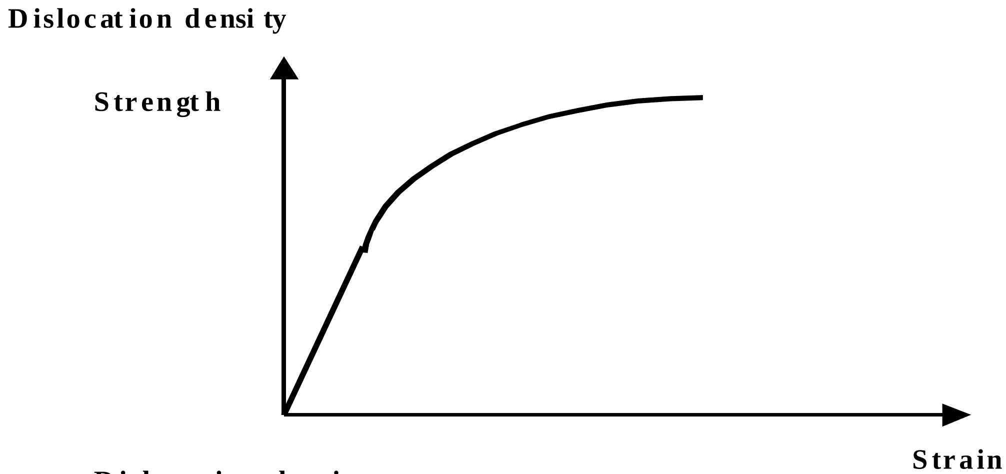
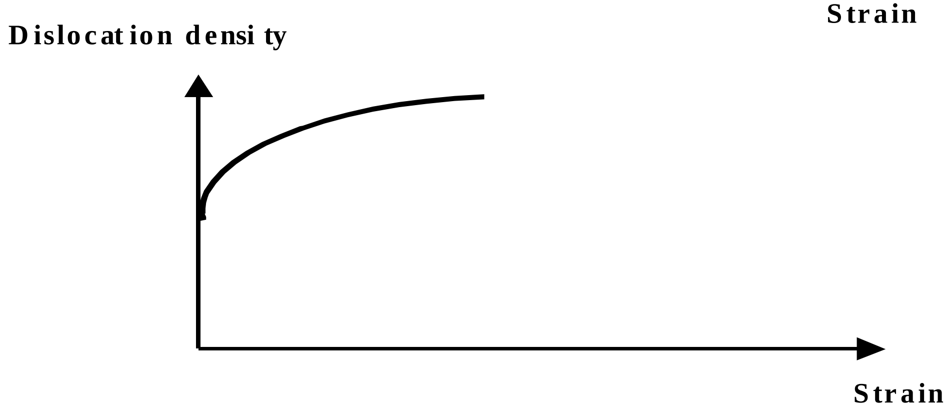
See Figure 8.4 in [Complexity].

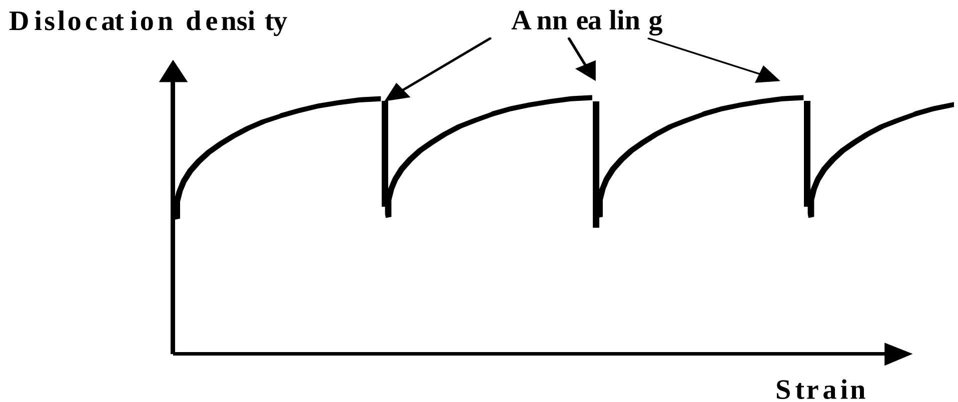
Functional Periodicity to Control Material Properties



Functional Periodicity to Control Material Properties







Functional Periodicity to Control Material Properties

- Functional periodicity for controlling material properties
  - Thin films
  - Superlattices
  - Annealing in wire drawing

Functional Periodicity to Control Material Properties -- Annealing during wire drawing

Figure removed for copyright reasons.
See Figure 8.7 in [Complexity].

Functional Periodicity to Control Material Properties -- Microcellular plastics

Figures removed for copyright reasons.
See Figure 8.8 and 8.9 in [Complexity].

Complexity Theory
and
the Stability of a System

- **For a system to be stable and survive for a long period of time, it must either**
  - **Be at *equilibrium***

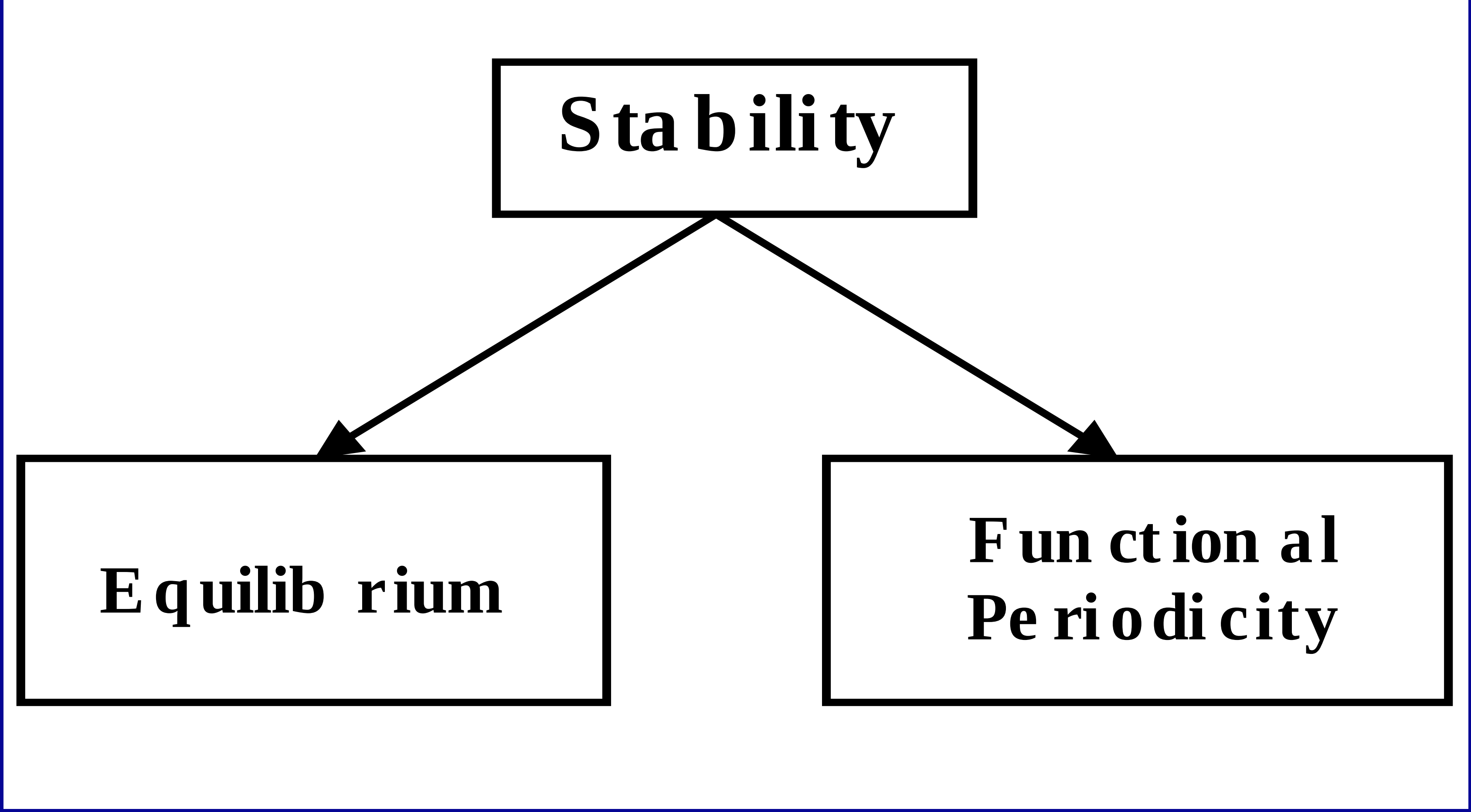
    or

  - **Have a *functional periodicity***

Examples of Functional Periodicity

Examples of Functional Periodicity	Examples in Nature	Examples in Engineered Systems
Temporal periodicity	Planetary system, solar calendar	Airline/train schedules, computers
Geometric periodicity	Crystalline solids,	Undulated surface for low friction, "woven" electric connectors
Biological periodicity	Cell cycle, life-death cycle, plants, grains,	Fermentation processes such as wine making
Manufacturing processing periodicity	Biological systems	Scheduling a clustered manufacturing system,
Chemical periodicity	Periodic table of chemical elements/atoms	Polymers
Thermal periodicity	Temperature of Earth,	Heat cycles (e.g., Carnot cycle),
Information processing periodicity	Language	Re-initialization of software systems, music
Electrical periodicity	Thunder storm	LCD, alternating current,
Circadian periodicity	Living beings,	Light sensitive sensors
Material periodicity	Wavy nature of matter, crystallinity,	Fabric, wire drawing, microcellular plastics,

Implications of the Complexity Theory



Implications of the Complexity Theory

<u>Equilibrium based physics</u>

Newtonian Mechanics

Thermodynamics

Implications of the Complexity Theory

Functional Periodicity based physics

Quantum Mechanics

String theory

Implications of the Complexity Theory

<u>Periodicity based physics</u>

Quantum Mechanics

Can we explain the particle/wave duality based on this stability argument?

Complexity of Socio-Economic Political Systems

- Functional Periodicity
  - Economic functional periodicity
  - Political functional periodicity
  - Organizational functional periodicity
  - Academic functional periodicity

Complexity of Socio-Economic Political Systems

- Case Studies
  - Economic development of ROK (1980-85)
  - National Science Foundation
  - Mechanical Engineering Department of MIT

Functional Periodicity

- The functional periodicity are the following types:

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(5) Chemical periodicity
(6) Thermal periodicity
(7) Information process periodicity
(8) Electrical periodicity
(9) Circadian periodicity
(10) Materials periodicity

Systems Biology

- **The goal is to relate the higher-level FRs to the behavior of biological molecules.**
- **Use the knowledge in curing patients.**
- **Use the knowledge in drug discovery.**

Systems Biology

- Based on the complexity theory, one may speculate that biological systems must have a functional periodicity.

- Based on axiomatic design theory and complexity theory, one may speculate that most biological systems are a decoupled or uncoupled systems.

- How do we relate the molecular behavior to the behavior of biological systems?

It seems that biological system follows the same principles as engineered systems.

- Robustness through functional independence
- Functional periodicity

FRs of a Cell

FR1 = Isolate the cell and its components from its environment.

FR2 = Obtain fuel.

FR3 = Convert the fuel to energy.

FR4 = Communicate with it surrounding.

FR5 = Reproduce itself.

FR6 = Control cell functions.

DPs of a Cell

DP1 = Plasma membrane (phospholipid bilayer)

DP2 = Diffusion of ions and transport of proteins

DP3 = Synthesis of ATP in mitochondria

DP4 = Receptors and signal transduction protein

DP5 = Reproduction mechanism

DP6 = Functional periodicity

Second Level Decomposition of FR/DPs of a Cell

- FR6 (Control cell functions) / DP6 (Functional periodicity) may be decomposed as

  FR61 = Regulate growth.

  FR62 = Prevent mutation.

  FR63 = Control cell functions.

  DP61 = Growth factor

  DP62 = DNA repair and apoptosis

  DP63 = cdk protein

Design Matrix of a Cell

		DP1	DP2	DP3	DP4	DP5	DP6		
							DP61	DP62	DP63
FR1		X	0	0	0	0	0	0	0
FR2		X	X	0	0	0	0	0	0
FR3		0	X	X	0	0	0	0	0
FR4		X	x	0	X	0	0	0	0
FR5		x	X	X	x	X	0	0	X
FR6	FR61	x	0	0	0	0	X	0	0
	FR62	0	0	0	0	0	0	X	0
	FR63	X	X	X	X	0	0	X	X

Decomposition of FR5 (Reproduce itself) and DP5 (Reproduction mechanism)

FR51 = Initiate the replication process.
FR52 = Start chromosome replication.
FR53 = Replicate proteins.
FR54 = Replicate DNA structures.
FR55 = Create cytoplasm skeleton.
FR56 = Form membranes of organelles.
FR57 = Induce mitosis.

Decomposition of FR5 (Reproduce itself) and DP5 (Reproduction mechanism)

DP51 = Start kinase/ "restriction point" for G_1 phase
DP52 = Chromosome replication kinase
DP53 = Cyclin-dependent protein kinase (cdk protein)
DP54 = DNA polymerase, ligase / mRNA
DP55 = Polymerization mechanisms
DP56 = "Membrane" kinase
DP57 = “Tensile force”

Decomposition of FR5 (Reproduce itself) and DP5 (Reproduction mechanism)

	DP51	DP52	DP53	DP54	DP55	DP56	DP57
FR51	X	0	0	0	0	0	0
FR52	X	X	0	0	0	0	0
FR53	X	0	X	0	0	0	0
FR54	X	0	0	X	0	0	0
FR55	X	0	0	0	X	0	0
FR56	X	0	0	0	0	X	0
FR57	0	0	0	0	X	X	X

Decomposition of FR57 (Induce mitosis) and DP57 ("Tensile force")

FR571= Adhere to a reference surface
FR572= Activate WASp family protein.
FR573= Nucleate cellular actin.
FR574= Polymerize G-actin to make F-actin filament.
FR575= Terminate the polymerization reaction.
FR576= De-polymerize the F-actin filament.

Decomposition of FR57 (Induce mitosis) and DP57 (“Tensile force”)

- DP571 = Active sites on the surface (protein fibronectin)
- DP572 = Integrin receptor on cell membrane that binds to fibronectin and initiates signal transduction.
- DP573 = Arp2/3 complex
- DP574 = Free actin/profilin
- DP575 = Capping protein
- DP576 = ATP hydrolysis within actin filaments and dissociation of Phosphate/ ADF(actin depolymerization factor)

Decomposition of FR57 (Induce mitosis) and DP57 ("Tensile force")

	DP571	DP572	DP573	DP574	DP575	DP576
FR571	X	0	0	0	0	0
FR572	x	X	0	0	0	0
FR573	x	X	X	0	0	0
FR574	0	X	X	X	0	0
FR575	0	X	0	0	X	0
FR576	0	X	0	0	0	X

Cell and Cell Cycle

(From Alberts, et al., 3rd Edition)

Figures removed for copyright reasons.

Possible “Lessons” from Biological Systems

- Every subsystems that make up the cell undergo periodic cycles as the entire cell.
- One of the important FRs of a biological seems to be the control of functional period.
- The consequence of the breakdown of the functional periods of cell may lead to failure of biological systems.

Lesson from Biological Systems

(from Alberts, et al., 3 rd edition)

Cell cycle control:

- **Controlled centrally by cyclin and cdk (cyclin-dependent protein kinases)**
- **Not by a mechanism of each of the major essential processes triggering the next event**
- **This behavior of biological systems is consistent with the complexity theory.**

Ultimate Goals of Systems Biology

- Better drug discovery process
- Better cure of disease
- Application of biological knowledge in engineering systems
- Linkage between biology and engineered systems

Conclusions

- The field of complexity may be a new emerging field in science and technology.
- The complexity presented in this talk provides a 40,000 feet view of the engineering systems and natural systems.
- It provides guidelines what to do and what not to do.

Conclusions

- Complexity must be defined in the "functional domain", not in the "physical domain".

- There are the following four types of complexity:
  - Time-independent real complexity
  - Time-independent imaginary complexity
  - Time-dependent combinatorial complexity
  - Time-dependent periodic complexity

Conclusions

- Time-independent real complexity is a measure of uncertainty in achieving a given set of FRs and thus is related to information content.
  - two orthogonal components: real complexity and imaginary complexity
- Time-dependent complexity is the complexity that changes as a function of time.
  - two types of complexity: combinatorial complexity and periodic complexity.

Conclusions

- Transforming a time-dependent combinatorial complexity into a periodic complexity increases the stability of the system and the system performance.

- The transformation is achieved by introducing (or maintaining) functional periodicity.

- The periodicity is introduced by re-initializing subsystems on a periodic interval of a set of FRs.