Design of Fluid Thermal Systems

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Introduction

- *Fluid thermal systems* is a very broad term that refers to many designs and devices.
- A pump and pipe combination is an example of a fluid system
- An air conditioner, a petrol engine, a gas turbine power plant, etc. are examples of fluid thermal systems, as heat transfer effects are important.
- Let us try to understand the meaning of design of air conditioning system.

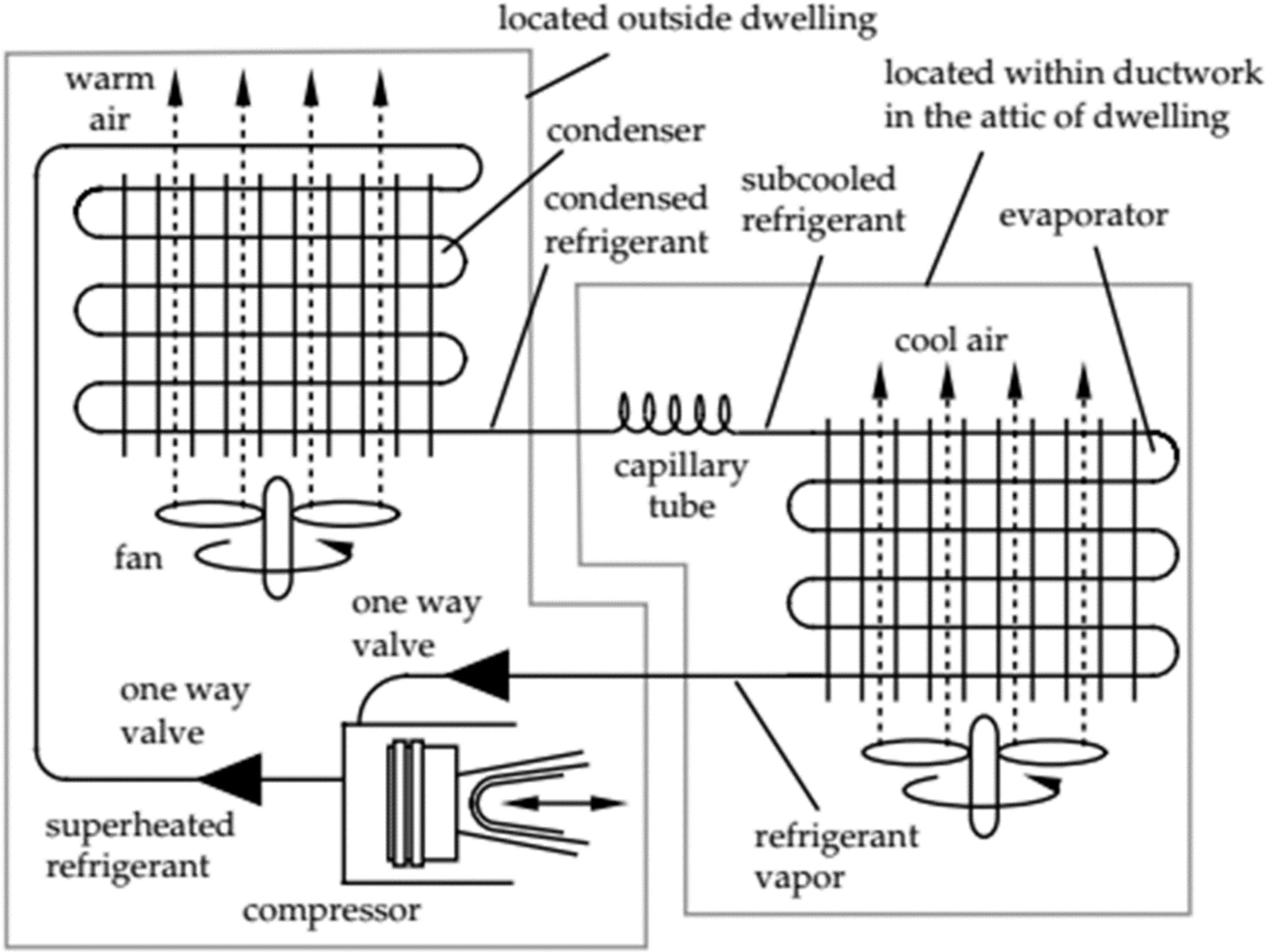


Fig. Sketch of an air conditioning unit

Outdoor unit

- The fluid within, known as a *refrigerant*, undergoes a cycle as it moves throughout the system.
- The fluid is compressed by the compressor and leaves as a superheated vapor.
- The vapor enters a *heat exchanger* (can be called as condenser). A fan supplies atmospheric air over the coils or tubes of the condenser.
- This condensed refrigerant enters a capillary tube and further looses its pressure and temperature.

Indoor unit

- The cold liquid refrigerant is then piped to an evaporator, a device similar to the condenser.
- Air inside the room moves past the evaporator coils.
- The liquid refrigerant takes energy from the room air and gets evaporated. As a result the room air gets cooled.
- This refrigerant in gaseous form again goes to the compressor in the outdoor unit and the cycle repeats.

Design considerations

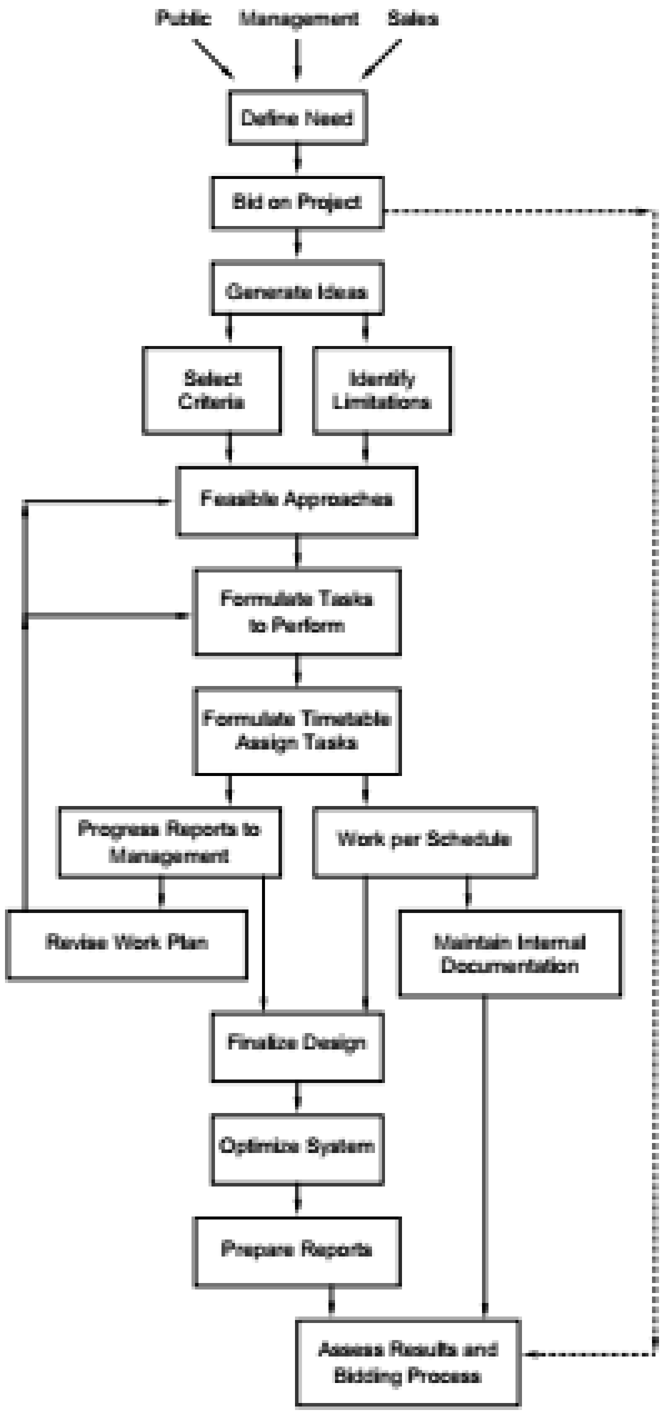
- The compressor power must be determined,
- the fluid conveying lines must be sized,
- the heat exchangers must be selected (piping and fan),
- The entire system must be housed, and
- the fluid itself must be chosen from among many fluids available.

The Design Process

- The design process ranges from accepting a “job” to producing a final report (not just merely finding a solution).
- In engineering design work, there may be many possible solutions to a design problem.
- The design activity can include looking at drawings, making decisions, gathering information, attending meetings, considering alternatives, etc.
- An engineer goes through this process to determine how best to use resources to accomplish a required job.

- An unfortunate aspect of design is that, in most cases, what the client wants may be unclear to both the engineer and to the client.
- For this reason a good design engineer will spend considerable time defining the problem and planning the way it will be solved.
- Defining the problem must include all specifications for the system to be designed. This includes its dimensions, characteristics, location, costs, expected life, operating conditions and limitations.
- Restrictions often encountered include available manufacturing processes, labor skills, materials to be used, etc.

Design process from defining a need to assessing results



Approaches to Engineering Design

1. Systems Approach:

- Writing an objective function for the problem at hand
- In some cases for the total cost of a system
  The total cost will include an initial cost (for equipment) and operating costs (for electricity or fuel)
- In a “good” design, we would seek to minimize the total cost, so we would differentiate the total cost expression and set it equal to zero.
- Usually other equations are required in order to solve the differentiated cost equation called constraint equations.

2. **Individual approach:**

- The cost of each device is minimized, thereby minimizing the total cost of the entire system.
- The advantage of this method is that the equations to solve are simplified.

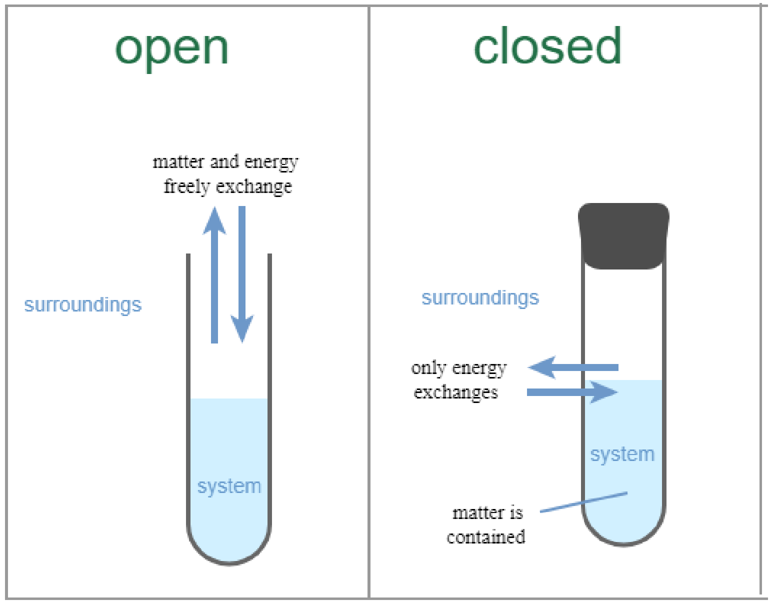
Fluid Flow Analysis

- In analysing a fluid motion, we might take one of the two paths:
- Differential approach:

  Describing fluid flow velocity, pressure, etc. at each and every point in the field (or control volume)
- Integral approach:

  Determining gross flow effects such as force on a body, pressure difference between inlet and outlet, etc.

- **Closed system** is defined as arbitrary quantity of mass of fixed identity.
- If the closed system has mass transactions with its surroundings then it is called **open system** or **control volume**.



- All the laws of physics are written for a closed system.

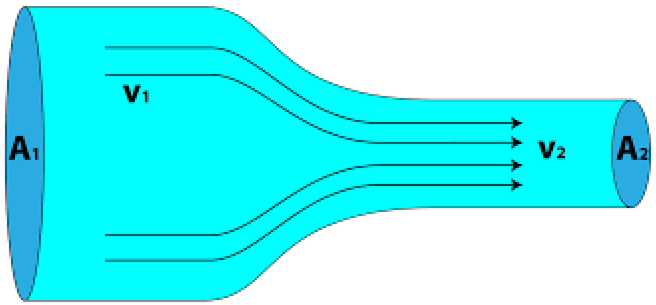
  ex: conservation of momentum-Newtons second law F=ma.
- To solve a fluid mechanics problem, we need to convert the equations to be applicable for open system.
- This conversion is done using Reynolds Transport Theorem.

Integral approach equations

- Conservation of mass

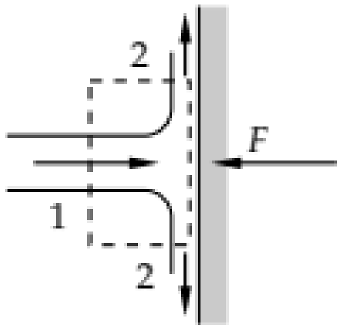
  (equation of continuity)

  $$A_1 V_1 = A_2 V_2$$



- Conservation of momentum

  $$\sum F = \dot{m}(V_{out} - V_{in})$$



- The Bernoulli equation

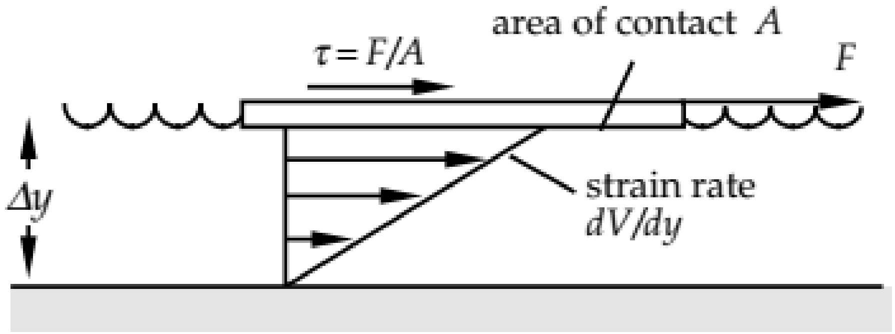
The Bernoulli Equation relates velocity, elevation, and pressure in a flow field.

$$\frac{P}{\rho g} + \frac{V^2}{2g} + z = const$$

Assumptions: Along a stream line, no friction, no heat transfer, no work transfer

- Viscosity (μ)

The viscosity of a fluid is a measure of the fluid's resistance to motion under the action of an applied shear stress.

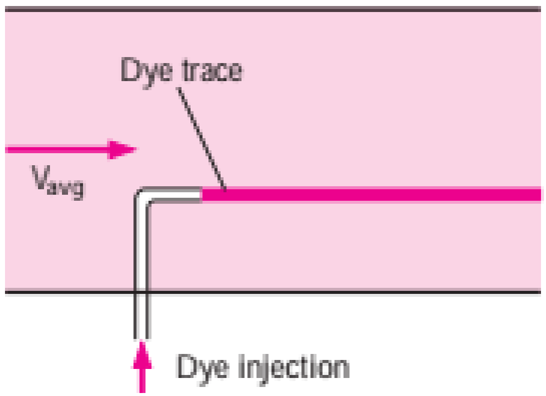


- For a Newtonian fluid

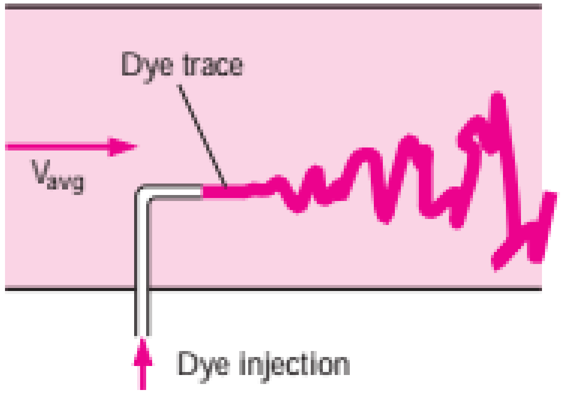
$$\tau = \mu \frac{dV}{dy}$$

Design of piping systems

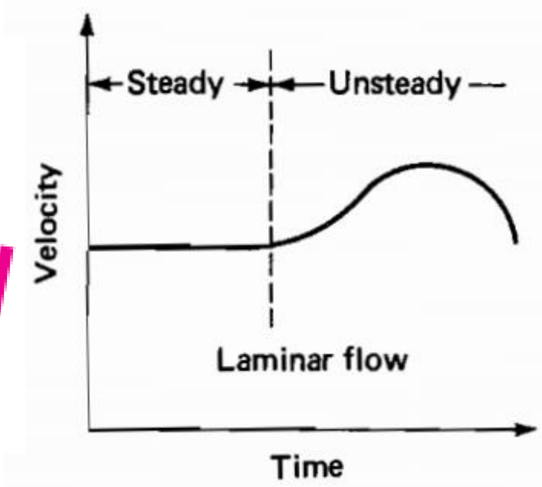
- Flow in closed conduits is an extremely important area of study because it is the most common way of transporting liquids.
- Flow in a duct can be either laminar or turbulent.
- When laminar flow exists, the fluid flows smoothly through the duct in layers called *laminae*



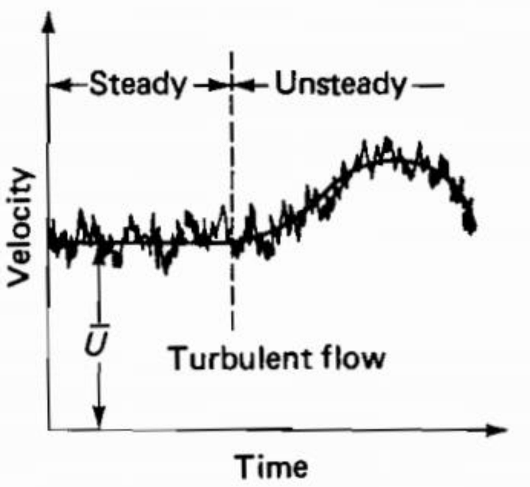
Laminar flow



Turbulent flow



Laminar flow



Turbulent flow

- The criterion for distinguishing between laminar and turbulent flow is the observed mixing action.

- Reynolds Number $Re = \frac{\rho V D}{\mu}$

For circular pipes

Re< 2000, laminar flow

Re=2000 to 4000, transition flow

Re>4000, turbulent flow

- V is the average flow velocity and D is the characteristic dimension

- For circular ducts, *D* is usually taken to be the inside diameter.
- For noncircular cross sections, *D* is usually taken to be the *hydraulic diameter* D_h

$$D_h = \frac{4 \cdot \text{area of flow}}{\text{wetted perimeter}} = \frac{4A}{P}$$

- For a rectangular duct of dimensions h x w

$$D_h = \frac{4hw}{2h + 2w} = \frac{2hw}{h + w}$$

Energy loss in pipes (Pressure drop)

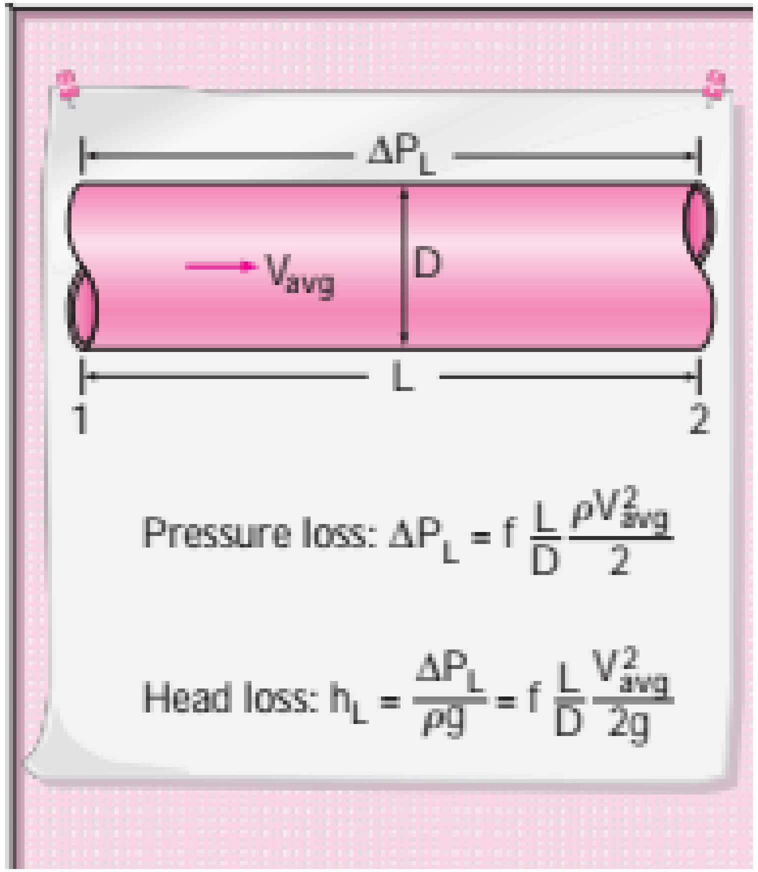
- A quantity of interest in the analysis of pipe flow is the *pressure drop* (ΔP)

$$\left(\frac{P}{\rho g} + \frac{V^2}{2g} + z\right)_1 = \left(\frac{P}{\rho g} + \frac{V^2}{2g} + z\right)_2 + h_L$$

- The pressure drop relation shown is valid for laminar or turbulent flows, circular or noncircular pipes, and pipes with smooth or rough surfaces

$$f = \frac{8\tau_w}{\rho V_{avg}^2}$$

- 'f' is the Darcy friction factor



Laminar flow

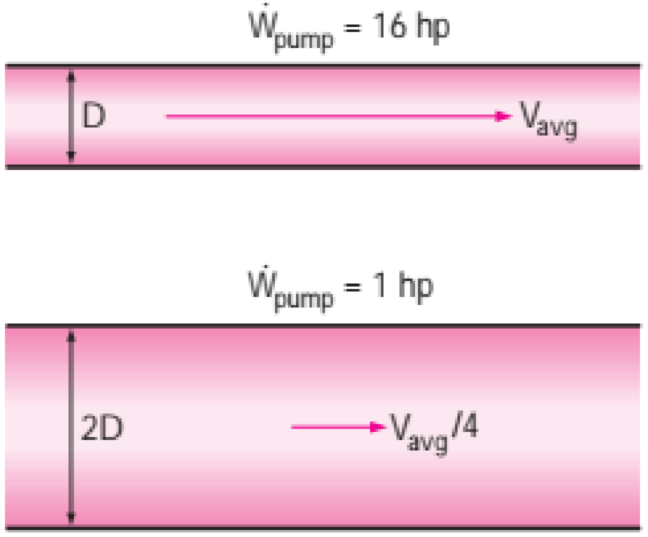
- For laminar flow $f = \frac{64}{Re}$
- Once the pressure loss (or head loss) is known, the required pumping power *to overcome the pressure loss* is determined from

$$\dot{W}_{pump, L} = \dot{V}\,\Delta P_L = \dot{V}\rho g h_L = \dot{m} g h_L$$

$\dot{V}$ is the volume flow rate and $\dot{m}$ is the mass flow rate.

- The volume flow rate for laminar flow through a horizontal pipe of diameter *D* and length *L* is

$$\dot{V} = \frac{\Delta P \pi D^4}{128 \mu L}$$



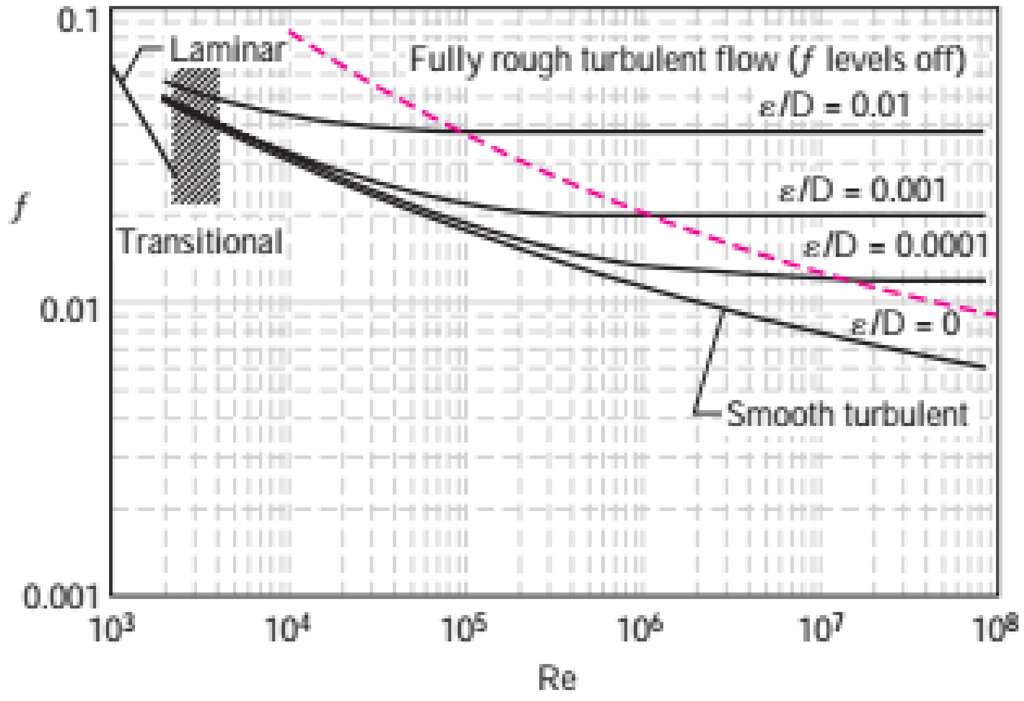
The pumping power requirement for a laminar flow piping system can be reduced by a factor of 16 by doubling the pipe diameter.

Turbulent flow

- The friction factor ‘f’ in fully developed turbulent pipe flow depends on the Reynolds number and the relative roughness ε/D
- The functional form of this dependence cannot be obtained from a theoretical analysis, and all available results are obtained from painstaking experiments

- Colebrook equation: $$\frac{1}{\sqrt{f}} = -2.0 \log\left(\frac{\varepsilon/D}{3.7} + \frac{2.51}{Re\sqrt{f}}\right)$$

Note: The equation need not be memorized



The Moody chart

- A steel pipe with inner diameter 10.23 cm conveys castor oil at a flow rate of Q= 0.01 m^3/s. The pipe is 250 m long. Determine the pressure drop experienced by the fluid.

castor oil $\rho = 960\ kg/m^3$ $\mu = 650 \times 10^{-3}\ N{\cdot}s/m^2$

Sol:

Let section 1 be pipe inlet and 2 be outlet

$$\left(\frac{P}{\rho g}+\frac{V^2}{2g}+z\right)1=\left(\frac{P}{\rho g}+\frac{V^2}{2g}+z\right)2+\frac{fLV^2}{2gD}$$

V_1 will be equal to V_2 (since A_1 equal to A_2)

Assuming horizontal pipe, $Z_1 = Z_2$

$$\Rightarrow \frac{P_1}{\rho g} - \frac{P_2}{\rho g} = \frac{f L V^2}{2 g D} \quad - (1)$$

find V: $V = \frac{Q}{A} = \frac{0.01}{\frac{\pi}{4} \times 10.23^2 \times 10^{-4}} = 1.22 \text{ m/s}$

verify Re: $Re = \frac{\rho v D}{\mu}$

$$= \frac{960 \times 1.22 \times 0.1023}{650 \times 10^{-3}}$$

$$= 184 < 2000$$

$\therefore$ Flow is Laminar

$\therefore f = \frac{64}{Re} = 0.348$

Substituting the values in Eqn (1)

$$P_1 - P_2 = \frac{f L \rho v^2}{2D} = \frac{0.348 \times 250 \times 960 \times 1.22^2}{2 \times 0.1023}$$

$$= 608 \text{ kPa}$$

- Chloroform flows at a rate of Q= 0.01m^3/s through a wrought iron pipe of 10.23 cm inner diameter. Calculate the pressure drop if the pipe length is 250 m.

  ρ= 1470 kg/m^3 μ=0.53 x 10^{-3} Ns/m^2

  wrought iron ε= 0.0046 cm

sol:

Let section 1 be pipe inlet and 2 be outlet

$$\left(\frac{P}{\rho g}+\frac{V^2}{2g}+z\right)1=\left(\frac{P}{\rho g}+\frac{V^2}{2g}+z\right)2+\frac{fLV^2}{2gD}$$

V_1 will be equal to V_2 (since A_1 equal to A_2)

$$\frac{P_1 - P_2}{\rho g} = \frac{fLV^2}{2gD} \quad \text{—} \ (1)$$

Avg vel: $V = \frac{Q}{A} = \frac{0.01}{82.19 \times 10^{-4}} = 1.22 \text{ m/s}$

$$Re = \frac{\rho V D}{\mu} = \frac{1470 \times 1.22 \times 0.1023}{0.53 \times 10^{-3}} = 3.46 \times 10^{5}$$

Flow is turbulent

$$\frac{\varepsilon}{D} = \frac{0.0046}{10.23} = 0.00045$$

from Moody chart $f\left(Re, \frac{\varepsilon}{D}\right) = 0.018$

Substituting in (1)

$$P_1 - P_2 = \frac{fL\rho V^2}{2D} = \frac{0.018 \times 250 \times 1470 \times 1.22^2}{2 \times 0.1023}$$

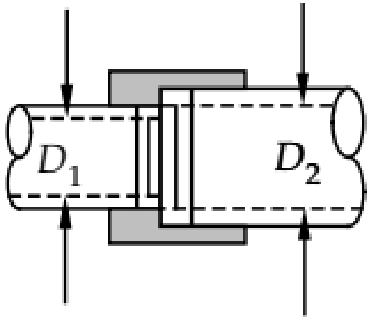
$$= 48.1 \text{ kPa}$$

observe that pressure drop is less in turbulent flow.

Minor losses

- The term **minor losses** refers to pressure losses encountered by a fluid as it flows through a fitting or a valve in a piping system.
- Fittings and valves are used to direct the flow, to connect conduits together, to re-route the fluid, and to control the flow rate.
- We treat this loss mathematically by assigning to each fitting a loss factor *K*. The pressure loss is then expressed as a multiple of the kinetic energy of the flow:

$$P_1 - P_2 = \sum K \frac{V^2}{2g}$$



Sudden expansion

$$K = ((D_2/D_1)^2 - 1)^2$$
$$1 < D_2/D_1 < 5$$

- The Bernoulli equation when written to include the effects of friction (major loss) and of minor losses becomes

$$\left(\frac{P}{\rho g} + \frac{V^2}{2g} + z\right)1 = \left(\frac{P}{\rho g} + \frac{V^2}{2g} + z\right)_2 + \frac{fLV^2}{2gD} + \sum K \frac{V^2}{2g}$$

Economic Pipe Diameter

- In a real design problem, many of the value of the variables $(\rho, Q, D, \Delta P, L, \varepsilon, \mu)$ are usually not known.
- On the one hand, the larger the pipe diameter, the greater the initial cost .
- On the other hand, fluid flowing through a small diameter pipe undergoes large friction loss and thus a larger pump is required. A larger pump means greater initial and operating costs.
- There exists a diameter that minimizes the total cost (initial + operating costs) of the pump, the pipe, and the fittings.
- This diameter is called the **optimum economic diameter** D_{opt}.

Least annual cost method

- Formulate an equation for the initial and operating costs of the pipe, fittings, installation, and pump, and express the result on a cost per-year basis.
- Next we differentiate the expression with respect to diameter to obtain the desired result—minimum cost.
- The initial cost of an entire system must first be converted to an equivalent annual cost.

Initial cost- Annualized

- The initial cost C_I of a piping system (or any system) can be converted to an annual cost C_A with the following equation:

$$C_A = aC_I = \frac{iC_I}{1 - \left[\frac{1}{1+i}\right]^m}$$

Where i is annual interest rate

Number of yearly payments=m

a is called amortization rate

- The pipe cost (C_P) in monetary units (MU) per length, ex: Rs/m

$$C_P = C_1 D^n$$

C_1 is the cost of a reference size and n is the (dimensionless) exponent.

- C_F is the cost of fittings, pump(s), valves etc.

$$C_F = F C_P = F C_1 D^n$$

F is a multiplying factor (approx 5 to 7 typically)

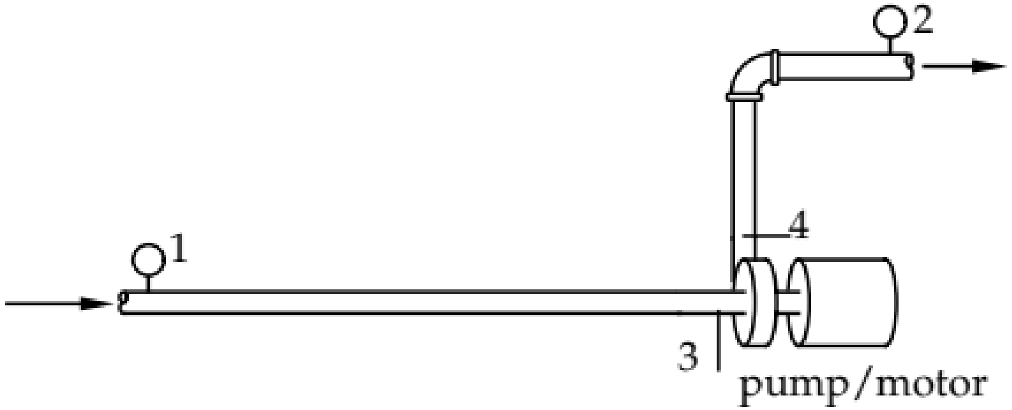
- The total cost C_{PF}

$$C_{PF} = C_P + C_F = C_1 D^n + F C_1 D^n = (1 + F) C_1 D^n$$

- Similarly, the maintenance cost of the installed system can be added

Operation cost- Annualized

- Consider a general piping system
- The pumping power required to
  Pump the fluid is estimated by using
  Bernouli equation



Section 1-3

$$\frac{p_1}{\rho g} + \frac{V_1^2}{2g} + z_1 = \frac{p_3}{\rho g} + \frac{V_3^2}{2g} + z_3 + \frac{fL}{D}\frac{V^2}{2g} + \Sigma K \frac{V^2}{2g}$$

Section 3-4

$$\frac{p_3}{\rho g} + \frac{V_3^2}{2g} + z_3 = \frac{p_4}{\rho g} + \frac{V_4^2}{2g} + z_4 + \frac{1}{\dot{m}\, g}\frac{dW}{dt}$$

Section 4-2

$$\frac{p_4}{\rho g} + \frac{V_4^2}{2g} + z_4 = \frac{p_2}{\rho g} + \frac{V_2^2}{2g} + z_2 + \frac{fL}{D}\frac{V^2}{2g} + \Sigma K \frac{V^2}{2g}$$

- Head is defined as

$$H = \left(\frac{p}{\rho g} + \frac{V^2}{2g} + z\right)$$

- Solving for the power

$$\frac{dW}{dt} = -\dot{m}\left((H_2 - H_1)\,g + \frac{fL}{D}\frac{V^2}{2}\right)$$

- The cost of operating the pump on a yearly basis is given by

$$C_{OP} = \frac{C_2\, t(-dW/dt)}{\eta}$$

Where η is the efficiency of the pump

- Now the total cost= Initial cost annualized + operating cost annualized

$$C_T = (a + b)(1 + F)C_1 D^n L + \frac{\dot{m}C_2 t}{\eta}(H_2 - H_1)\frac{g}{g_c} + \frac{8fL\dot{m}^3}{\pi^2\rho^2 D^5 g_c}\frac{C_2 t}{\eta}$$

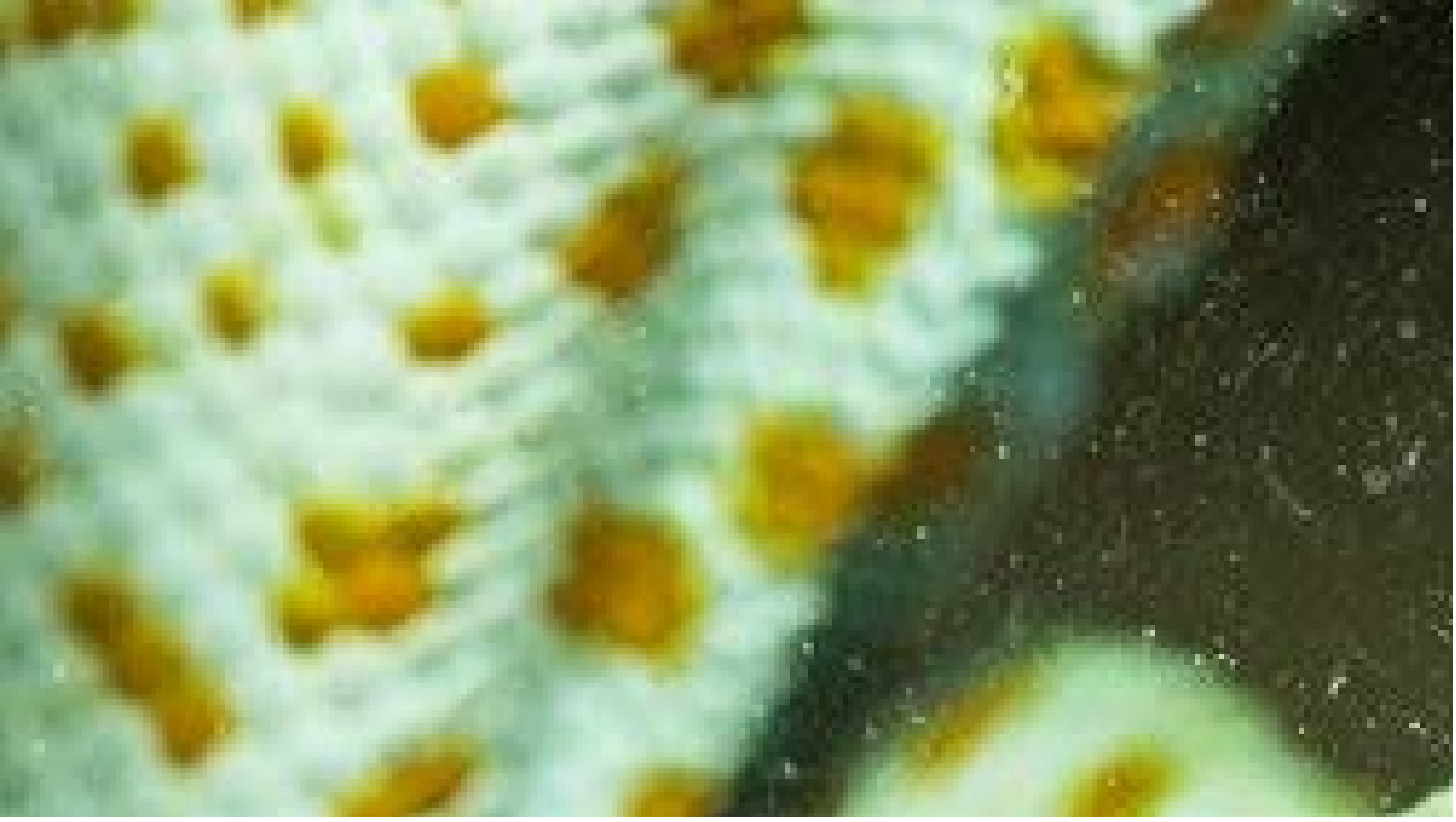
- The optimum economic diameter is the one that minimizes this equation for total cost.

$$\frac{\partial C_T}{\partial D} = 0$$

$$D_{\text{opt}} = \left[\frac{40f\dot{m}^3 C_2 t}{n(a + b)(1 + F)C_1 \eta \pi^2 \rho^2 g_c}\right]^{\frac{1}{n+5}}$$

Note: The equations need not be memorized by the student. Understanding of the basic principle is sufficient.

Symbol	Definition	Dimensions (Units)
D_{opt}	the optimum economic diameter	L (ft or m)
$\dot{m}$	mass flow rate	M / T
f	friction factor	—
C_2	cost of energy	MU/(F-L) [$/(kW·hr)]
t	time during which system operates per year	(hr/yr)
n	exponent of D in curve fit of pipe cost data	—
a	amortization rate	1/T (1/yr)
b	yearly maintenance cost fraction	1/T (1/yr)
F	multiplier of pipe cost representing cost of fittings, pump, installation, etc.	—
C_1	constant in curve fit of pipe cost data	MU/L^{n+1}
η	efficiency of pump	—
ρ	density of liquid	M/L^3 (lbm/ft^3 or kg/m^3)



Development of A

Definition and Te

- **Biomimetics:** *design and pr*
  modelled on biological enti

Why Biomimetics?

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Types

- *Forward biomimetics:* se
  might use it. (Velcro)
- *Reverse biomimetics:* Fin

Top-down

Reverse Biomimet

The ch
to biolo
Design

Levels of Biomim

- **Organism-level biomim**
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Attempts and

- The earliest recorded a

- Otto Lilienthal began to s
the aerodynamics of th
developed a glider in whi
body, much as hang glide
and tended to pitch dow

[redacted]

- Wright brothers realized
direction was inadequate
- They had spent a lot of ti
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Hook and loop fa

- Swiss engineer George de

HOOK

Few Simpl

Inspiration

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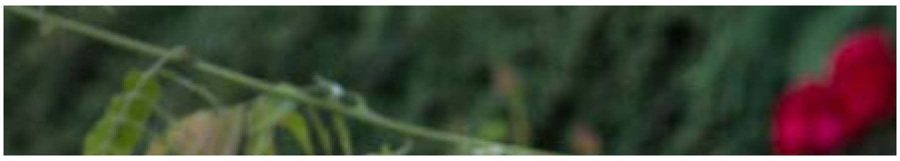

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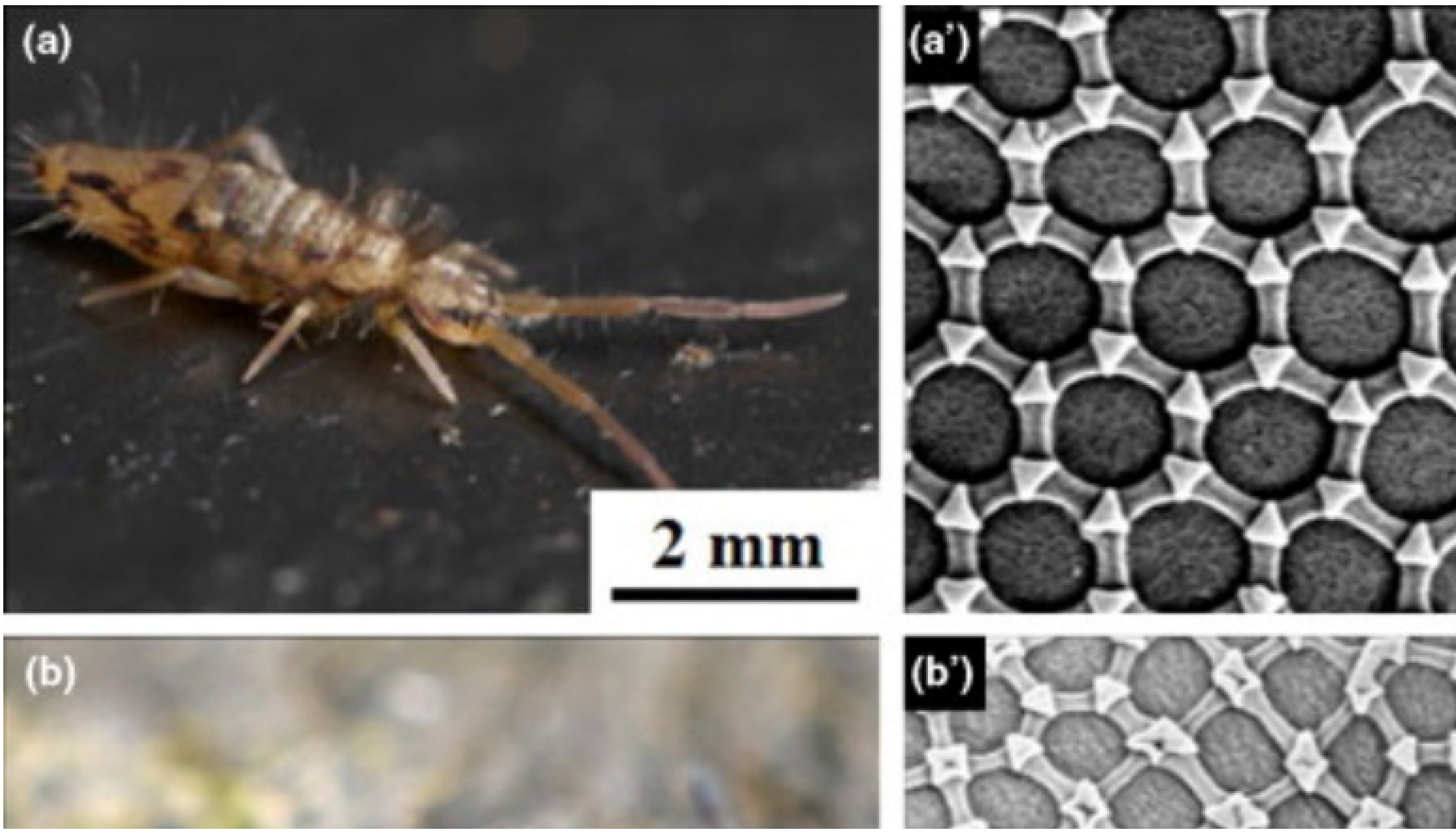
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(a')
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Moth-eye effe

Moth-eye effect is relatec
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- All anti-ice fluids off

Anti-icing tricks o

- Antarctic penguins live

Darkling beet

Ability of a desert beetle to
on its back using the **hydro**

Water strider

Water strider effect is relate
of insects to walk on w
capillary forces

Bioinspired Alg

- A genetic algorithm

Other exa

Case Study-1:

- Lotus-effect *surface*
- Rose-effect *surface*

Stratification c

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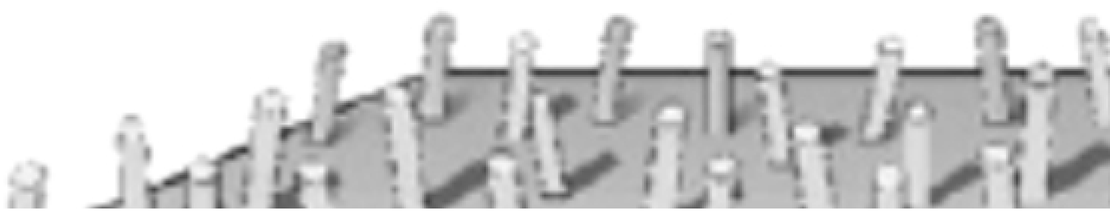

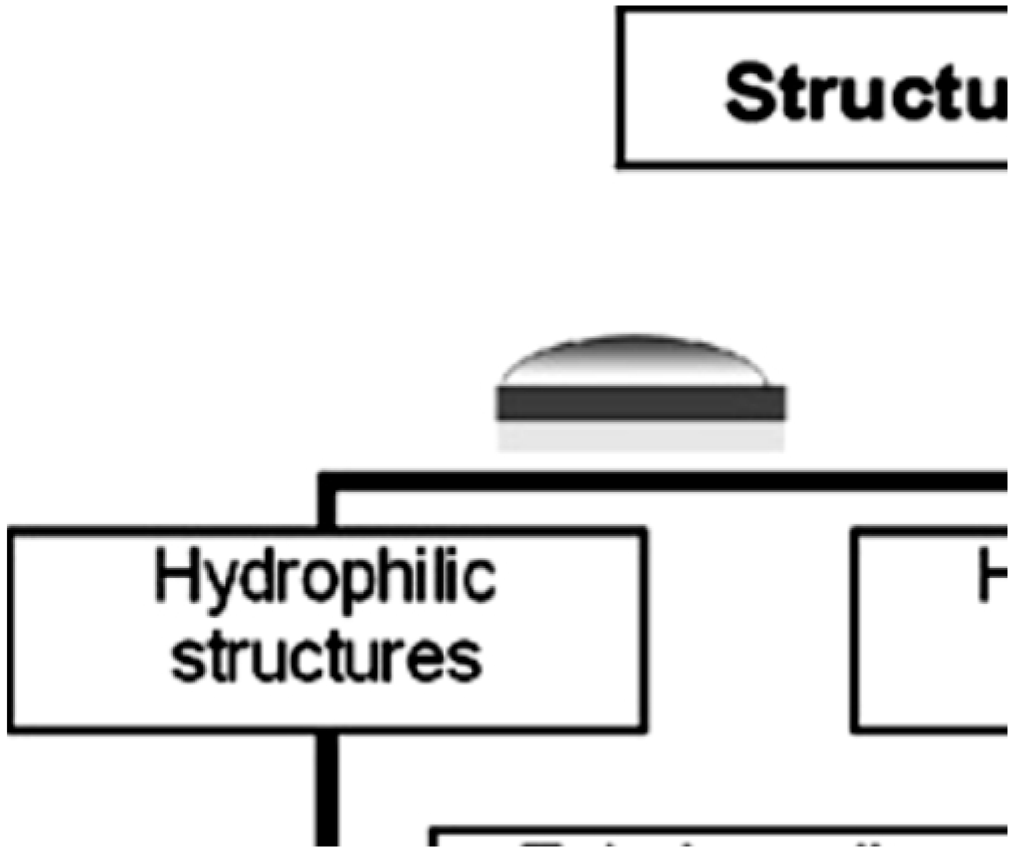
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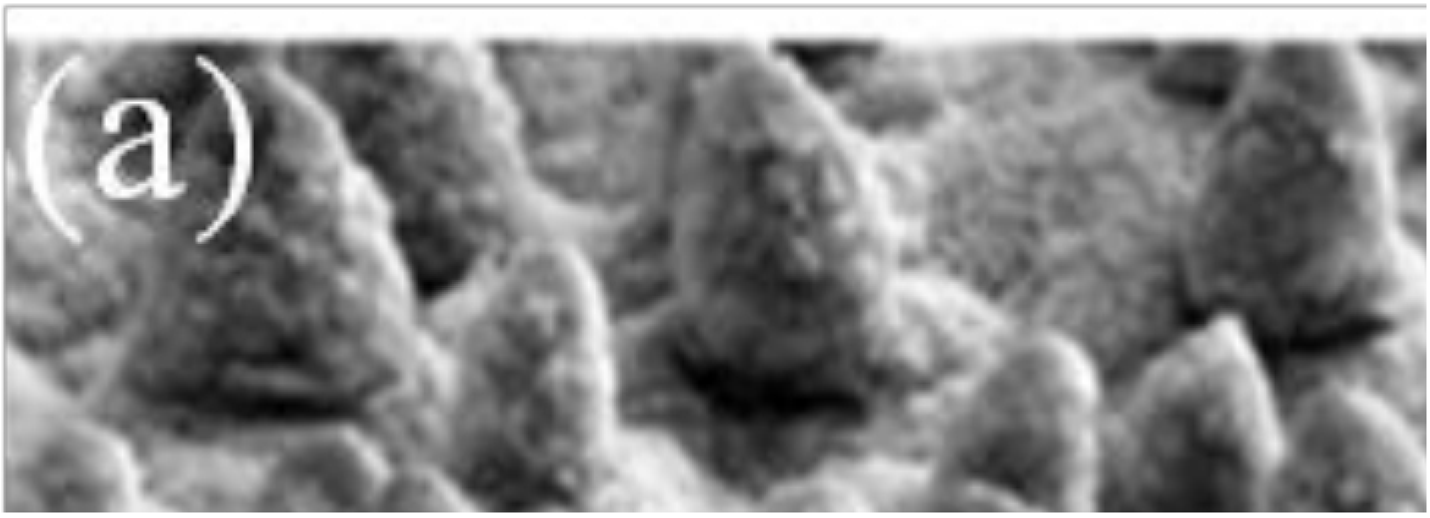
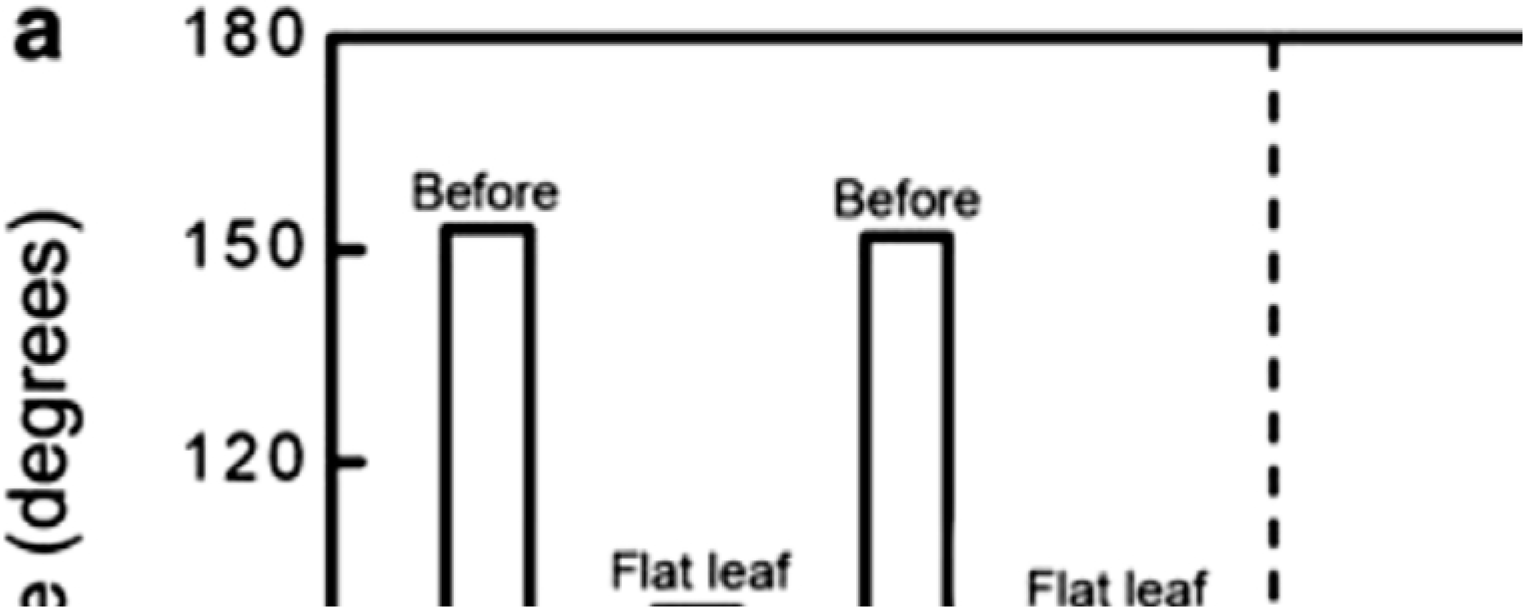
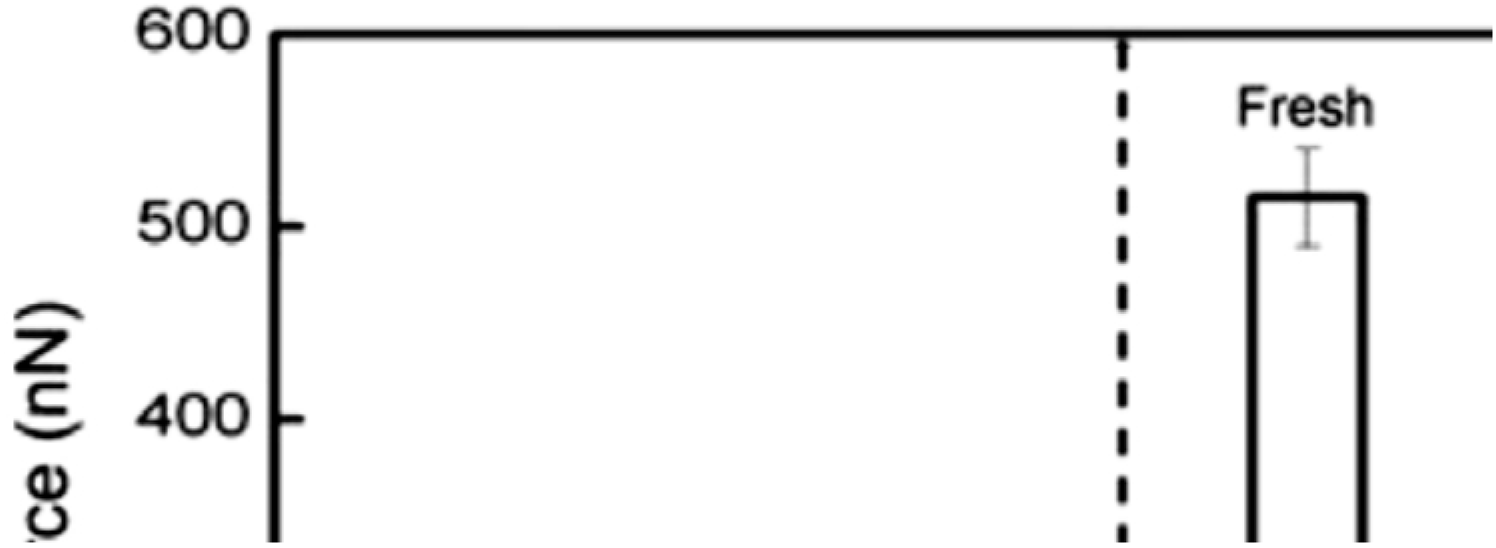


Contact angle for various leaves befor
surface layer and calculated valu



Adhesive force and coefficient of friction
and hydrophilic leaves using 15 μn



- **In case of fresh leaf, there i**
  be soft, and when the tip
  deform, and a larger real
  the adhesive force will incre
- **After the leaf has dried, the**

Rose Pe

a

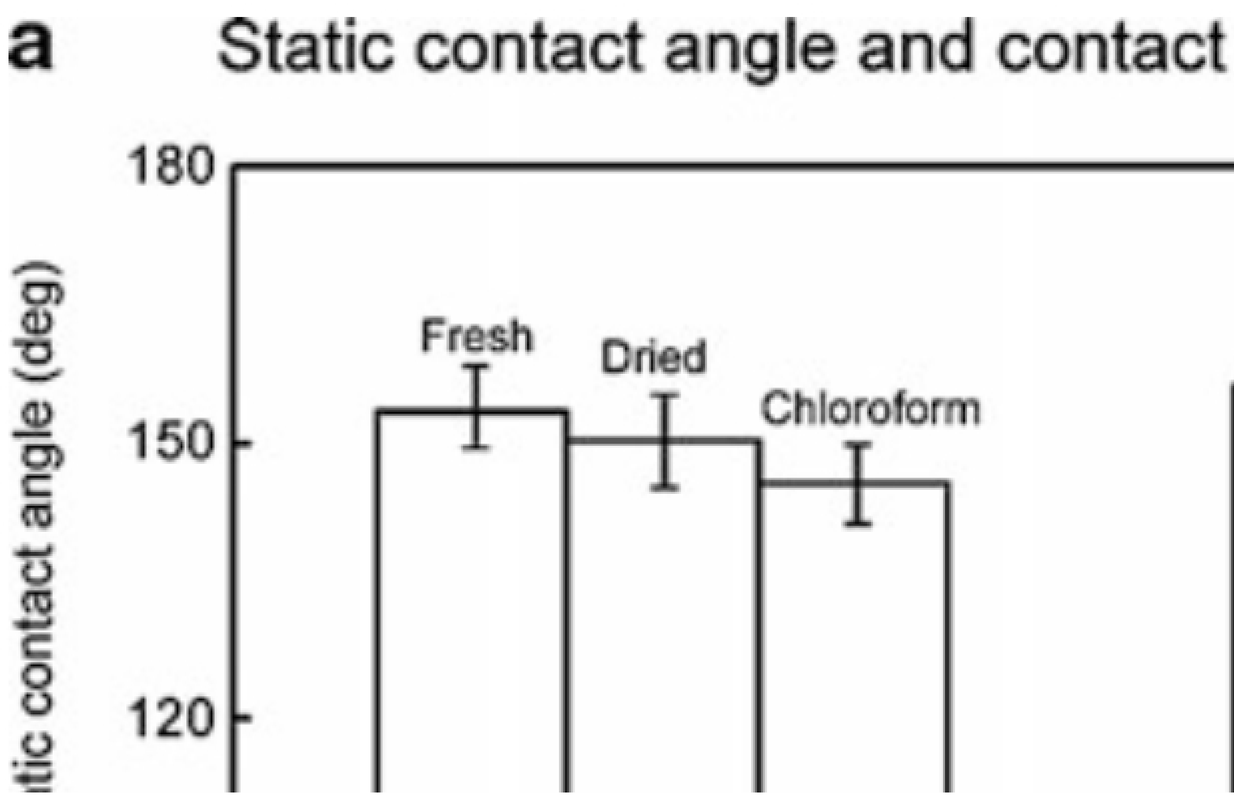
Roses with superhydrophobic

with high adhesion

wit

Microbump map statistics for rose peta

	Peak-to- height (
Rosa cv. Bairage (High adhesion)	6.8
Rosa cv. Showtime	8.4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- Little was underst
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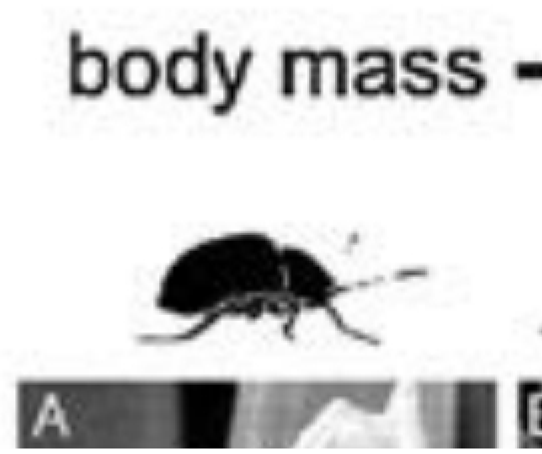
- Common man-made a
  of wet adhesives t
  surfaces

Hairy A

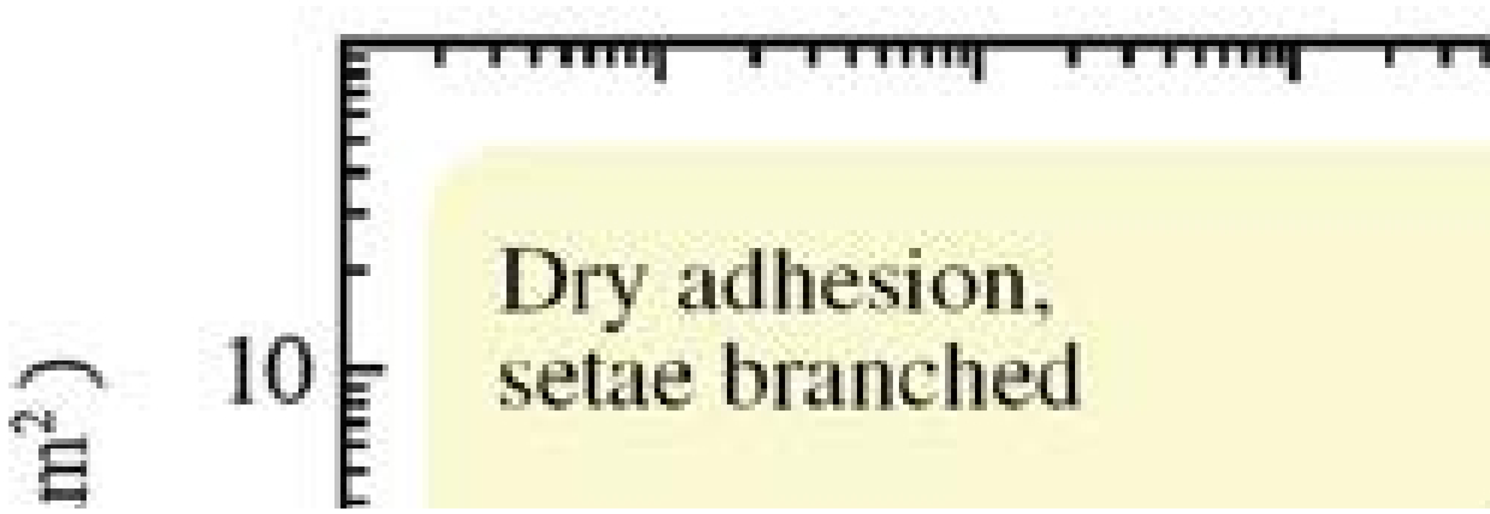
- There are commo
relatively smooth a

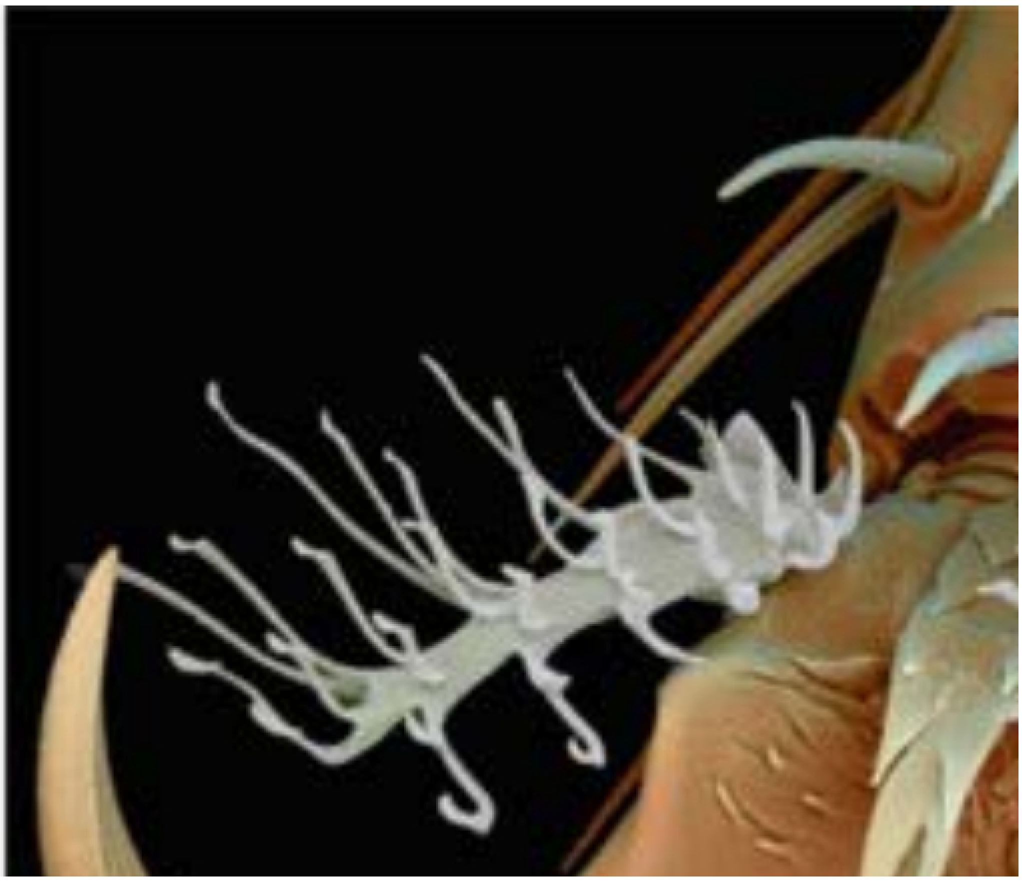
- **Tree frog toe attachme of a hexagonal array epidermal cells about separated by approxi wide mucus-filled chann**

- **Type 2: hairy types w are found in many lizards.**



$$\log \rho_A = 13.8$$





Tokay

Physical dimensions of f
measured adhesive forc
keratin = 1–20 GPa

Component	Size

- Soft Lamellae for c
- Setae extend fro
approximately 14,

Peeling at v

- Geckos are capable
- They retain the

Machine Design:

Machine design is defined as the use of scientific principles, technical information & imagination in the description of a machine or a mechanical system to perform specific functions with maximum economy & efficiency. Machine Design is defined as the creation of new design or improving the exist one.

Basic Procedure of MACHINE DESIGN

Market Survey

↓

Define Specification of Product

↓

Study alternative Mechanism for Product
Select Proper Mechanism

↓

Prepare General Layout of Configuration
and Select joining method of individual Product

↓

Design Individual Component

↓

Prepare Assembly and Detail Drawings and Modify Drawing
after Testing Prototype model

Step 1: Product Specifications

For example, while designing a scooter, the list of specifications will be as follows:

(i) Fuel consumption = 40 km/l
(ii) Maximum speed = 85 km/hr
(iii) Carrying capacity = two persons with 10 kg luggage
(iv) Overall dimensions
Width = 700 mm
Length = 1750 mm
Height = 1000 mm
(v) Weight = 95 kg
(vi) Cost = Rs 40000 to Rs 45000

Step 2: Selection of Mechanism

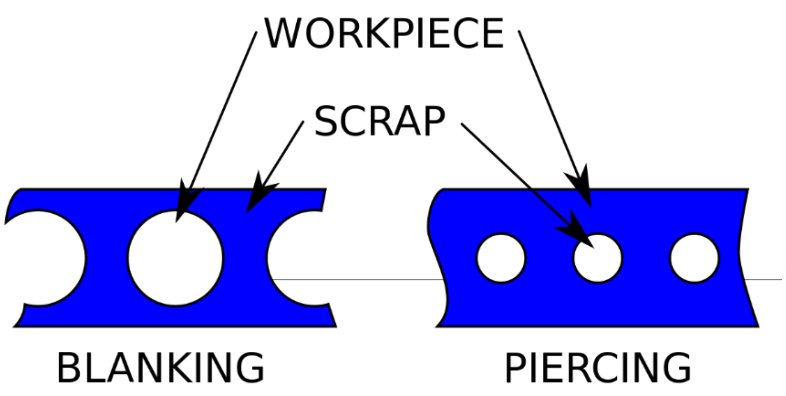
For example,

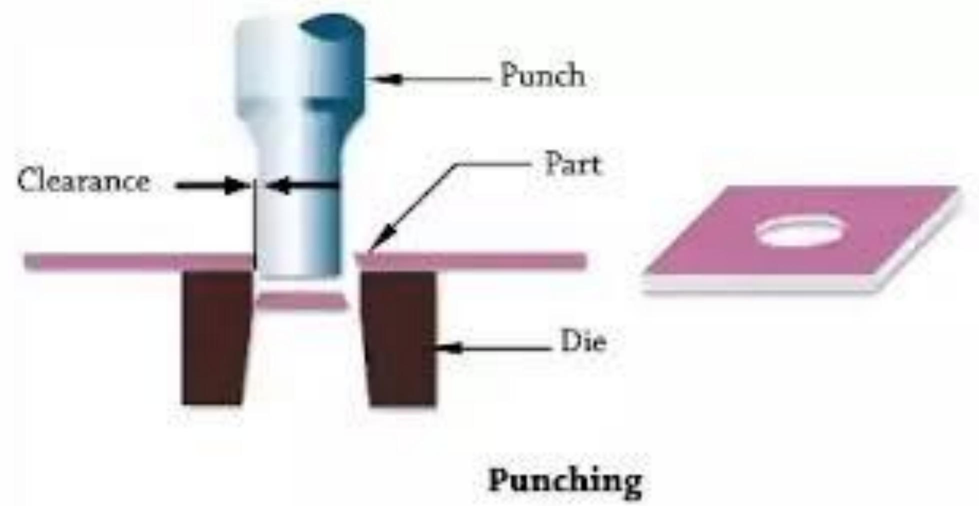
while designing a blanking or piercing press, the following mechanisms are possible:

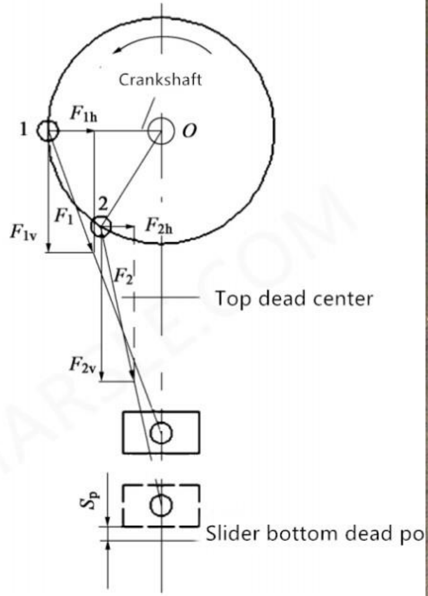
(i) a mechanism involving the crank and connecting rod, converting the rotary motion of the electric motor into the reciprocating motion of the punch;

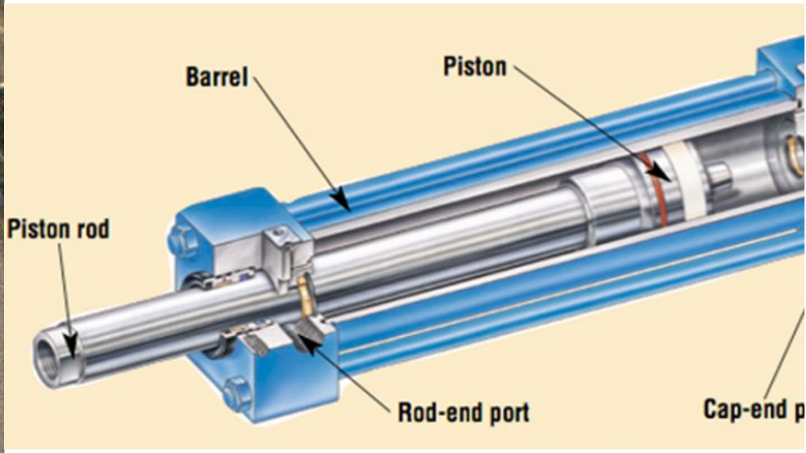
(ii) a mechanism involving nut and screw, which is a simple and cheap configuration but having poor efficiency; and

(iii) a mechanism consisting of a hydraulic cylinder, piston and valves which is a costly configuration but highly efficient.









Ref: Open sources

Step 3: Layout of Config

The next step in a design procedure is to
diagram showing the general layout of th
configuration.

For example, the layout of an Electrically-operated Overhead Travelling (EOT) crane will consist of the following components:

(i) electric motor for power supply;

(ii) flexible coupling to connect the motor shaft to the clutch shaft;

(iii) clutch to connect or disconnect the electric motor at the will of the operator;

(iv) gear box to reduce the speed from 1440 rpm to about 15 rpm;

(v) rope drum to convert the rotary motion of the shaft to the linear motion of the wire rope;

(vi) wire rope and pulley with the crane hook to attach the load; and

(vii) brake to stop the motion.

Step 4: Design of Individual Components

The design of individual components or machine elements is an important step in a design process. It consists of the following stages:

(i) Determine the forces acting on the component.

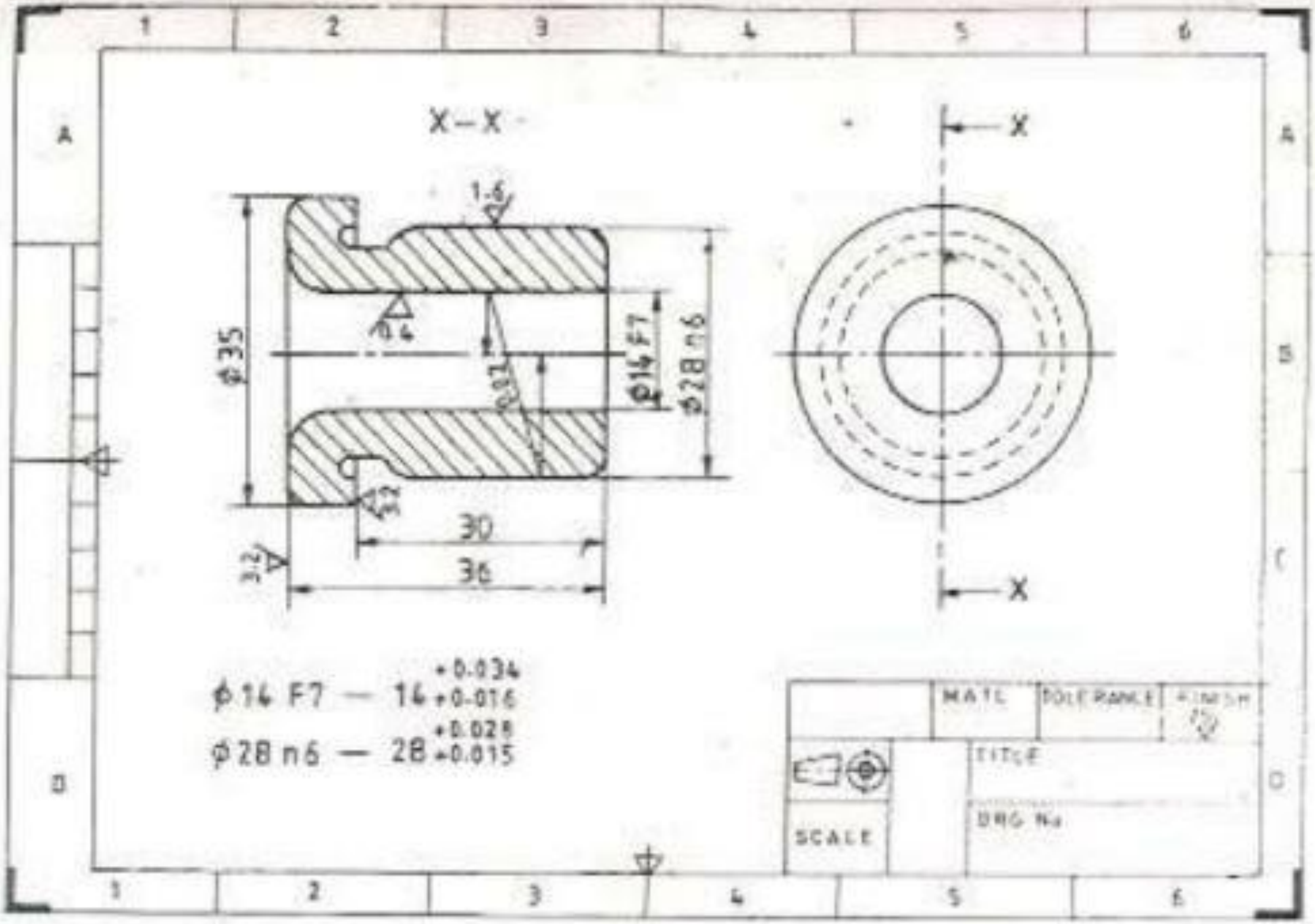
(ii) Select proper material for the component depending upon the functional requirements such as strength, rigidity, hardness and wear resistance.

(iii) Determine the likely mode of failure for the component and depending upon it, select the criterion of failure, such as yield strength ultimate tensile strength, endurance limit or permissible deflection.

(iv) Determine the geometric dimensions of the component using a suitable factor of safety and modify the dimensions from assembly and manufacturing considerations

Step 5: Preparation of Drawings

The last stage in a design process is to prepare drawings of the assembly and the individual components. On these drawings, the material of the component, its dimensions, tolerances, surface finish grades and machining symbols are specified. The designer prepares two separate lists of components—standard components to be purchased directly from the market and special components to be machined in the factory. In many cases, a prototype model is prepared for the product and thoroughly tested before finalising the assembly drawings.



Ref: Open sources

Basic Requirement of Machine Element

- Strength
- Rigidity
- Wear resistance
- Minimum Dimensions and Weight
- Manufacturability
- Safety
- Conformance to Standards
- Reliability
- Maintainability
- Minimum Life Cycle Cost

Example: Design of a chair

A number of factors need be considered first:

(a) The **purpose** for which the chair is to be designed such as whether it is to be used as an easy chair, an office chair or to accompany a dining table.

(b) Whether the chair is to be designed for a **grown up person or a child.**

(c) **Material** for the chair, its strength and cost need to be determined.

(d) Finally, the **aesthetics** of the designed chair.

Types of design

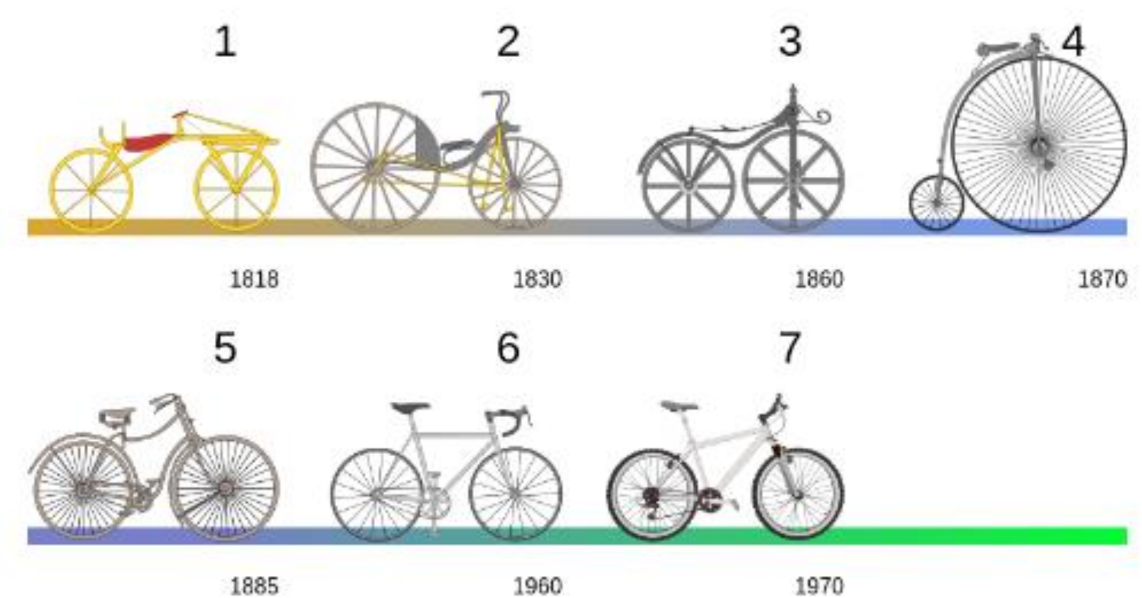
Adaptive design :

This is based on existing design, for example, standard products or systems adopted for a new application. Adaptive design is the process in which the parameters of the existing design or engineering device is slightly modified to improve quality or to suit a new trend in the market.

Ref: Open sources

It is normally a responsive design to consumer behavior. In this process, designer makes a minor modification in existing design or form new member without changing the existing structure of the product. The adaptive design does not require much knowledge or skill, it can be done by the designer of ordinary technical training. In great majority of instance, designer's job is to make an adaptive design.

Examples: Designing of the bicycle, mechanical watch etc.



Ref: Open sources

Developmental design:

Development design also starts from existing design to bring a new idea, though the final product may differ significantly/moderately from existing design. In development design, design engineer uses the working principle of one machine on another machine and bring an entirely new product which may possess good quality in working, size, etc. The adopting of new method of manufacturing, or adopting new engineering material are also a reason for development design. Development design demands considerable knowledge and design ability.

Examples:

Combining the principle of bicycle and internal combustion engine and develop the motorcycle.

New design:

This type of design is an entirely new one but based on existing scientific principles. No scientific invention is involved but requires creative thinking to solve a problem. Examples of this type of design may include designing a small vehicle for transportation of men and material on board a ship or in a desert. Some research activity may be necessary.

Examples:
Zipline

The California-based startup Zipline intends to use drones to save lives. The company uses its drones in remote areas across the world to deliver vital supplies and even the delivery of blood.

Their latest drone invention can carry up to almost **2 kilograms** at **128 kmph** for up to **160 kilometers** round trip.

Ref: Open sources

Solar Charged Jacket

Created by U.K.-based sports-gear startup, Vollebak, the Solar Charged Jacket phosphorescent membrane absorbs light during the day and releases its "kryptonite green energy" for those who need to be safe after dark.

Types of design based on methods

Rational design:

This type of design depends upon mathematical formulae of principle of Mechanics. This is based on determining the stresses and strains of components and thereby deciding their dimensions.

Examples:

Pressure Vessels

DESIGN SPECIFICATION
Design pressure = 700 psi
Design temperature = 700° F
Material:
Shell SA-516 Gr. 70
Head SA-181 Class 70
Nozzle SA-106 Gr. B
Weld efficiency factor = 1.0 = E
(full radiographic examination)
Shell Thickness

$$t_s = \frac{PR}{SE - 0.6P}$$
$$= \frac{700(30)}{16\,600(1.0) - 0.6(700)}$$
$$= 1.30 \text{ in.} \quad \textit{Use } 1\tfrac{1}{2}'' = T_s$$

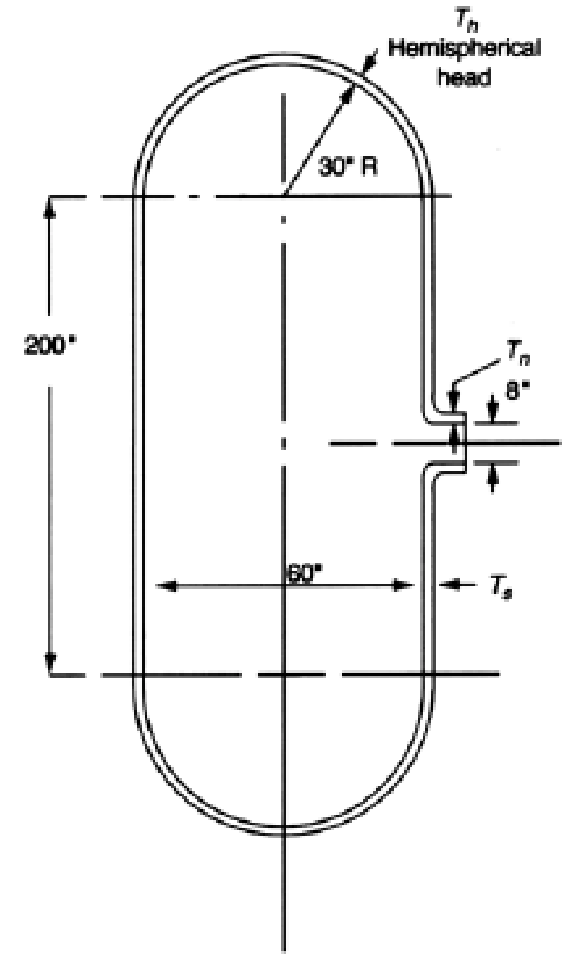
P = 700 psi
R = 30 in.
E = 1.0
S = 16 600 psi (SA-516 Gr. 70, Table 9.2)

Hemispherical Head Thickness

$$t_h = \frac{PR}{2SE - 0.2P}$$
$$= \frac{700(30)}{2(16\,600)(1.0) - 0.2(200)}$$
$$= 0.64 \text{ in.} \quad \textit{Use } 1'' = T_h$$

Nozzle Thickness

$$t_n = \frac{PR}{SE - 0.6P}$$



Empirical design:

This is based on empirical formulae which in turn is based on experience and experiments. For example, when we tighten a nut on a bolt the force exerted or the stresses induced cannot be determined exactly but experience shows that the tightening force may be given by P=284d where, d is the bolt diameter in mm and P is the applied force in kg. There is no mathematical backing of this equation but it is based on observations and experience.

Example

Empirical equations and models for estimating time of concentration (Tc) in hours (h)

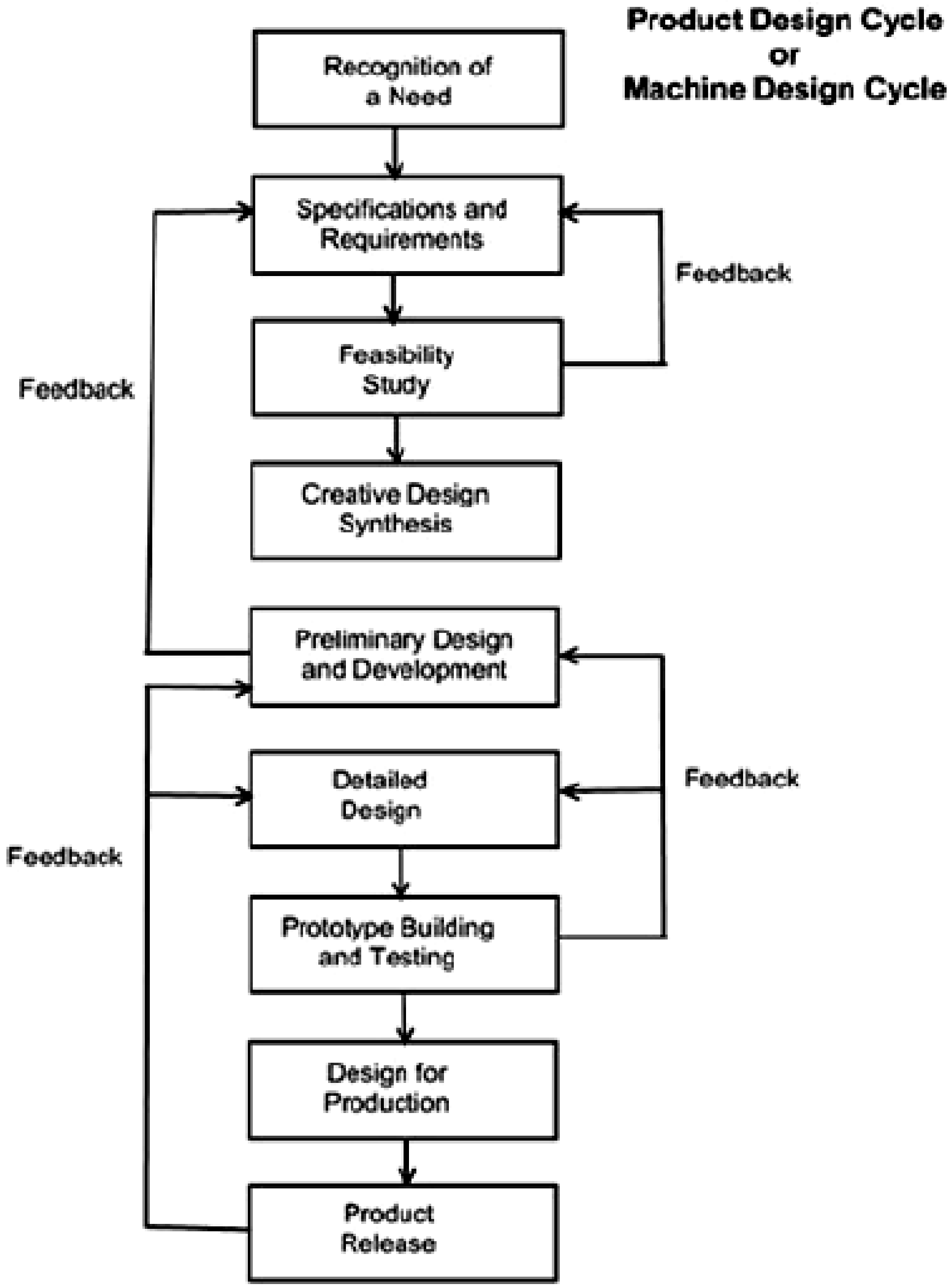
Author	Equation
Williams (1922)	$T_c = 0.272 \cdot \frac{L_c A^{0.4}}{(D \cdot S_c^{0.2})}$
Kirpich (1940)	$T_c = 0.066 \cdot \left(\frac{L_c}{\sqrt{S_c}}\right)^{0.77}$
Chow (1962)	$T_c = 0.000003035 \cdot \left(\frac{L_c}{\sqrt{S_c}}\right)^{0.64}$
Kennedy and Watt (1967)	$T_c = 0.397 \cdot \left(\frac{L_c}{\sqrt{S_c}}\right)^{0.75} ST^{1.3}$
Watt and Chow (1985)	$T_c = 0.0014 \cdot \left(\frac{L_c}{\sqrt{S_c}}\right)^{0.79}$
NRCS Velocity Method (1986)	$T_c = T_{sheet} + T_{shallow} + T_{channel}$; $T_{sheet} = \frac{0.0018 {L_{sheet}}^{0.6} \cdot n^{0.6}}{i^{0.4} \cdot S_w^{0.3}}$; $T_{shallow} = \frac{L_{shallow}}{3.6C\sqrt{S_w}}$; $T_{channel} = \frac{0.44 \cdot L_c \cdot n^{0.75}}{i^{0.25} A^{0.125} \cdot S_c^{0.375}}$
Haktanir and Sezen (1990)	$T_c = 0.734 \cdot L_c^{0.841}$
Arizona DOT (1993)	$T_c = 0.00031 \cdot A^{0.1} L^{0.25} L_{ca}^{0.25} S_w^{-0.2}$
Sharifi and Razaz (2014)	$T_c = 0.39\sqrt{A} + DD^2$

Industrial design :

These are based on industrial considerations and norms viz. market survey, external look, production facilities, low cost, use of existing standard products.

Feasibility Study:

- **Technical Feasibility (Technology and system feasibility)**
- **Financial/Economic feasibility**
- **Social and Environmental Feasibility**
  - **Legal feasibility**
  - **Operational feasibility**
  - **Schedule feasibility**



Product Design Cycle
or
Machine Design Cycle
Recognition of a Need
Specifications and Requirements
Feasibility Study
Creative Design Synthesis
Preliminary Design and Development
Detailed Design
Prototype Building and Testing
Design for Production
Product Release
Feedback
Feedback
Feedback
Feedback

Thanks

INTRODUCTION TO OPTIMIZATION

Dr. Divya Shrivastava

INTRODUCTION

Suppose you have a great idea for a new product. Even better, suppose people wanted to buy it.

First, congratulation!

INTRODUCTION

Second??????????

How you are going to make it?

How many workers will you need?

How many items they can produce?

What kind of system will help them to make more?

What kind of resources will they need to make it?

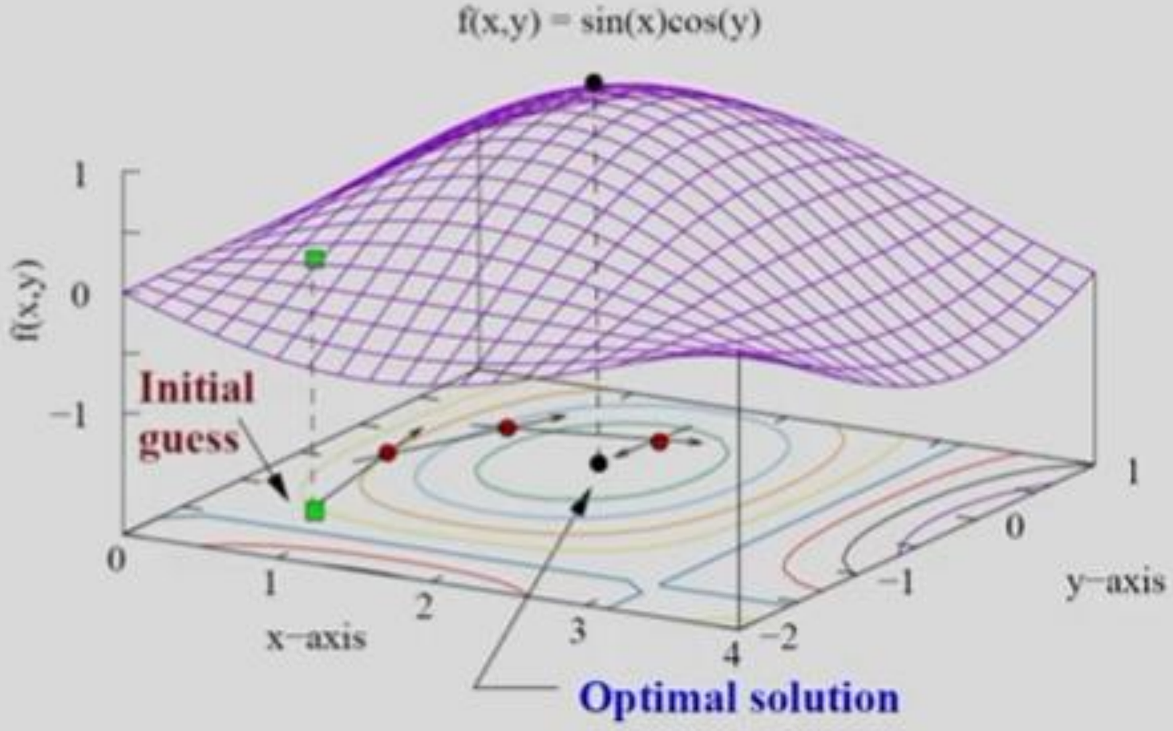
How much should you keep on hand?

SEARCH AND OPTIMIZATION

Definition: A task of searching for a set of decision variables which would minimize or maximize objective function subjected to satisfying constraints.

Maximize: $f(x, y)$

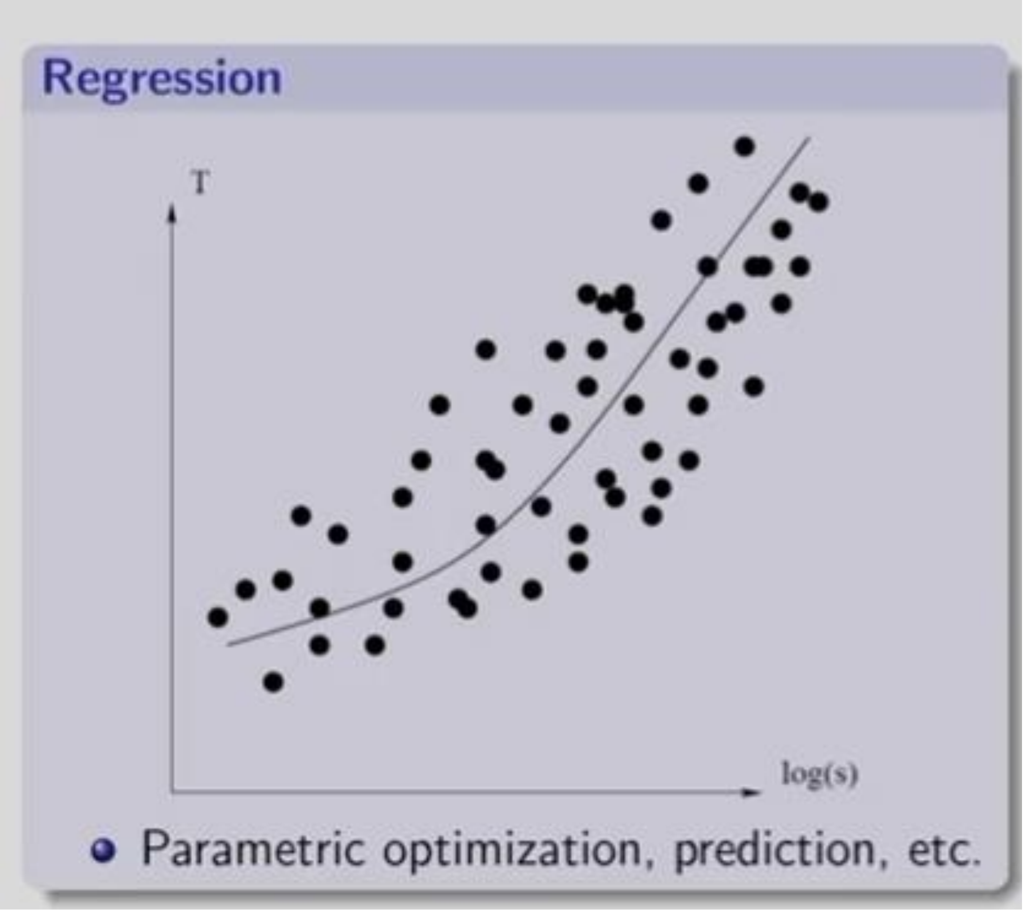
- Decision variables: (x, y)
- Objective function: $f(x, y)$

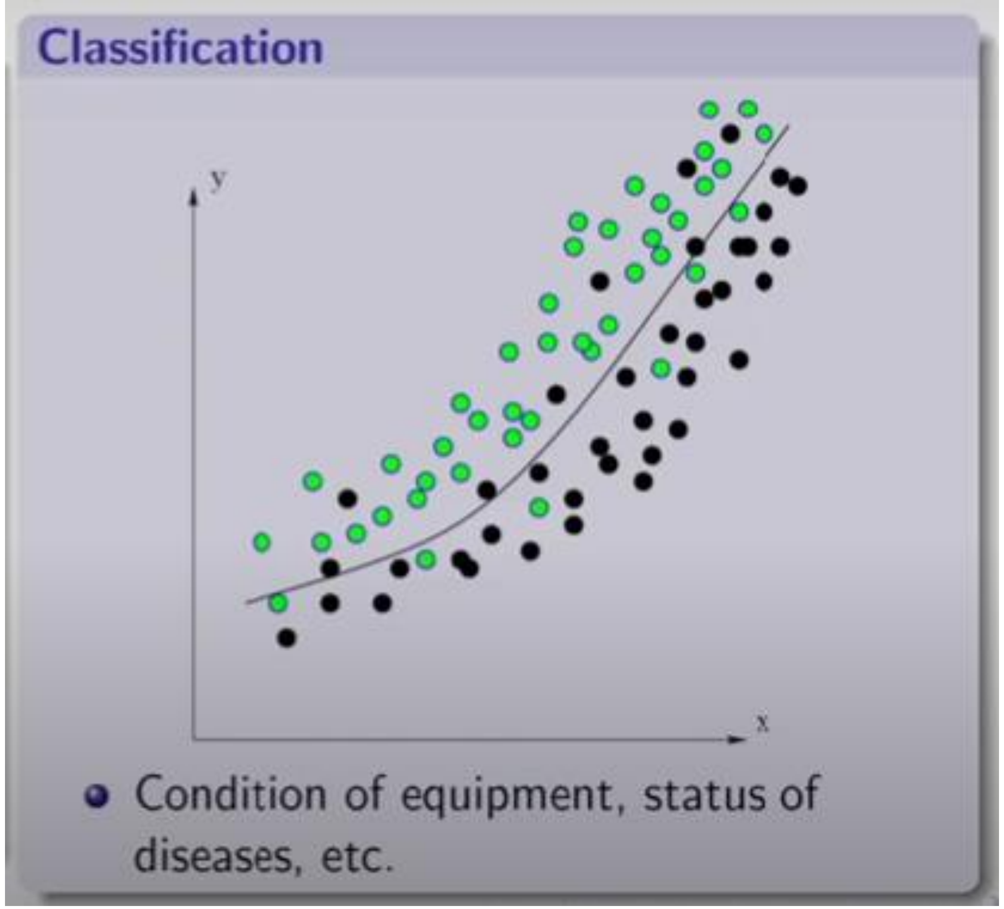


APPLICATION AREA

- Automotive Design: Best combination of material with best engineering to provide faster, lighter, more fuel efficient and safer vehicle.
- Engineering Design: To optimize the structural and operational design of building, factories, machines, designof heat exchanger, robot gripping arm, satellite booms etc.
- Robotics: Intelligence and learning in robotics like robot path planning, robot vision, robot speech, robot behaviour etc.
- Evolvable Hardware Design: Electronic circuit design optimization.
- Travelling Salesman Problem: Optimize the shortest route for the salesman
- Telecommunication Routing Problem: optimizing project cost for dynamic and anticipatory routing of circuits for telecommunication networks.

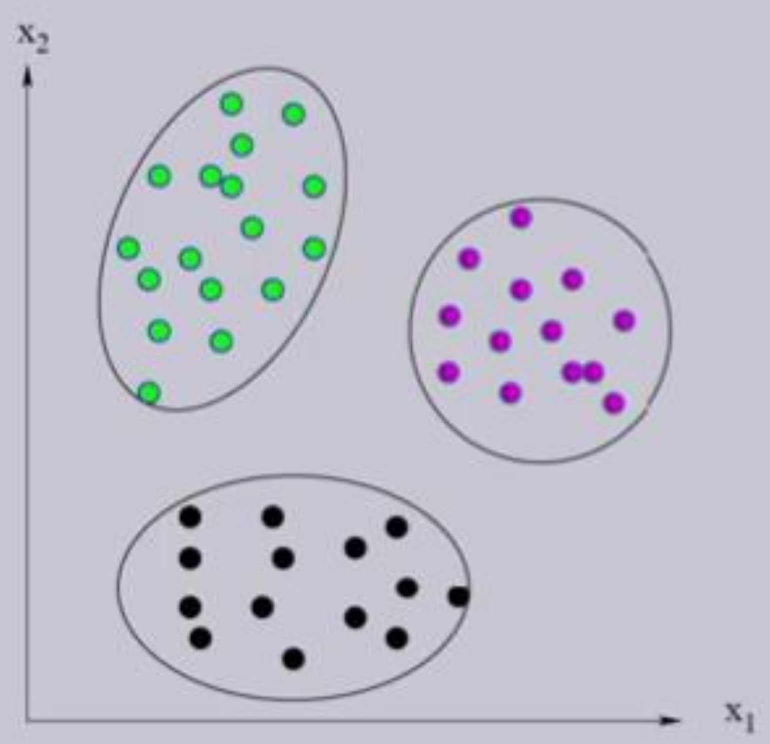
DATA MINING


Regression
T
log(s)
Parametric optimization, prediction, etc.


Classification
y
x
Condition of equipment, status of diseases, etc.

DATA MINING

Clustering



- Pattern recognition, image processing, etc.

OTHER APPLICATION AREA

Computer architecture

Bioinformatics

Quality control

Production scheduling

Flexible manufacturing systems

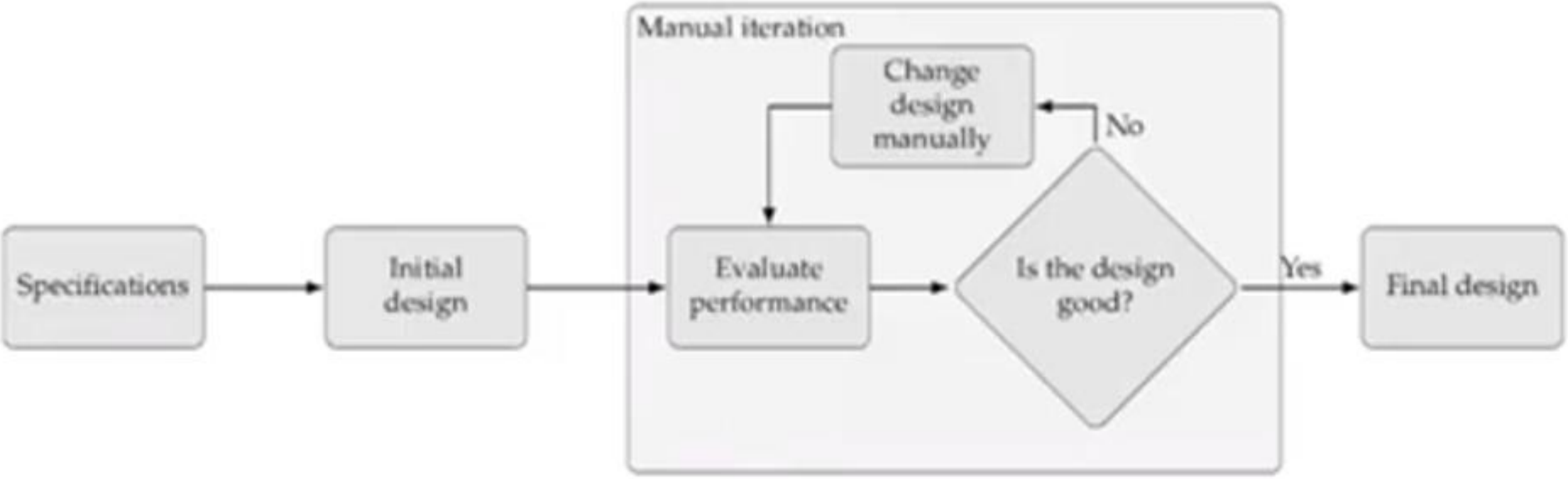
Game Theory

Queuing Theory

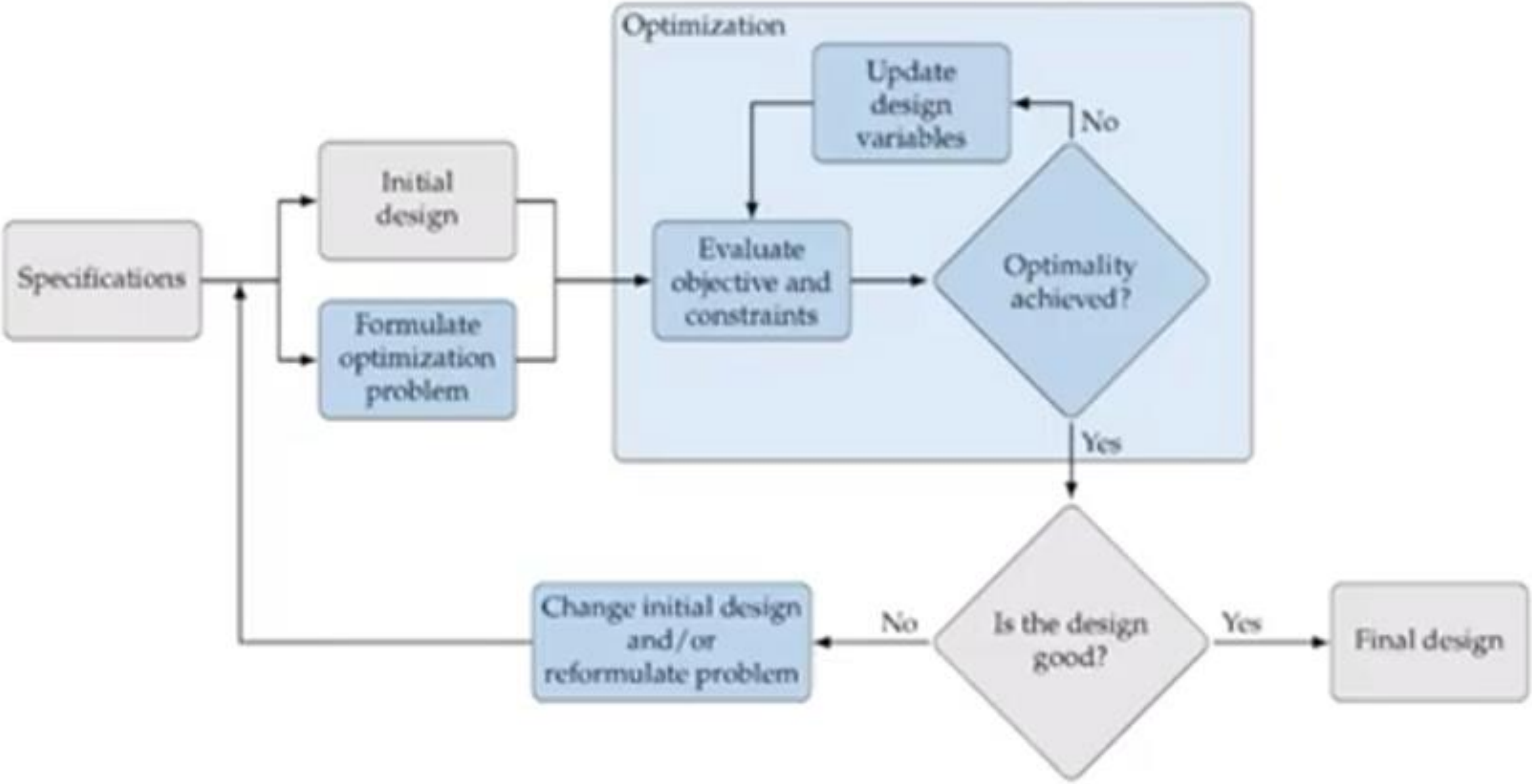
Project management

Etc……………………..

CONCEPTUAL OPTIMIZATION



CONCEPTUAL OPTIMIZATION



PROBLEM FORMULATION

A multi-variable single-objective optimization problem is given as

$$
\begin{array}{lll}
\text{Minimize:} & f(\mathbf{x}), & \\
\text{subject to} & g_j(\mathbf{x}) \geq 0, & j = 1, 2, \ldots, J, \\
& h_k(\mathbf{x}) = 0, & k = 1, 2, \ldots, K, \\
& x_i^{(L)} \leq x_i \leq x_i^{(U)}, & i = 1, 2, \ldots, N.
\end{array}
$$

- $\mathbf{x} = \{x_1, \ldots, x_i, \ldots, x_N\}^T$ is the decision-variable vector.
- $f(\mathbf{x})$ is the objective function.
- $g_j(\mathbf{x})$ is the j-th inequality constraint.
- $h_k(\mathbf{x})$ is the k-th equality constraint.
- $x_i^{(L)}$ and $x_i^{(U)}$ are the lower bound and upper bound on the i-th decision variable.

OPTIMAL PROBLEM FORMULATION

An **optimization problem** is the problem of finding the best solution out of all feasible solutions.

Need for Optimization .... cost, efficiency , safety

Choose Design Variable .... high sensitive to proper working design

Formulate constraints .... represents functional relationship between design variable :

- **equality**....usually replaced by two inequality constraints
- **inequality** .... Practical cases

Constrained optimization problems are **problems** for which a function is to be minimized or maximized subject to **constraints** .

Formulate objective function .... **Single objective**

Multi objective

- one primary single objective
- rest are constraints

Setup variable bounds .... **Upper bound**

lower bound

Choose an optimization algorithm

Obtain solution

The power of optimization methods to determine the best solution without actually testing all possible solutions comes through the use of mathematics and at the cost of performing iterative numerical calculations, using clearly defined logical procedures or algorithms implemented on computing machines.

DECISION VARIABLES

- Identify the underlying design/decision variables

Design variables

- A design problem usually involves many design parameters
  - List any and every parameter related to the problem
- Parameters sensitive to the given design or problem can be considered as design variables in the parlance of optimization procedure
  - Sensitivity analysis, etc.
  - Experience of the users can be used.
- Specify the type of each parameter (binary, discrete, real)
- First thumb rule of an optimization problem: Choose as few variables as possible
  - Efficiency and speed of optimization algorithm depend, to a large extent, on the number of chosen design variables.

CONSTRAINTS

- Constraints represent limit on certain resource or on certain physical phenomenon, *for example*, satisfy stress limitation, current or voltage restriction, etc.
- Identify the constraints associated with the optimization problem

Types of Constraints

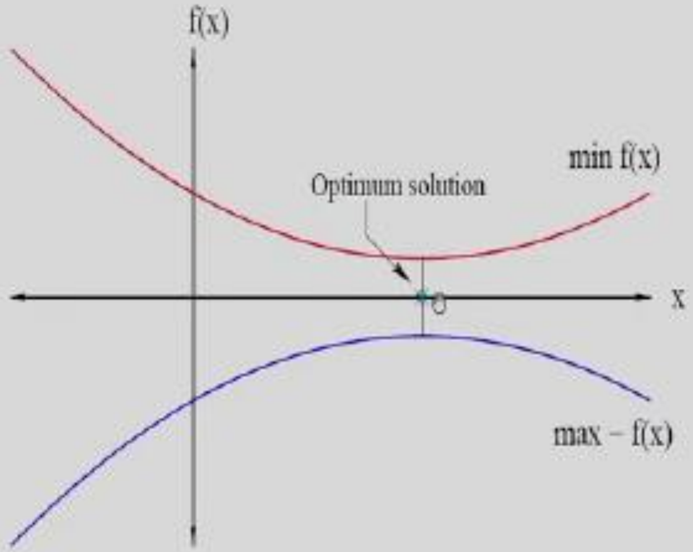
- **Inequality constraint**: $g(\mathbf{x}) \geq 0$ or $g(\mathbf{x}) \leq 0$
  - mostly encounter in engineering design problems
- **Equality constraint**: $h(\mathbf{x}) = 0$, difficult to handle
- Handling of equality constraint, *for example*, deflection of beam, say $\delta(\mathbf{x}) = 0.35$ mm, can be converted it into two inequality, say $\delta(\mathbf{x}) \geq 0.25$ and $\delta(\mathbf{x}) \leq 0.45$
- Second thumb rule in the formulation of optimization problem: The number of complex equality constraints should be kept as low as possible

OBJECTIVE

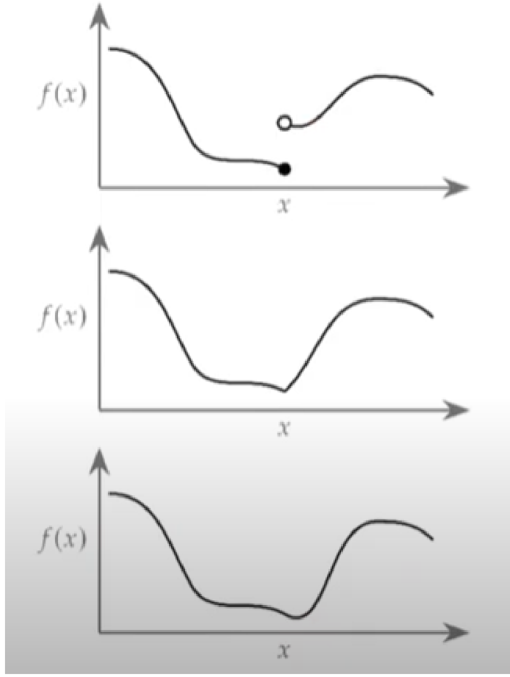
Objective Function

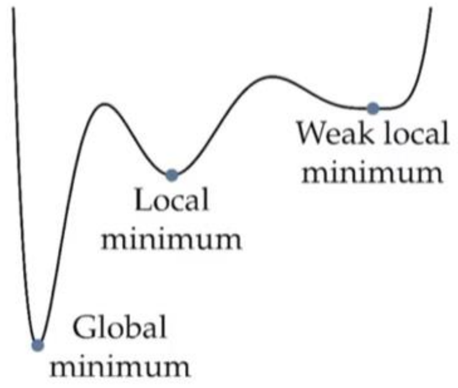
- Minimize or Maximize $f(\mathbf{x})$, which is written in terms of design variables and other parameters
- Optimization algorithms usually written either for minimization or maximization

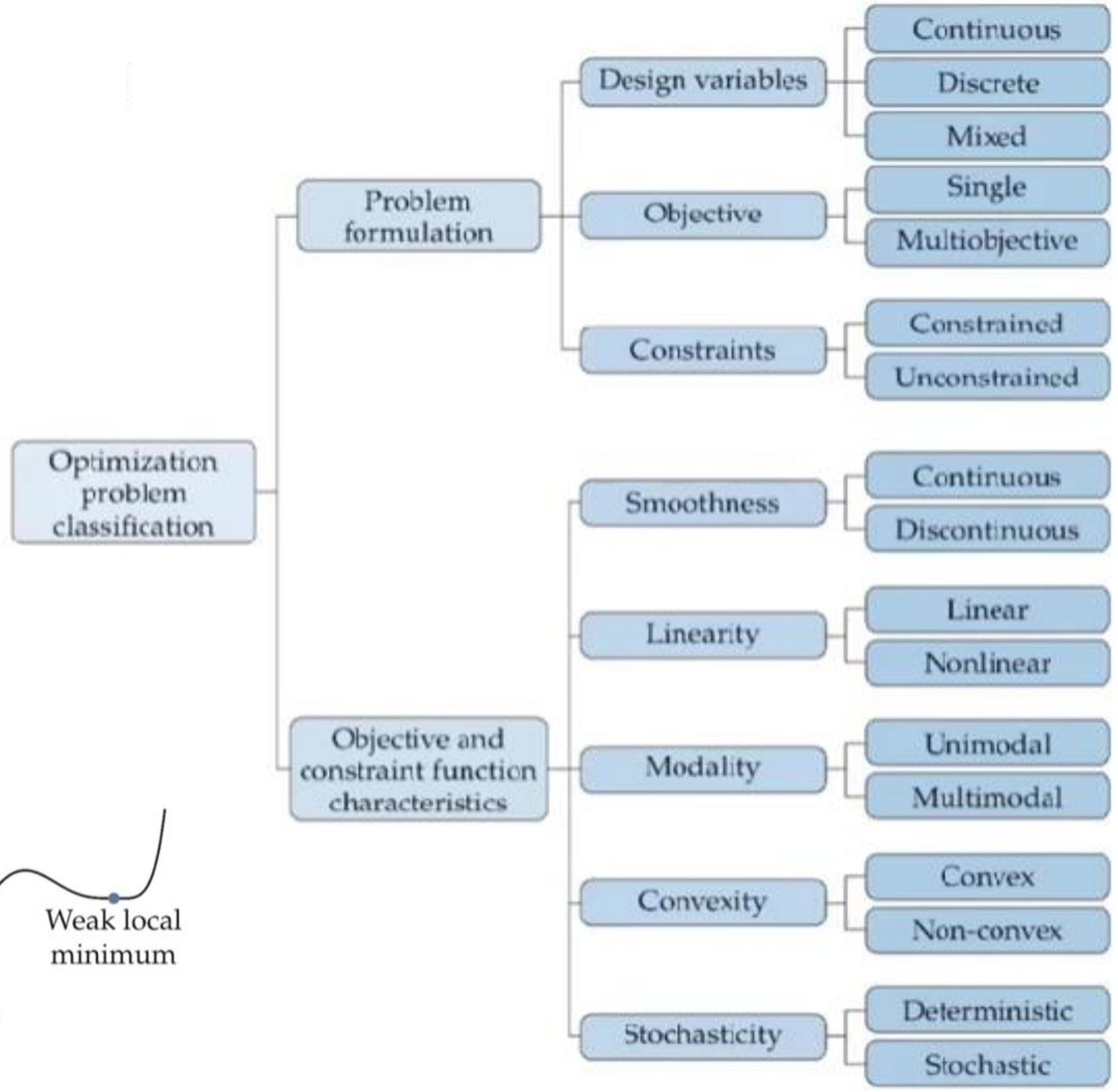
- Duality principle helps unification, $\min f(\mathbf{x}) = \max F(\mathbf{x})$, where $F(\mathbf{x}) = -f(\mathbf{x})$



CLASSIFICATION







OPTIMIZATION

Optimization Algorithm

It provides systematic and efficient ways of creating and comparing new design solutions in order to achieve an optimized design solution.

- Optimization algorithm works on a mathematical model of the optimal design problem.
- Time consuming and computationally expensive procedure because it requires comparison of a number of design solutions.

CRITICAL REMARK ON NUMERICAL OPTIMIZATION TECHNIQUE

- One method is not applicable in many optimization problems
- Constrained handling is sensitive to the penalty parameters
- Not efficient in handling discrete variables
- Local perspective for searching
- Uncertainties in decision and state variables
- Noisy/dynamic optimization problems
- Multiple objectives optimization problems

Need for an innovative and flexible optimization algorithm

COMPLEXITY OF THE PROBLEM

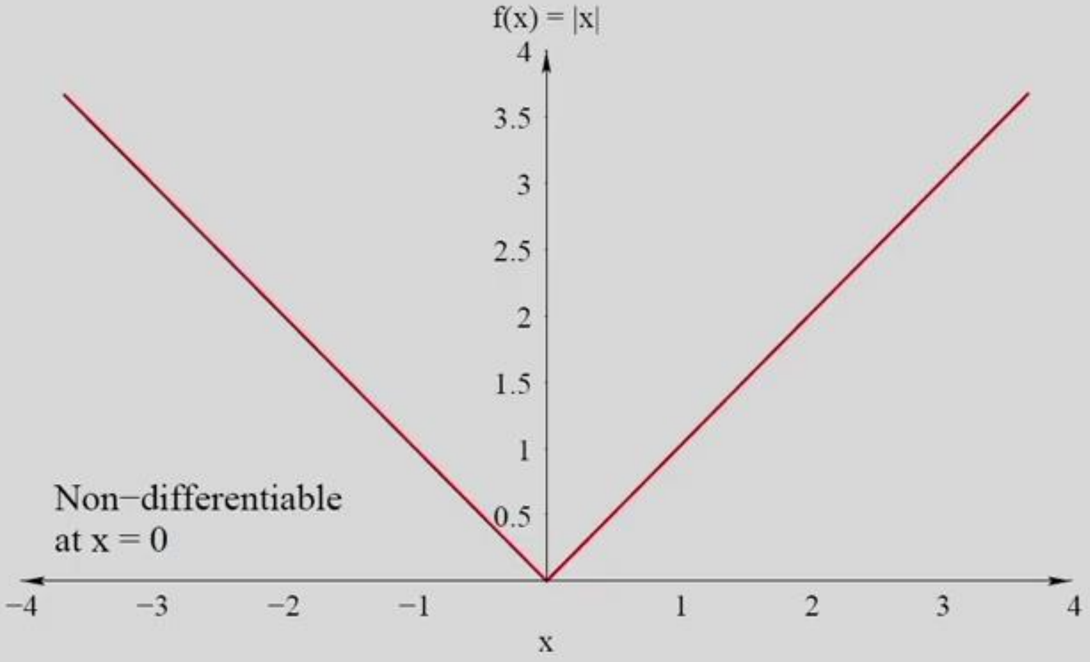
With n jobs to be processed on m machines the number of possible sequences is $(n!)^m$

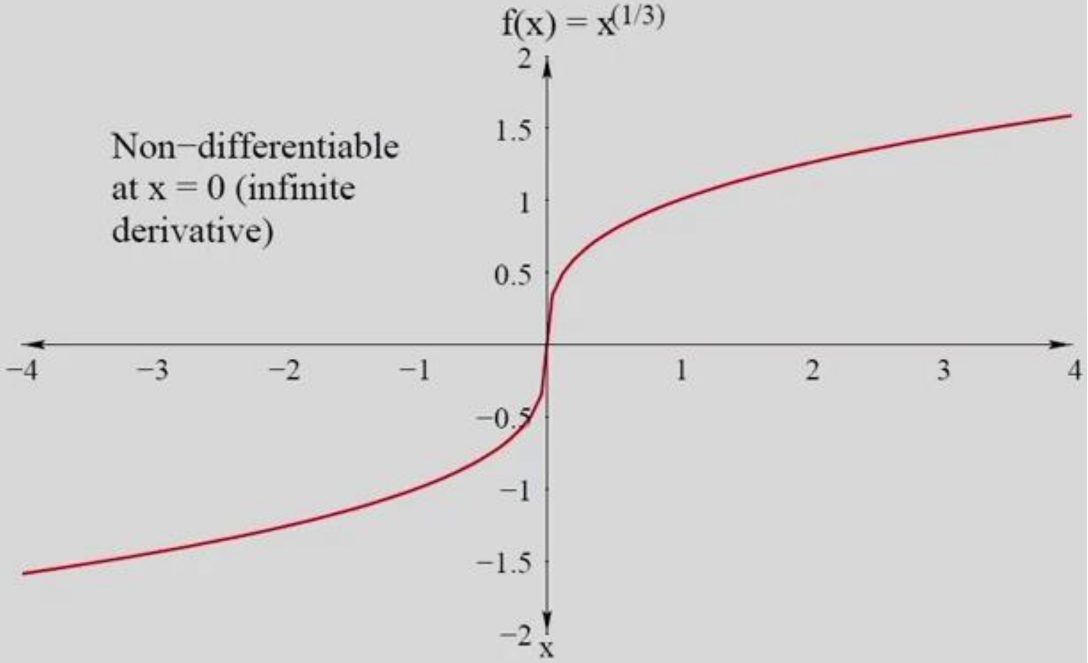
n	5	10	15	20
m	2	4	5	5
$(n!)^m$	14400	$1,73x10^{26}$	$3.8x10^{60}$	$8.5x10^{91}$

PROPERTIES OF OPTIMIZATION TECHNIQUES

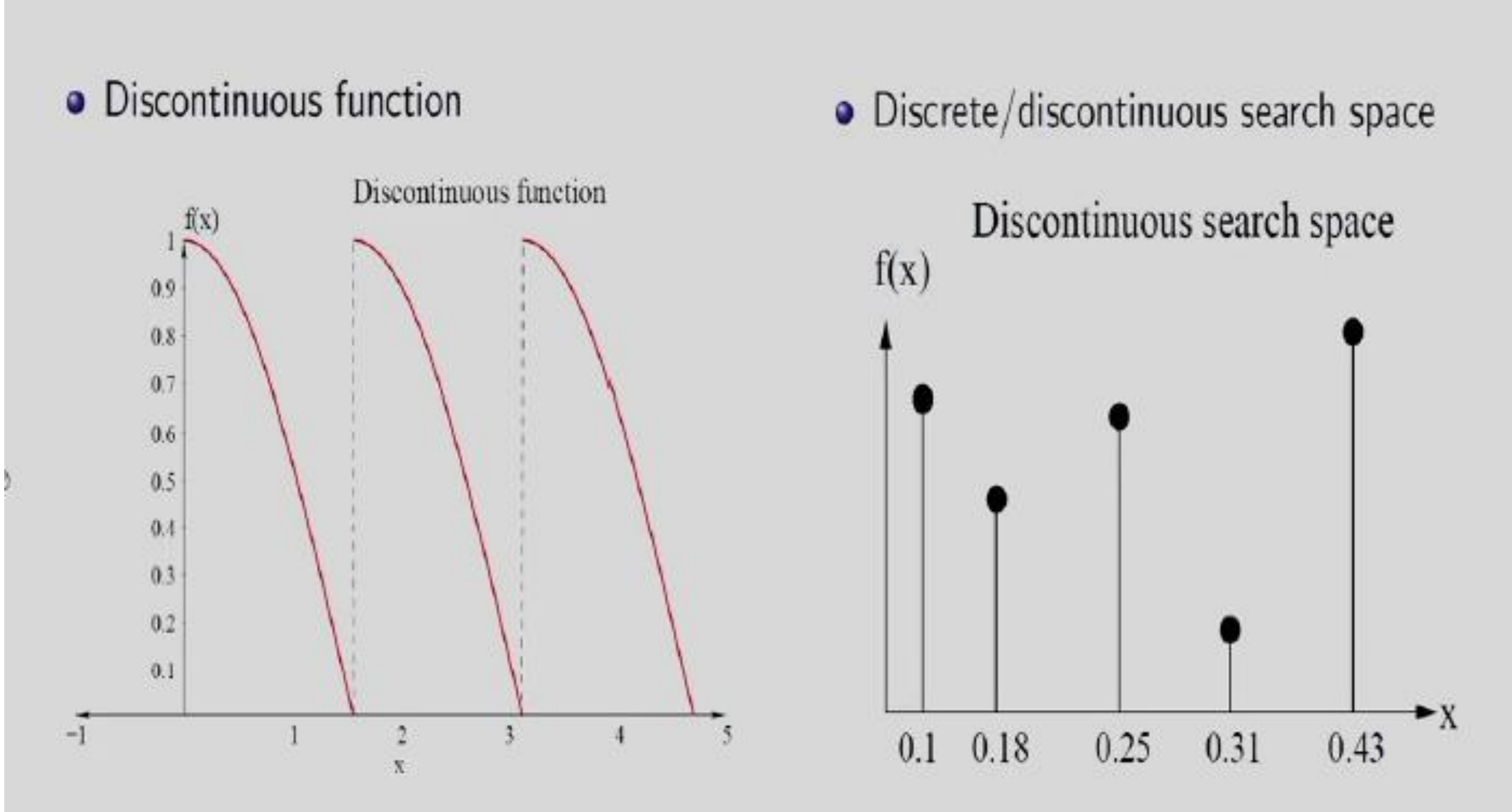
PROPERTIES OF PRACTICAL OPTIMIZATION PROBLEMS

- Non-differentiable functions and constraints

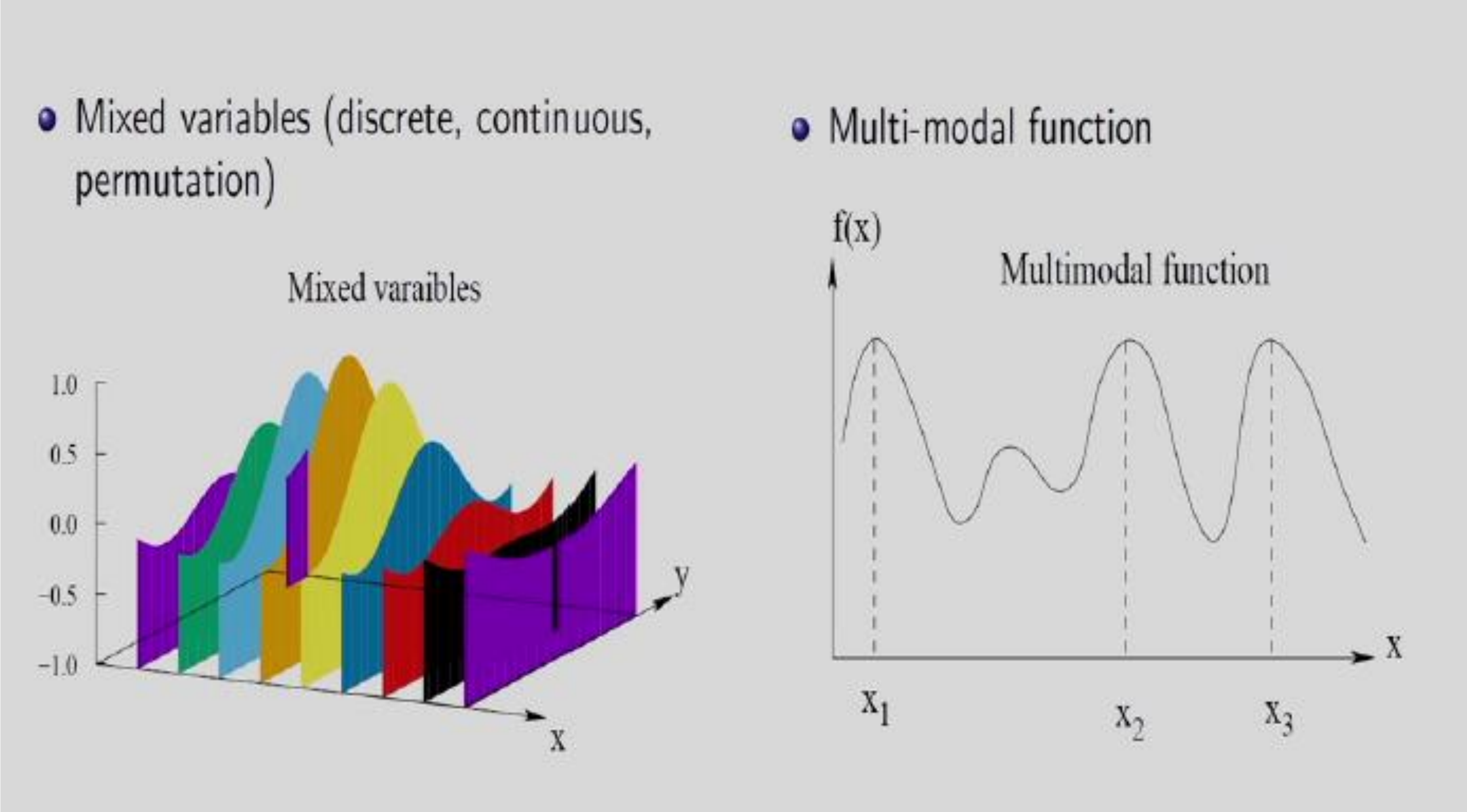




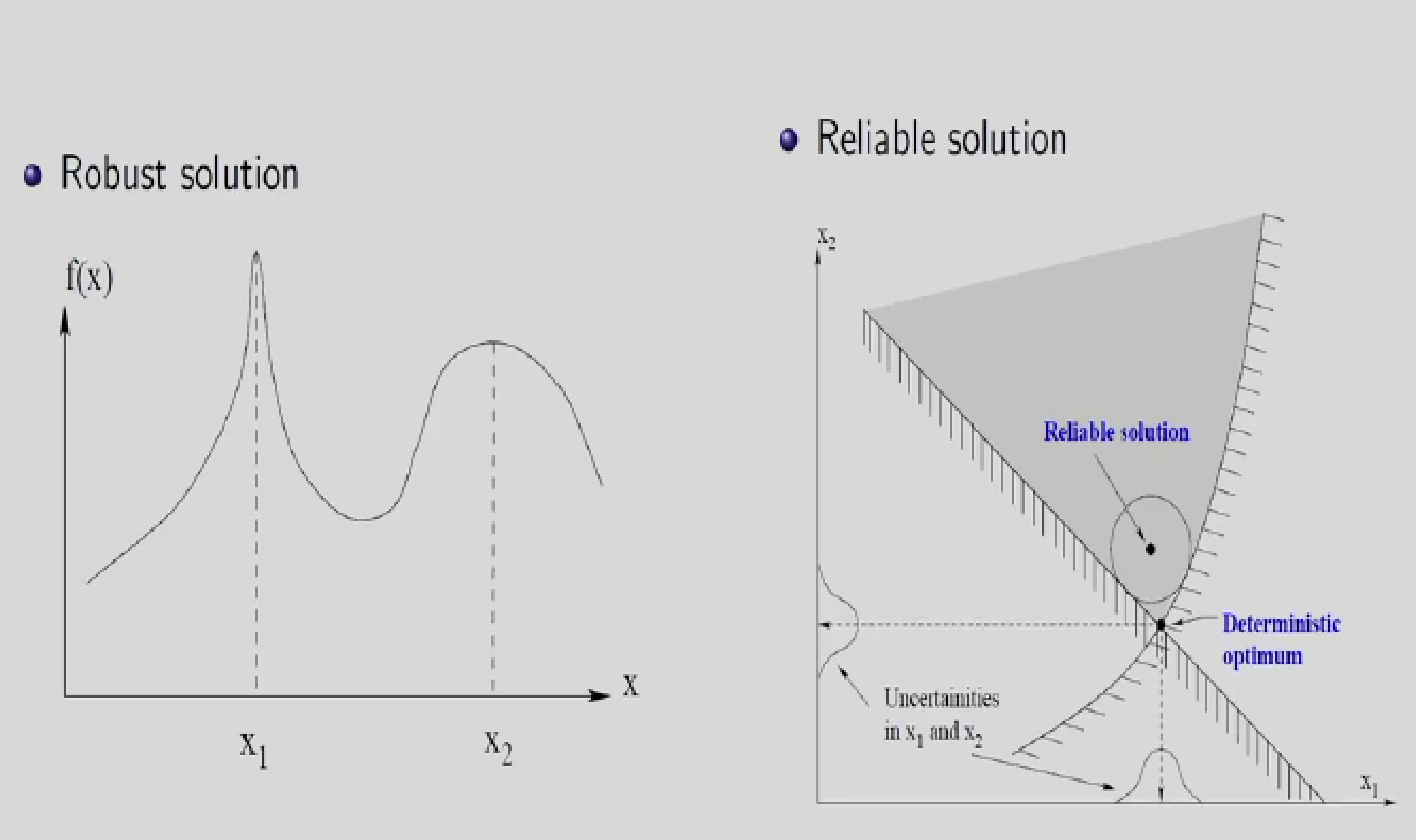
PROPERTIES OF PRACTICAL OPTIMIZATION PROBLEMS



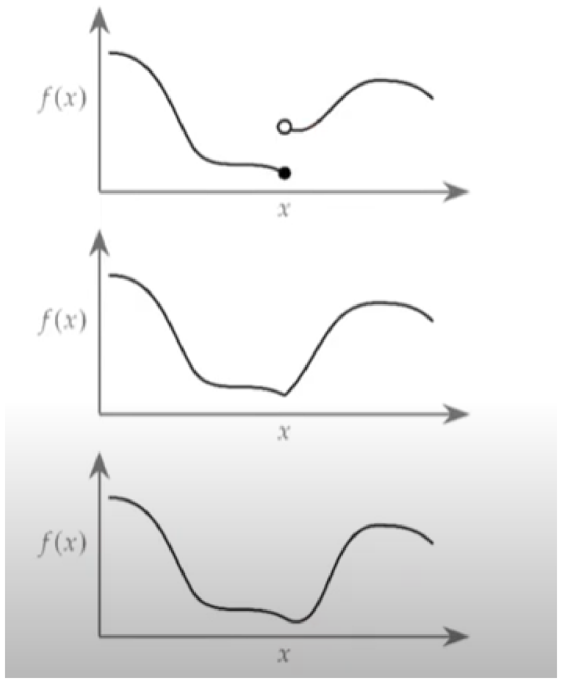
PROPERTIES OF PRACTICAL OPTIMIZATION PROBLEMS

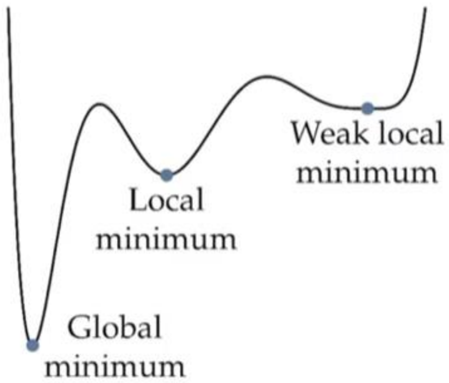


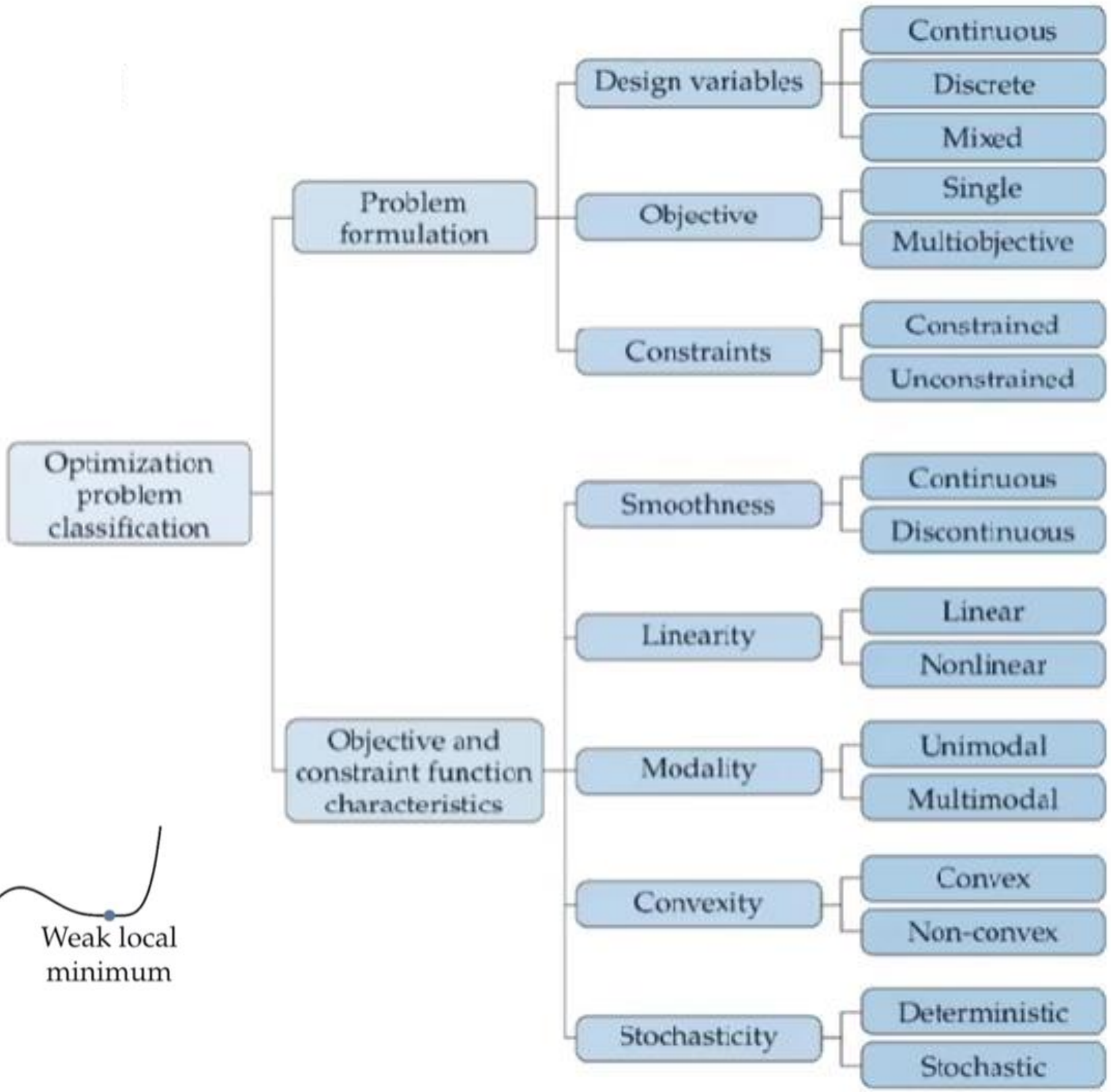
PROPERTIES OF PRACTICAL OPTIMIZATION PROBLEMS



CLASSIFICATIC



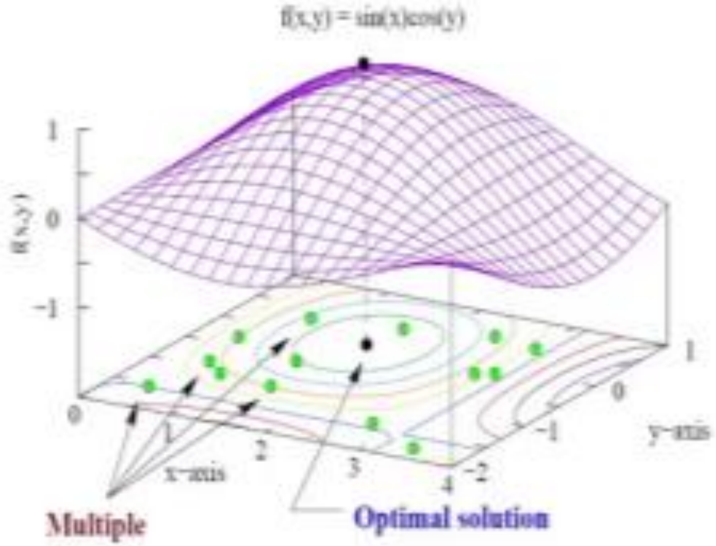




INTRODUCTION TO EVOLUTIONARY COMPUTATION

- Nature inspired algorithm (but not copied).
  - Mimic natural or biological phenomena or process
- Based on natural evolution + genetics.
  - **Natural evolution**: Offspring (new solutions) are created by variation operators, such as crossover, mutation etc.
  - **Survival of the fittest**: Good solutions are retained and bad are deleted.
  - **Genetics**: Information is coded.

- Evolutionary computation (EC) techniques can be used in optimization, learning and design.
- EC techniques are population-based algorithms.
  - Many solutions or points



NATURE INSPIRED OPTIMIZER

- Nature as structural engineer
  - Stem, Bamboo, insect trachea, bee-hive
- Nature as a CFD solver
  - Birds, fishes
- Nature as a drag reducer
  - Penguin body

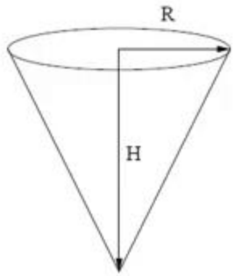
GENETICS

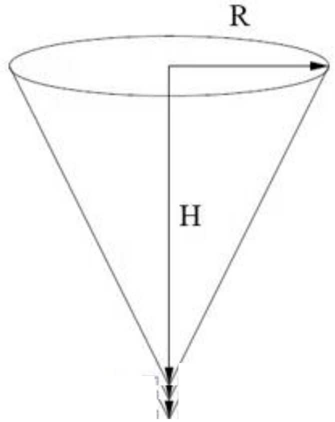
Genotype

Cone 1
Chromosome = {01001 01010}
$(R, H) = (9, 10)$cm

Cone 2
Chromosome = {01100 01111}
$(R, H) = (12, 15)$cm

Phenotype





NATURAL EVOLUTION

- Crossover between two parents at the random site (say at 6th site)

P1:	1 0 1 0 1 1 | 0 0 1 0
P2:	0 1 0 1 0 0 | 0 1 1 0

O1:	1 0 1 0 1 1 | 0 1 1 0
O2:	0 1 0 1 0 0 | 0 0 1 0

- Mutation at the random bit position (say at 4th position)

$$1\ 0\ 1\ \boxed{0}\ 1\ 1\ 0\ 1\ 1\ 0$$

$$\downarrow$$

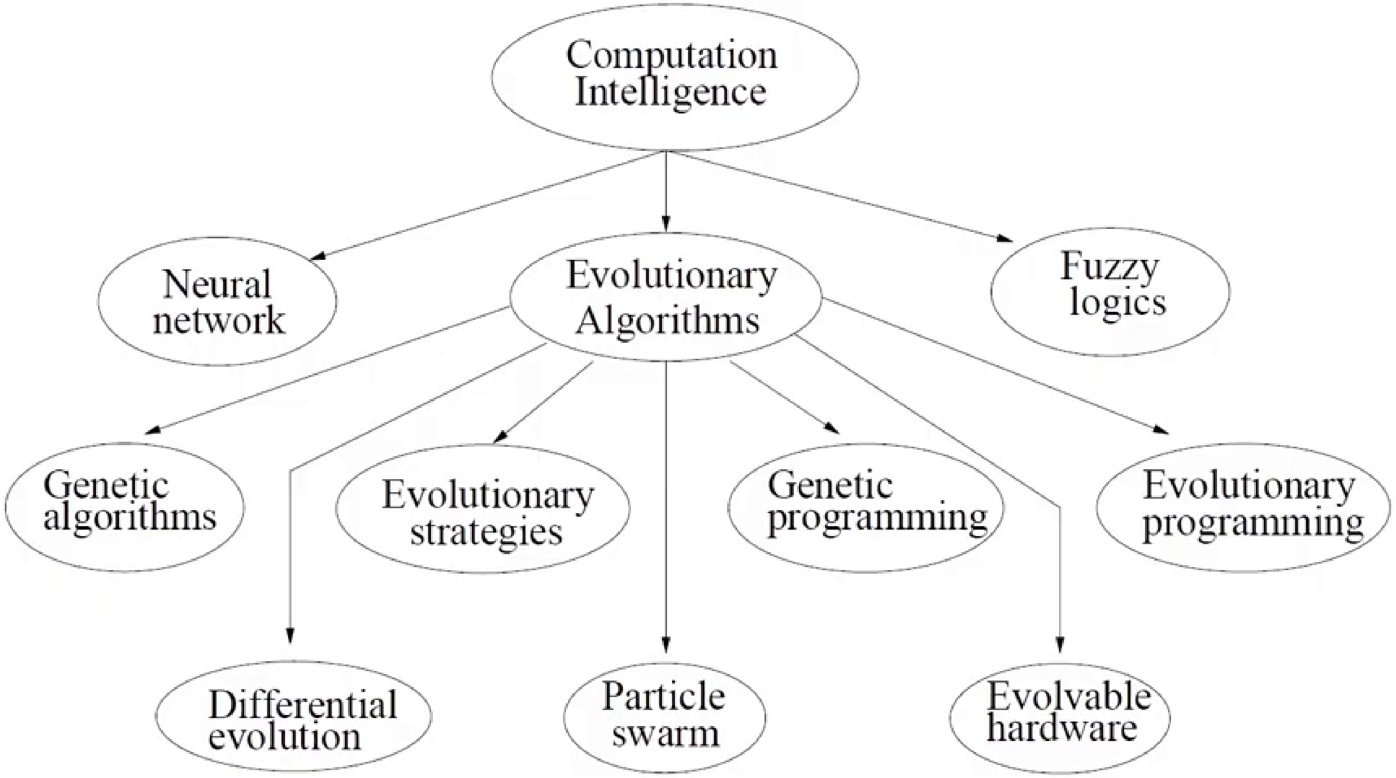
$$1\ 0\ 1\ \boxed{1}\ 1\ 1\ 0\ 1\ 1\ 0$$

SURVIVAL OF THE FITTEST

- Darwin's principle of evolution
  - **Survival of the fittest**: Stronger candidate has more chance of survival than weaker candidates in an environment of limited sources like food, etc.
  - Diversity: Due to crossover, offspring will be evolved from stronger parents
  - Chances are more that offspring will possess good traits of strong parents which can be further improved by mutation
  - **Diversity drives changes** in the population

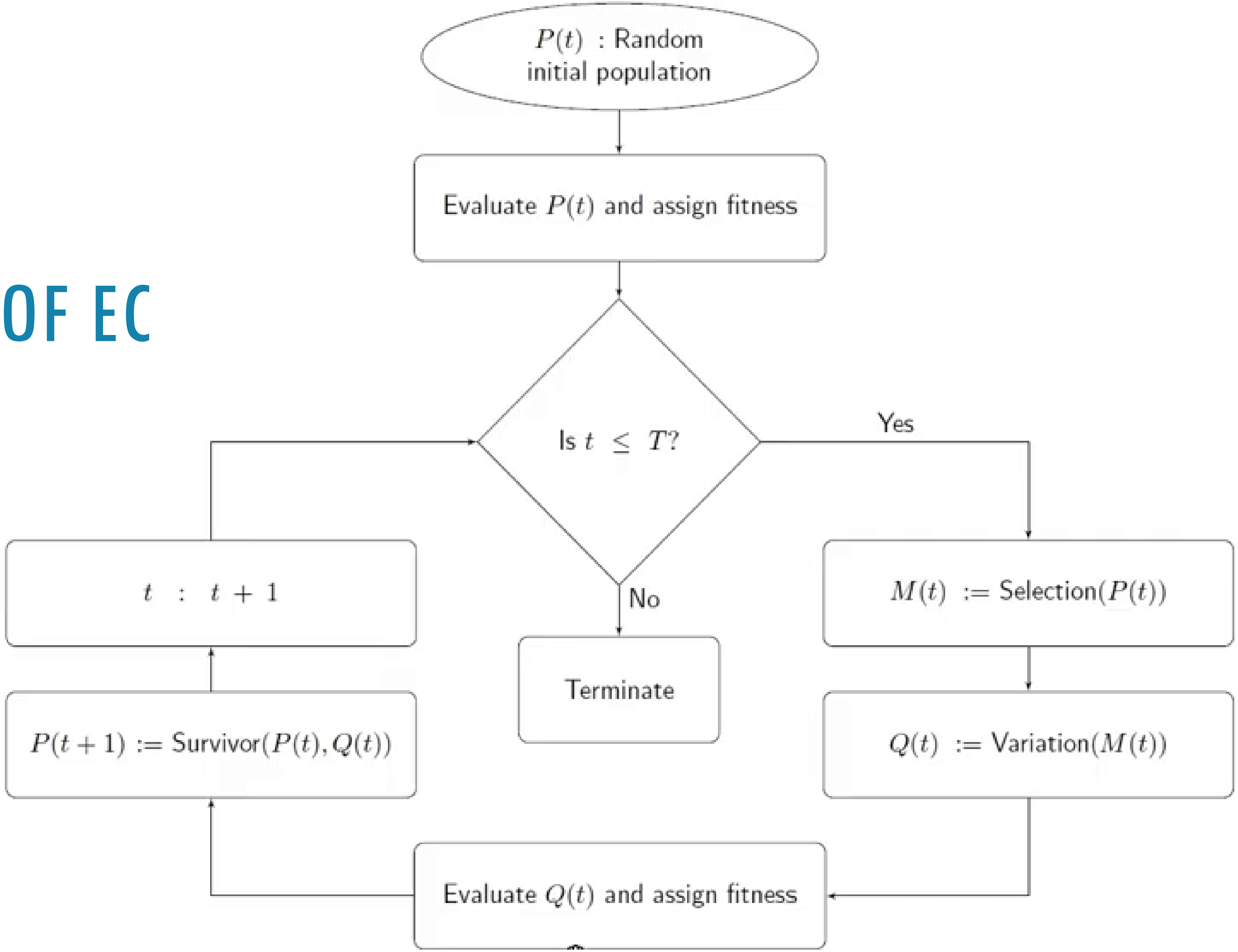
COMPUTATIONAL INTELLIGENCE AND EA'S

EC techniques are also referred as evolutionary algorithms (EAs).



We treat EA as a search and optimization tool

FLOW CHART OF EC TECHNIQUE



GENERALIZE FRAMEWORK FOR EC TECHNIQUE

Algorithm 1 Generalized Framework

Solution representation %Genetics

Input: $t := 1$ (Generation counter), Maximum allowed generation $= T$

Initialize random population $(P(t))$; %Parent population

Evaluate $(P(t))$; %Evaluate objective, constraints and assign fitness

while $t \leq T$ **do**

    $M(t) :=$ Selection$(P(t))$; %Survival of the fittest

    $Q(t) :=$ Variation$(M(t))$; %Crossover and mutation

    Evaluate $Q(t)$; %Offspring population

    $P(t+1) :=$ Survivor$(P(t), Q(t))$; %Survival of the fittest

    $t := t + 1$;

end while

ADVANTAGES OF EC TECHNIQUES

- Applicable in problems where no (good) method is available
  - Multi-modalities, discontinuities, non-linear problems
  - Noisy problems
  - Implicitly defined problems (simulation models)
  - Discrete variable space
- Most suitable in problems where multiple solutions are sought.
  - Multi-modal optimization problems
  - Multi-objective optimization problems
- No presumptions with respect to problem space
- Low development costs, i.e., costs to adapt to new problem spaces
- Parallel implementation is easier for computationally expensive problems

DISADVANTAGES OF EC TECHNIQUES

- No guarantee for finding optimal solutions in a finite amount of time
  - However, asymptotic convergence proofs are available
- Parameter tuning mostly by trial-and-error
  - Self-adaptation is a remedy
- Population approach may be expensive
  - Parallel implementation is a remedy

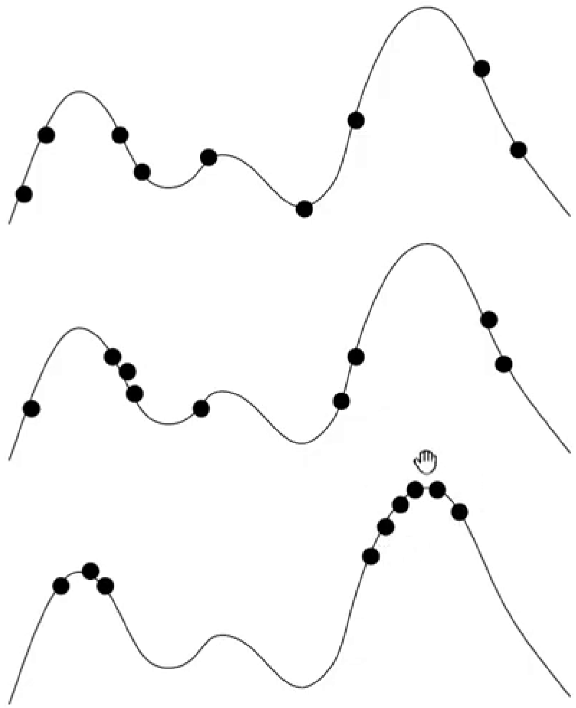
DIFFERENCE WITH NUMERICAL OPTIMIZATION TECHNIQUES

- Different types of variables can be used with EC techniques
  - A problem requires mixed-variable can be handled.
  - Variables such as permutation, continuous, discrete can be used together.
- EC techniques are population-based metaheuristics.
  - The number of solutions can provide safety against premature convergence that can lead to a global perspective to EC techniques.
  - Implicit parallelism
- Operators of EC techniques are probabilistic in nature.
  - It reduces the chance of getting stuck at the local optima.
- EC techniques do not require any gradient information.
- EC techniques are ideal for parallel computation.
  - Evaluations can be distributed the computing processors and threads.

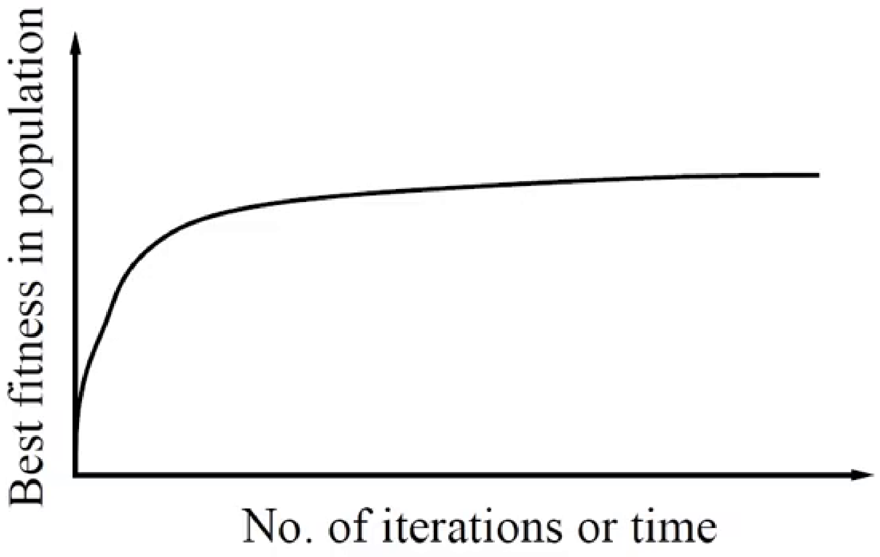
TYPICAL BEHAVIOUR OF EC TECHNIQUE

Phases in optimization on a 1-dimensional fitness landscape

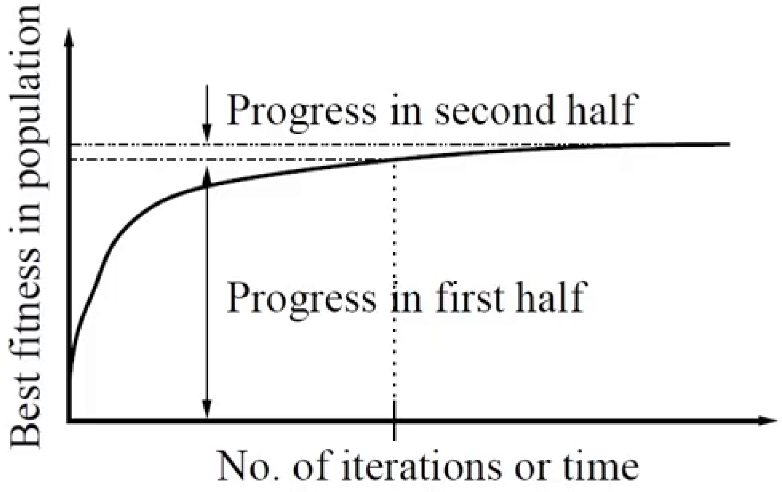
- **Early phase**: quasi-random population distribution
- **Mid-phase**: population arranged around/on hills
- **Late phase**: population concentrated on high hills



CONVERGENCE PLOT



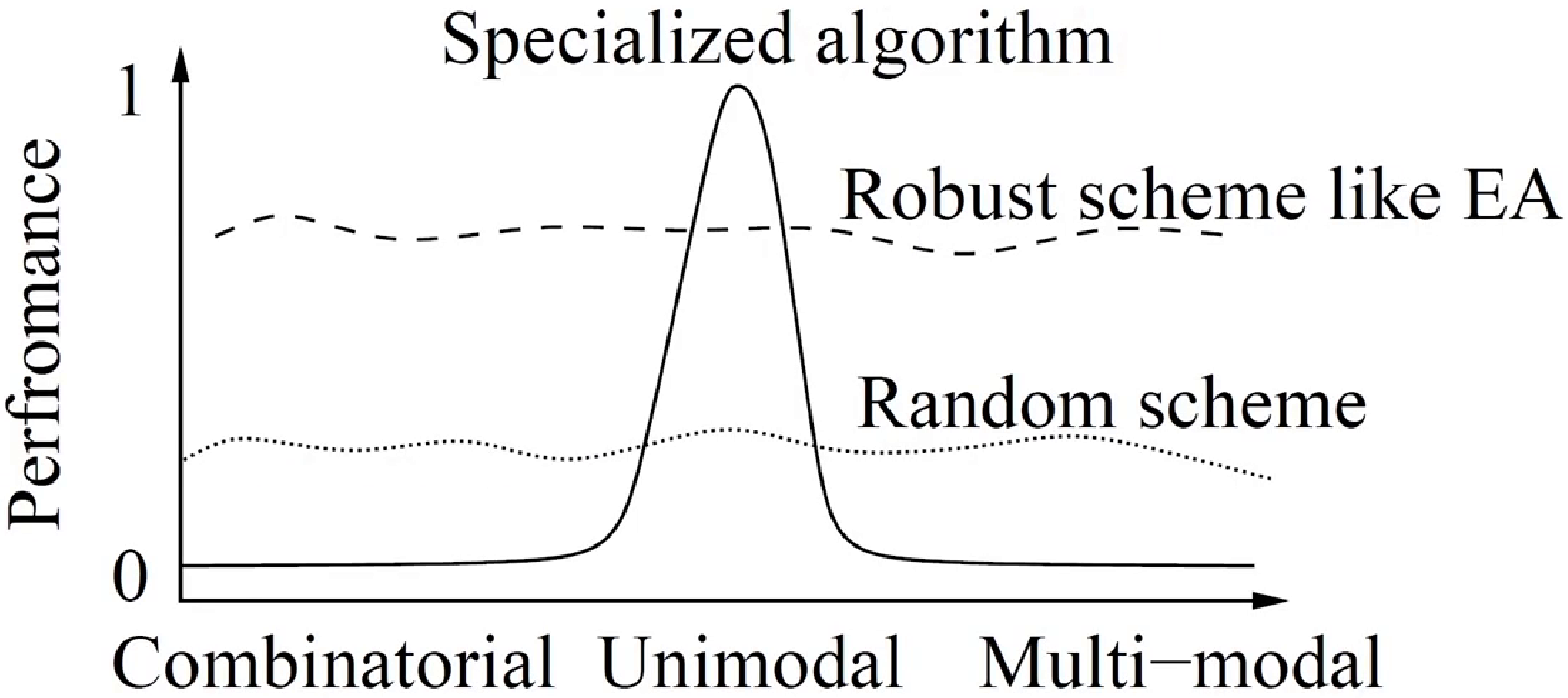
Are long runs beneficial?



Answer:

- It depends how much you want the last bit of progress.
- It may be better to do more shorter runs.

GENETIC ALGORITHM

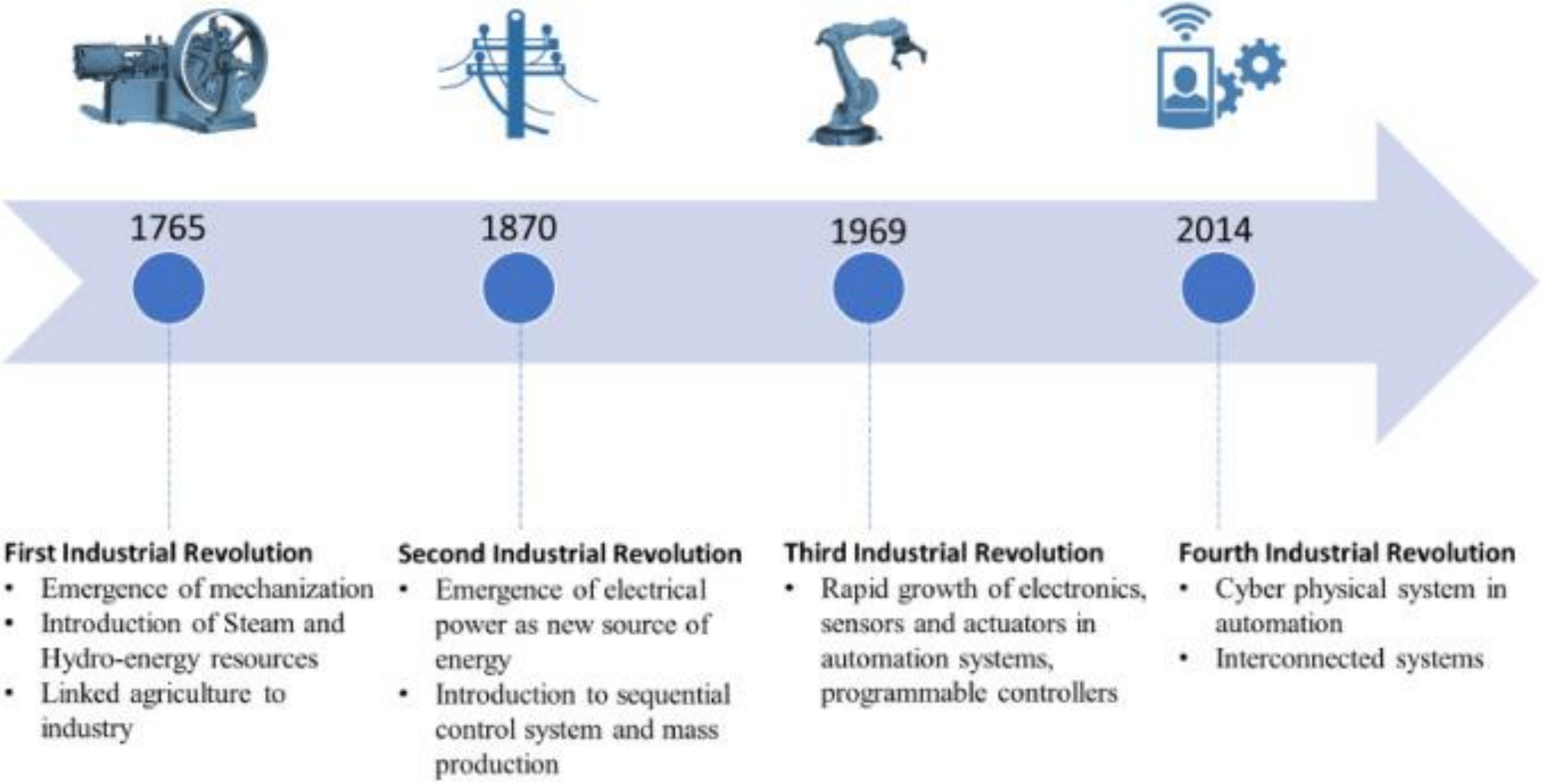


NO FREE LUNCH (NFL): THEOREM FOR OPTIMIZATION

- In the context of optimization
  - D. H. Wolpert and W. G. Macready, "No Free Lunch Theorems for Optimization", IEEE Transactions on Evolutionary Computation, 1(1),67-82, 1997.
  - A framework is developed to explore the connection between effective optimization algorithms and the problems they are solving.
  - For any algorithm, any elevated performance over one class of problems is offset by performance over another class.
  - Algorithms $A1$ and $A2$
  - All possible problems F in one class
  - Performances $P1$ and $P2$ using $A1$ and $A2$ for a fixed number of evaluations
  - $P1 = P2$
- NFL breaks down for a narrow class of problems or algorithms

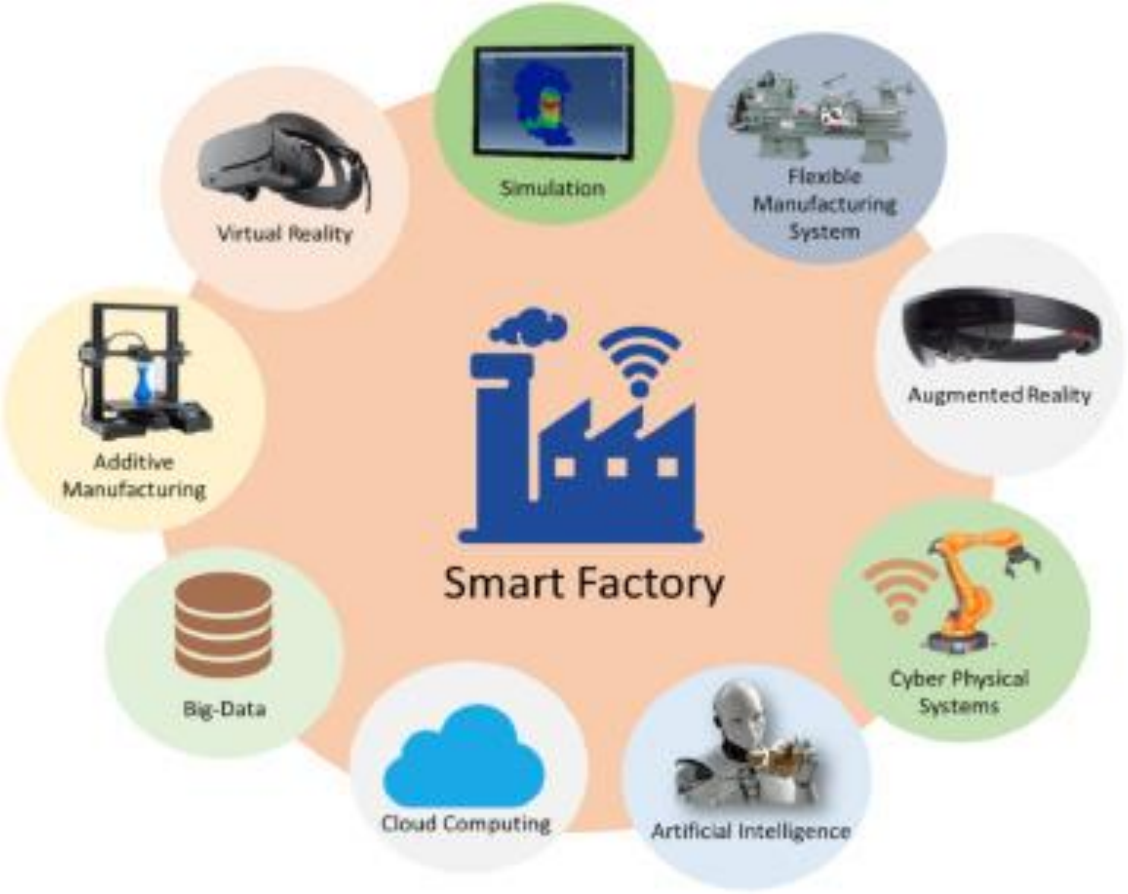
INDUSTRY 4.0 (SMART MANUFACTURING)

HISTORICAL BACKGROUND OF MANUFACTURING



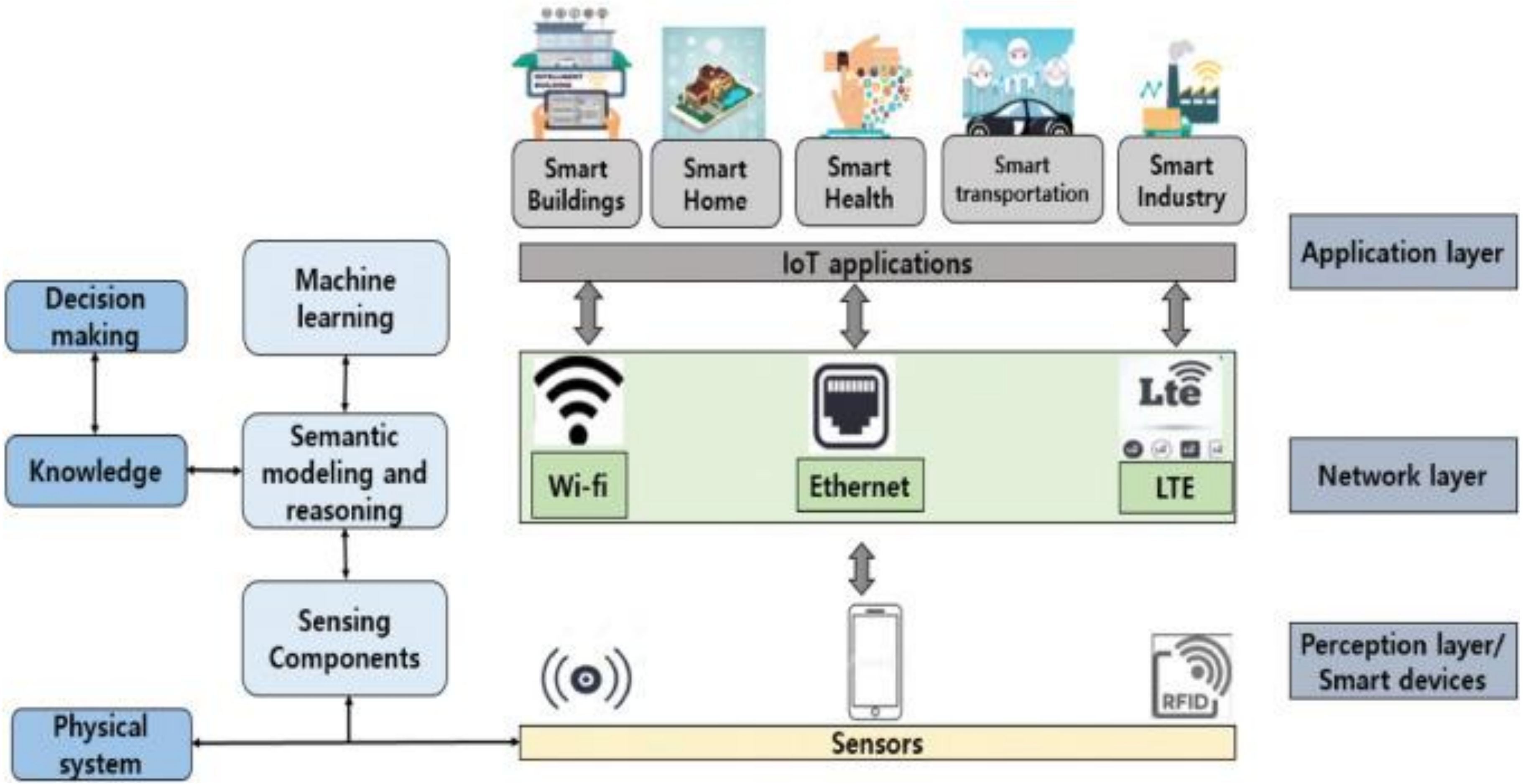
Source: S.Phuyal, D.Bista, R.Bista, Challenges, Opportunities and Future Directions of Smart Manufacturing: A State of Art Review, Sustainable Futures, Volume 2, 2020,

TECHNOLOGIES ASSOCIATED WITH SMART MANUFACTURING



- Virtual Reality (VR)
- Augmented Reality (AR)
- Cyber-Physical Systems
- Additive Manufacturing (3D printing)
- Big Data Analytics
- Machine Learning (ML)
- Flexible and Reconfigurable Manufacturing Systems
- Artificial Intelligence
- IoT and IIoT
- Simulation

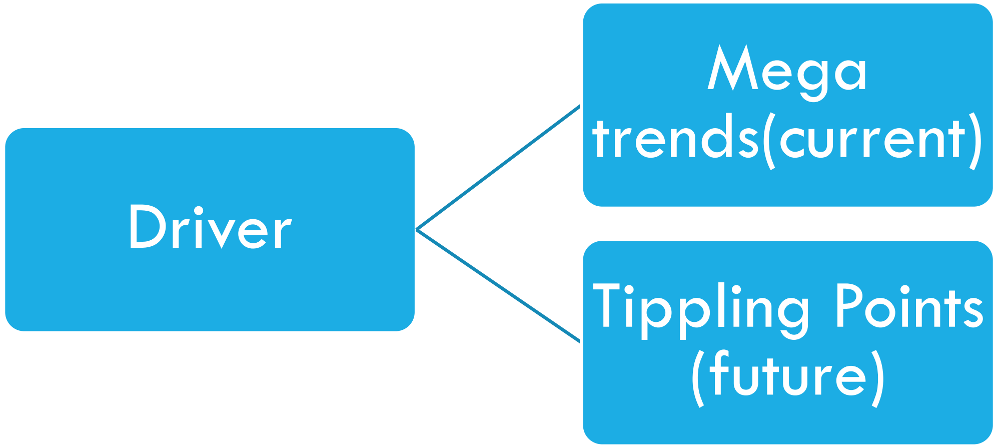
IOT ARCHITECTURE



INDUSTRY 4.0 DRIVERS

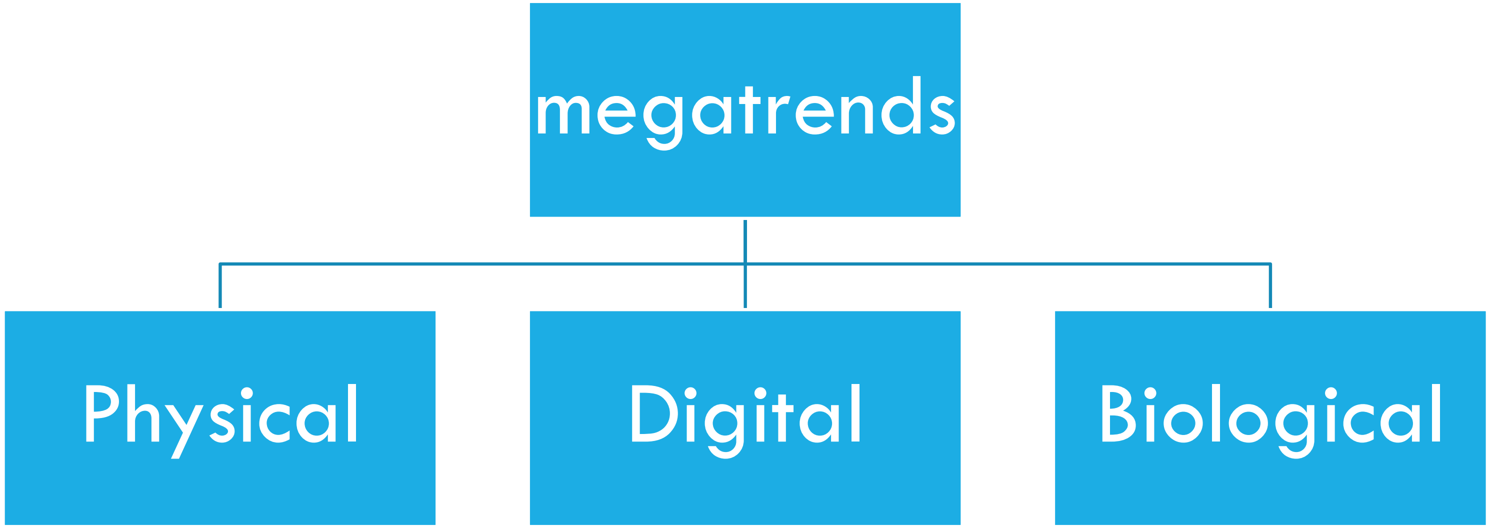
Various aspect that drive the fourth industrial revolution

- Scientific Breakthrough
- New technologies

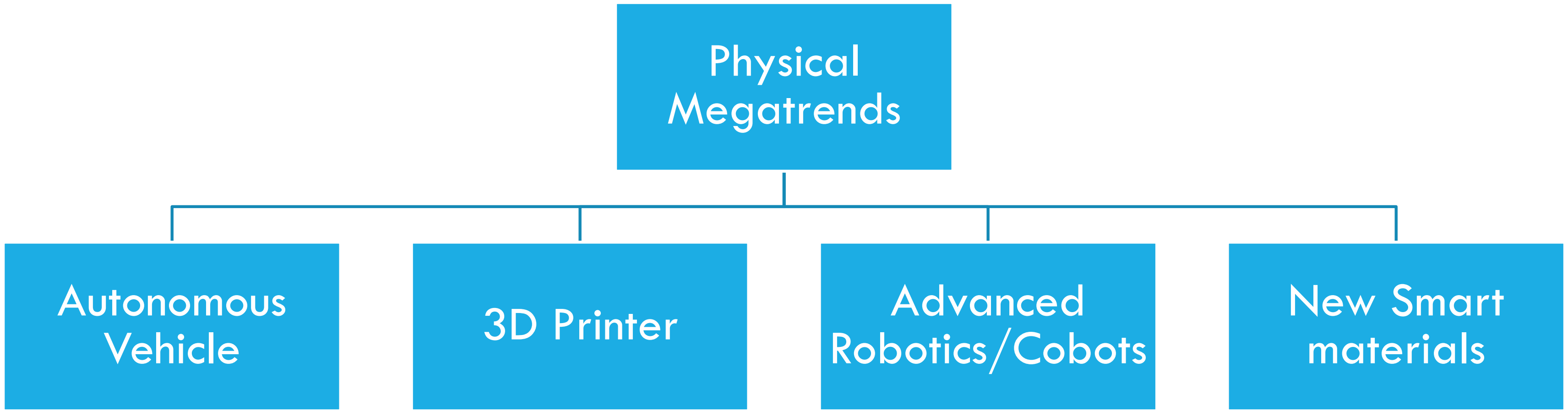


MEGATRENDS

All recent technologies and development that leverages the pervasive potential of digitization and information technologies



PHYSICAL



- Driverless Vehicle Like Drones, Aircraft, Boat, Truck
- Lighter, stronger, recyclable, and adaptive smart material

DIGITAL

Internet of things

Application of IOT in Industry

- RFID
- Tracking of package delivery
- Complex supply chain
- Monitoring systems

Bitcoin and block chain

Uber/OLA model of transportation

BIOLOGICAL

Genetic sequencing

DNA writing

Recommender System (IBM Watson)

Cell modification

Genetic Engineering(CRISPER)

TIPPING POINTS

Tipping points represent the radical changes that are required in near future

Probable tipping points in 2025

- Cloths connected to the internet
- Unlimited free storage
- 1 trillion sensors connected to the internet
- Robotics Pharmacist, etc.

Thank You