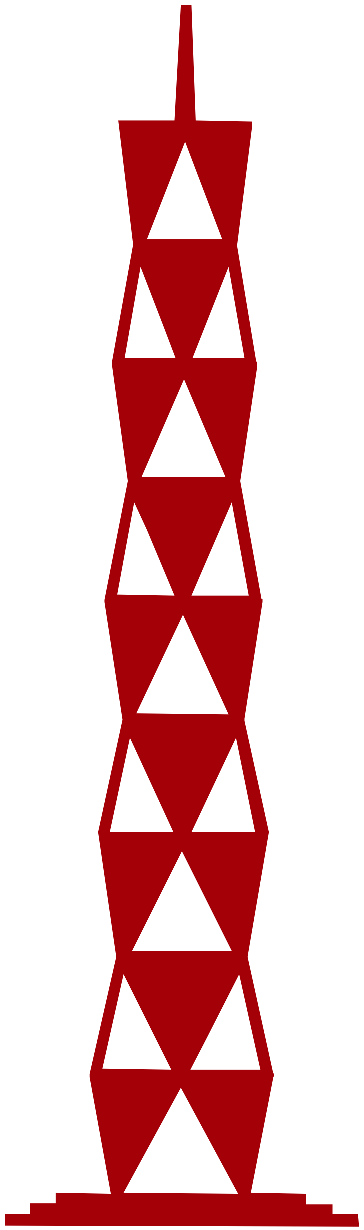


SI100B Introduction to Information Science and Technology (Part 3: Electrical Engineering)

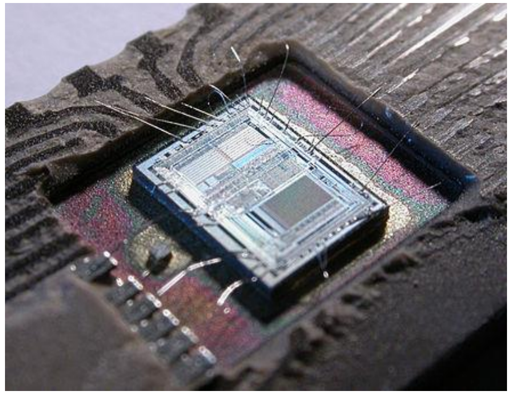
Lecture #7
Dynamic Systems and Control

Instructor: Junrui Liang (梁俊睿)

Oct. 28th, 2022

The Theme Story

Devices (1)



Circuits (4/4)

Systems (1)

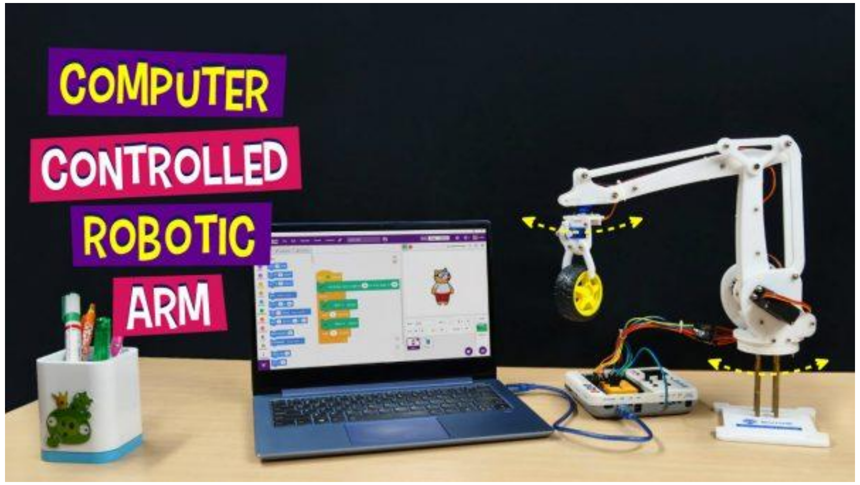
(Pictures are from the Internet)

Study Purpose of Lecture #7

- 哲学（bao'an）三问
  - Who are you?
  - Where are you from?
  - Where are you going?

To answer those questions throughout your life

- In this lecture, we ask
  - How to model a dynamic system?
  - What is the principle of a feedback control system 反馈控制系统?
  - What are the features of future Internet of things (IoT) 物联网 and cyber physics systems (CPS) 信息物理系统 towards industry 4.0?

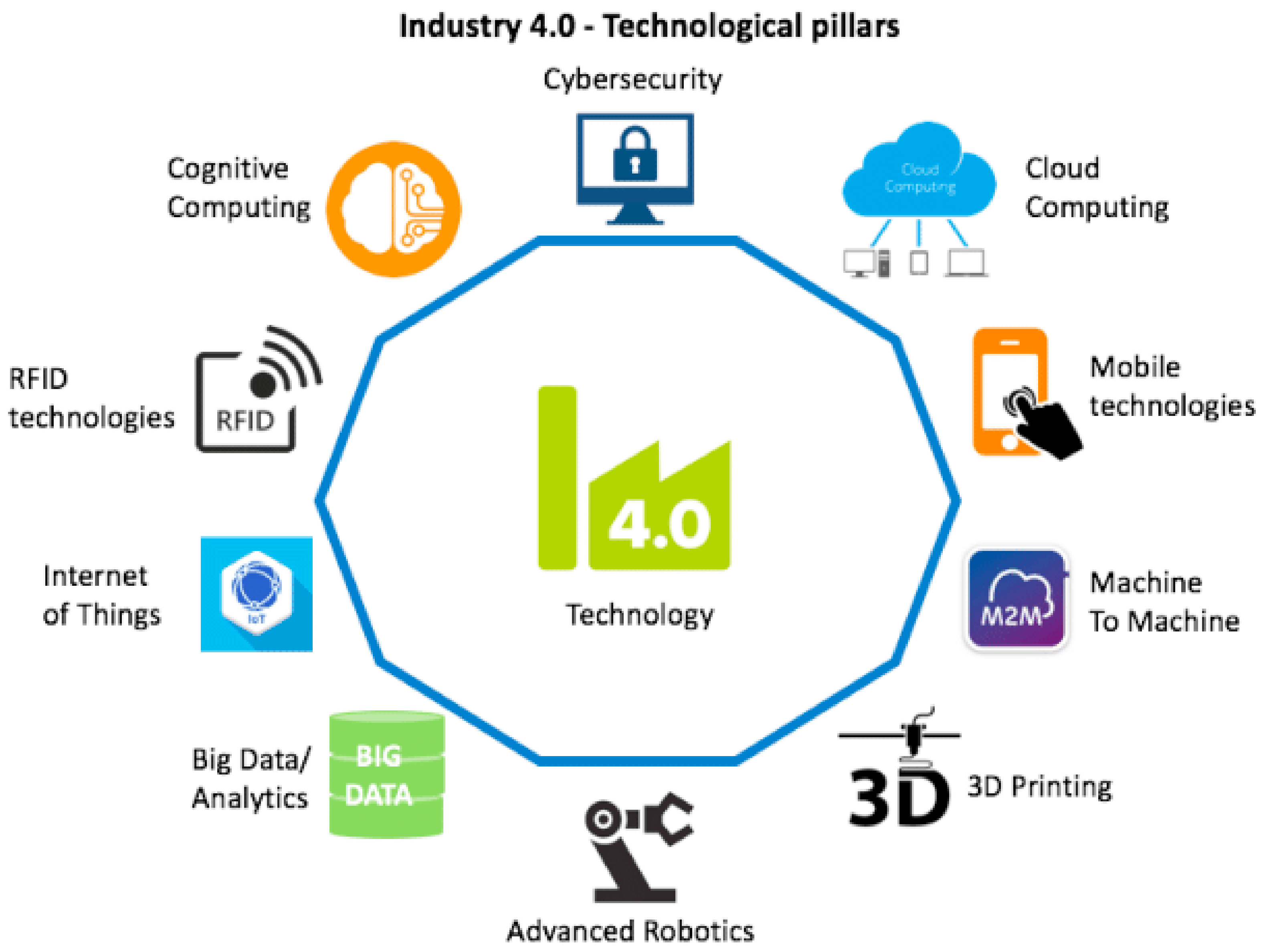


(Pictures are from the Internet)

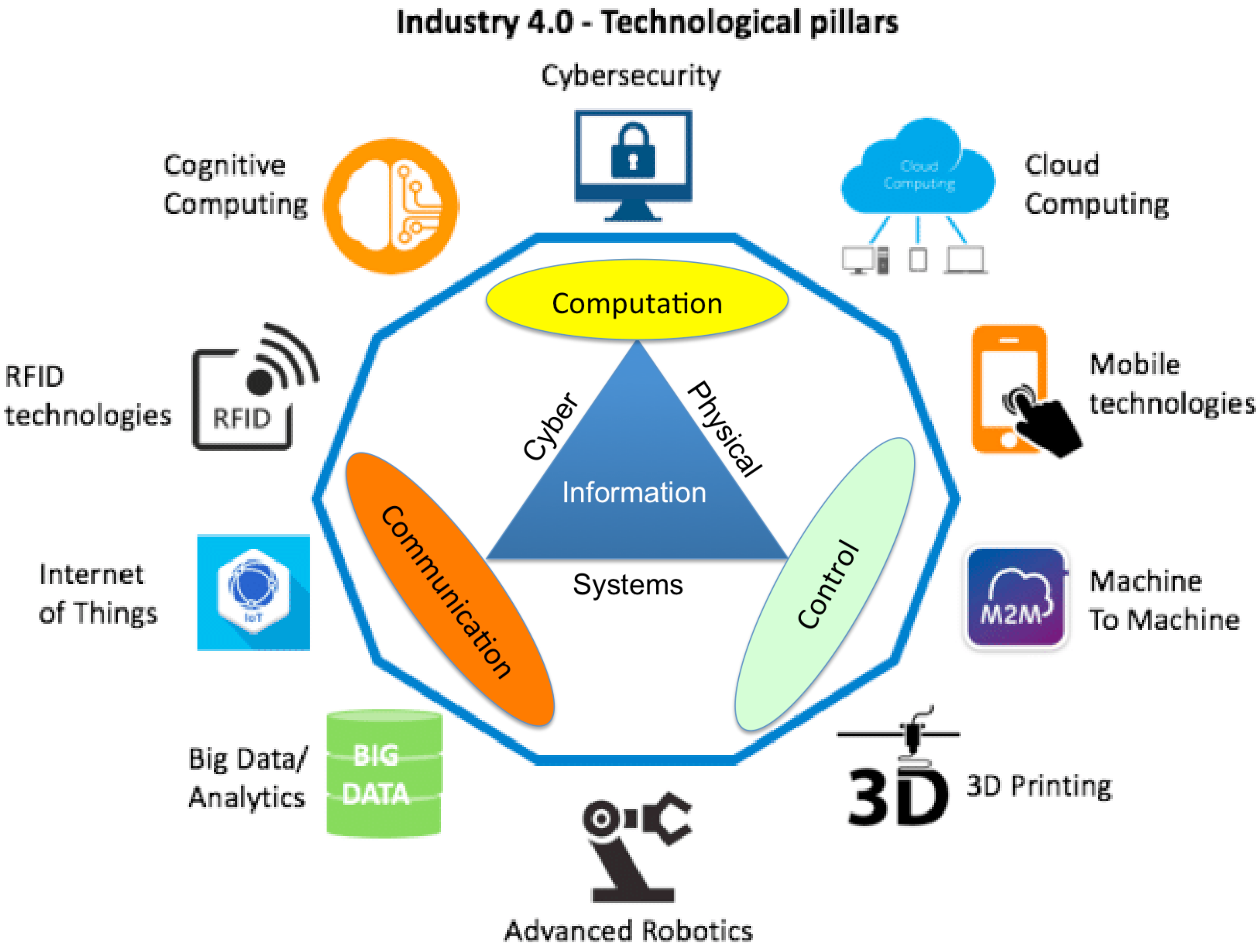
Lecture Outline

- Control and connectivity towards Industry 4.0
- Mathematical model of a dynamic system 数学模型
- Feedback control system 反馈控制系统
  - Block diagram
  - Examples
- Controller 控制器
- Cyber physical system (CPS) 信息物理系统
- Internet of things (IoT) 物联网

Industry 4.0

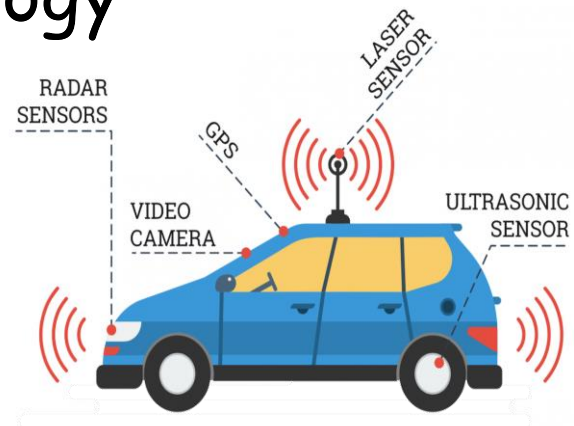

Industry 4.0 - Technological pillars
Cybersecurity
Cloud Computing
Mobile technologies
Machine To Machine
M2M
3D Printing
3D
Advanced Robotics
Big Data/ Analytics
BIG DATA
Internet of Things
IoT
RFID technologies
RFID
Cognitive Computing
4.0
Technology

Industry 4.0


Industry 4.0 - Technological pillars
Cybersecurity
Cognitive Computing
Cloud Computing
Cloud Computing
RFID technologies
RFID
Mobile technologies
Internet of Things
IoT
Machine To Machine
M2M
Big Data/ Analytics
BIG DATA
3D
3D Printing
Advanced Robotics
Computation
Cyber
Physical
Information
Systems
Communication
Control

Control & communication

- Control technology

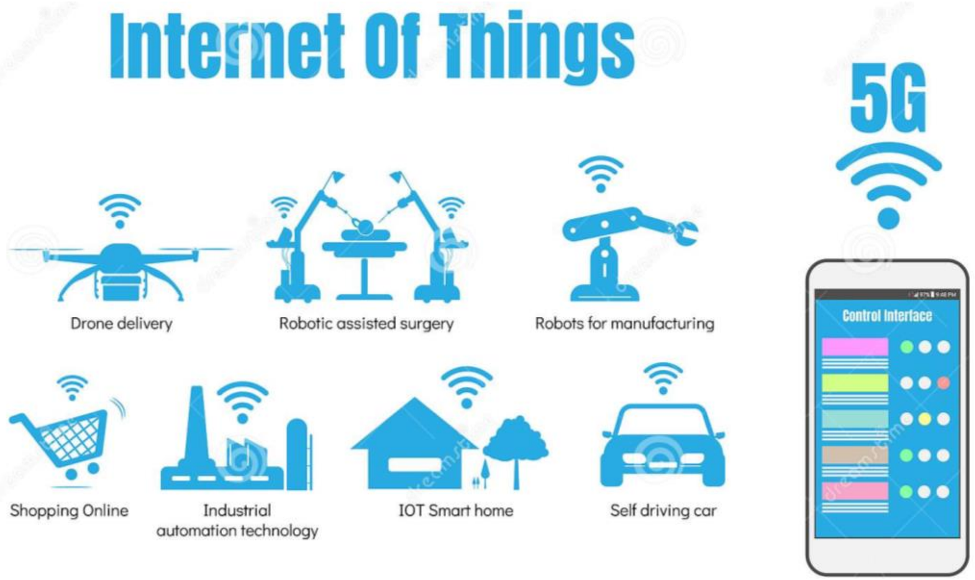


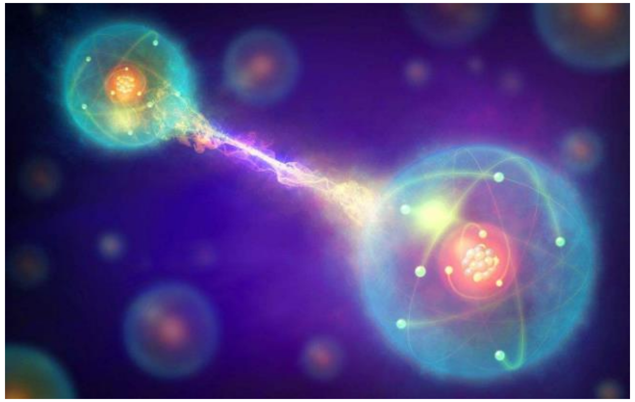
  - Any relation with the AI trend?

To understand something with AI

To control something with AI

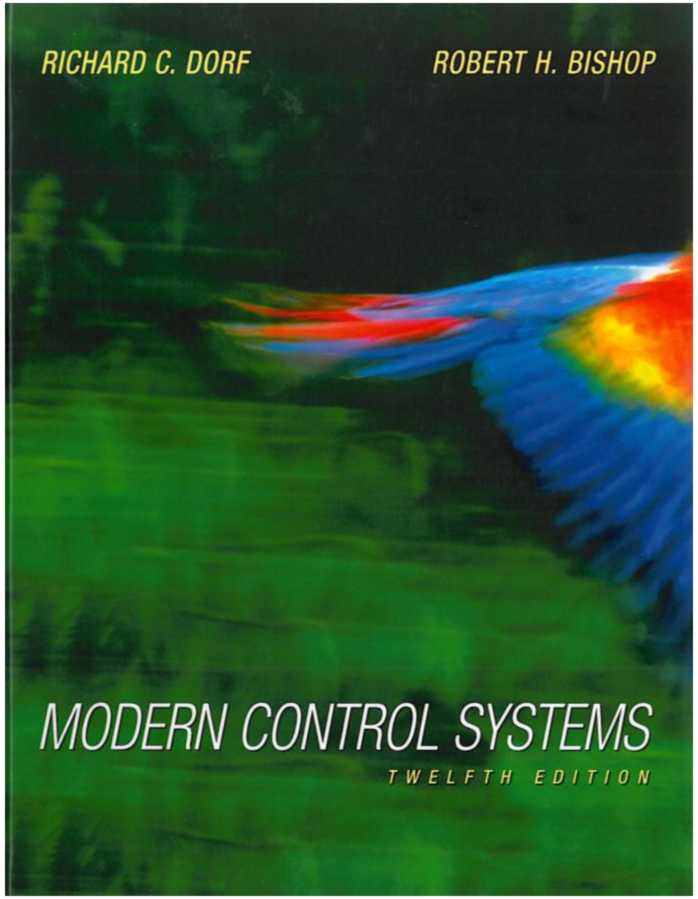
- Communication
  - Faster 更快, more 更多, safer 更安全





Mathematical models of systems

- Reference book
  - Dorf, Richard C., and Robert H. Bishop. "Modern control systems (12ed)." Prentice Hall, 2010.



- Across-variable "跨变量" & through-variable "通过变量"
- Example: a torsional spring 旋转弹簧

T_a

ω_s
T_s
ω_a
T_a

Torque 力矩 equation:

$$T_a(t) - T_s(t) = 0$$

Rotational speed 转速 equation:

$$\omega(t) = \omega_s(t) - \omega_a(t)$$

Across- and through-variables

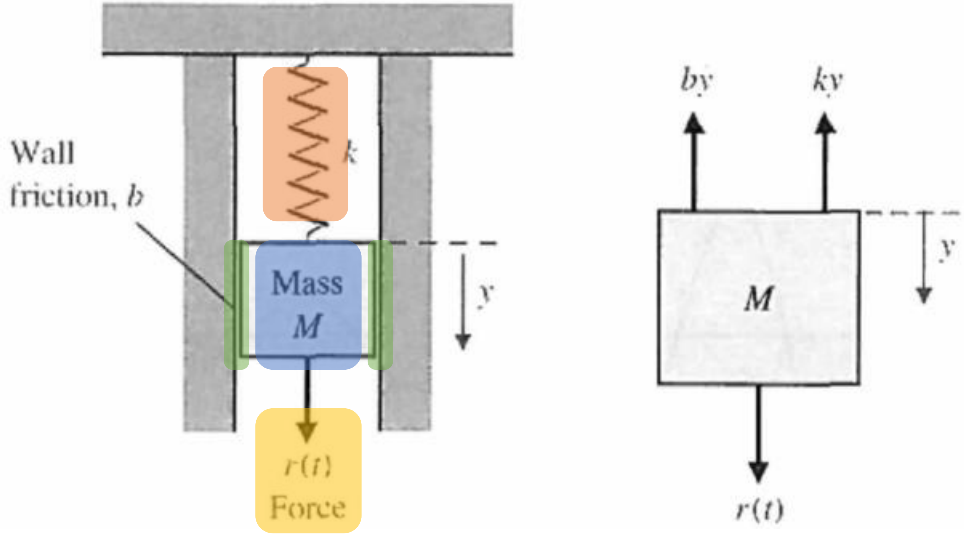
Table 2.1 Summary of Through- and Across-Variables for Physical Systems

	System	Variable Through Element	Integrated Through-Variable	Variable Across Element	Integrated Across-Variable
电学	Electrical	Current, i	Charge, q	Voltage difference, v_{21}	Flux linkage, λ_{21}
力学平动	Mechanical translational	Force, F	Translational momentum, P	Velocity difference, v_{21}	Displacement difference, y_{21}
力学转动	Mechanical rotational	Torque, T	Angular momentum, h	Angular velocity difference, ω_{21}	Angular displacement difference, θ_{21}
流体	Fluid	Fluid volumetric rate of flow, Q	Volume, V	Pressure difference, P_{21}	Pressure momentum, γ_{21}
热学	Thermal	Heat flow rate, q	Heat energy, H	Temperature difference, $\mathcal{T}_{21}$	

Dorf, Richard C., and Robert H. Bishop. “Modern control systems (12ed).” Prentice Hall, 2010.

Differential equations for dynamic modeling

- Governing equation



Mass 质量		Damping 阻尼		Spring 弹簧		Force 力

$$M\frac{d^2y(t)}{dt^2} + b\frac{dy(t)}{dt} + ky(t) = r(t)$$

Table 2.2 Summary of Governing Differential Equations for Ideal Elements

Type of Element	Physical Element	Governing Equation	Energy E or Power $\mathcal{P}$	Symbol
Inductive storage	Electrical inductance	$v_{21} = L\frac{di}{dt}$	$E = \frac{1}{2}Li^2$	v_2 L i v_1
	Translational spring	$v_{21} = \frac{1}{k}\frac{dF}{dt}$	$E = \frac{1}{2}\frac{F^2}{k}$	v_2 k v_1 F
	Rotational spring	$\omega_{21} = \frac{1}{k}\frac{dT}{dt}$	$E = \frac{1}{2}\frac{T^2}{k}$	ω_2 k ω_1 T
	Fluid inertia	$P_{21} = I\frac{dQ}{dt}$	$E = \frac{1}{2}IQ^2$	P_2 I Q P_1
Capacitive storage	Electrical capacitance	$i = C\frac{dv_{21}}{dt}$	$E = \frac{1}{2}Cv_{21}{}^2$	v_2 i C v_1
	Translational mass	$F = M\frac{dv_2}{dt}$	$E = \frac{1}{2}Mv_2{}^2$	F v_2 M $v_1 =$ constant
	Rotational mass	$T = J\frac{d\omega_2}{dt}$	$E = \frac{1}{2}J\omega_2{}^2$	T ω_2 J $\omega_1 =$ constant
	Fluid capacitance	$Q = C_f\frac{dP_{21}}{dt}$	$E = \frac{1}{2}C_fP_{21}{}^2$	Q P_2 C_f P_1
	Thermal capacitance	$q = C_t\frac{d\mathcal{T}_2}{dt}$	$E = C_t\mathcal{T}_2$	q $\mathcal{T}_2$ C_t $\mathcal{T}_1 =$ constant
Energy dissipators	Electrical resistance	$i = \frac{1}{R}v_{21}$	$\mathcal{P} = \frac{1}{R}v_{21}{}^2$	v_2 R i v_1
	Translational damper	$F = bv_{21}$	$\mathcal{P} = bv_{21}{}^2$	F v_2 b v_1
	Rotational damper	$T = b\omega_{21}$	$\mathcal{P} = b\omega_{21}{}^2$	T ω_2 b ω_1
	Fluid resistance	$Q = \frac{1}{R_f}P_{21}$	$\mathcal{P} = \frac{1}{R_f}P_{21}{}^2$	P_2 R_f Q P_1
	Thermal resistance	$q = \frac{1}{R_t}\mathcal{T}_{21}$	$\mathcal{P} = \frac{1}{R_t}\mathcal{T}_{21}$	$\mathcal{T}_2$ R_t q $\mathcal{T}_1$

Frequency-domain & time-domain expressions

$$M\frac{d^2y(t)}{dt^2} + b\frac{dy(t)}{dt} + ky(t) = r(t)$$

- Transfer function 传递函数
  - Describing the dynamic relationship of the system in the **frequency domain 频域**

Laplace transform

$$Ms^2Y(s) + bsY(s) + kY(s) = R(s)$$

Input/output relation

$$\frac{\text{Output}}{\text{Input}} = \text{G}(s) = \frac{Y(s)}{R(s)} = \frac{1}{Ms^2 + bs + k}$$

- State variable & state equation 状态变量与状态方程
  - describing the present configuration of a system in the **time domain 时域**

Define state vector

$$\mathbf{x} = \begin{bmatrix} y(t) \\ \dot{y}(t) \end{bmatrix}$$

input vector

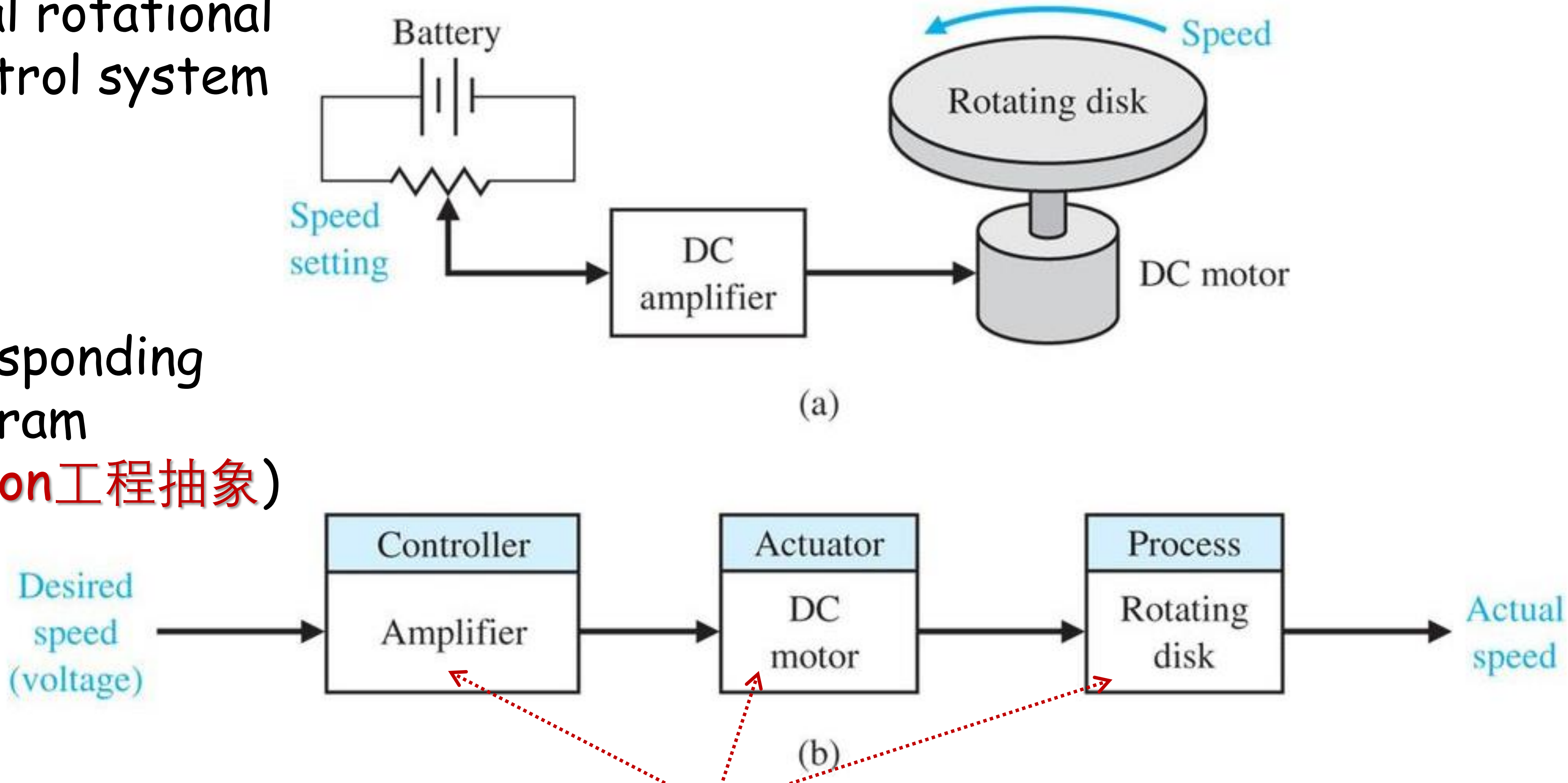
$$\mathbf{u} = \begin{bmatrix} 0 \\ r(t) \end{bmatrix}$$

$$\dot{\mathbf{x}} = \frac{1}{M}\begin{bmatrix} 0 & 1 \\ -k & -b \end{bmatrix}\mathbf{x} + \frac{1}{M}\begin{bmatrix} 0 \\ 1 \end{bmatrix}\mathbf{u}$$

Block diagram 框图

A practical rotational speed control system

The corresponding block diagram (abstraction工程抽象)

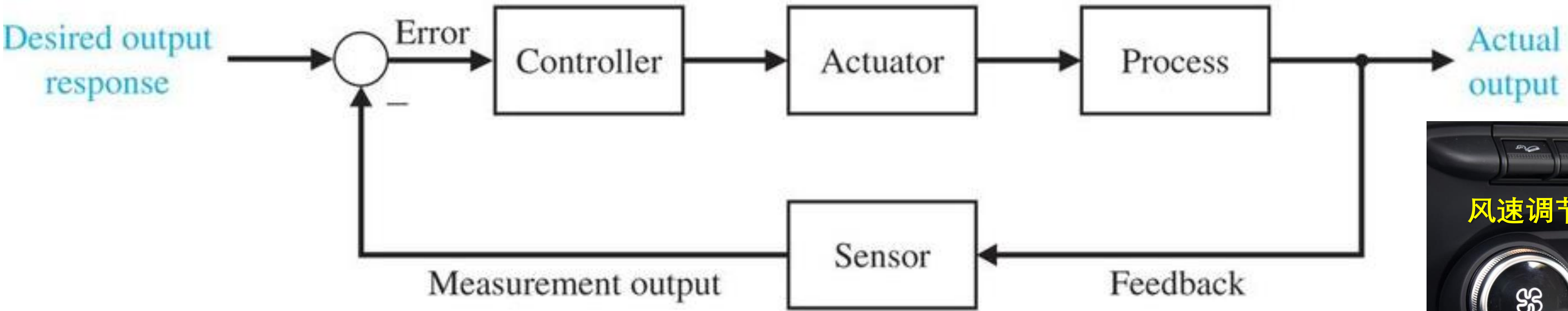


Representing a time-domain or frequency-domain (mathematical) model

Feedback control system

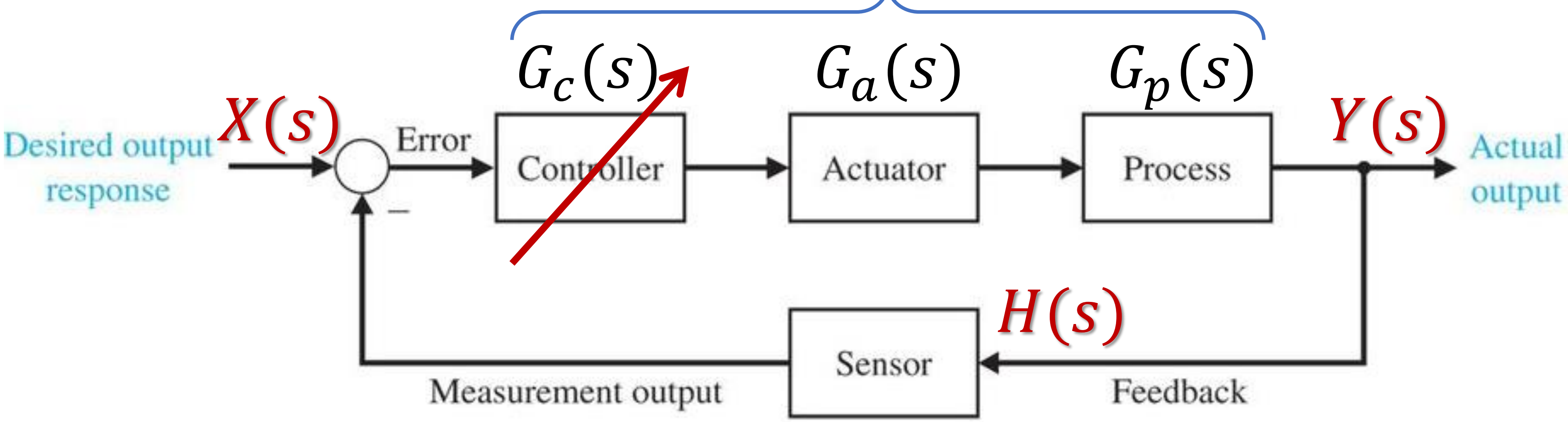
- Open-loop system 开环系统

- Close-loop system 开环系统



Mathematical model of feedback control system

$$G(s) = G_c(s)G_a(s)G_p(s)$$



Tuning the close-loop system characteristics by changing the controller characteristics

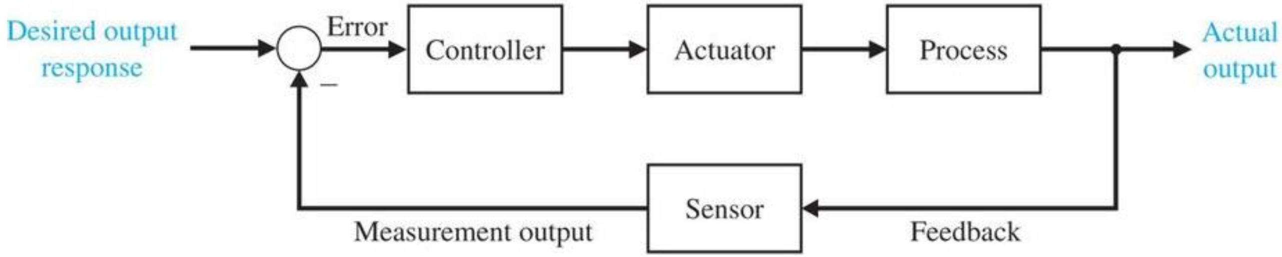
通过改变控制器的特性实现对闭环系统整体动态特性的调整

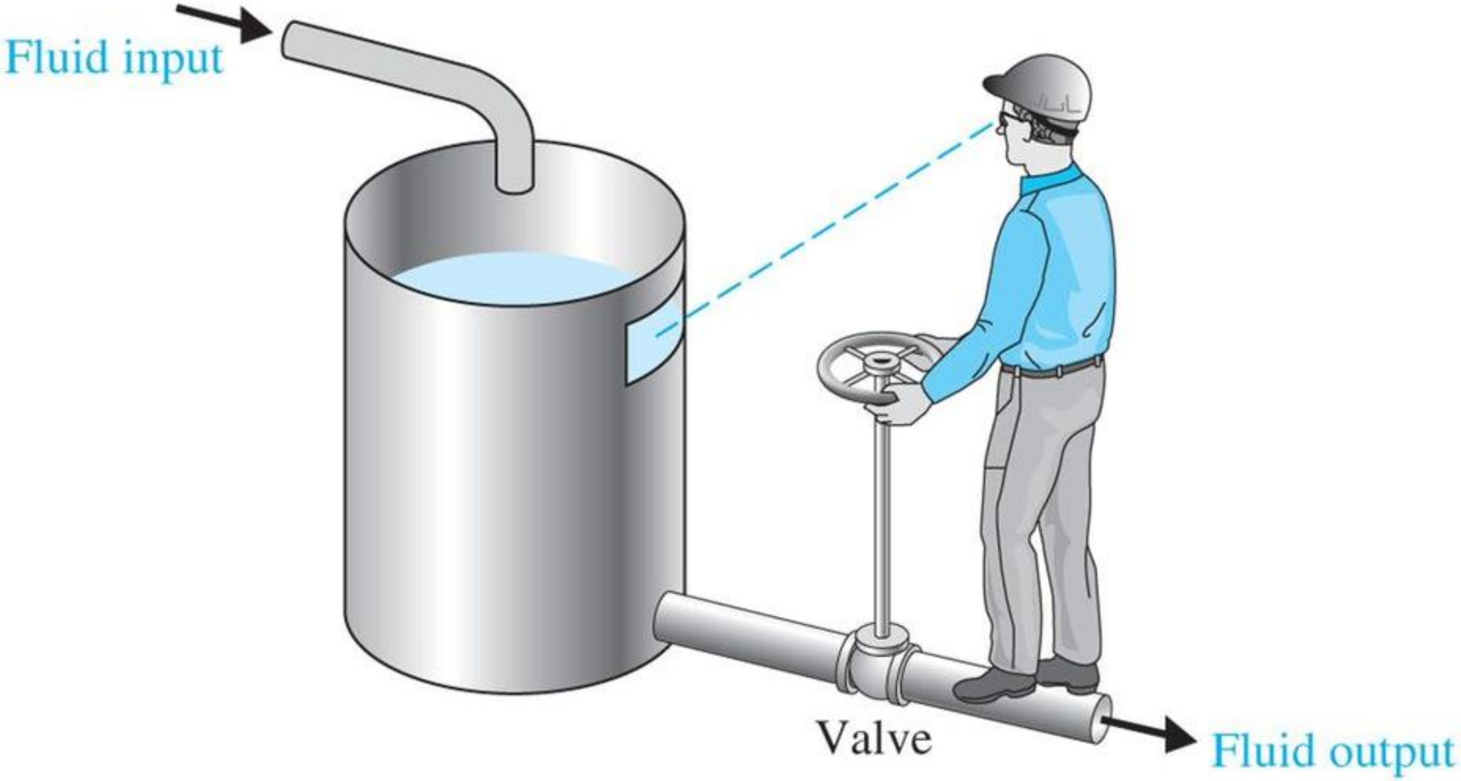
Open-loop gain $\frac{Y(s)}{X(s)} = G(s)$

Close-loop gain $Y(s) = G(s)[X(s) - H(s)Y(s)] \Rightarrow \frac{Y(s)}{X(s)} = \frac{G(s)}{1 + G(s)H(s)}$

Example 1: manual control system

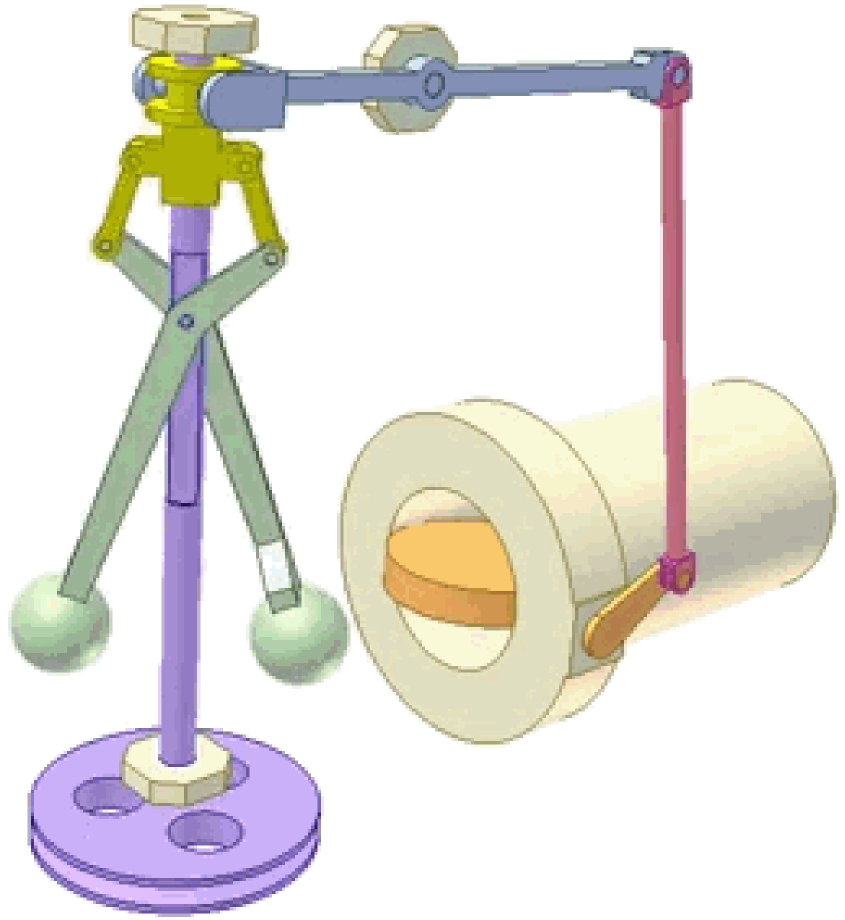
- In this manual control valve system, which one corresponds to the
  - Process
  - Actuator
  - Sensor
  - Controller
  - Desire output
  - Actual output
  - Error



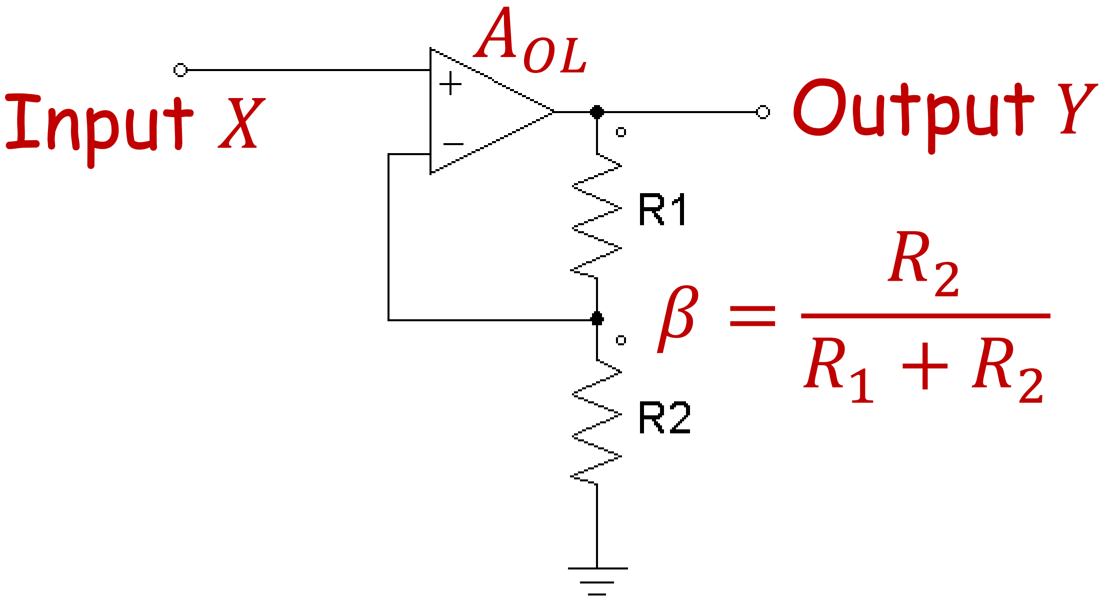


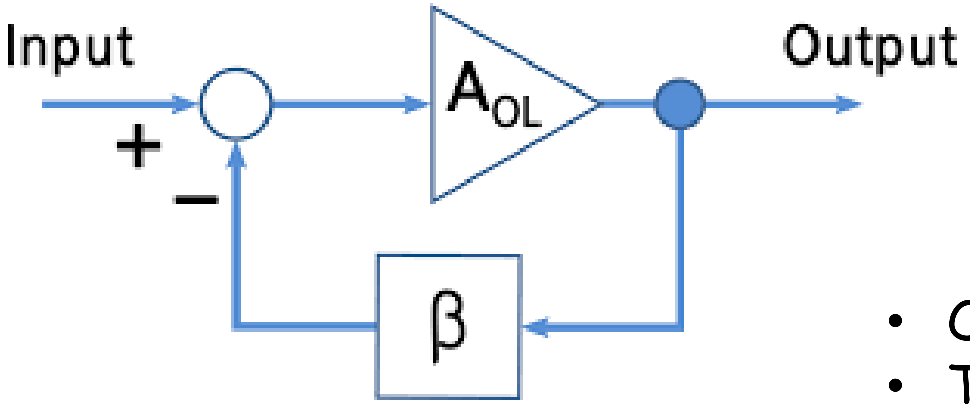
Example 2: Centrifugal governor

- A centrifugal governor is a specific type of governor with a feedback system that controls the speed of an engine by regulating the flow of fuel or working fluid, so as to maintain a near-constant speed.
- It uses the principle of proportional control
- James Watt designed his first governor in 1788 following a suggestion from his business partner Matthew Boulton



Example 3: Feedback amplifier



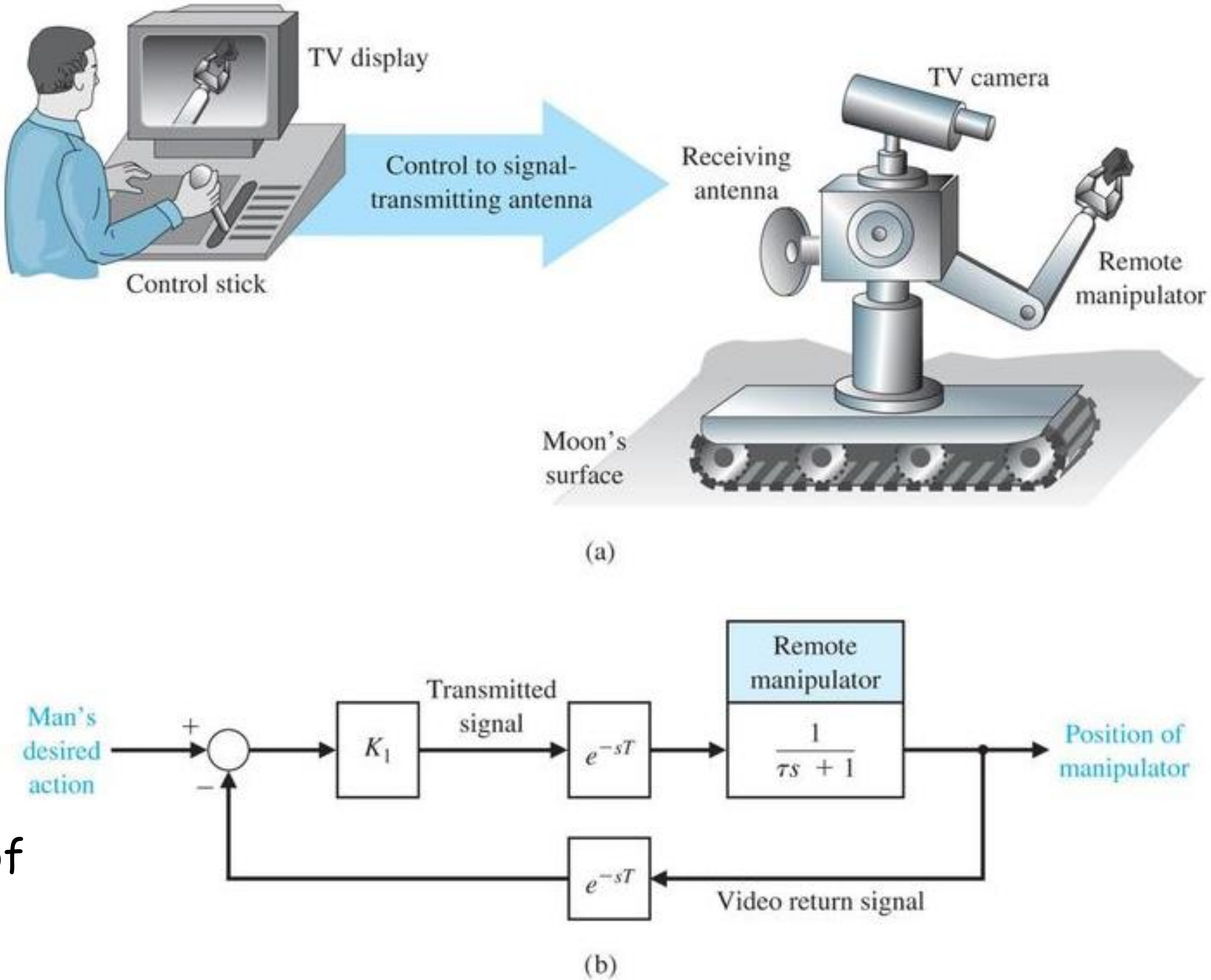


$$Y = A(V_+ - V_-)$$
$$= A(X - \beta Y)$$

$$\frac{Y}{X} = \frac{A}{1 + A\beta}$$
$$\approx \frac{1}{\beta} \quad \text{(when } A \gg 1\text{)}$$

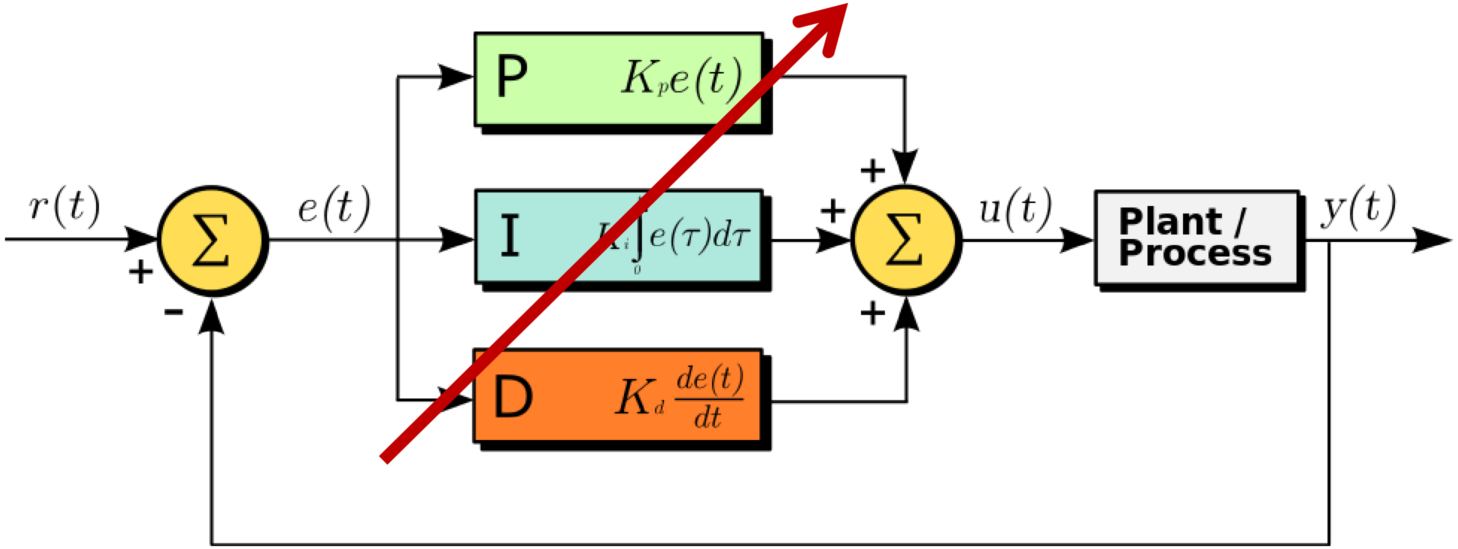
- Only considered the DC characteristics 静态增益
- The AC characteristics are more complicated

Example 4: Moon robot



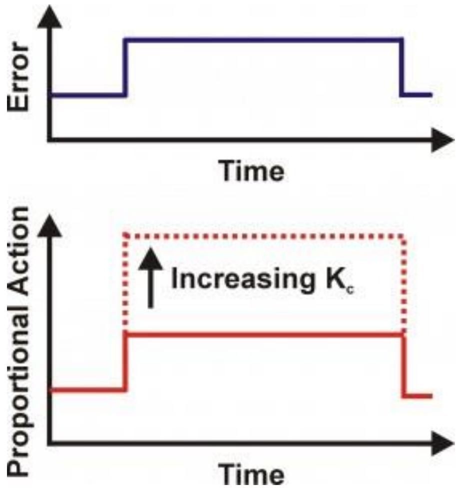
e^{-sT} models the time delay T in transmission of a communication signal

PID (比例、积分、微分) controller

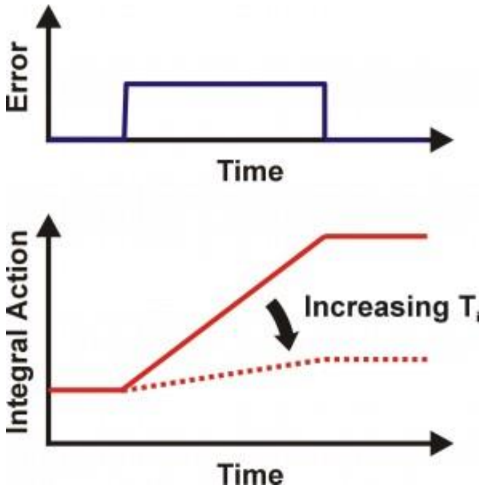


PID控制理论是由观察舵手的动作而来

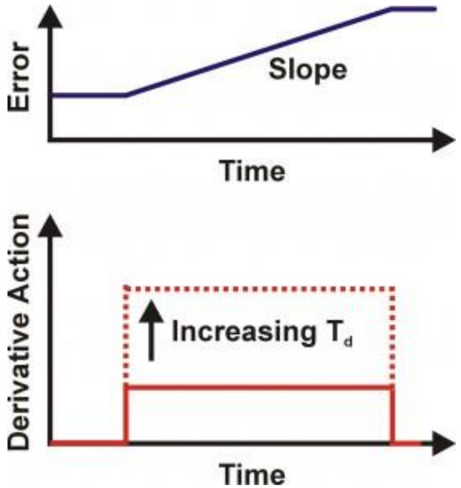
Current error 现在



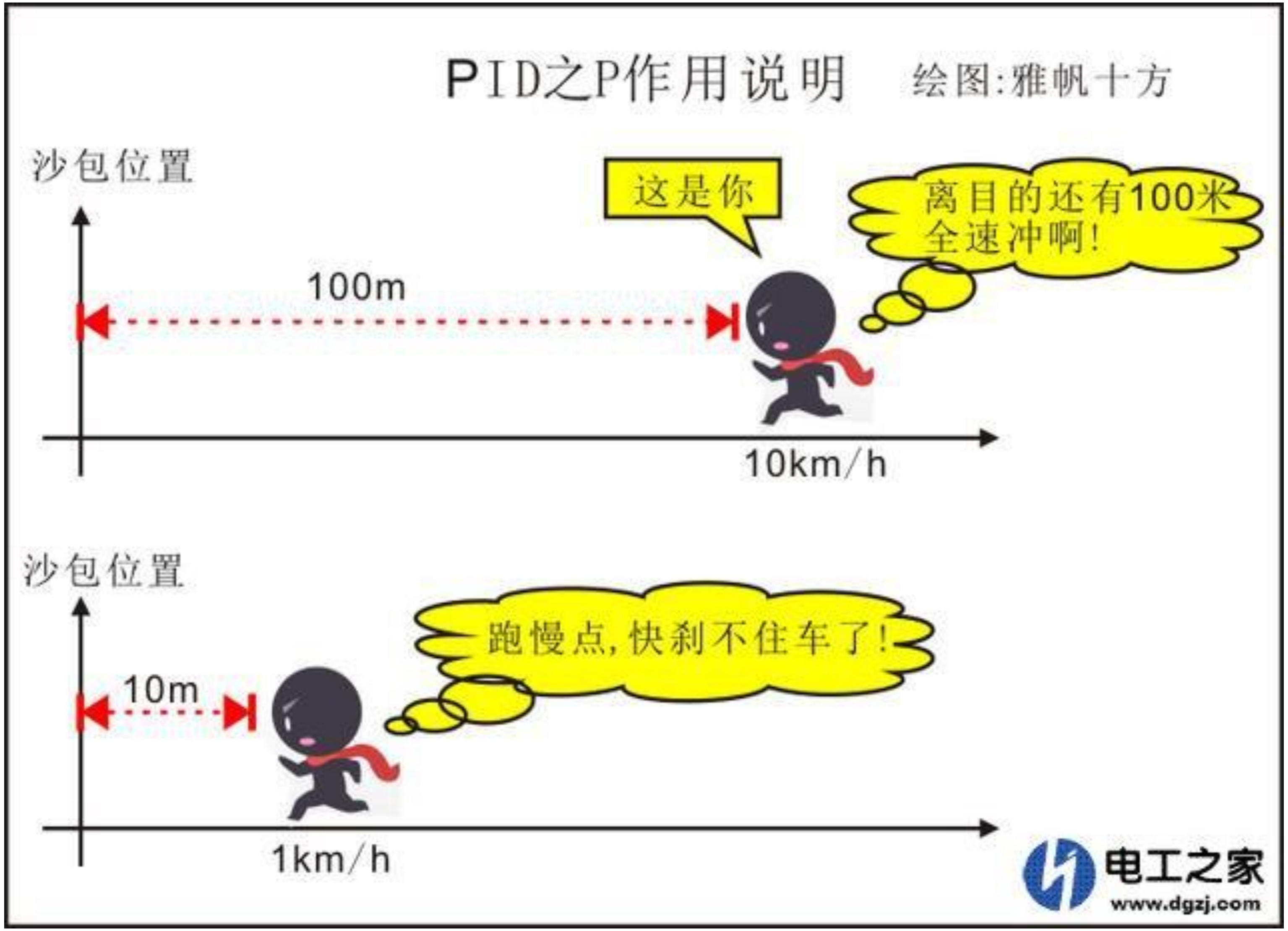
Past error 过去



Future error 未来



PID controller



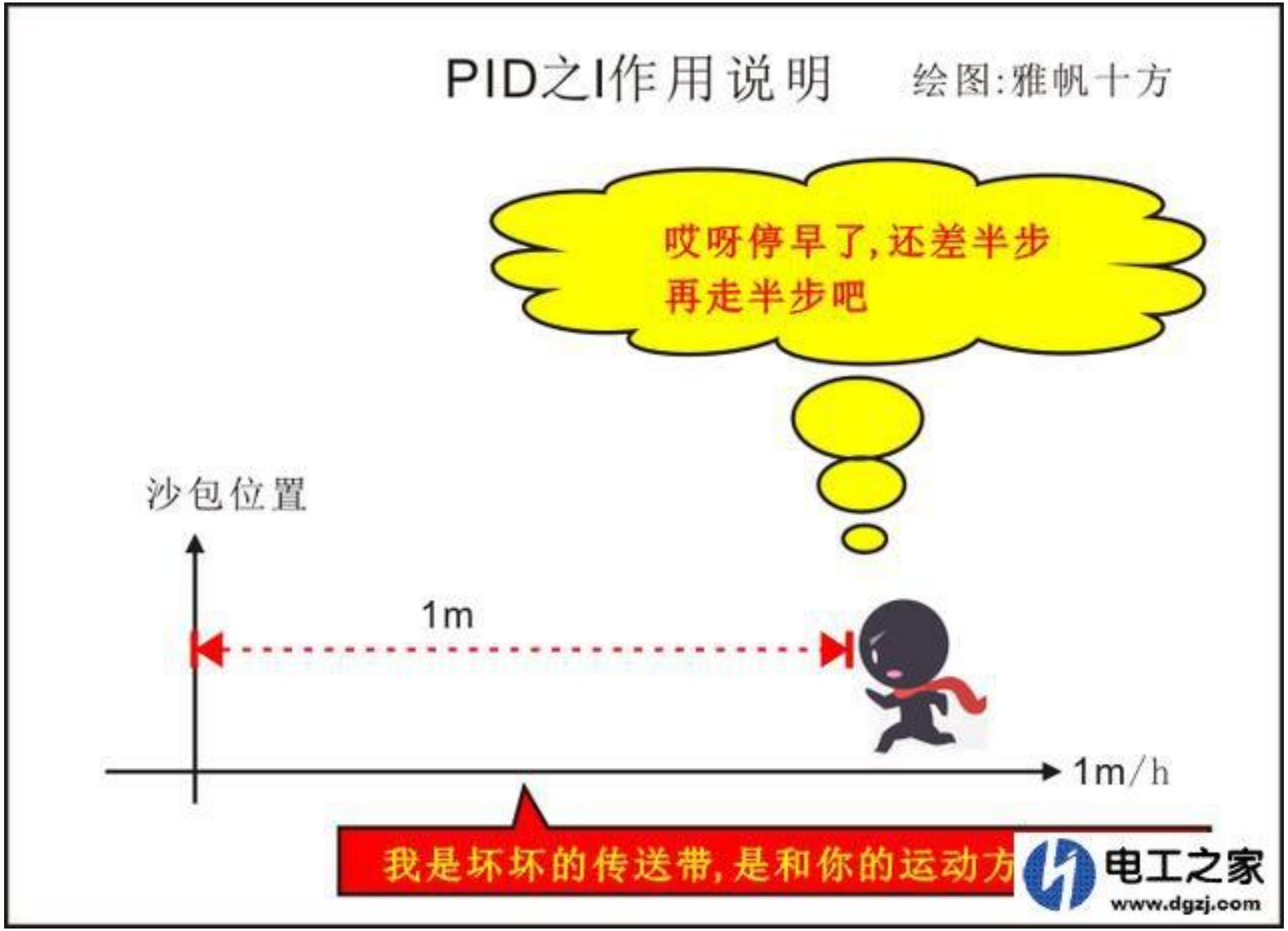
Proportional

比例控制

考虑当前误差

(https://www.dgzj.com/gongkong/99984.html)

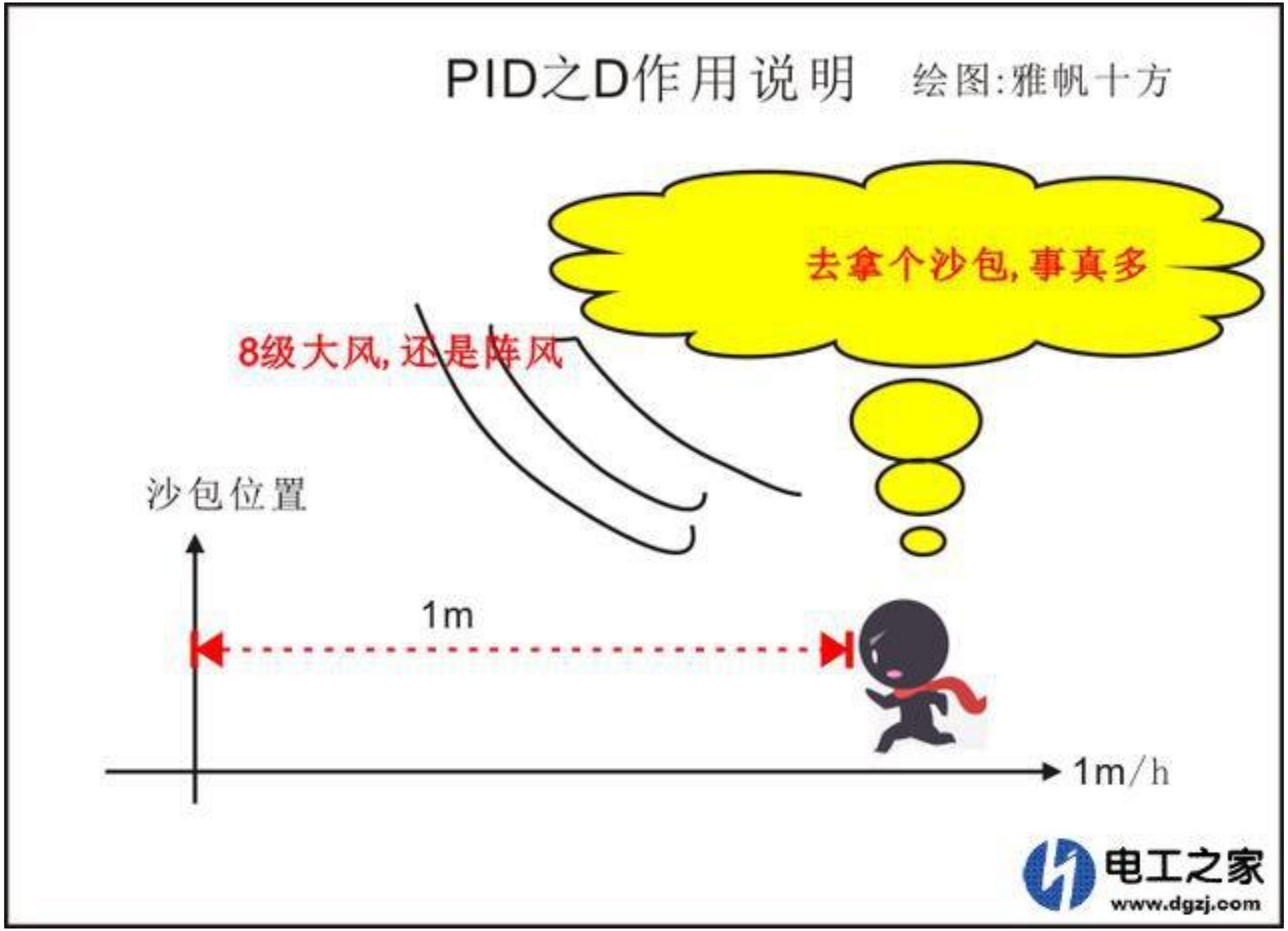
PID controller



Integral
积分控制
考虑过去误差

(https://www.dgzj.com/gongkong/99984.html)

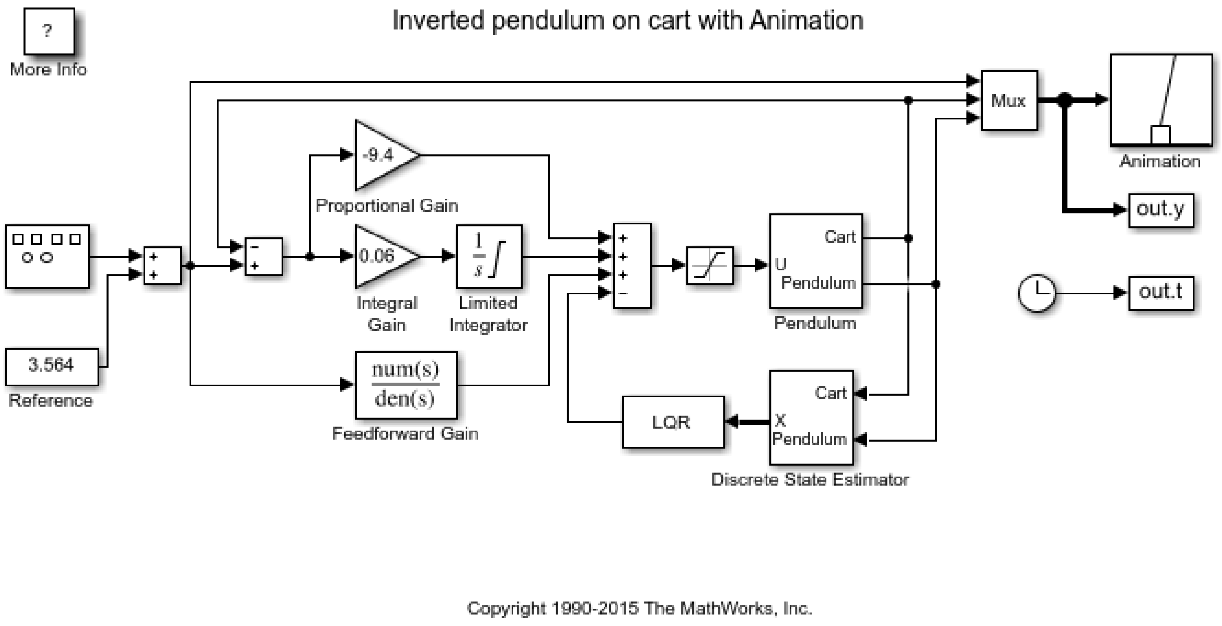
PID controller

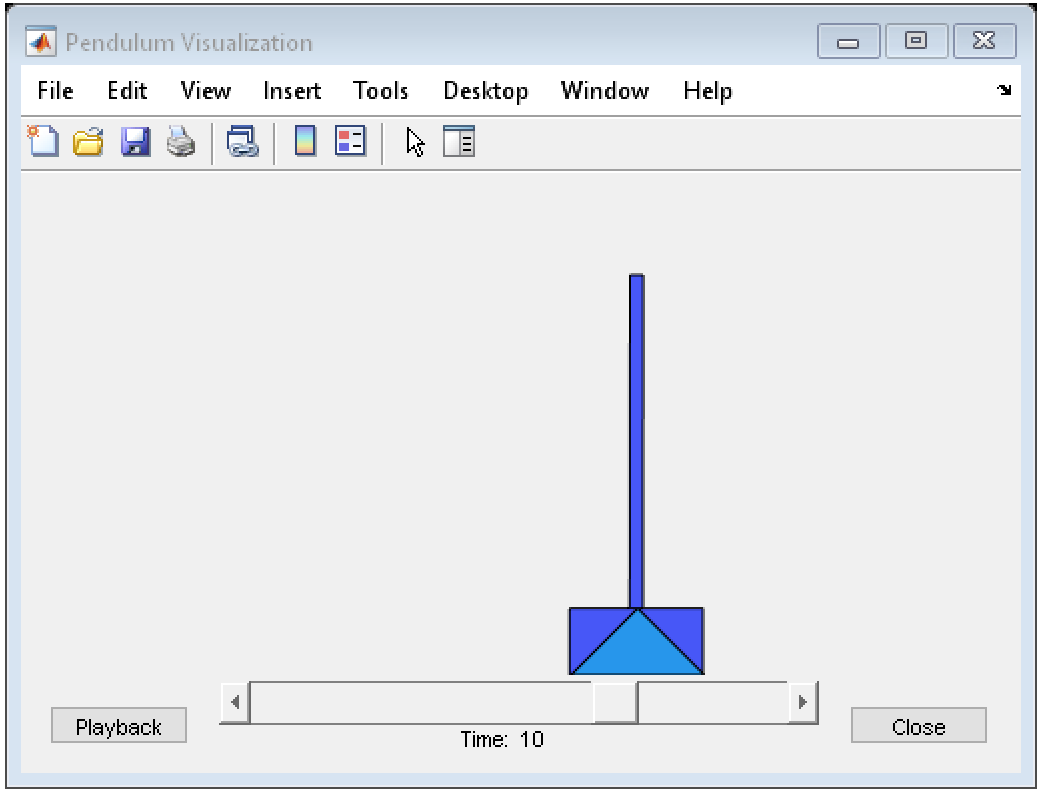


(https://www.dgzj.com/gongkong/99984.html)

Derivative
微分控制
考虑将来误差

Inverted pendulum example in Matlab



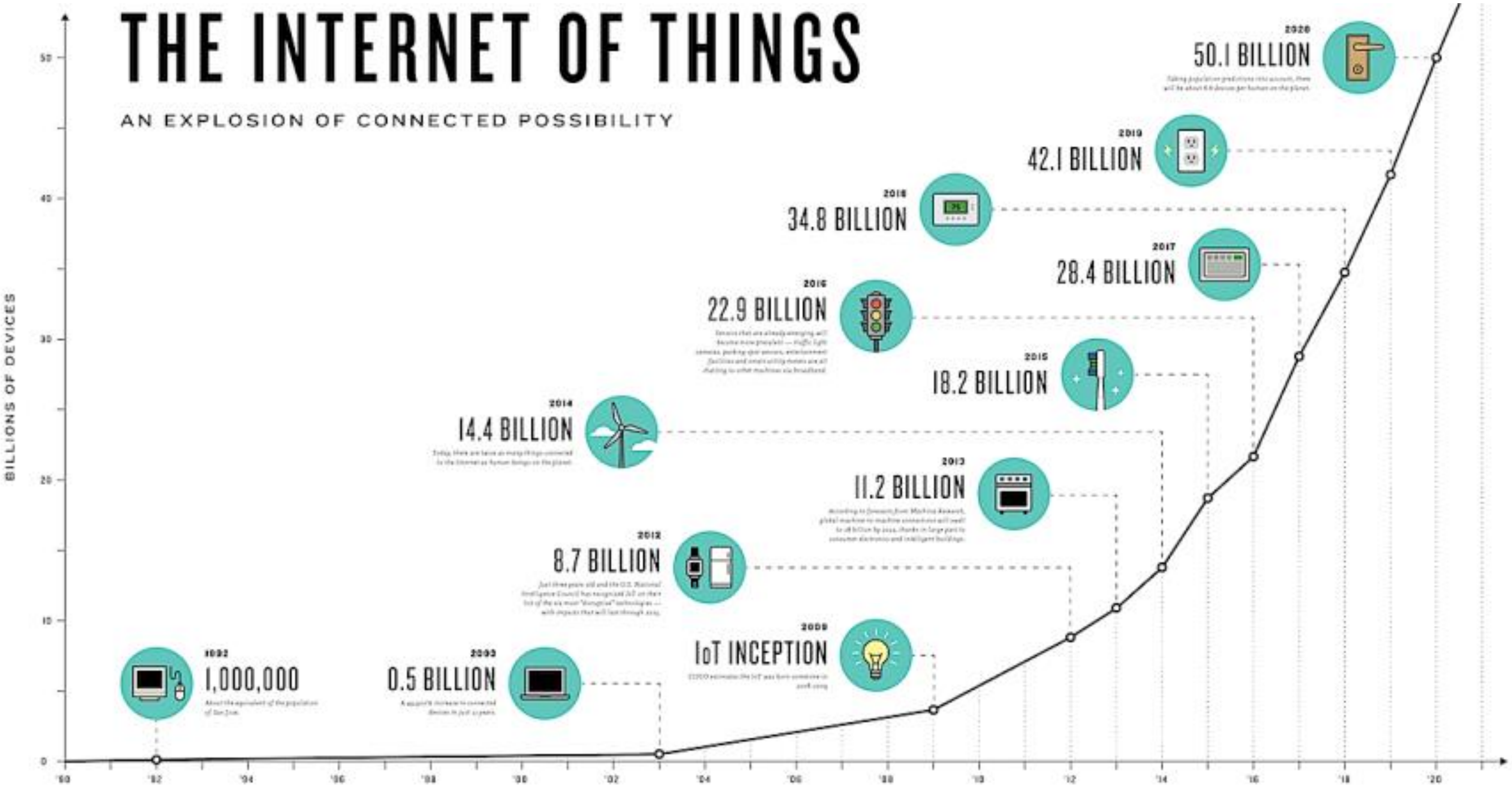


Key in the command:

\>> openExample('simulink_general/penddemoExample')

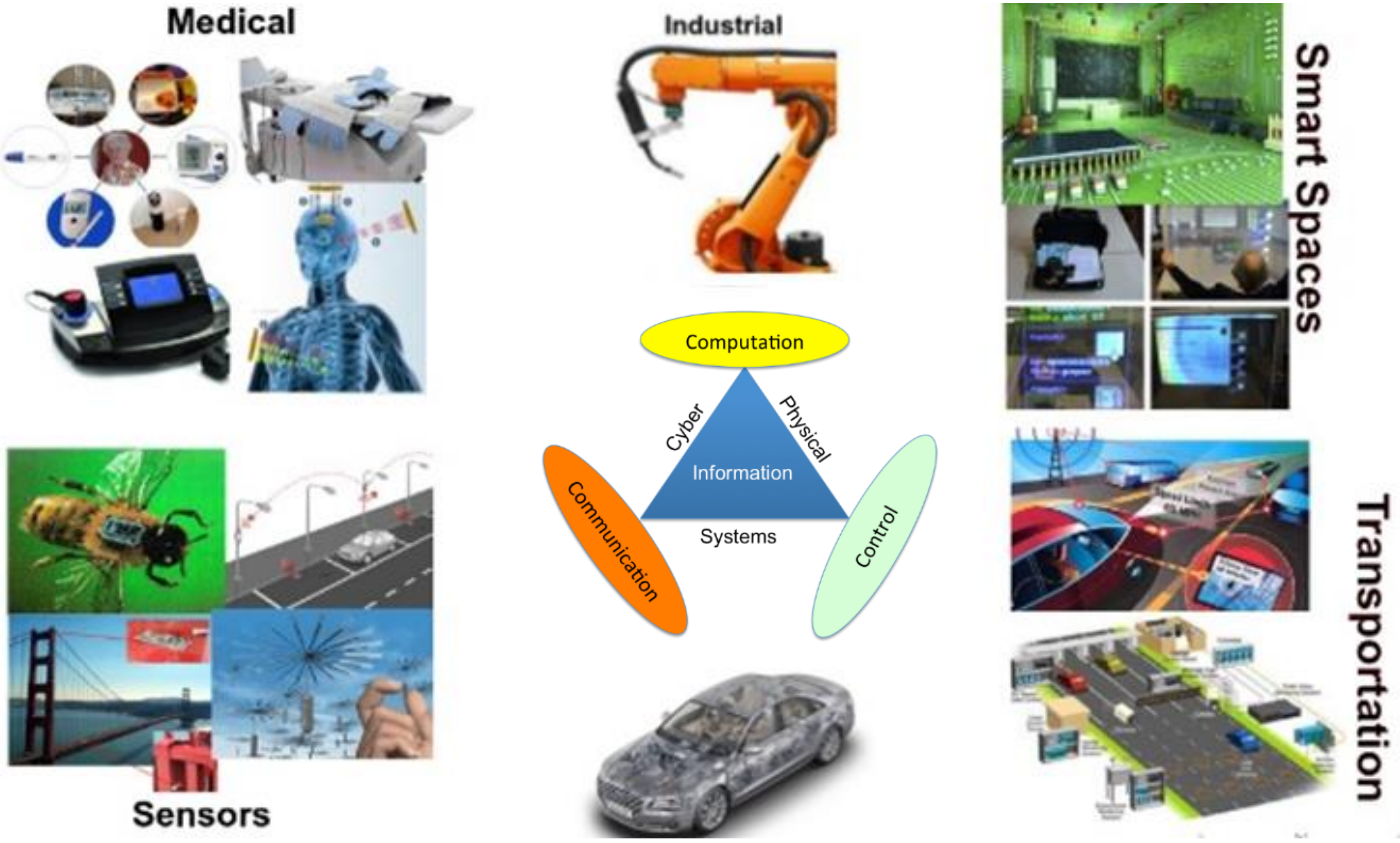
Internet of Things (IoT) 物联网

- The Internet of Things (IoT) is the internetworking of physical devices, vehicles, buildings, and other items—embedded with electronics, software, sensors, actuators, and network connectivity that enable these objects to collect and exchange data



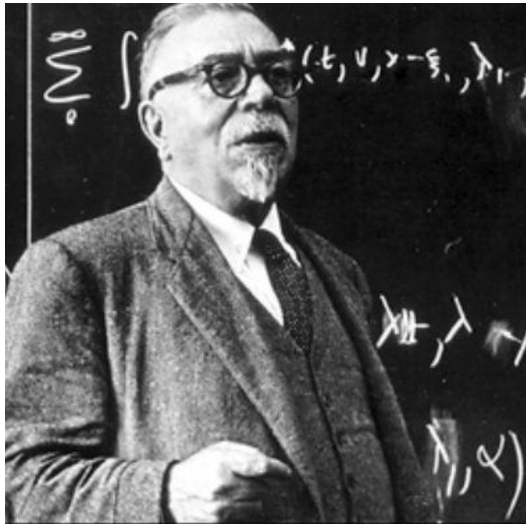
Cyber Physical Systems (CPS) 信息物理系统

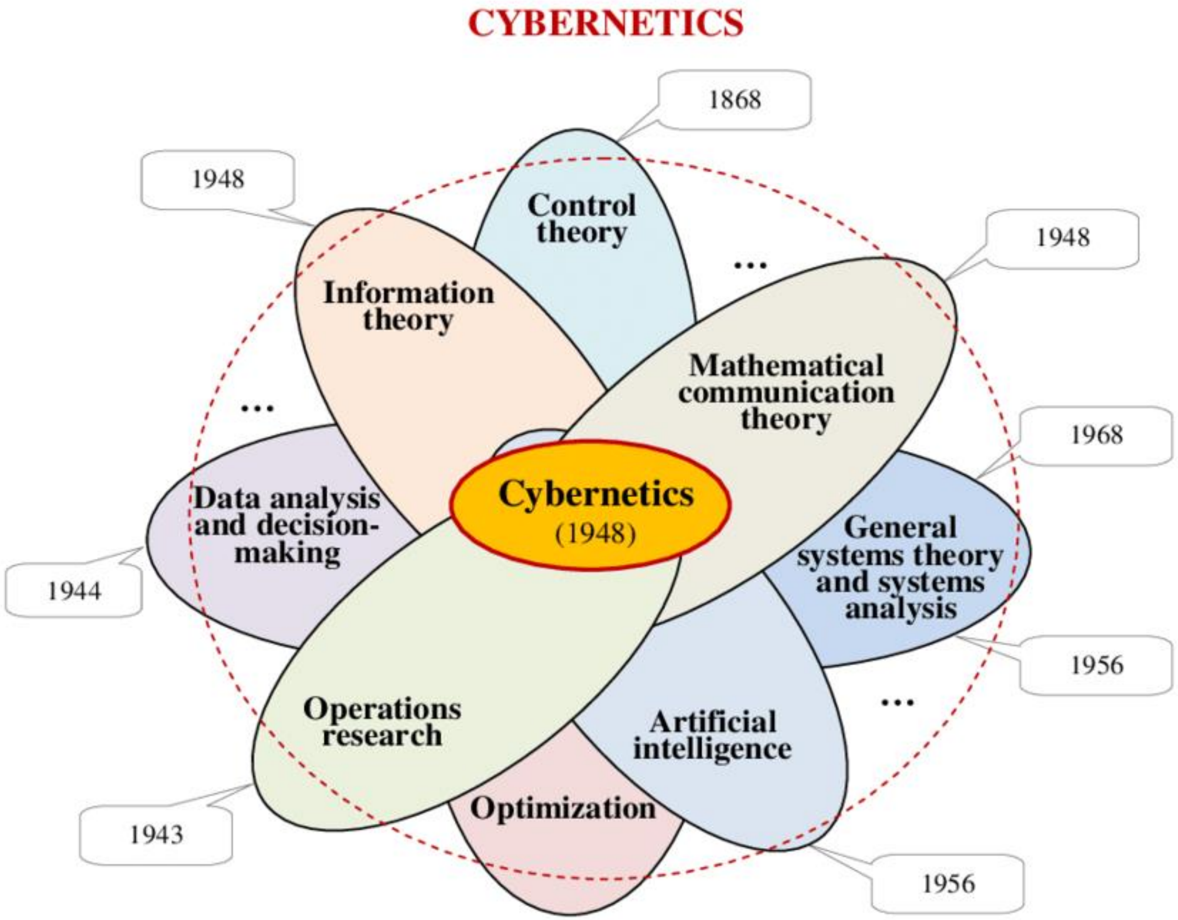
- In cyber-physical systems, physical and software components are deeply intertwined, able to operate on different spatial and temporal scales, exhibit multiple and distinct behavioral modalities, and interact with each other in ways that change with context.



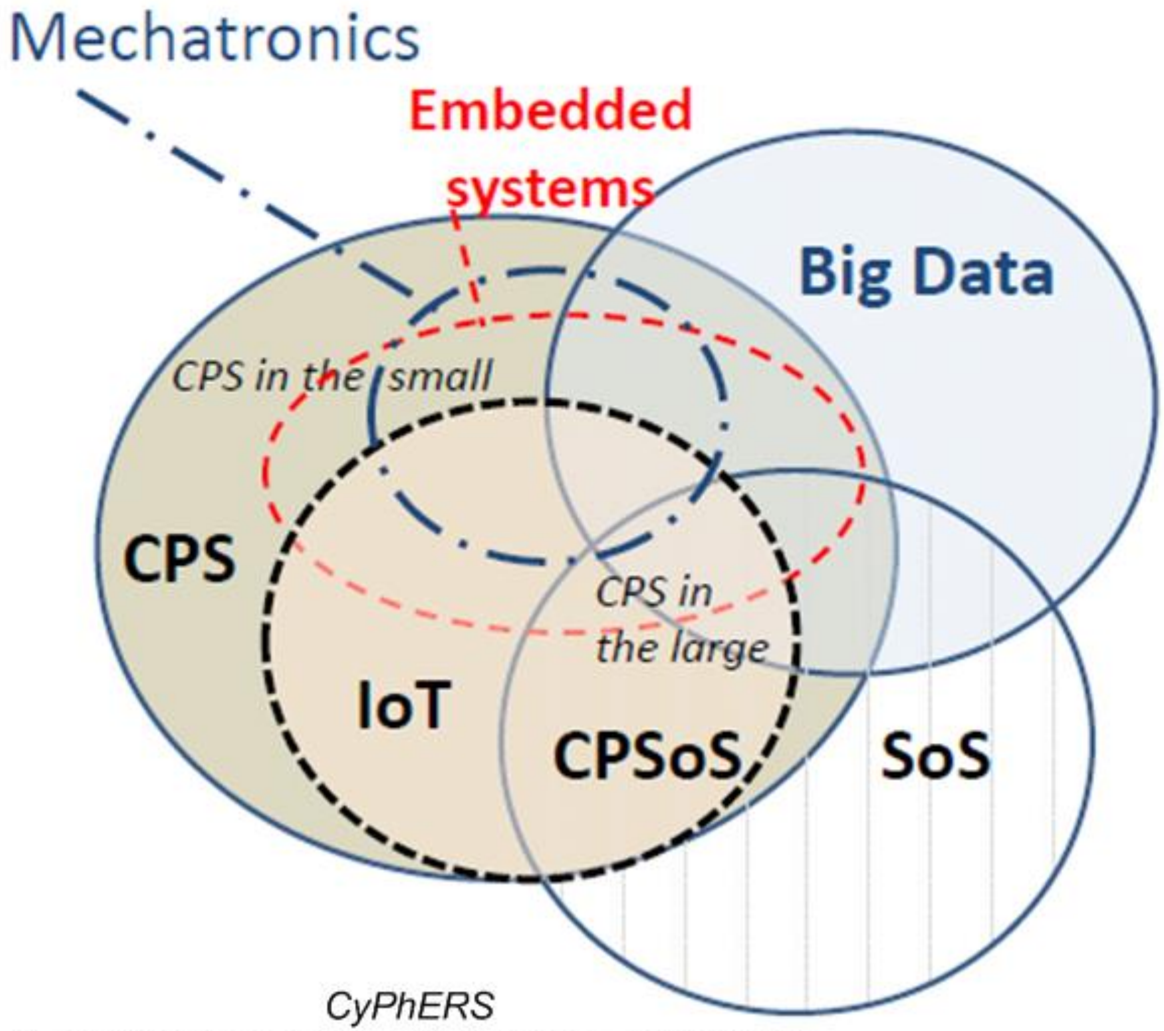
Cybernetics 控制论

- Cybernetics is a transdisciplinary approach for exploring regulatory systems 调节系统—their structures, constraints, and possibilities.
- Norbert Wiener 维纳 defined cybernetics in 1948 as "the scientific study of control and communication in the animal and the machine."





The future trend of CPS



CyPhERS
Cyber-Physical European Roadmap & Strategy
CPS: Significance, Challenges and Opportunities
http://www.cyphers.eu/sites/default/files/D5.2.pdf

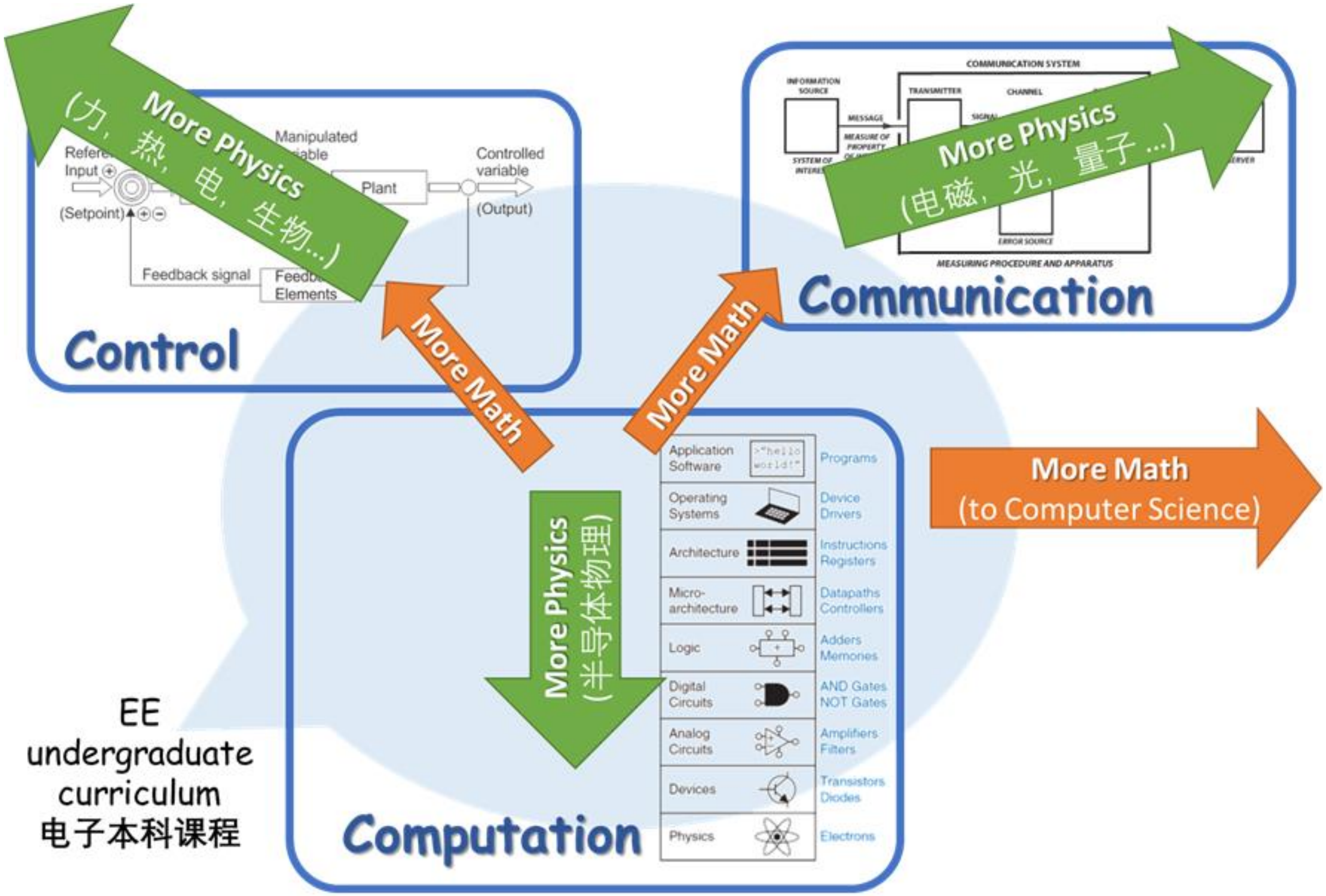
- Embedded systems 嵌入式系统
- Internet of Things (IoT) 物联网
- Industrial Internet 工业互联网
- System of systems (SoS) 系统集成
- Industry 4.0 工业4.0
- Internet of Everything (IoE) 万物互联
- Smart Everything 智能万物

≈ Cyber-physical systems 信息物理系统

Getting ready for your future study

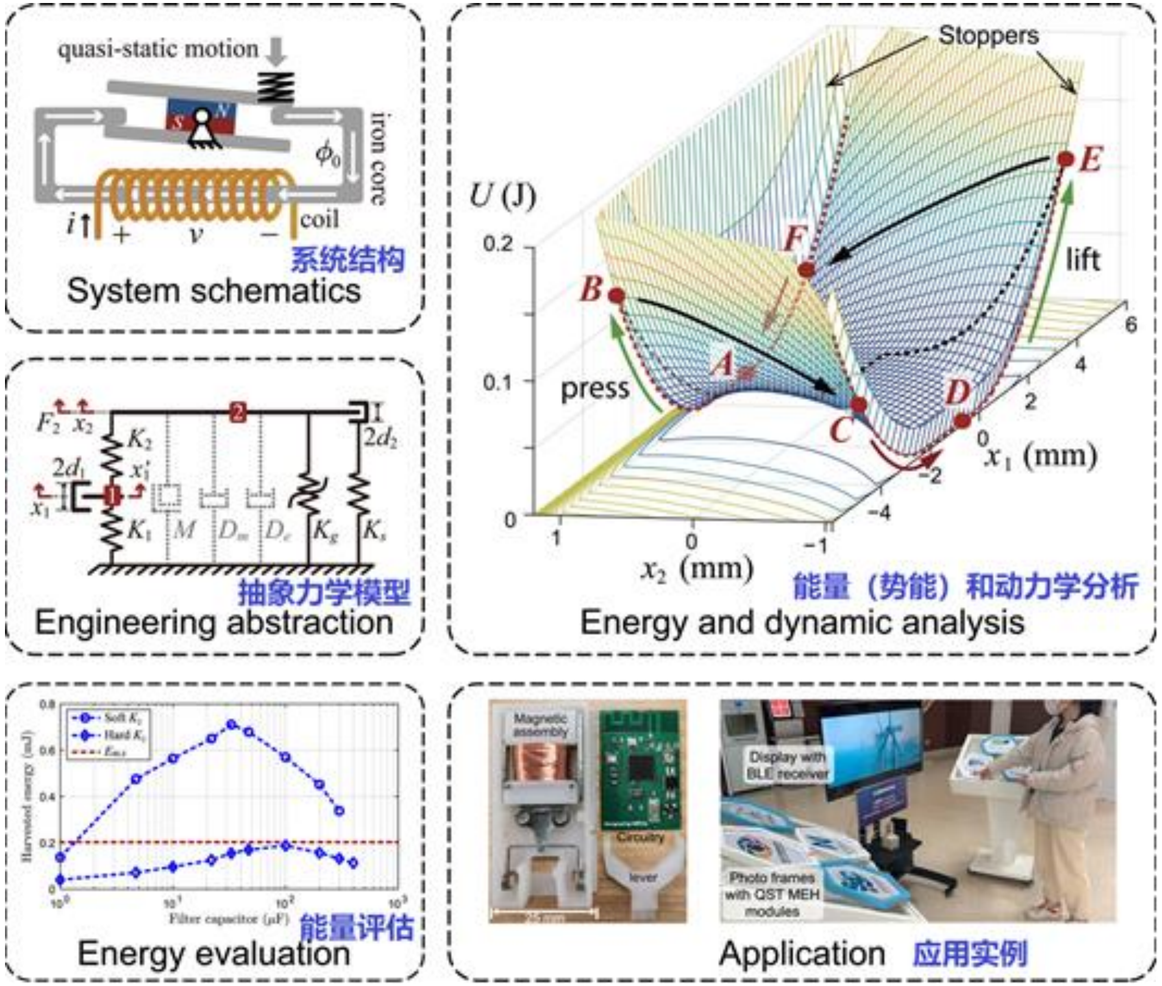
- The emphases on (3C)
  - computation 计算,
  - control 控制, and
  - communication 通信

  in our EE curriculum



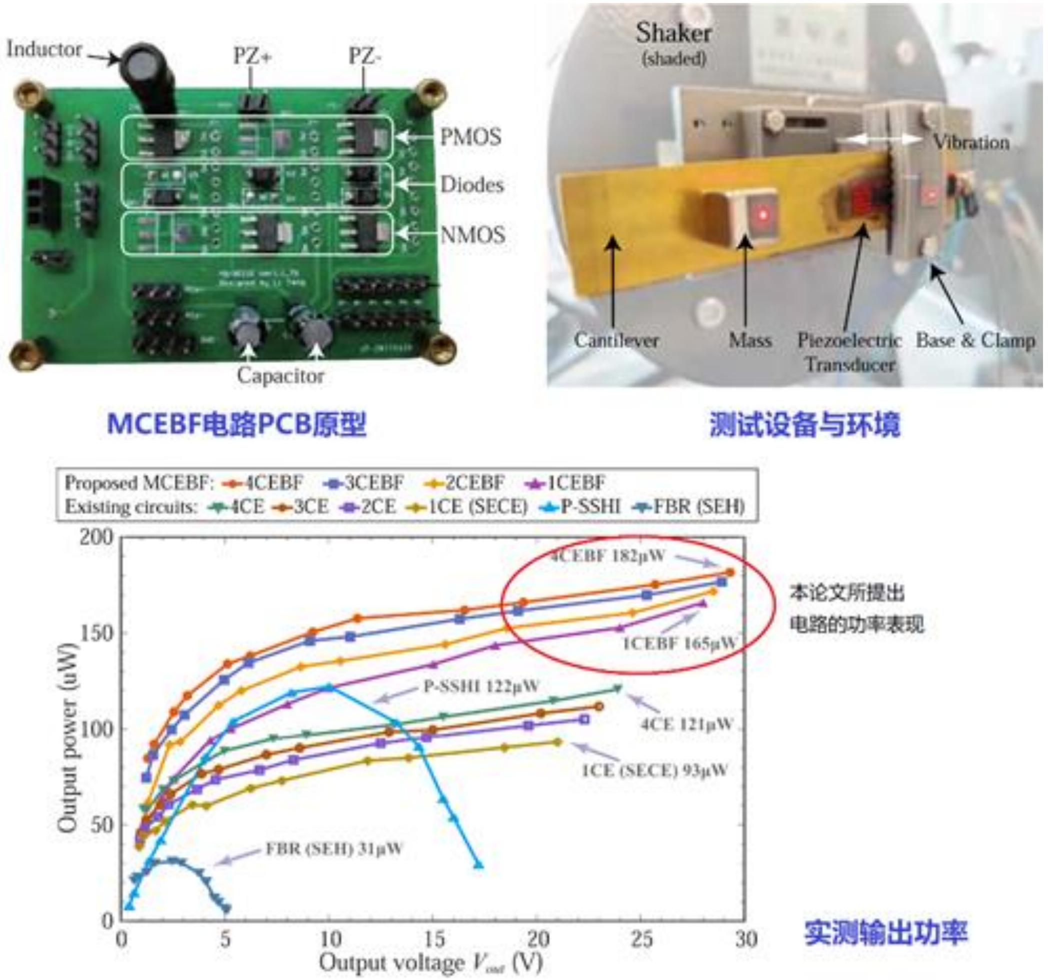
METAL课题组

- 机械设计



(Liu et al., Nano Energy 2022)

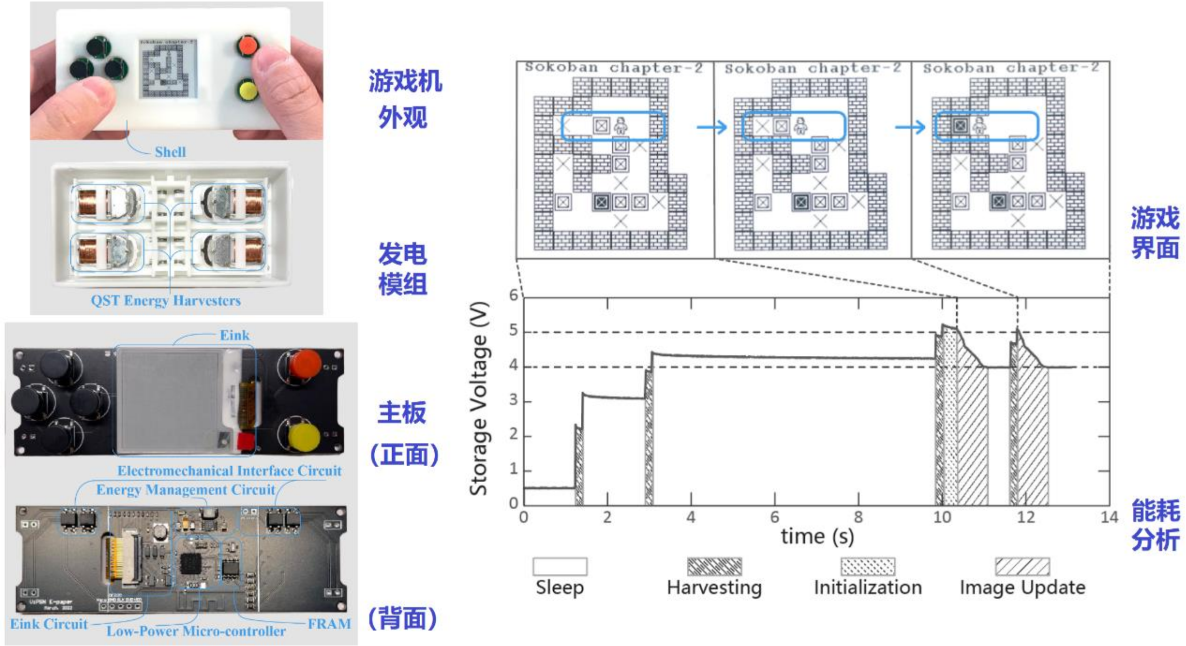
- 电路设计



(Teng et al., IEEE JESTPE 2022)

METAL课题组

- 超低功耗计算系统设计
  - 无电池电子游戏机
    Motion-powered Gameboy



(Zhu et al., ACM SenSys 2022)

- 无源物联网科普介绍（@bilibili）

Independent Study

High-school style 中学模式	University style 大学模式
Specific space (固定教室)	Open environment (开放式环境)
A few subjects (科目少)	Many subjects (许多科目)
Repeating contents (反复复习)	Few recitation (极少重复)
Monotonous media (媒介单一)	Multi-media (多种媒介)
Learning for exams (在考中学)	Learning by doing (尝试在做中学)
Single purpose (高考独木桥)	Diversity (出路差异化)
知识改变命运	见识决定宽度，能力决定高度

(Pictures are from the Internet)