Keynote Speech

# Key Steps Toward Development of Humanoid Robots

## Acknowledgement

This research is mainly financed by the grants from Future Systems Directorate, Singapore Government

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# ABOUT NTU

## Vision and Mission

**A great global university founded on science and technology, nurturing leaders and creating societal impact through interdisciplinary education and research.**

## Leadership


**Professor Ho Teck Hua**
President and Distinguished University Professor

**Professor Christian Wolfrum**
Deputy President and Provost

## Ranked Among the Best in the World

- 3rd — Nature Index Young University Rankings
- 1st — Times Higher Education Young University Rankings
- 3rd — US News and World Report Best Global Universities in Asia
- 4th — Times Higher Education Asia University Rankings
- 15th — QS World University Rankings
- 4th — QS Asia University Rankings
- 27th — US News and World Report Best Global University Rankings
- 30th — Times Higher Education World University Rankings
- 10th — QS World's Most Photogenic Universities

## Ranked Among the Best in the World

## NTU 2025 Strategic Plan

**NTU 2025 reinforces NTU's strong commitment to the four core pillars of the University:**

- Education
- Research
- Innovation
- Community


**Addressing humanity's grand challenges:**

- Mitigating our impact on the environment
- Harnessing the science, art and technology of learning
- Addressing technology's impact on humanity;
- Responding to the needs and challenges of healthy living and ageing

## 15-Year Sustainability Manifesto

### Solidifying the University's position as a global leader in sustainability

- NTU's sustainability manifesto goals: carbon neutrality by 2035, halve net energy utilisation and new sustainability courses
- First university in the world to launch a sustainability-linked bond with an AAA credit rating from Moody's
- Sustainable campus with eight zero-energy buildings, the most amongst organisations in Singapore
- Home to two of Asia's largest wooden buildings, Gaia and The Wave
- Winner of ISCN's Whole Systems Approach Excellence Award in recognition of sustainable practices in the areas of research, education, community engagement, and infrastructure developments

## Main Campus

200 hectares

State-of-the-art-facilities

25 halls of residence

**The NTU Smart Campus is a living testbed of tomorrow's technologies and frequently named among the most beautiful campuses in the world.**

## Medical Campus


School of Medicine

Learning and research

Sports and recreation

**Home to the Lee Kong Chian School of Medicine in Novena, Singapore's healthcare district. The school aims to be a model for innovative medical education and a centre for transformative research.**

## At a Glance


**35,400 students**

24,800 undergraduates
10,600 postgraduates

**8,000**

faculty, researchers and staff from 73 countries

**300,900 alumni**

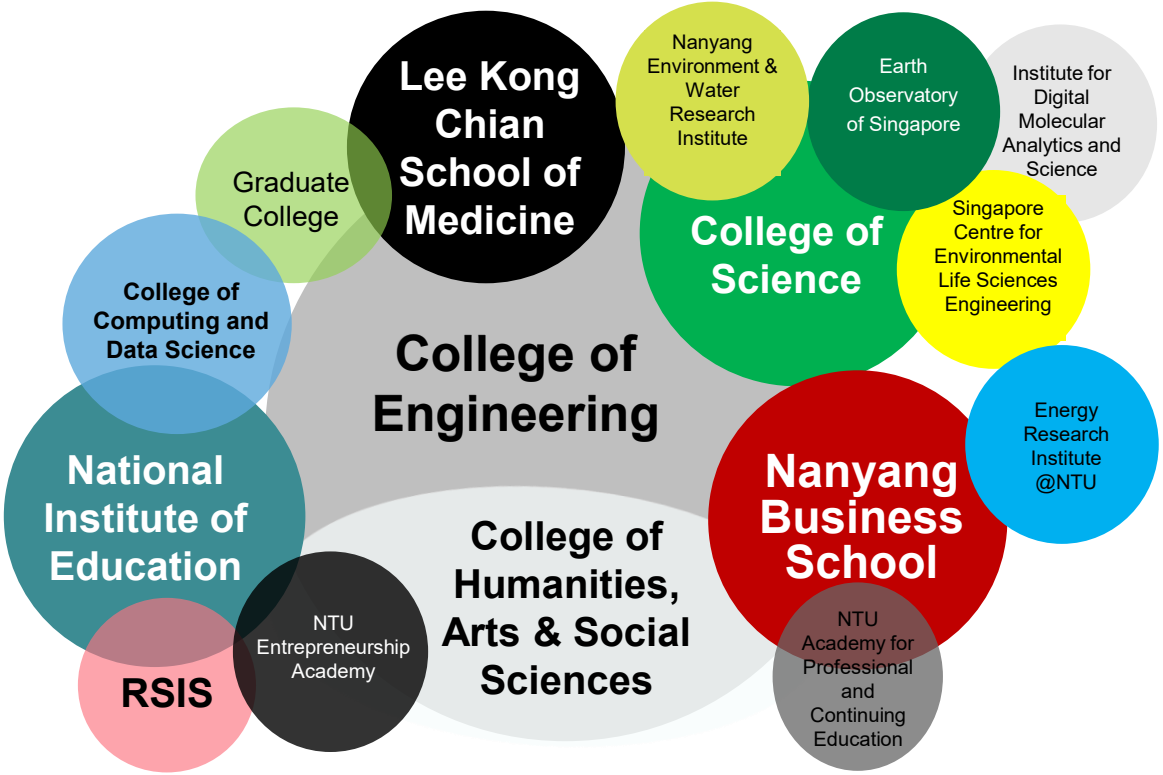
representing 172 nationalities

## At a Glance

**6**
**Colleges**

**15**
**Schools**

**World-class institutes & research centres**



## NTU Academy for Professional and Continuing Education

- Consolidates continuing education and training capabilities and expertise within the University
- Enriches the lifelong learning experience of adult learners, including the University's alumni, making it easier for them to take charge of their own continuing education
- The FlexiMasters programme for continuing education at the Master's degree level, launched in 2020, has grown to more than 35 curricular offerings from all parts of the University

## Global Alliance of Industries @ NTU


- Catalysing new university-industry partnerships through multiple consortia, corporate laboratories, multidisciplinary institutes and technology invention disclosures
- Over 250 industry partners and 20 corporate and joint labs with global entities such as Alibaba, Continental, Hewlett-Packard, Nanofilm Technologies, Rolls-Royce and Schaeffler

## Top Industry Partners

## Top Academic Partners


UC Berkeley

Northeastern University


Australian National University


University of British Columbia


Imperial College London

Karolinska Institute


TUM


Seoul National University


Indian Institute of Technology, Madras


University of Toronto


Tsinghua University


University of Pennsylvania

NANYANG TECHNOLOGICAL UNIVERSITY

## School of Mechanical & Aerospace Engineering

Design, Machine, Control, Intelligence


# Welcome You to NTU

# ABOUT SPEAKER

Professor Xie Ming has been:

- Dean/Professor, School of Electrical Engineering and Control Science, Nanjing Tech University, China.
- Guest Professor, Huazhong University of Science and Technology, China.

Professor Xie Ming is now:

- President, Robotics Society of Singapore
- Editor-in-Chief, International Journal of Humanoid Robotics.
- Associate Professor, Nanyang Technological University, Singapore.

Professor Xie Ming has published:

- Three books in English
- Two edited books in English
- Two books in Chinese
- Over 40 International Journal Papers
- Over 100 International Conference Papers

Professor Xie Ming has received many awards and over 10 granted patents.

# Ming XIE

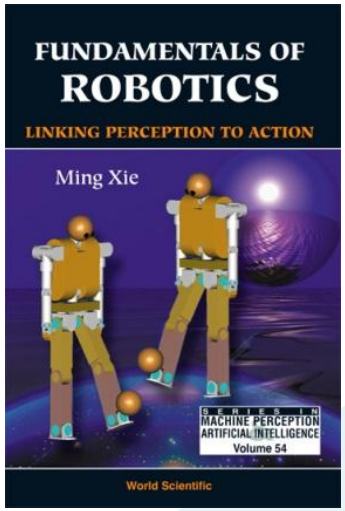
**Associate Professor (1999 - present)**
**http://personal.ntu.edu.sg/mmxie**

1984: B.Eng (China)
1986: Msc (France)
1989: Ph.D (France)

Recipient of
Chinese Government's
Overseas Scholarship
(1984 - 1989)

Knowledge
Innovation

2003

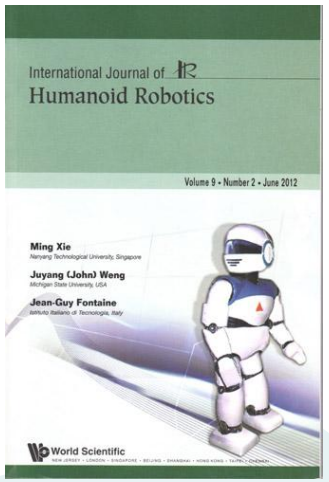



Technology
Innovation

2008


Product
Innovation
(Robot Driver)
(Robot Worker)

2004

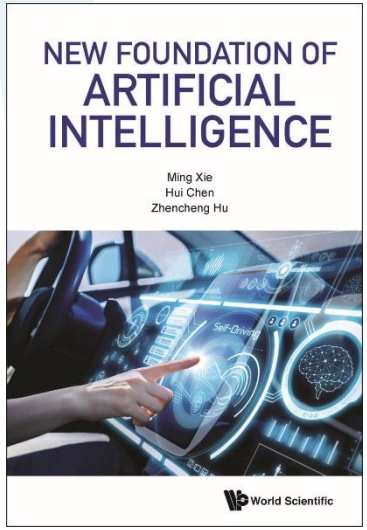



Social
Service

2010

RSS
Robotics Society of Singapore

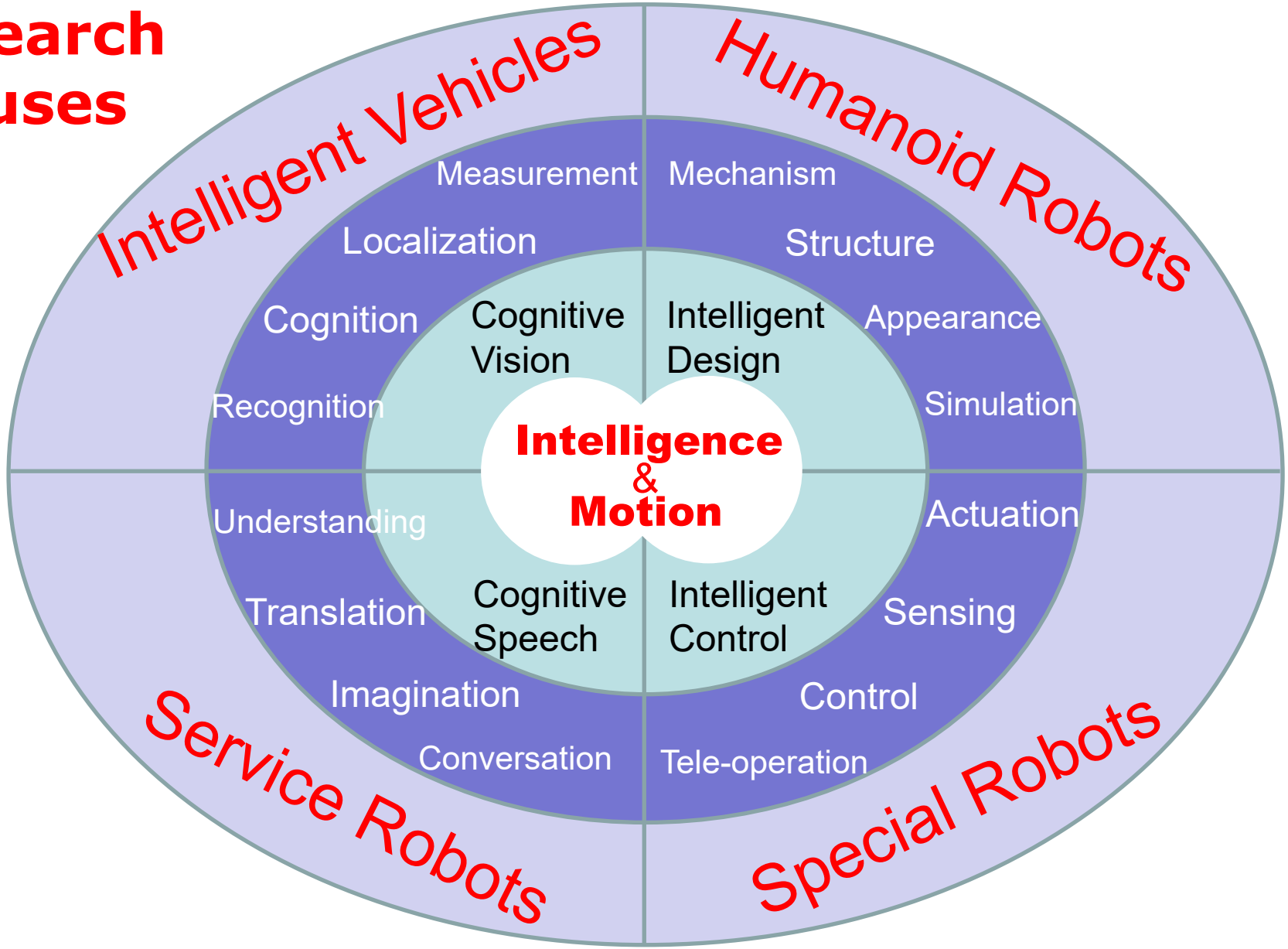
2021




## Teaching Portfolio

1. Sensors
2. Robotics
3. Microprocessors
4. Machine Intelligence

# Research Focuses

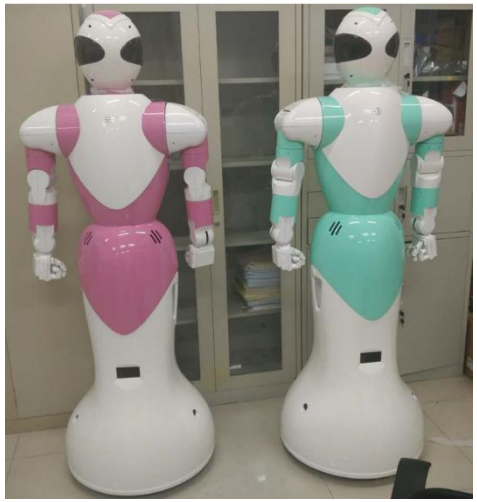



CCTV 新闻
重播


Small-sized Humanoid Robot



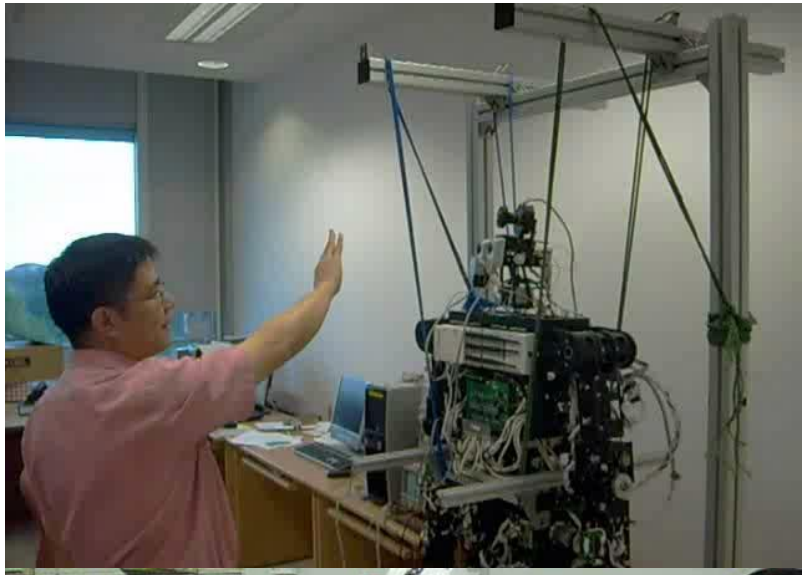


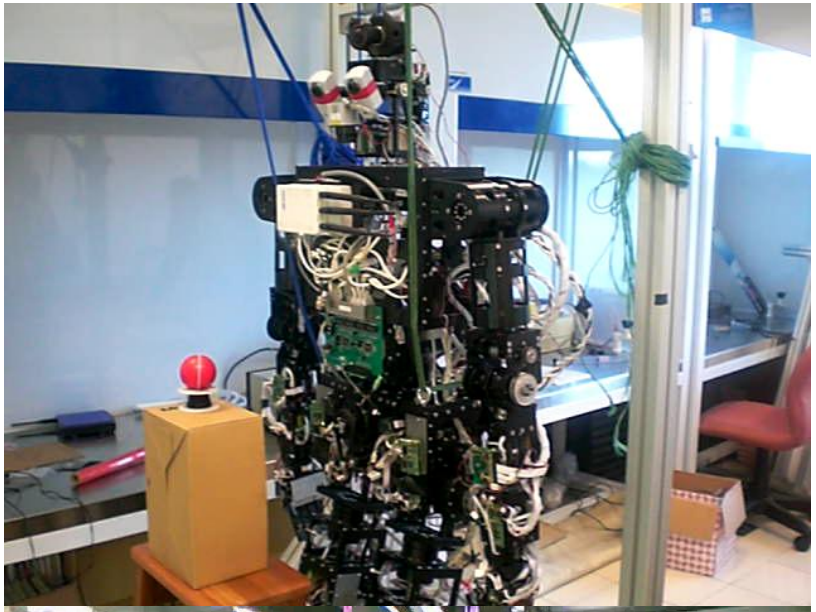


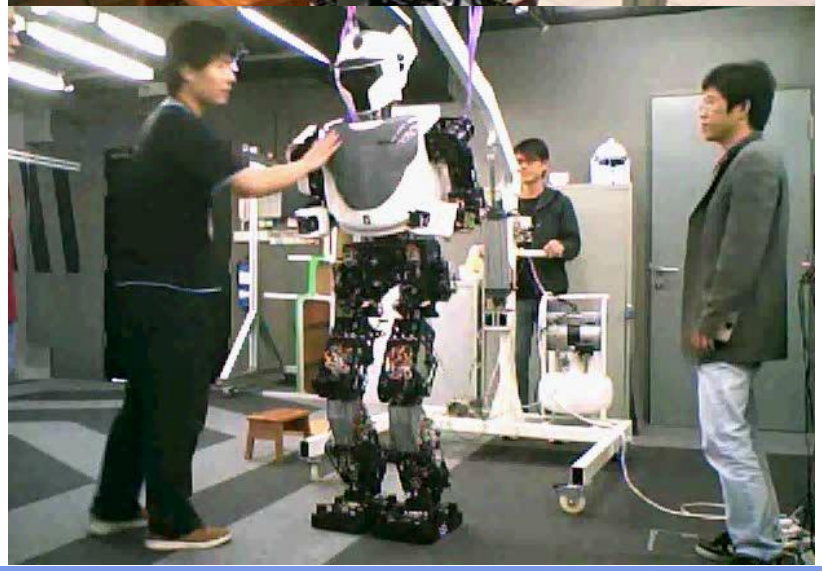
Medium-sized Humanoid Robot

Full-sized Humanoid Robot

# Some Demonstrations ...







# Key Takeaways: Understanding of …

- One Definition: Robot with Outlook of Human Being

- Three Domains of Knowledge: Body, Brain and Mind

- Five Key Steps of Development: They are the effective ways to translate the three domains of know-hows into the achievements of these five layers of:
  - Material Flow Inside Humanoid Robots
  - Energy Flow Inside Humanoid Robots
  - Signal Flow Inside Humanoid Robots
  - Motion Flow Inside Humanoid Robots
  - Knowledge Flow Inside Humanoid Robots

# Outline of Today's Talk

- What is humanoid robot?
- What are the domain knowledge behind humanoid robot?
- What are the key steps toward development of humanoid robot?
  - Material Flow Inside Humanoid Robots
  - Energy Flow Inside Humanoid Robots
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  - Knowledge Flow Inside Humanoid Robots
- Concluding Remarks

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- Concluding Remarks

# Three Big Questions

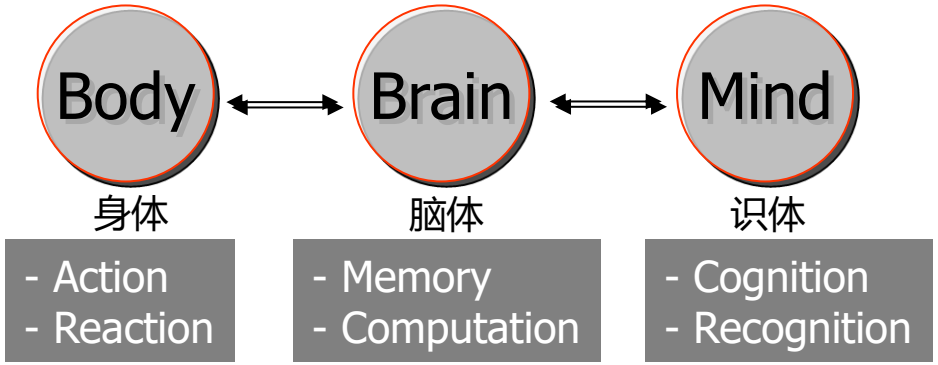
- What is humanoid robot by definition?
- What is humanoid robot from the viewpoint of applications?
- Why are humanoid robots so special and so important?

# Definition of Humanoid Robots

- A humanoid robot is a human-made creature which includes human-like body, human-like brain, and human-like mind, for the purpose of doing:

1. Execution of Motion
2. Performance of Tasks
3. Interaction with People

# Why to explicitly separate brain from mind?




**Discoveries in Religion**

- Coarse Mind
- Subtle Mind
- Deep Mind

- Intelligence arises from mind
- Biological body is not life/soul

# Astonishing Truths …

- Life never dies
- Life reincarnates
- One body has one brain
- One brain could house different minds

# Astonishing Truths …

- Life never dies
- Life reincarnates
- One body has one brain
- One brain could house different minds
- One mind has multiple settings


# Applications of Humanoid Robots

- Humanoid robot is a mini-version of Internet of Things
- Humanoid robot is a mega actuator
- Humanoid robot is a mega sensor
- Humanoid robot is a mega emitter (e.g. to trigger emotions)
- Humanoid robot is a mega speaker (e.g. speech and body language)
- Humanoid robot is a mega performer
- Humanoid robot is a mega worker, driver, and operator, etc.

# Importance of Humanoid Robot

- Humanoid robot is the best platform for advancing research in science and engineering.
- Humanoid robot is the best platform for advancing and promoting education.
- Humanoid robot is the best platform for advancing product innovations in industry.

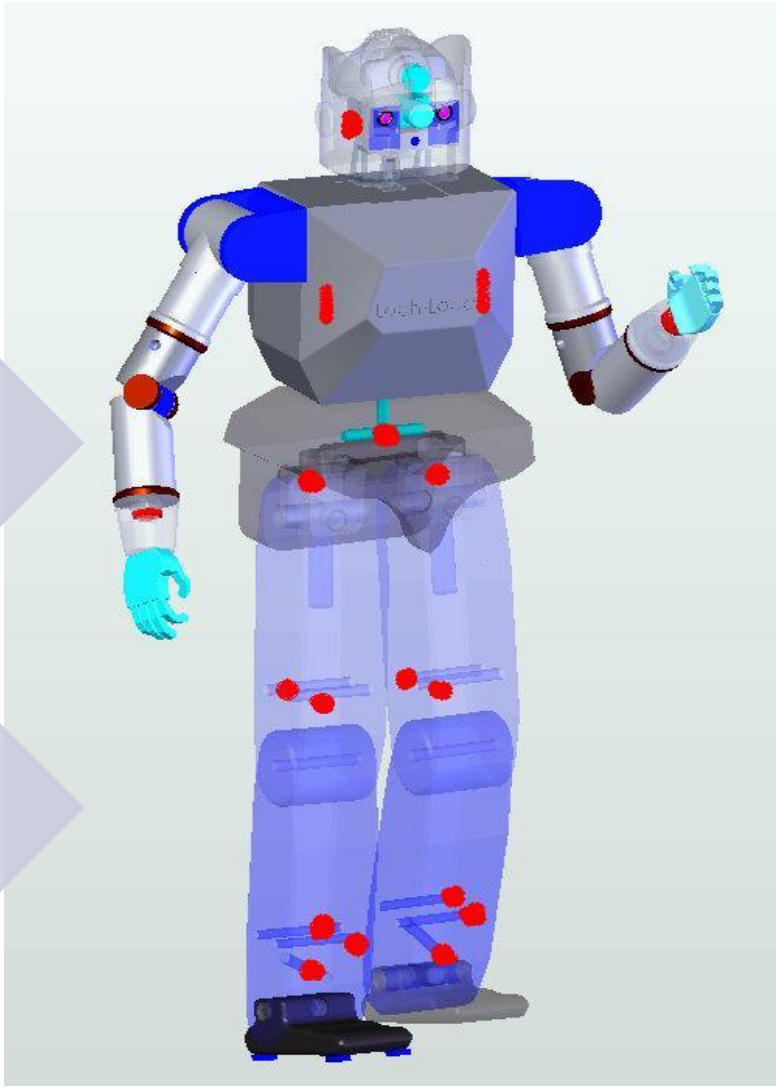
**No.1: Humanoid robots are best platforms for research. This is because humanoid robots enable both discoveries and inventions in some better ways.**

**Human-like Skills**

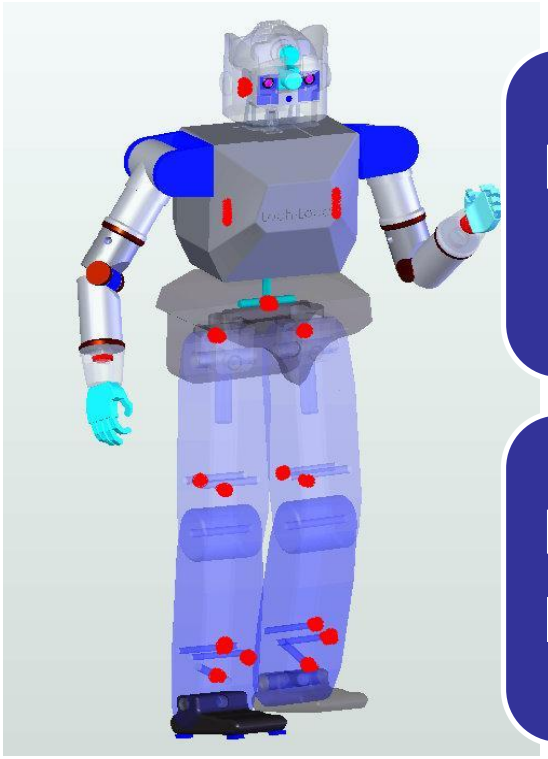
- Sensor Technology
- Actuator Technology
- Mechanism
- Computing
- Communication
- Real-time System

**Human-like Intelligence**

- Vision System
- Speech System
- Decision-making System
- Planning and Control
- Cognition and Recognition
- Cooperation



**No.2: Humanoid robots are best platforms for education. This is because humanoid robots facilitate learning and teaching STEM in schools.**



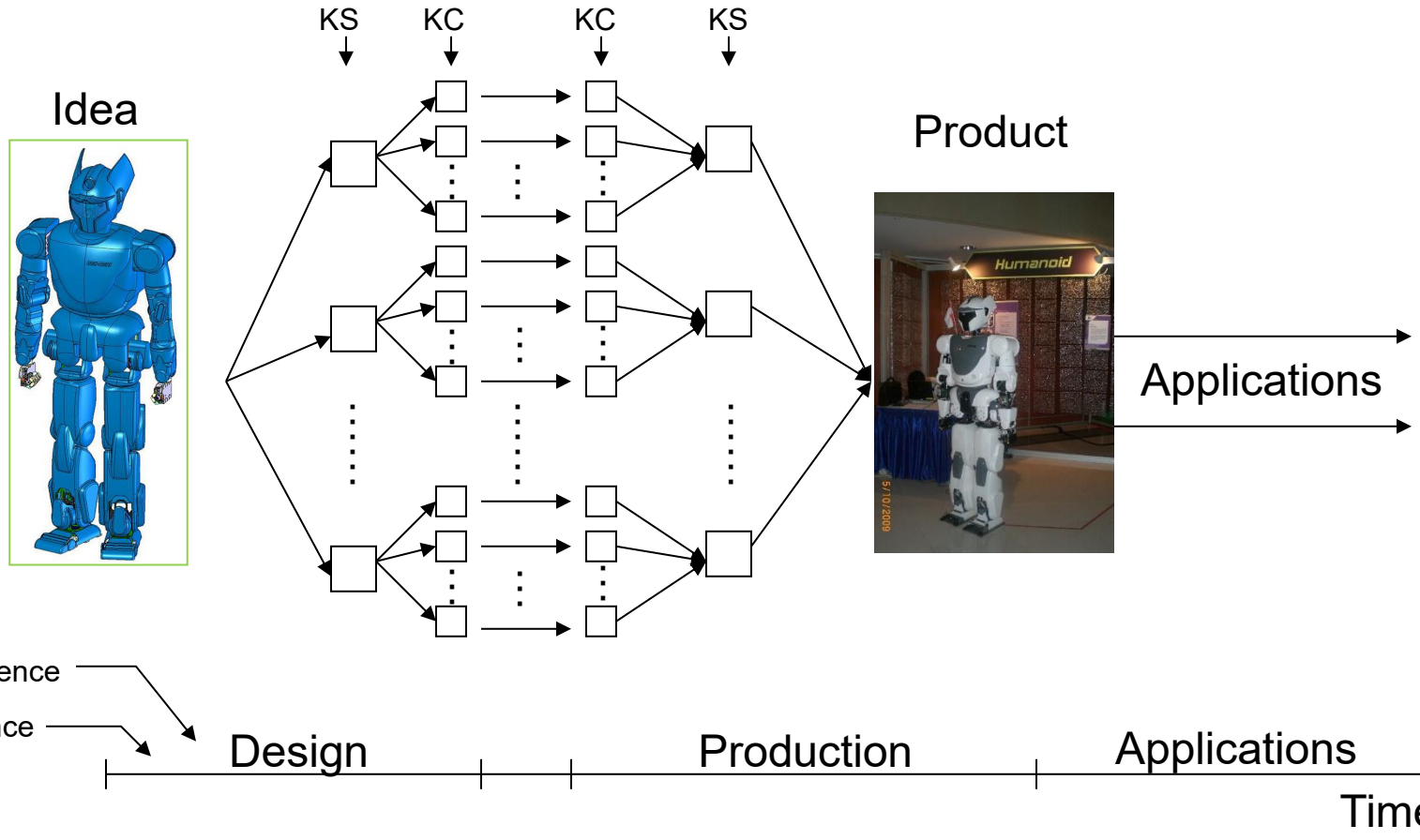
**Human-like Skills**

- Sensor Technology
- Actuator Technology
- Mechanism
- Computing and Communication
- Real-time System

**Human-like Intelligence**

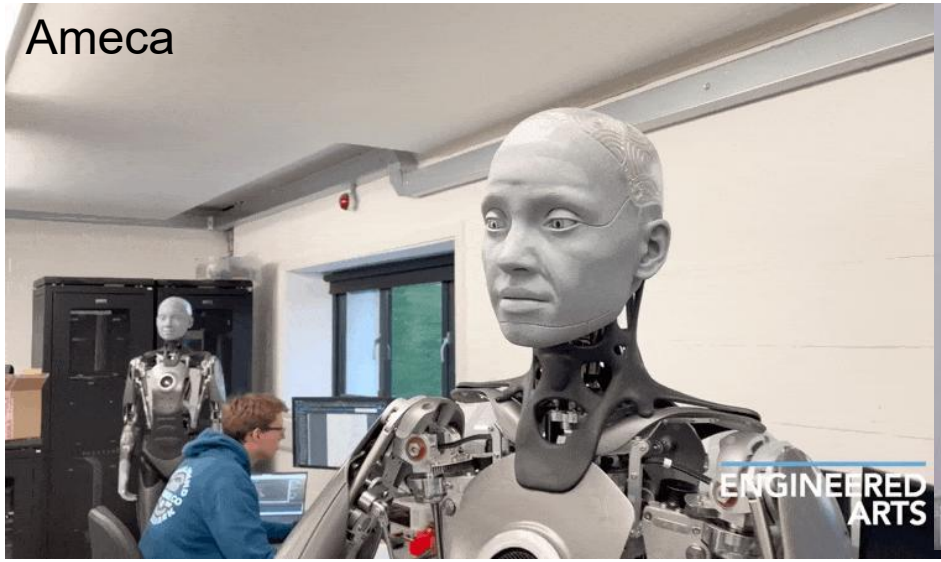
- Vision System
- Speech System
- Decision-making System
- Planning and Control
- Cognition and Recognition
- Cooperation

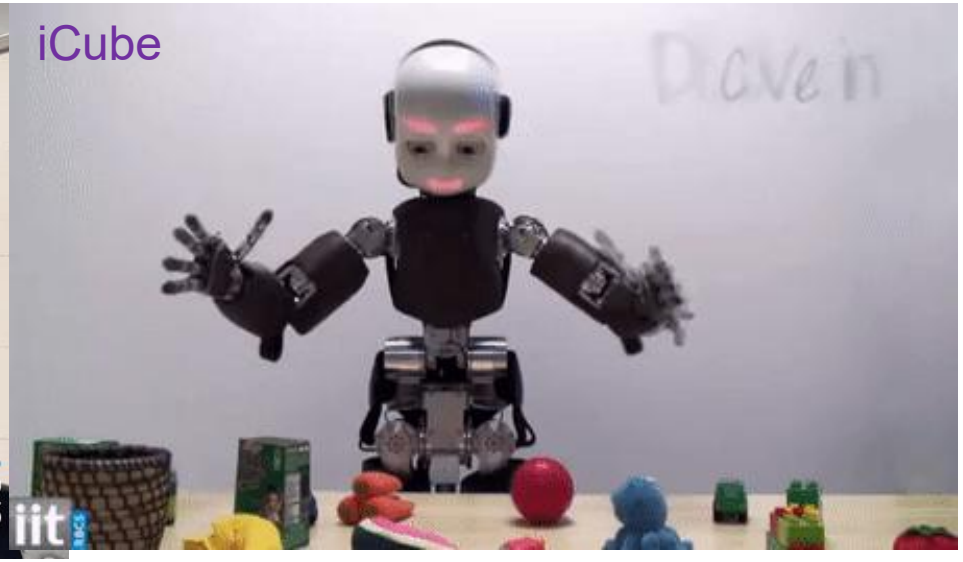
**No3: Humanoid robots are best platforms for prototyping. This is because humanoid robots' technologies enable the upgrade of existing industries, and also the creation of new products and new services.**



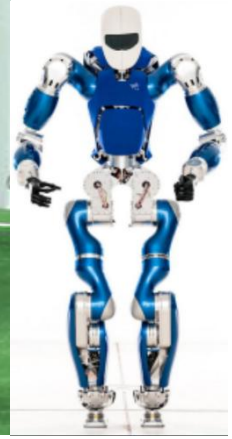
# Top Players of Humanoid Robots (1)

France, Italy, United Kingdom, Germany



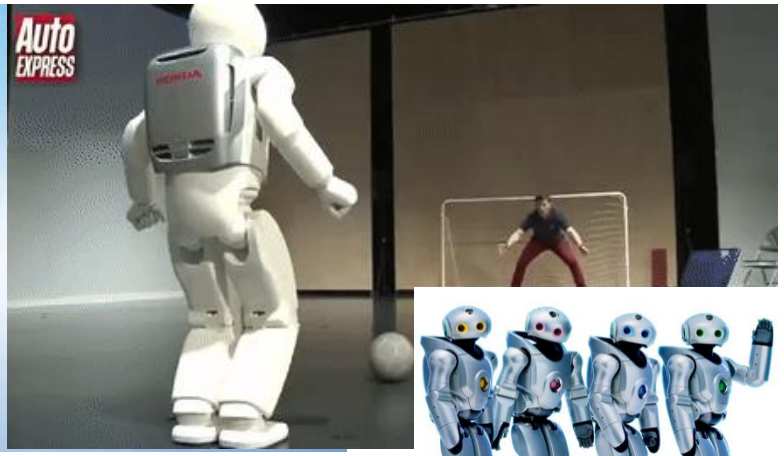




# Top Players of Humanoid Robots (2)

Japan, South Korea, China

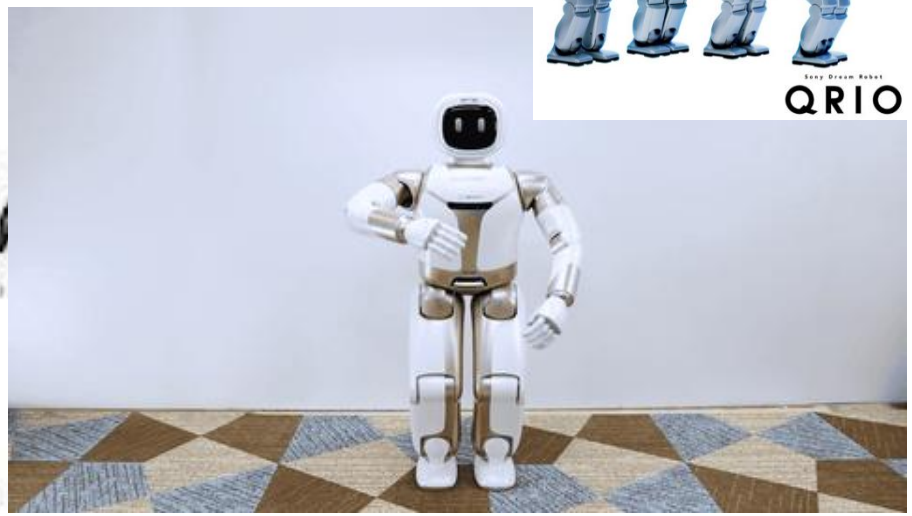
ASIMO



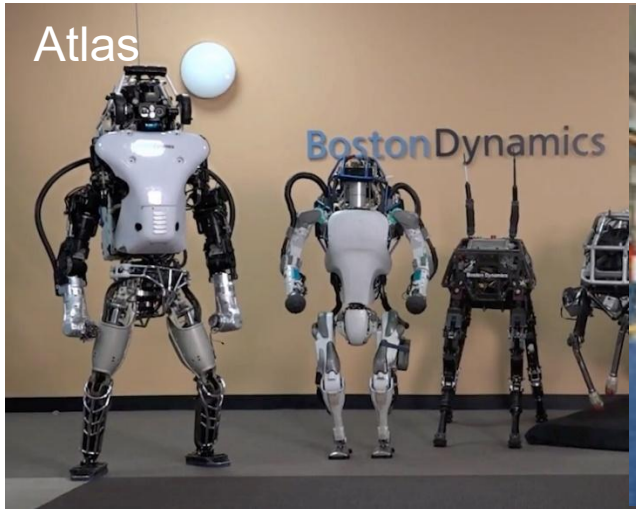


HUBO

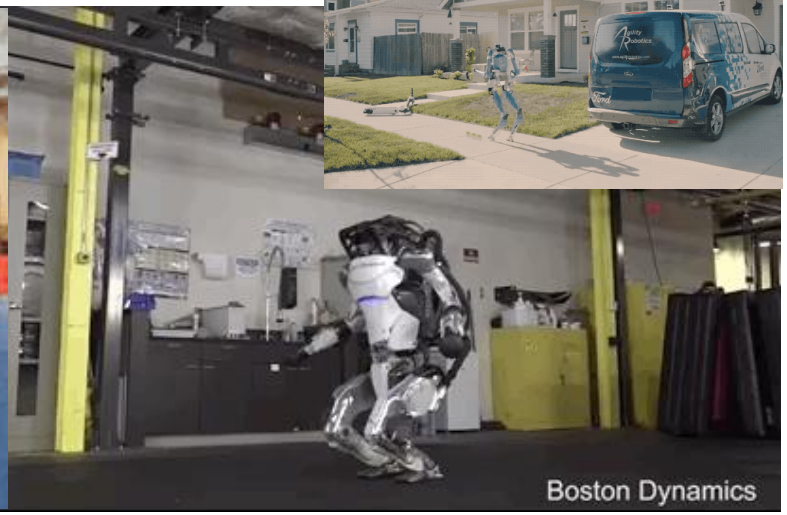



# Top Players of Humanoid Robots (3)

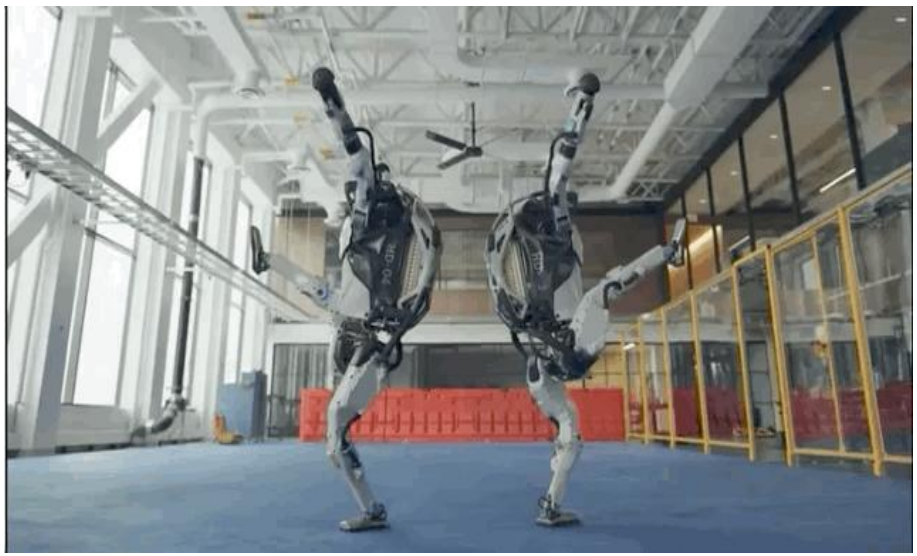
United States











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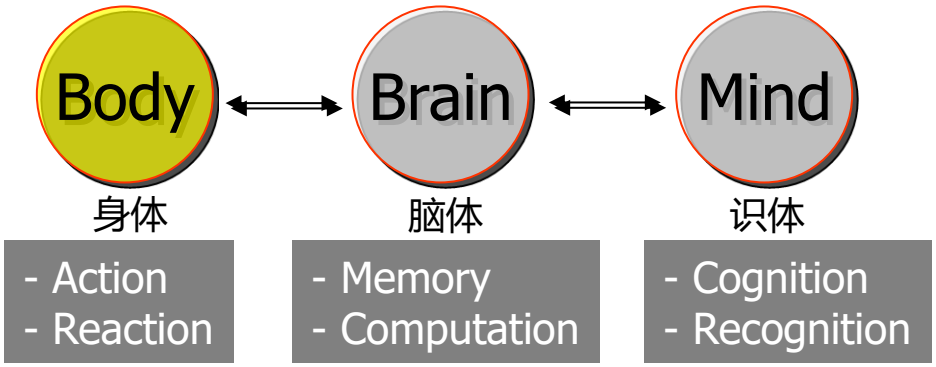
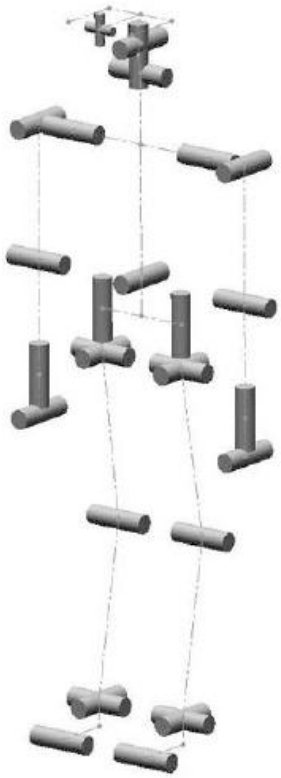
# Three Domains of Knowledge underlying the R&D of Humanoid Robots

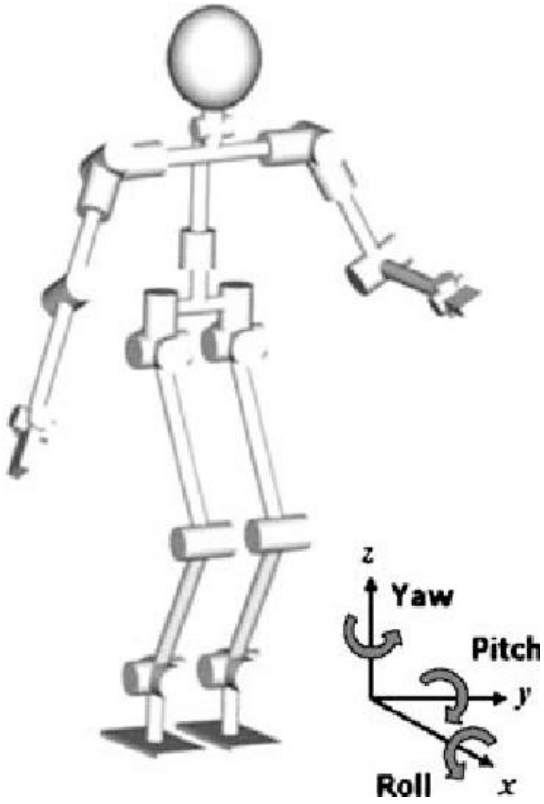
- Domain No.1:
  - Artificial Body (Primary Focus of Robotics)
- Domain No.2:
  - Artificial Bain (Primary Focus of Computer Engineering)
- Domain No.3:
  - Artificial Mind (Primary Focus of Artificial Intelligence, Cognitive Science, or Science of Mind)

# Domain No.1: Artificial Body



**How to design a body which is a network of rigid links with actuators, sensors and controllers, for the purpose of delivering actions and reactions?**



# History of Inventing Robots in China

Puppets could be considered as the first generation of robots!

Shadow puppetry or Pi Ying in Chinese was very popular during the Tang (618 - 907) and Song (960 - 1279) dynasties in many parts of China.

Shadow puppets were first made of paper sculpture, later from the leather of donkeys or oxen.

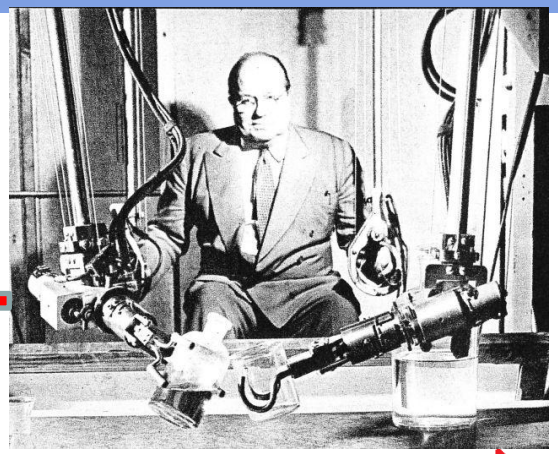
Human-like Statues

470-220 BC


GE in 1948

# First Generation of Teleoperated Robots (Puppets Invented in China)

# History of Inventing Robots in Western Countries



GE's Tele-operated Arm in 1948

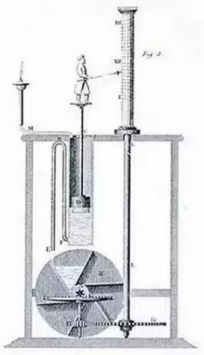
Birth of Terminology "Robotics"

Three Laws

1926

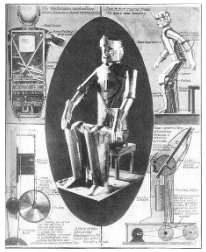
-270 | 1818 | 1921 | 1941 | 1942 | 1948 | 1956 | 1961 | 1963 | 1970 | 1979

-270 Greek engineer made water clocks with movable figures



1818: Mary Shelley writes 'Frankenstein', an artificial lifeform

1921: Czech play 'Rossum's Universal Robot' uses the term 'robot' for the first time



Robot is a creature without soul

1941: term 'robotics' use by writer Isaac A. to describe technology of robots

1942: Isaac writes 'Runaround' describing 3 laws of robotics
1.robots cannot injure a human and or let a human harm (through inaction)
2.robots must obey orders of humans, except harming someone else
3.robots must protect themselves if it does not contradict 1st and 2nd law

1948:William G.W creates 'Elmer' and 'Elsie' that imitate lifelike behaviour

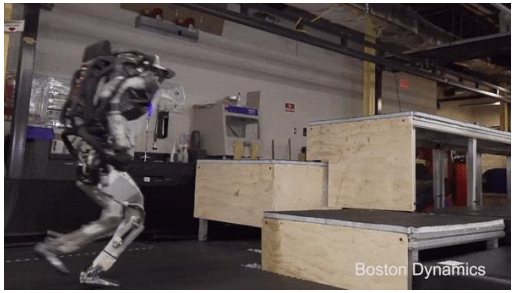
1956:George D. and Joe E. from the 1st robot company

1961:'UNIMATE', the first industrial robot is put online

1963:1st robotic arm controlled by a computer is created (for handicaps)

1970:'Shakey', the first mobile robot controlled by artificial intelligence is produced by the SRI International

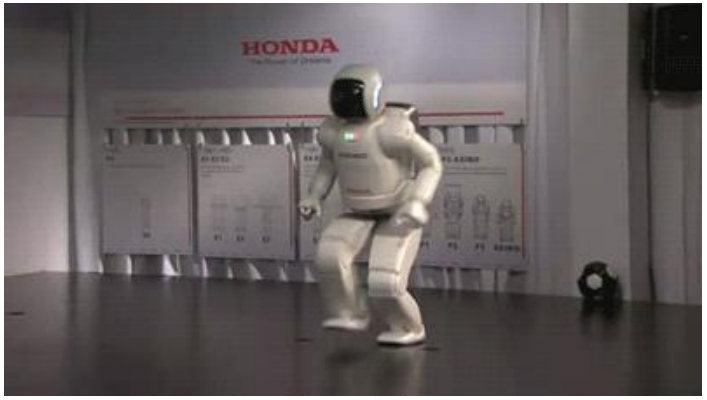
1979:'Standford cart' movilised itself through a chair-filled room using a tv camera that took pictures from different angles and sent them to a computer to process the next movement

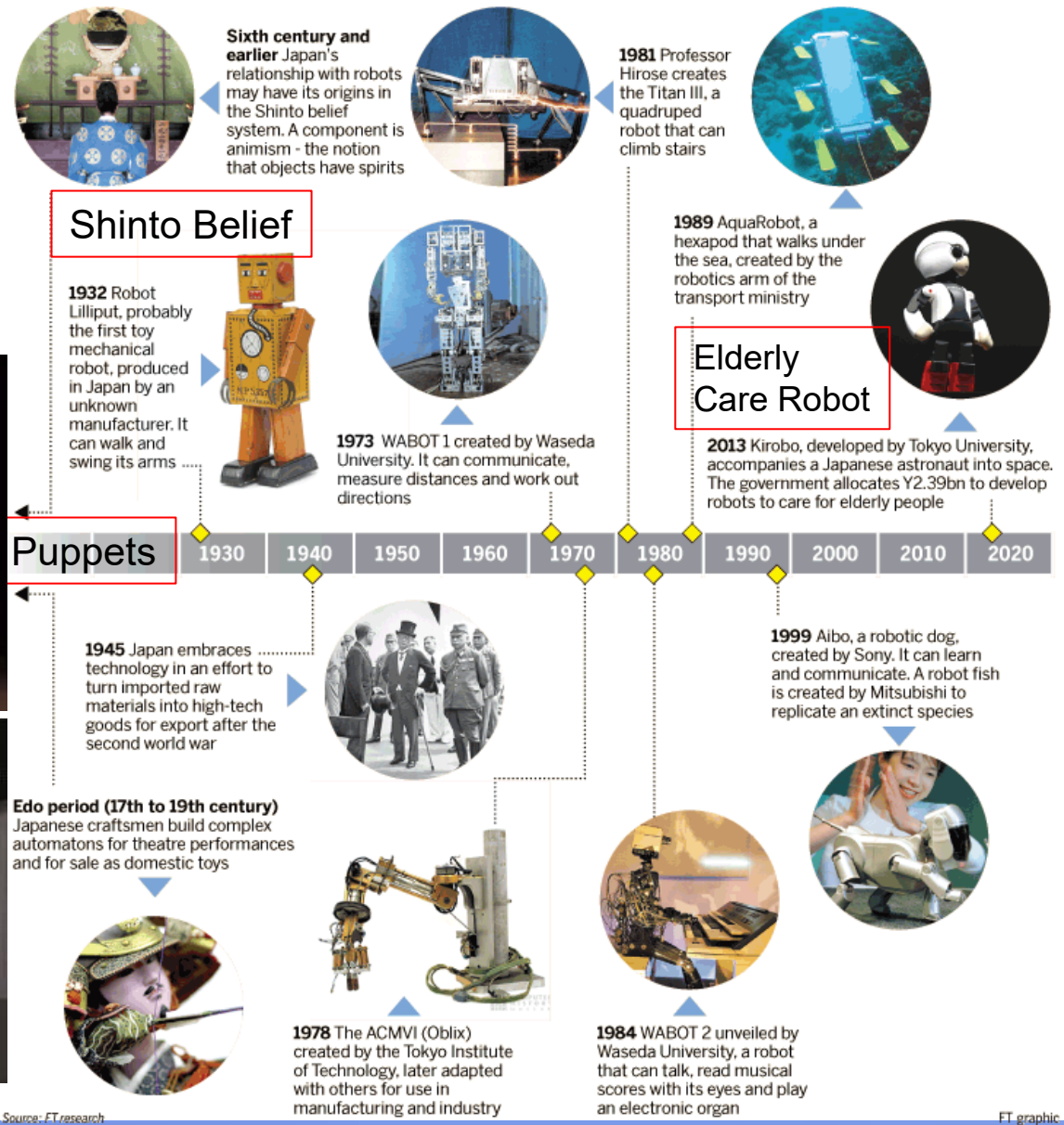



Birth of Terminology "Robot"

Birth of Industrial Robot

# History of Inventing Robots in Japan

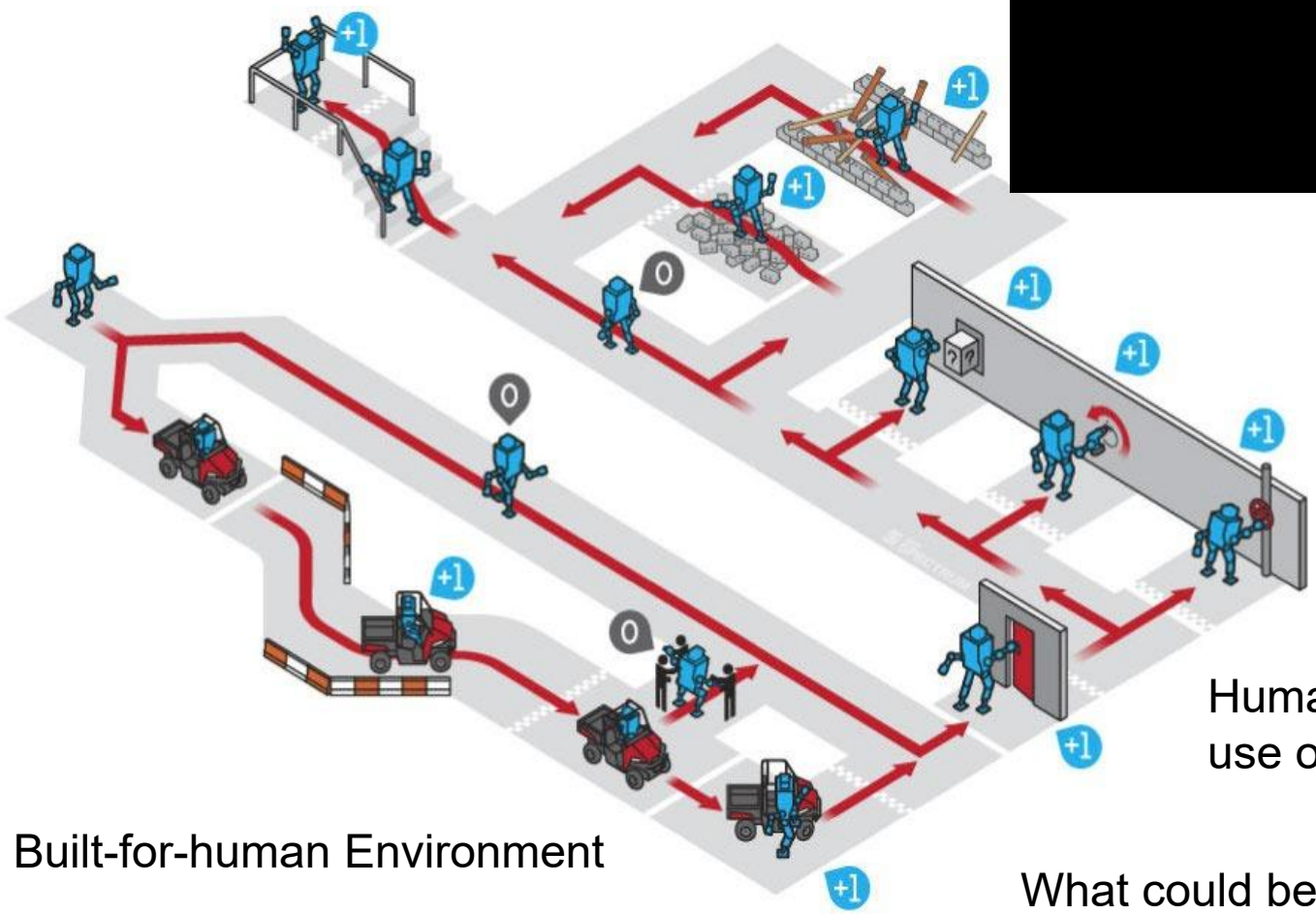


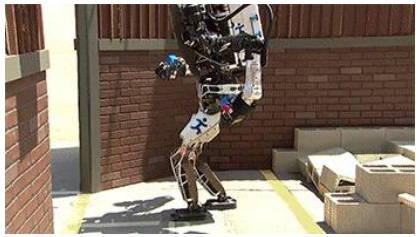
# DARPA's Humanoid Robot Challenge

- In June 2015, the finale of the DARPA Humanoid Robot Challenge (DHRC), a competition of robot systems and software teams vying to develop robots capable of assisting humans in responding to natural and man-made disasters, unfolded at the Fairplex in Pomona, Calif.
- A preliminary DHRC Trials event had taken place in late 2013 at Florida's Homestead Miami Speedway. Participating teams, representing many of the most advanced robotics research and development organizations in the world, developed the hardware, software, sensors, and human-machine control interfaces to enable their robots to take on and sometimes complete a series of challenging tasks selected by DARPA for their relevance to disaster response.
- Taking first place and the $2 million in prize money that went with it was Team Kaist of Daejeon, Republic of Korea, and its robot DHRC-Hubo. Coming in second and taking home $1 million was Team IHMC Robotics of Pensacola, Florida, and its robot Running Man. The third-place finisher, earning the $500,000 prize, was Tartan Rescue of Pittsburgh, and its robot CHIMP.

DARPA Humanoid Robot Challenge 2015



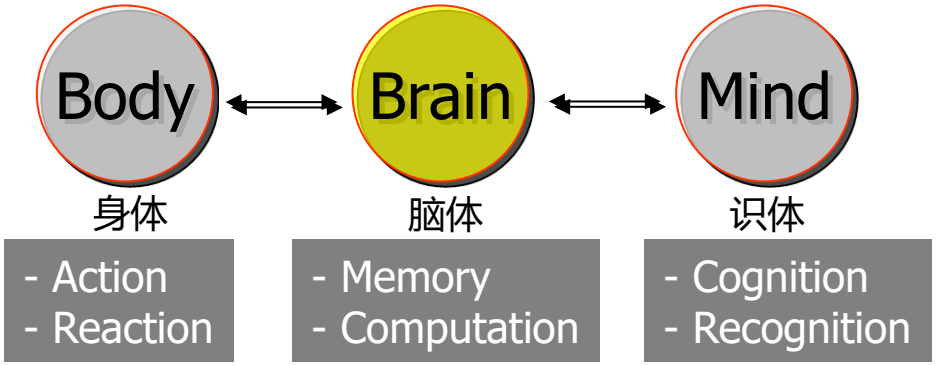

Built-for-human Environment



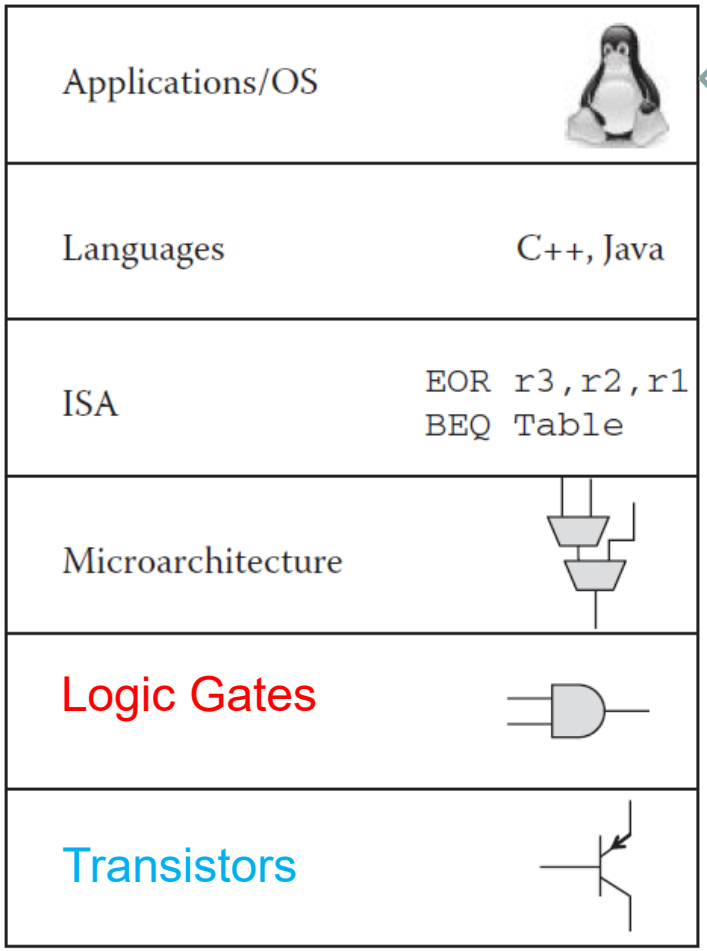
Human-like skills require the use of human-like brains

What could be human-like brain?

# Domain No.2: Artificial Brain

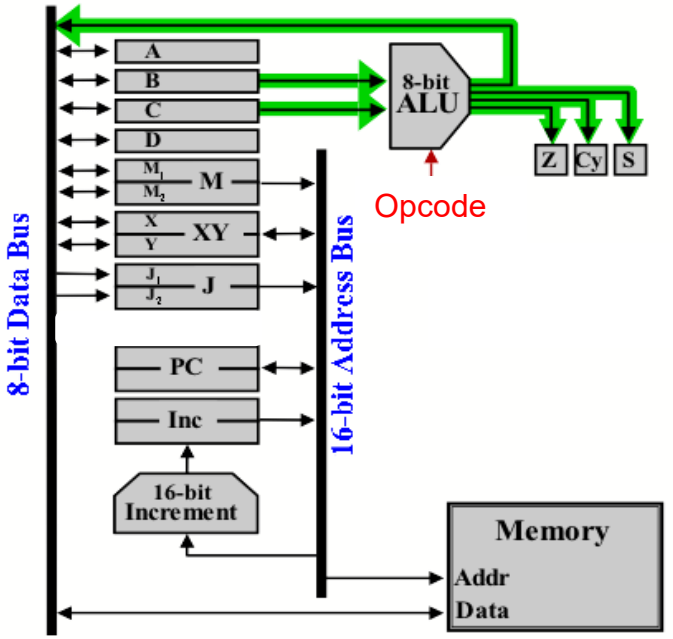


# How to design a brain which is a massive network of logic devices, for the purpose of creating numerous CPUs and huge memories?

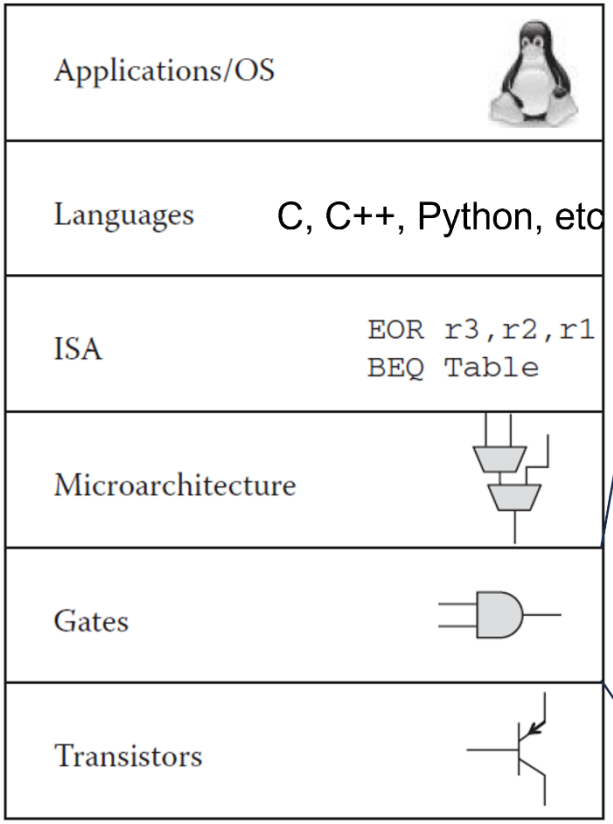



Algorithms or Solutions

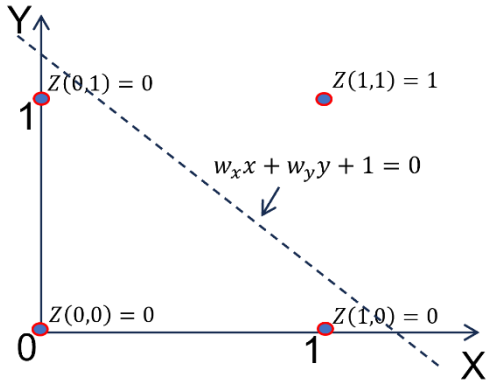
Problems to be solved



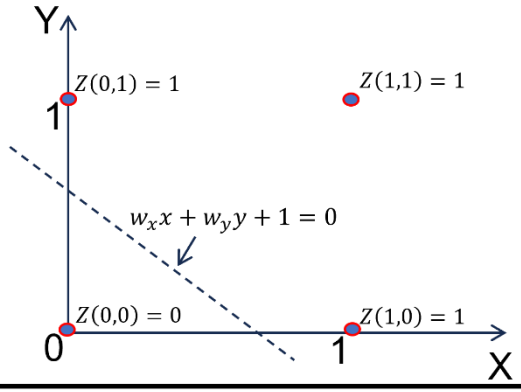
**A biological brain system is a massive network of logic gates and devices for the purpose of supporting computation … (neurons are very likely the foundation of logic gates)**

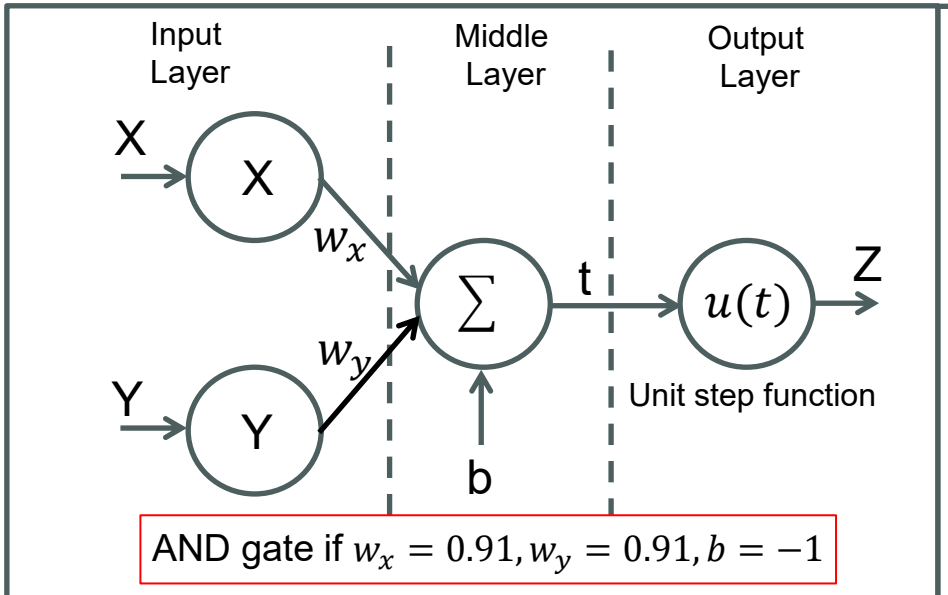



| Truth Table of AND Gate | | |
|---|---|---|
| X | Y | Z |
| 0 | 0 | 0 |
| 0 | 1 | 0 |
| 1 | 0 | 0 |
| 1 | 1 | 1 |

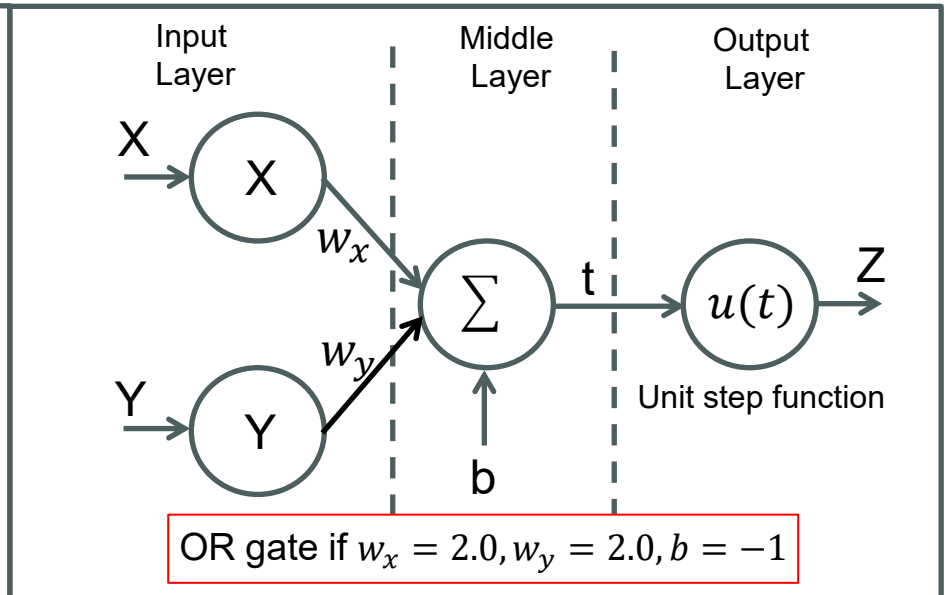



| Truth Table of OR Gate | | |
|---|---|---|
| X | Y | Z |
| 0 | 0 | 0 |
| 0 | 1 | 1 |
| 1 | 0 | 1 |
| 1 | 1 | 1 |

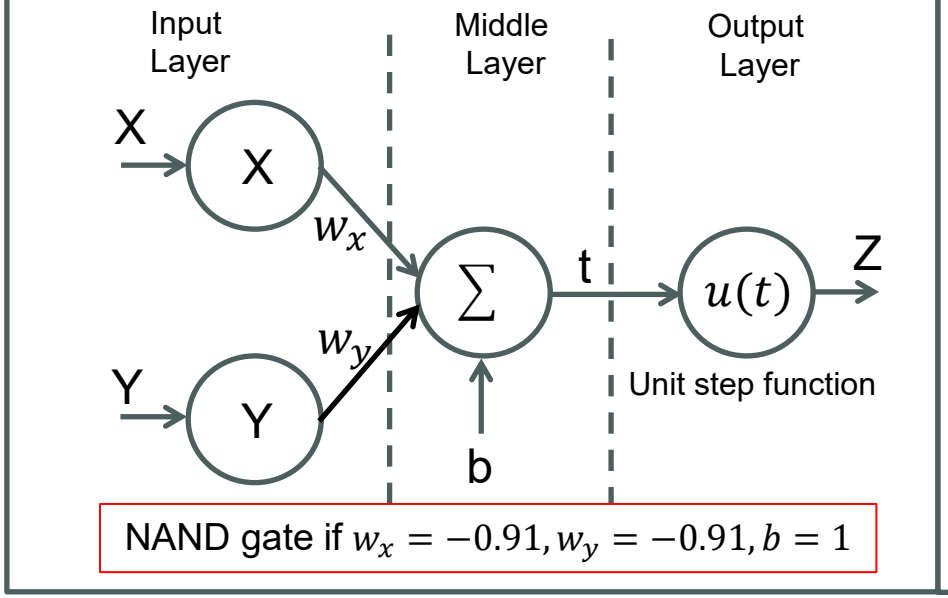




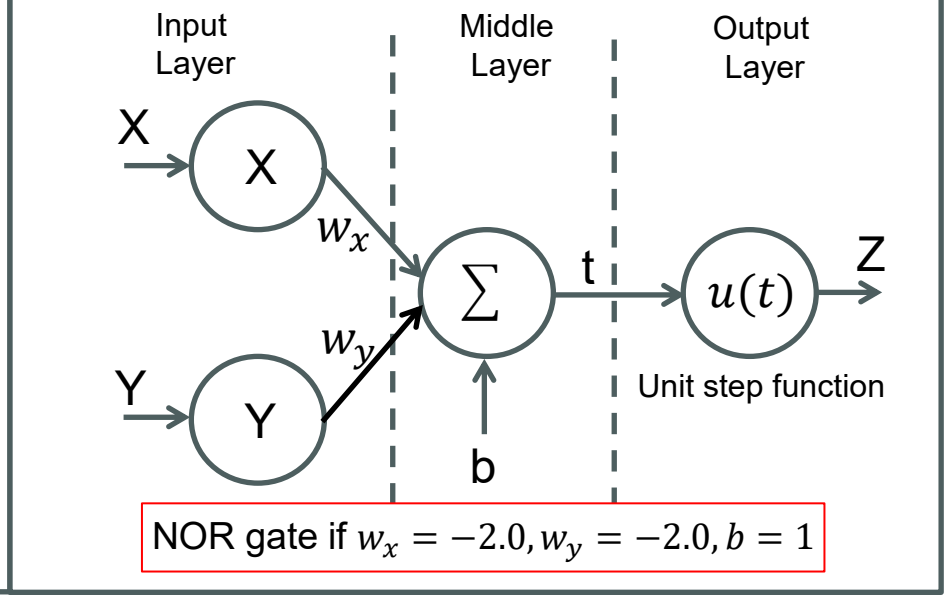

AND gate if $w_x = 0.91, w_y = 0.91, b = -1$




OR gate if $w_x = 2.0, w_y = 2.0, b = -1$




NAND gate if $w_x = -0.91, w_y = -0.91, b = 1$




NOR gate if $w_x = -2.0, w_y = -2.0, b = 1$

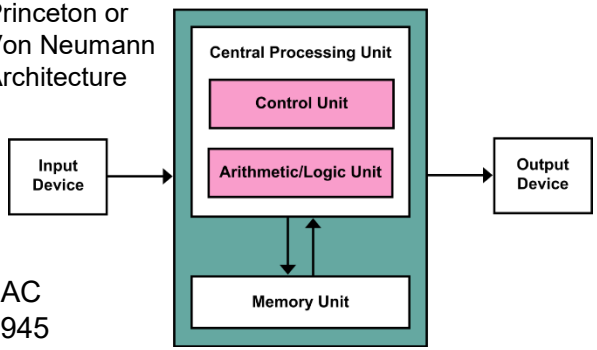
| Truth Table of XOR Gate | | |
|---|---|---|
| X | Y | Z |
| 0 | 0 | 0 |
| 0 | 1 | 1 |
| 1 | 0 | 1 |
| 1 | 1 | 0 |

Equations of Designing XOR Gate

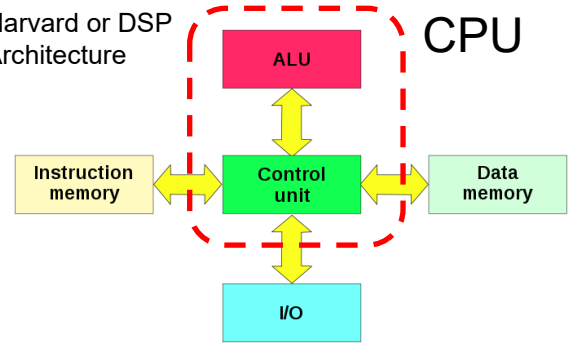
| | |
|---|---|
| $Z_{AND} = Z_{AND}(X, Y)$ | $Z_{NAND} = Z_{NAND}(X, Y)$ |
| $Z_{OR} = Z_{OR}(X, Y)$ | $Z_{NOR} = Z_{NOR}(X, Y)$ |
| $Z_{XOR} = Z_{XOR}(X, Y) = Z_{NOR}(Z_{AND}(X, Y), Z_{NOR}(X, Y))$ | |

# History of Electronic Computer or Brain (v1)

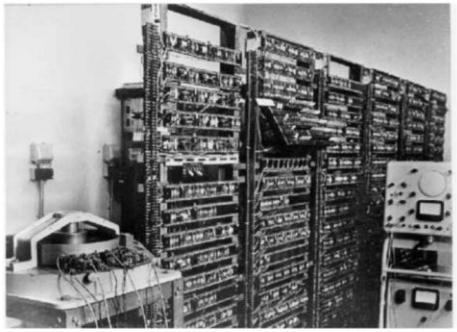
Princeton or Von Neumann Architecture




Harvard or DSP Architecture



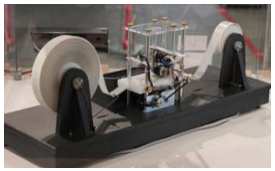

ENIAC
In 1945
First Electronic Computer



First Generation 1946-1959

Second Generation 1959-1965

Third Generation 1965-1971



Allan Turing's Invention: Computing Machine

Charles Babbage's Invention: Mechanical Computer

Fourth Generation 1971-1980

1980 - Present

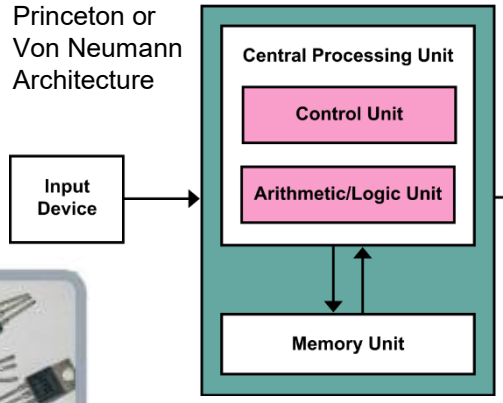
Herman Hollerith's Invention: Tabulator

What Will Be The Fifth Generation?

# History of Electronic Computer or Brain (v2)

Toward achieving human-brain-like computers

Princeton or Von Neumann Architecture




1

Use of Vacuum Tubes

Invention of John Ambrose Fleming

2

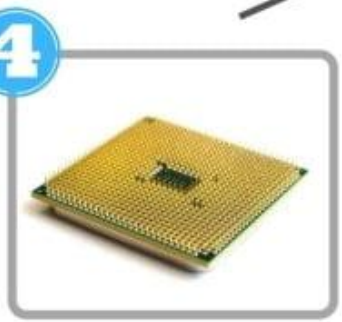
Invention of Bell Lab

Use of Transistors

5

Human-Brain-Like Computer

4



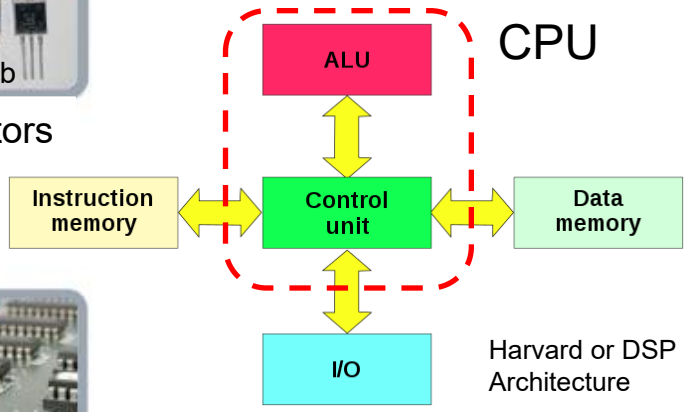
Use of Very Large-scale Integrated Circuits

Use of Ultra Large-scale Integrated Circuits

3

Use of Integrated Circuits

Invention of Kilby and Noyce Also, many others




Harvard or DSP Architecture

Driving Force for Fifth Generation?

# History of Electronic Computer or Brain (v3)

Humanoid robotics will contribute to the development of the 5th generation of computers which is:

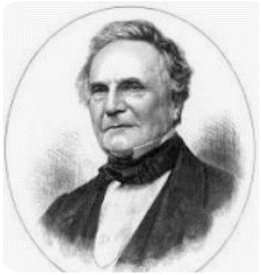
Human-brain-like Computers

Electronic Brains

Robot Brains

1st Gen.

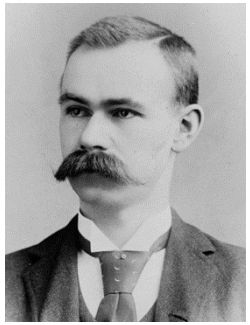
2nd Gen.



Charles Babbage

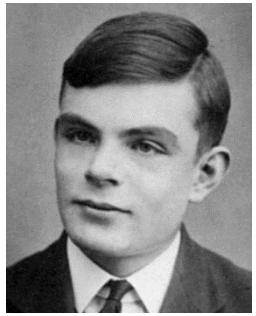
3rd Gen.

4th Gen.

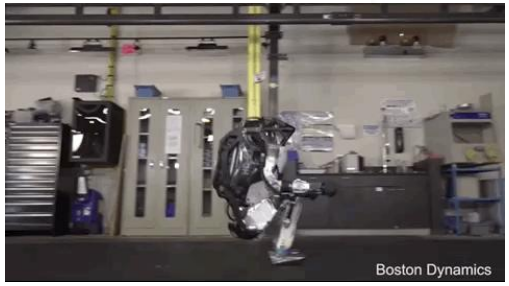


Herman Hollerith

5th Gen.



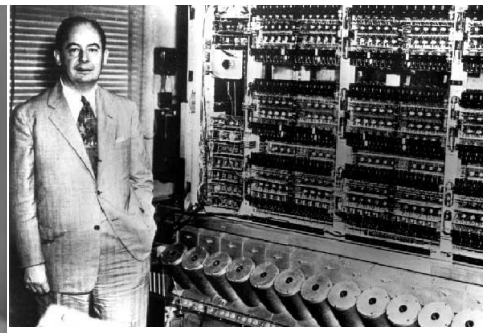
Allan Turing



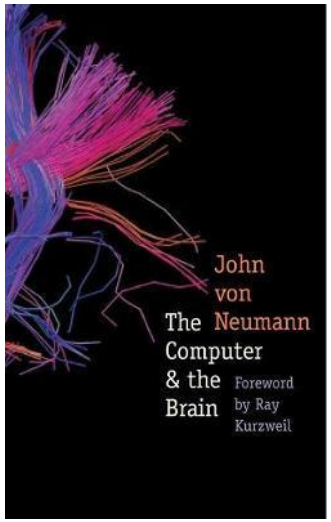
# John von Neumann's Book

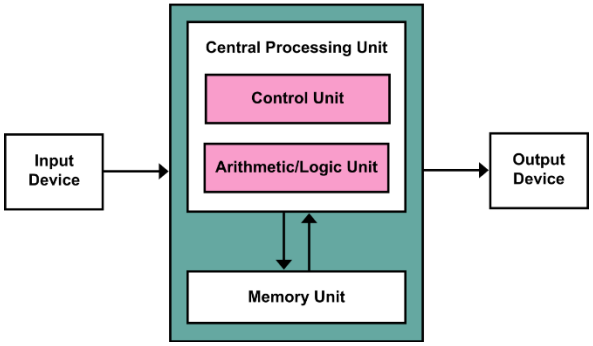
- In this classic work, one of the greatest mathematicians of the twentieth century explores the analogies between computing machines and the living human brain. John von Neumann, whose many contributions to science, mathematics, and engineering include the basic organizational framework at the heart of today's computers, concludes that the brain operates both digitally and analogically, but also has its own peculiar language (i.e., instruction set).

- In his foreword to this new edition, Ray Kurzweil, a futurist who is famous in part for his own reflections on the relationship between technology and intelligence, places von Neumann's work in a historical context and shows how it remains relevant today.



John von Neumann

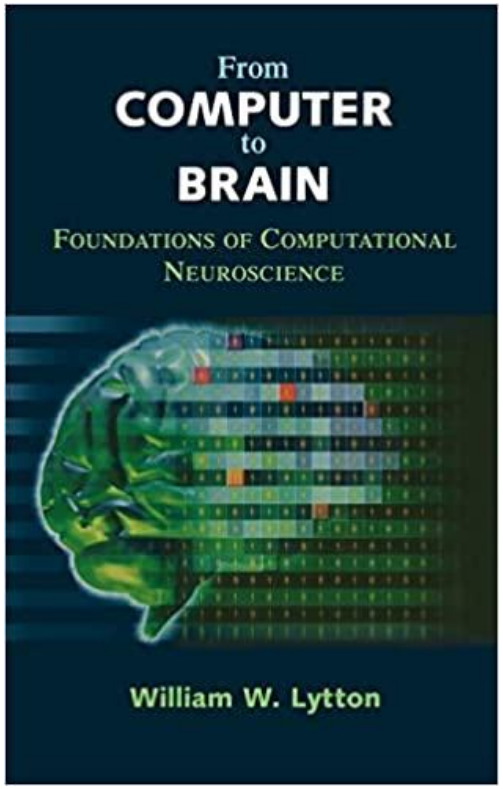


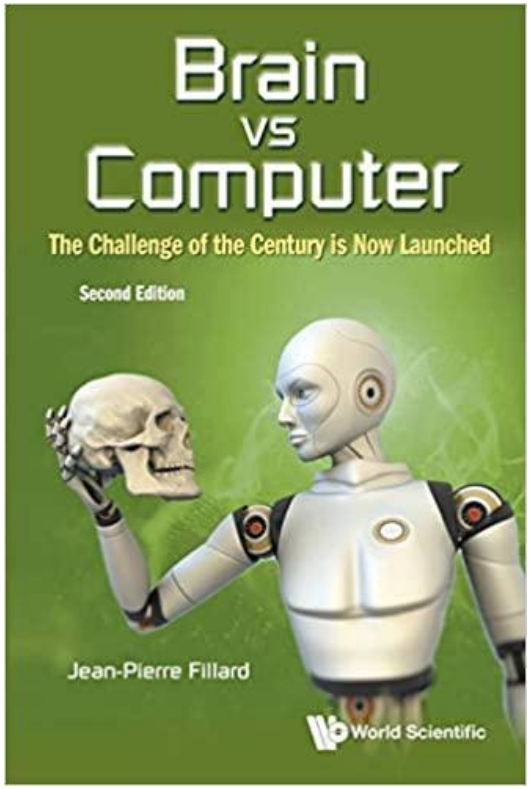



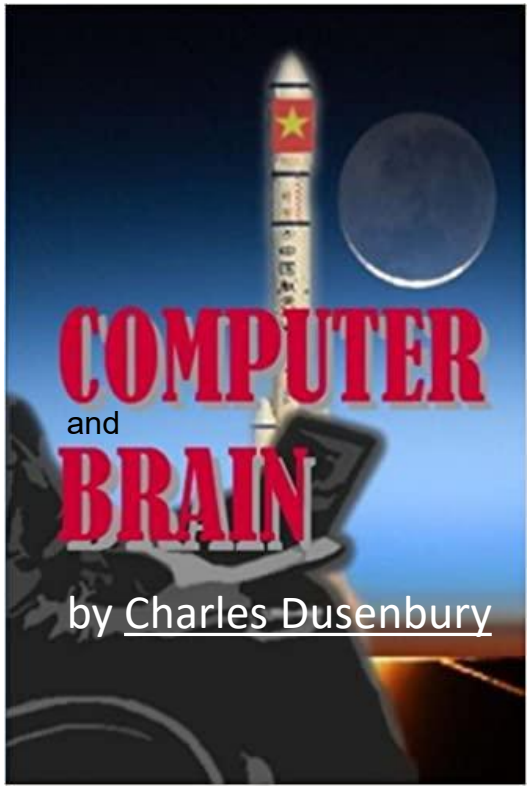

First Edition, 1958
Latest Edition, 2012, 144 Pages,
Yale University Press

# Other books of similar topics …

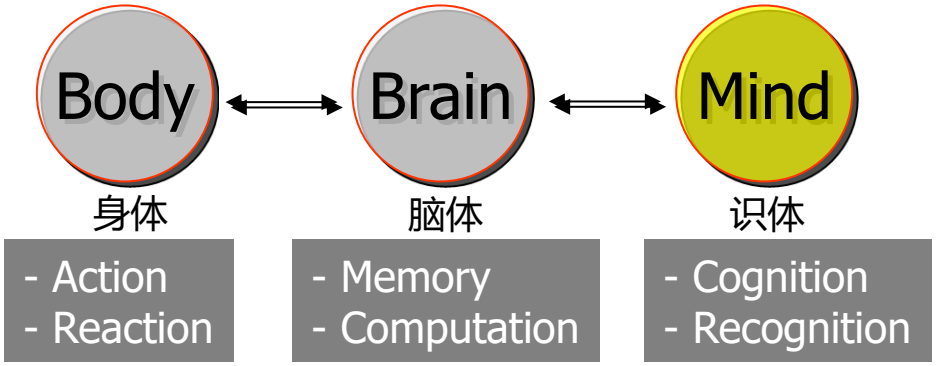
The word “computer” was first in use in **1613** as a label for a person that performed calculations.



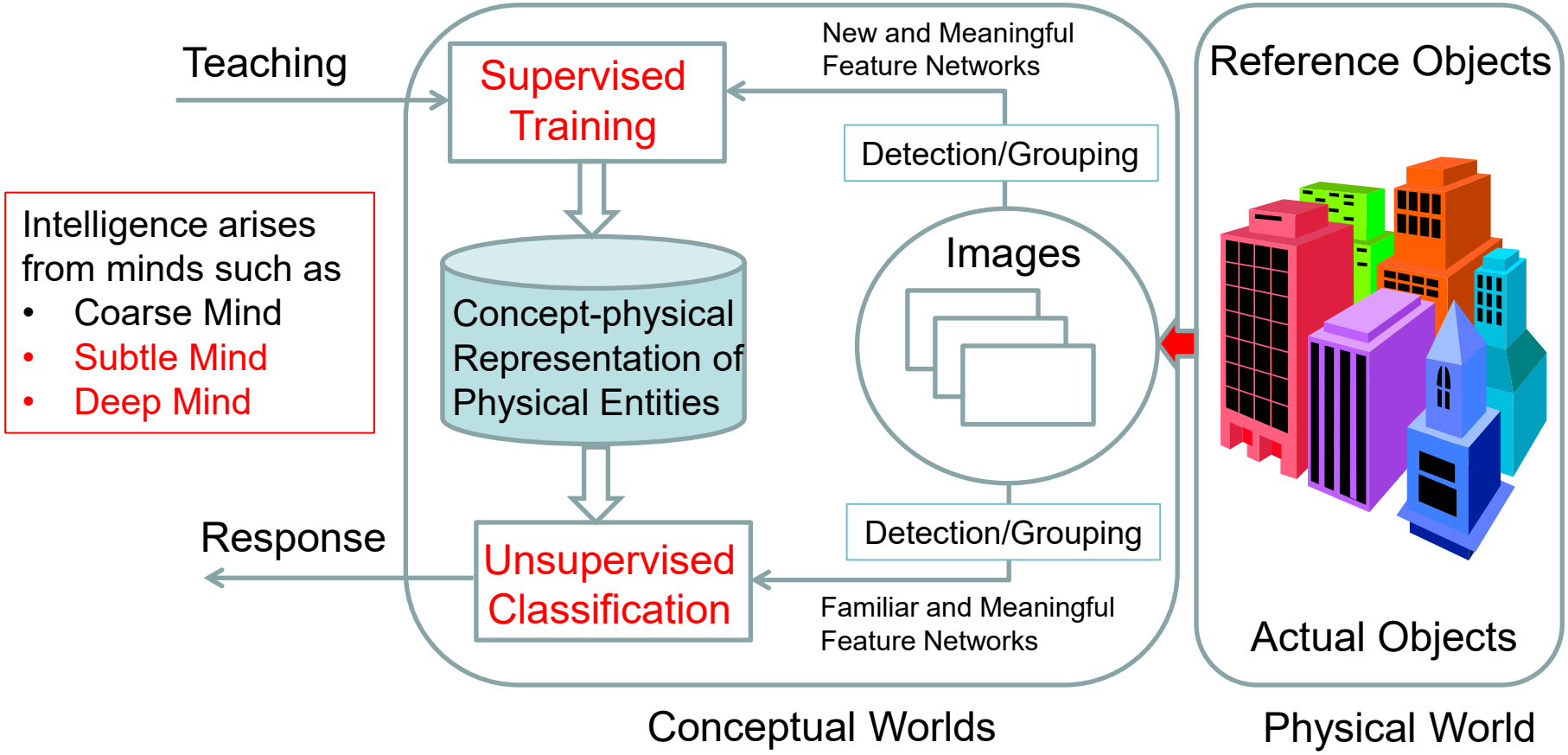



# Domain No.3: Artificial Mind

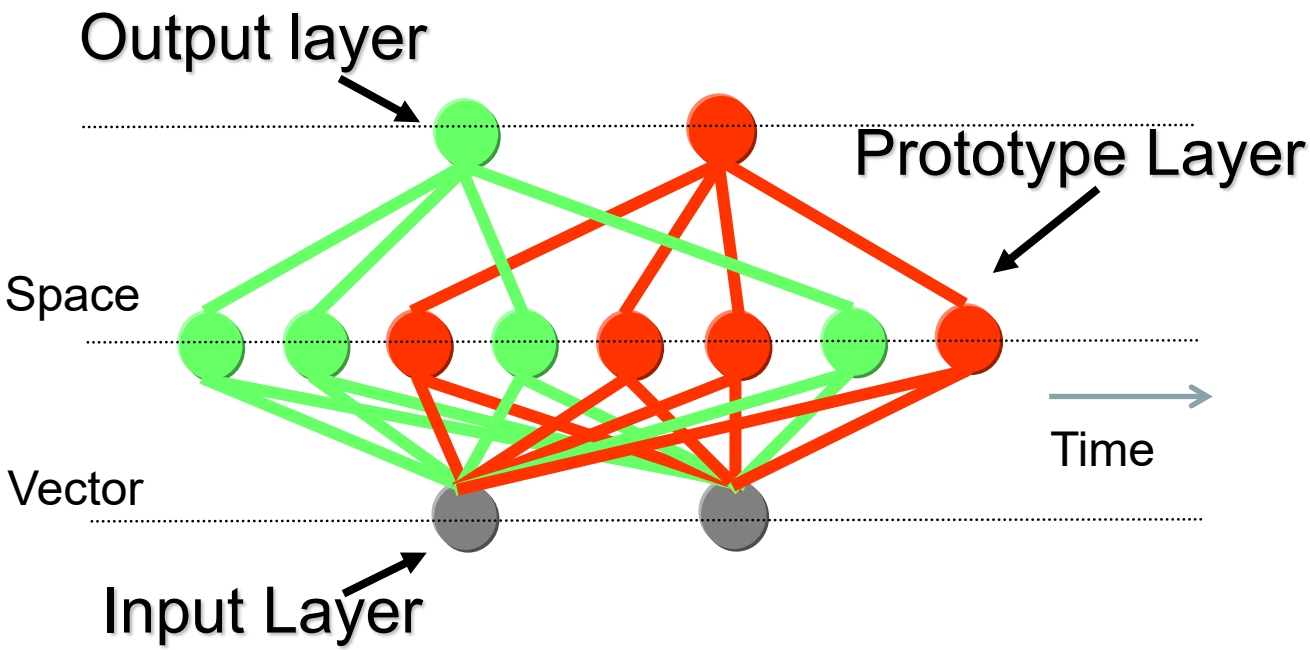


# How to design a mind which is a massive network of cognition modules (learners), recognition modules (classifiers) and memorized knowledge?

By default, mind refers to coarse mind



**A brain system is also a massive network of logic gates and devices for the purpose of supporting cognition, recognition and memorization of learnt knowledge …**




It is the effective implementation of Space-Vector-Time model in any knowledge domain.

RCE Neural Network which was discovered by Nobel Laureate Leon N. Couper's Team in 1970s

- Prototypes refer to feature vectors describing reference features.
- RCE stands for **Restricted Coulomb Energy (RCE).**
- **RCE-NN is a MIMO system which is equal to the sum of MISO.**

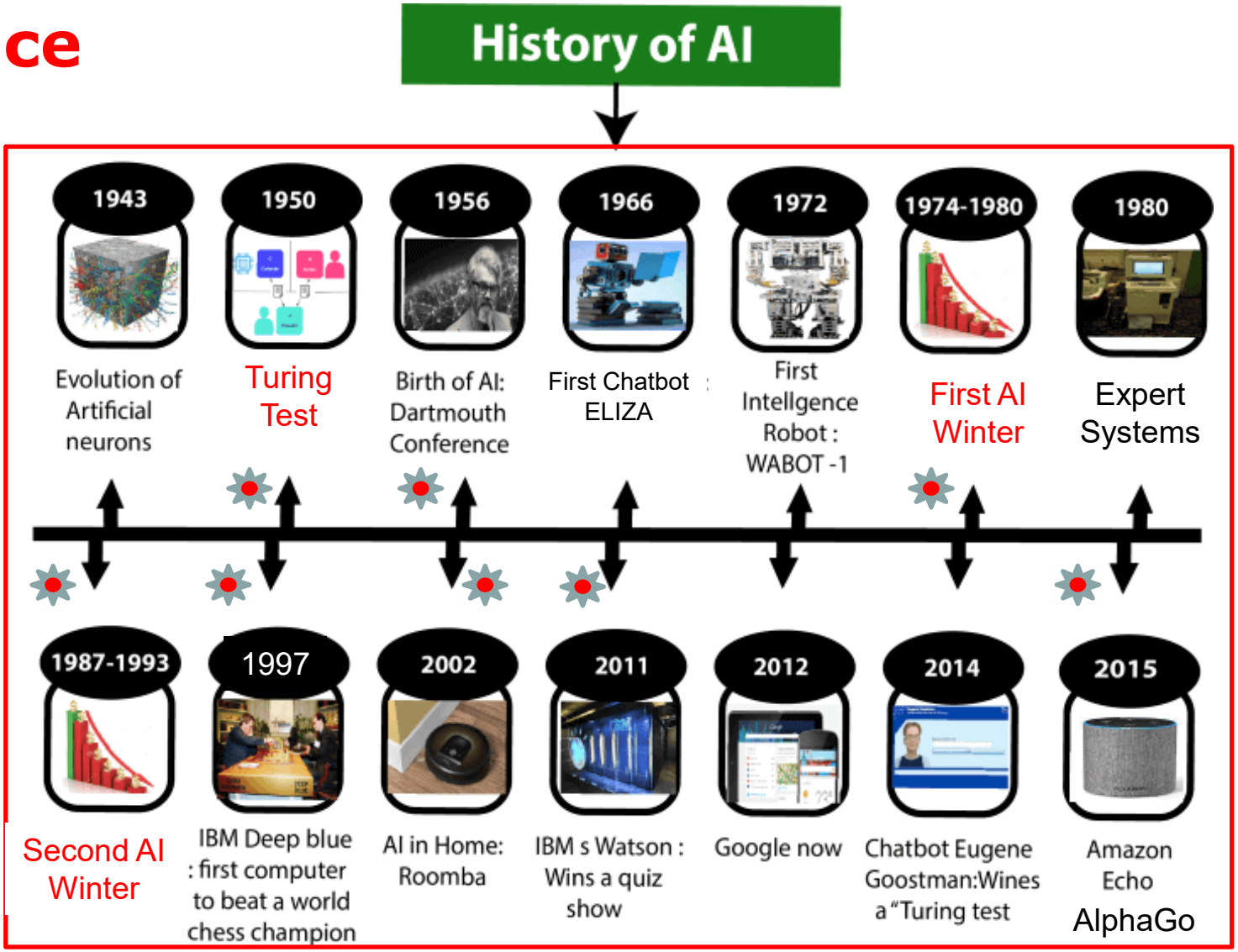
Tuning is not learning!

- Neuroscience
- Fuzzy Theory
- Control Theory

# History of Artificial Intelligence

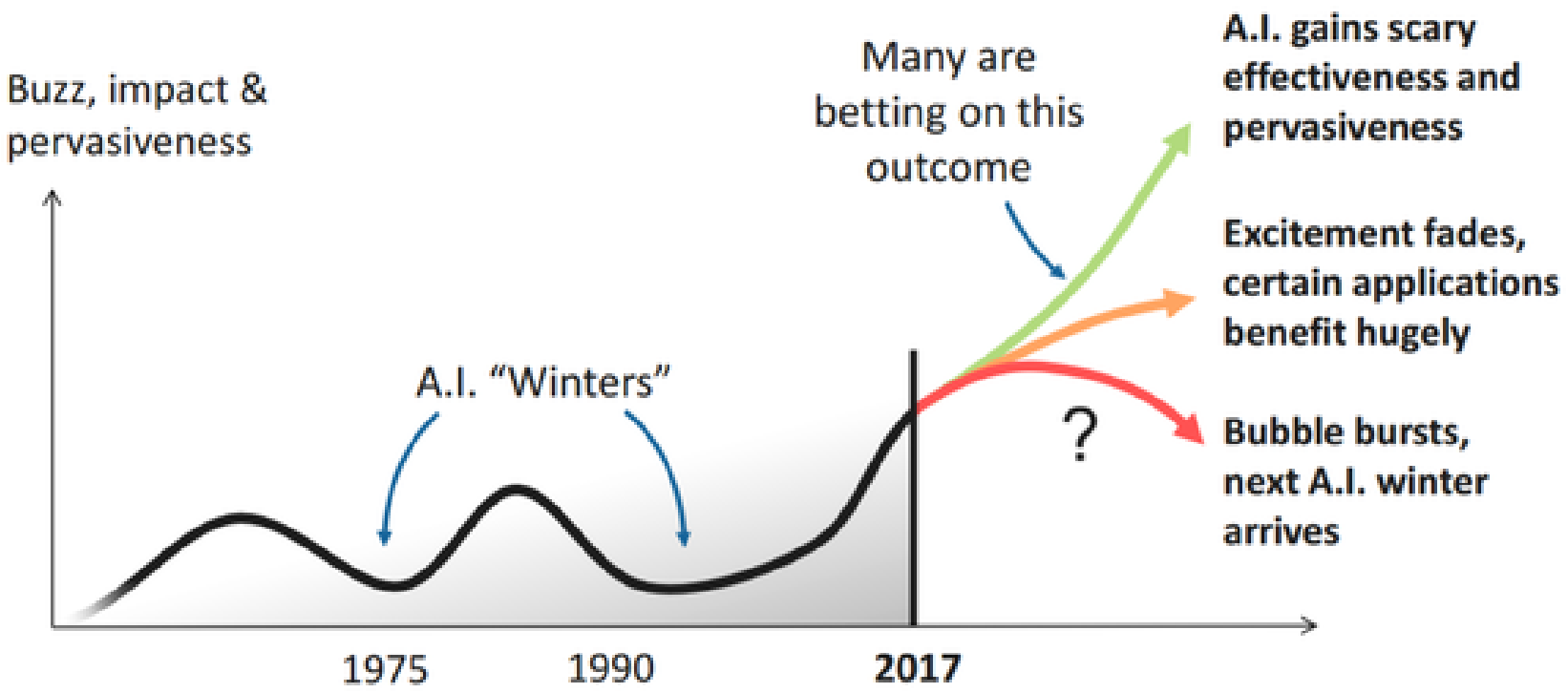
Big Question:

Does intelligence arise from brain or mind?



# Special Pattern of AI's History

**AI is enjoying significant hype and investment**




| | |
|---|---|
| 2009 | AI 3.0 (Machine's Self-Intelligence) (机器内智) (自具之智，人赋) |
| 2000 | AI 2.0 (Machine Learning) (机器学习) |
| 1956 | AI 1.0 (Machine Thinking) (机器思考) |

# MIT's Opinion About Deep Fake Learning

# One Example of Machine's Fake Learning

GYSS SINGAPORE

8-12 JANUARY 2024

GLOBAL YOUNG SCIENTISTS SUMMIT

EXCITE • ENGAGE • ENABLE

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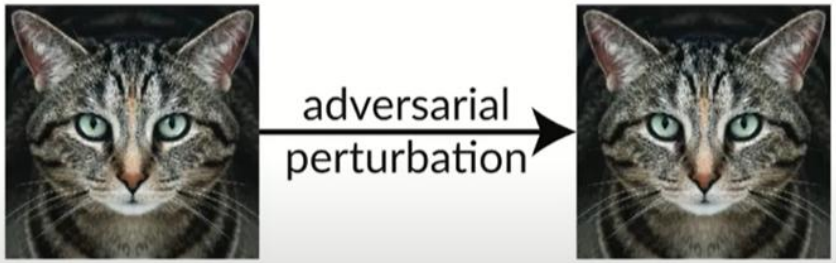
NATIONAL RESEARCH FOUNDATION
PRIME MINISTER'S OFFICE
SINGAPORE

## Adversarial Examples:

- Were discovered in 2013 by Szegedy et al and Biggio et al
- Have major security implications and applications




Salad made of avocado

# Another Example of Machine's Fake Learning

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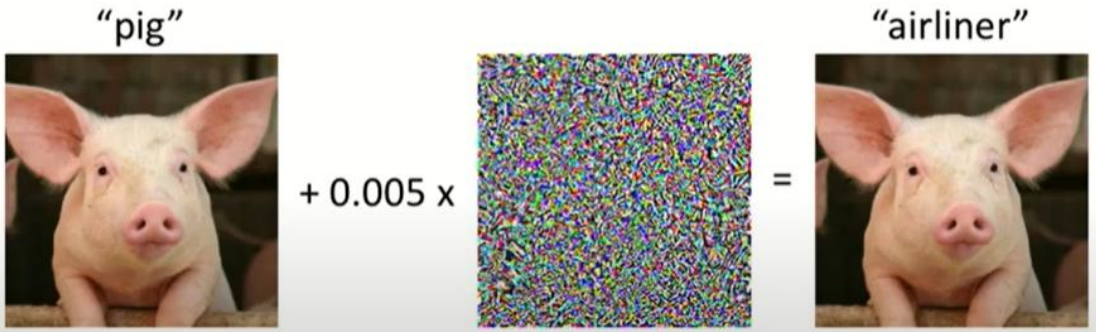
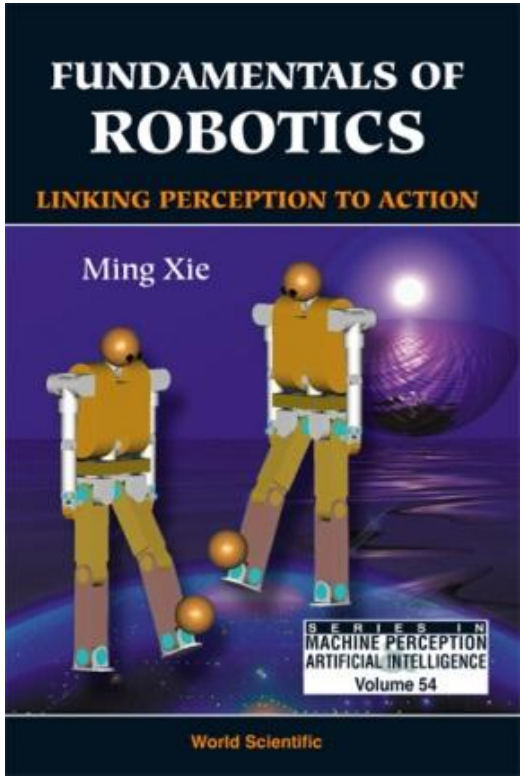
## Pigs can fly:



# Intelligence arises from educable mind (i.e., to have innate learning capabilities) …

- In my book published in 2003, I said that the necessary condition for a humanoid robot to be able to learn is to be educable.

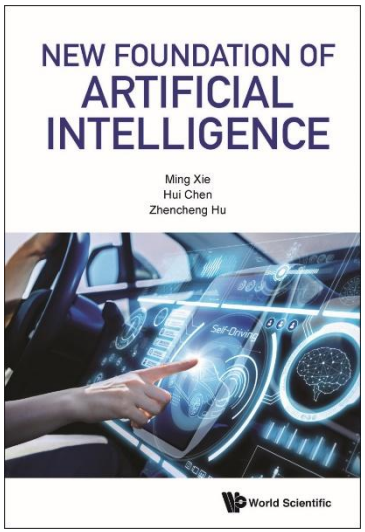
- How much promise remains for entrepreneurs? Plenty, Gates insisted during a tour of several top universities in 2004. In a stop at MIT, a student asked Bill Gates if another tech company could ever match Microsoft's success. "**If you invent a breakthrough in artificial intelligence so machines can learn," he responded, "that is worth 10 Microsoft.**"

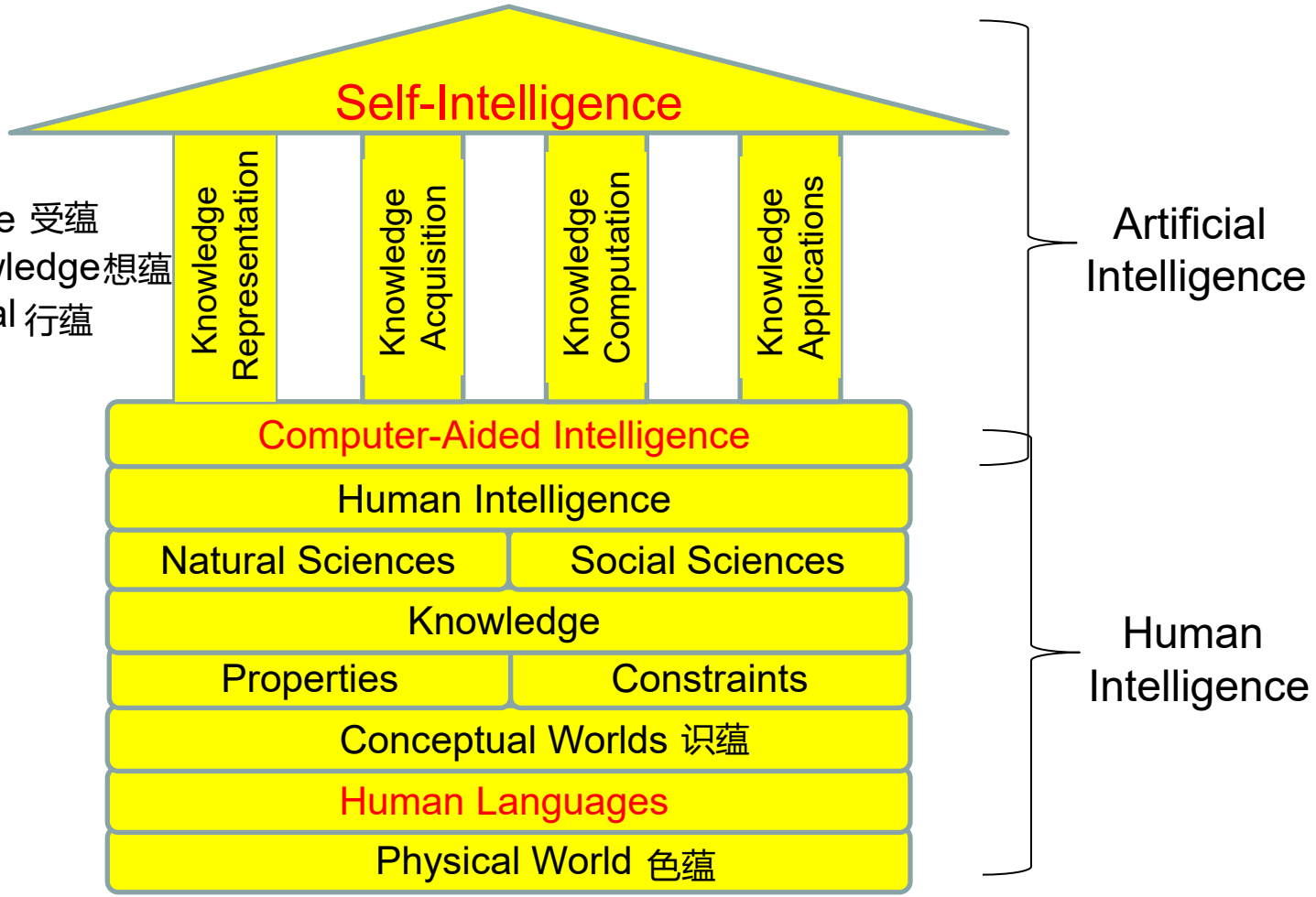


# New Foundation of AI: How to achieve a humanoid robot's self-intelligence? …

- One Tool
- Two Worlds
- Three Intelligences
- Four Pillars

- Signal to Knowledge 受蕴
- Knowledge to Knowledge想蕴
- Knowledge to Signal 行蕴



# New Era of AI: Third Generation of AI or AI 3.0 …

Intelligence arises from mind, but not from brain.

Brain develops while mind learns.

1943-1956 **AI 1.0**
John McCarthy
Marvin Minsky
Nathaniel Rochester
Claude Shannon
1956 Dartmouth Workshop

推导与演绎
Inference and Reasoning

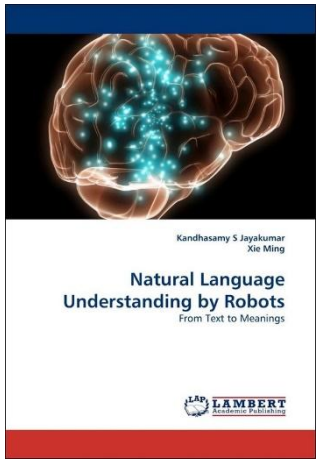
1992-2000 **AI 2.0**
John Weng
James McCelland
Alex Pentland
2000 MSU Workshop

发育与学习
Development and Learning

2003-2009 **AI 3.0**
Ming Xie et al.
2009 IJHR Paper

2010

语言与认知
Language and Cognition




AI's Foundation

Third Generation of Artificial Intelligence

Second Generation of Artificial Intelligence

First Generation of Artificial Intelligence

Finding the Root of AI

寻根问源

# New Definition of Artificial Intelligence

## Old Definition of AI

- Artificial intelligence refers to computer-aided human intelligence, which aims at programming human ways of doing perception, planning and action.

- Computer-aided Intelligence is not equal to Computer Intelligence!

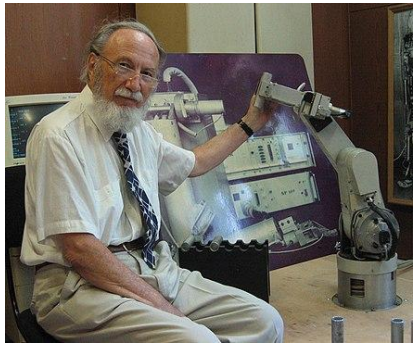
## New Definition of AI

- Artificial intelligence refers to machine's self-intelligence, which aims at discovering and implementing the principles behind the transformations from signals to cognitive states of knowing the meanings inside the signals and vice versa.

# Outline of Today's Talk

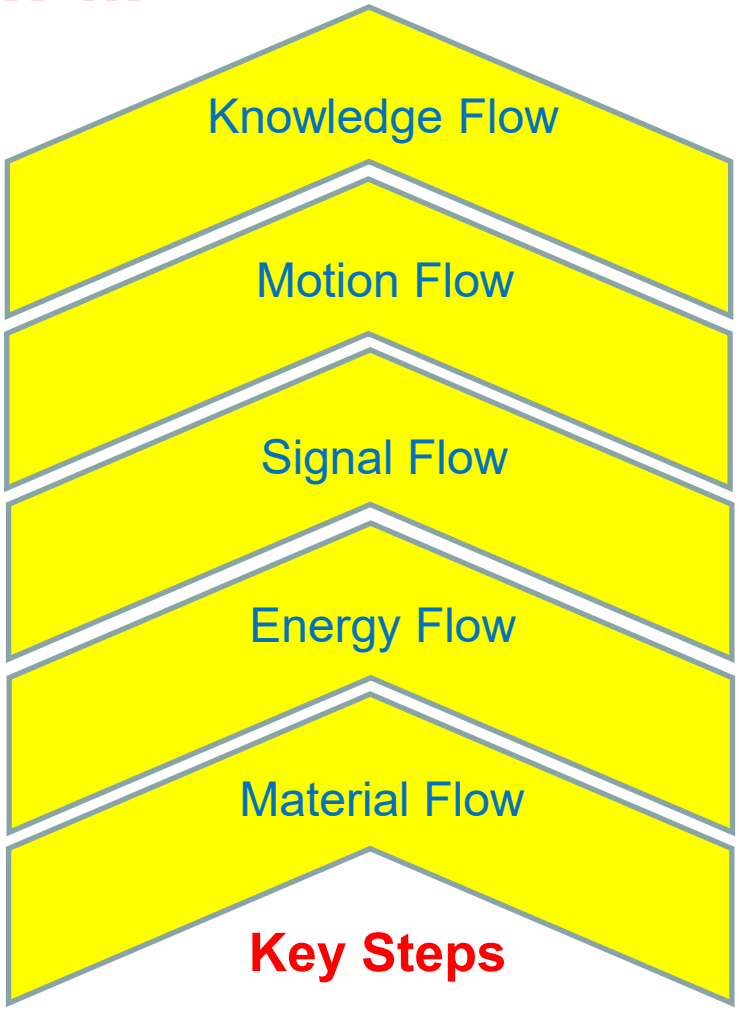
- What is humanoid robot?
- What are the domain knowledge behind humanoid robot?
- What are the key steps toward development of humanoid robot?
  - Material Flow Inside Humanoid Robots
  - Energy Flow Inside Humanoid Robots
  - Signal Flow Inside Humanoid Robots
  - Motion Flow Inside Humanoid Robots
  - Knowledge Flow Inside Humanoid Robots
- Concluding Remarks

# The key solutions underlying the development of humanoid robot could be grouped into these five layers of flow …



Miomir Vukobratovic
(1931-2012)
Discovery of ZMP

Any smart dynamic system has a physical body and brain




- Cognition
- Recognition
- Interaction

- Perception
- Planning
- Control

- Motion Kinematics
- Motion Dynamics

- Position Sensors
- Velocity Sensors
- Force/Torque Sensors
- Visual/Acoustic Sensors

- Power Suppliers
- Actuators and Controllers

- Appearance
- Structure
- Mechanism

- Computing
- Memory

# Material flow is important to the design of …

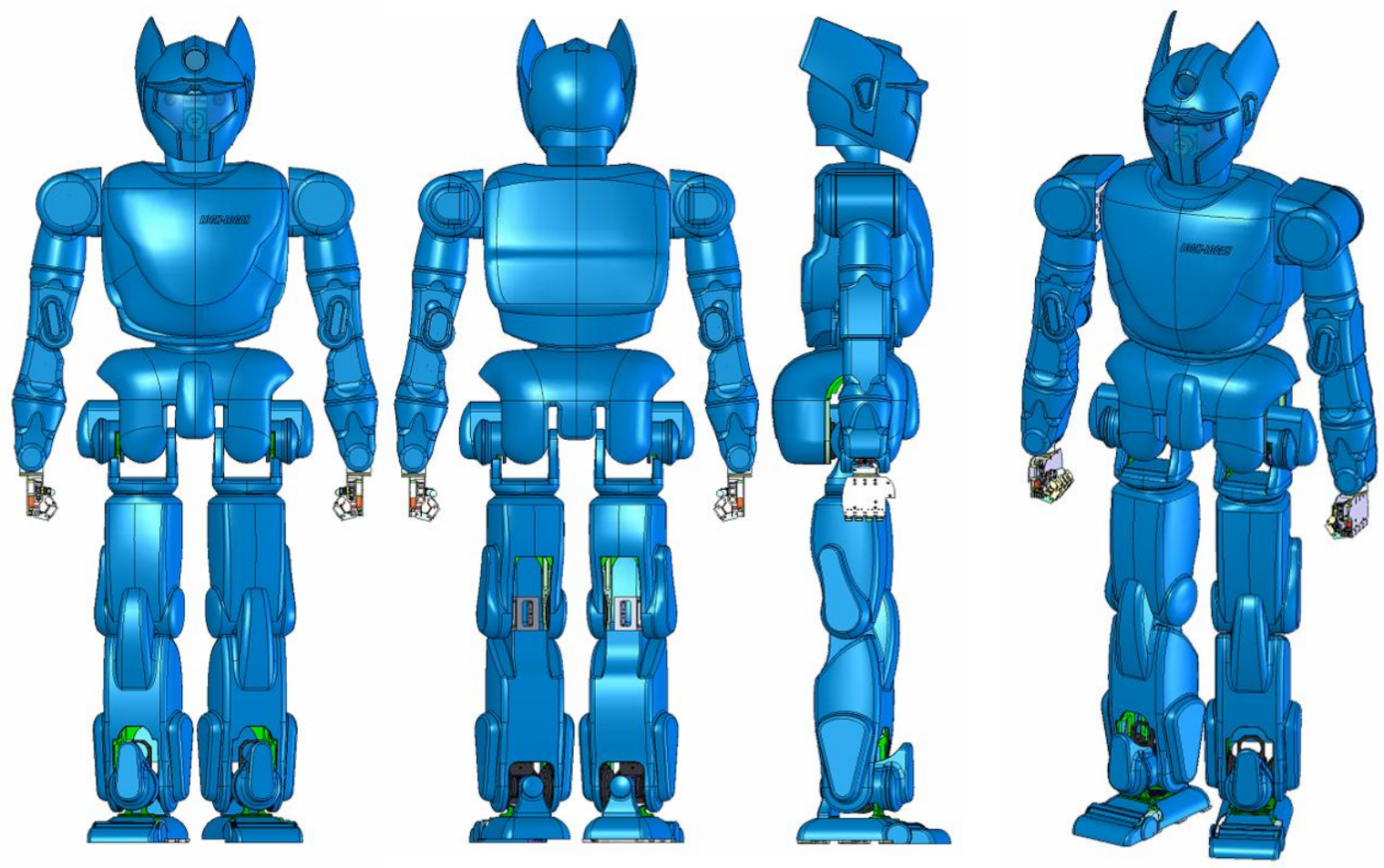
## Mechanical Body

- Which is a network of rigid links, actuators, sensors and controllers.
- Links form mechanisms
- Links form structures
- Links form appearances

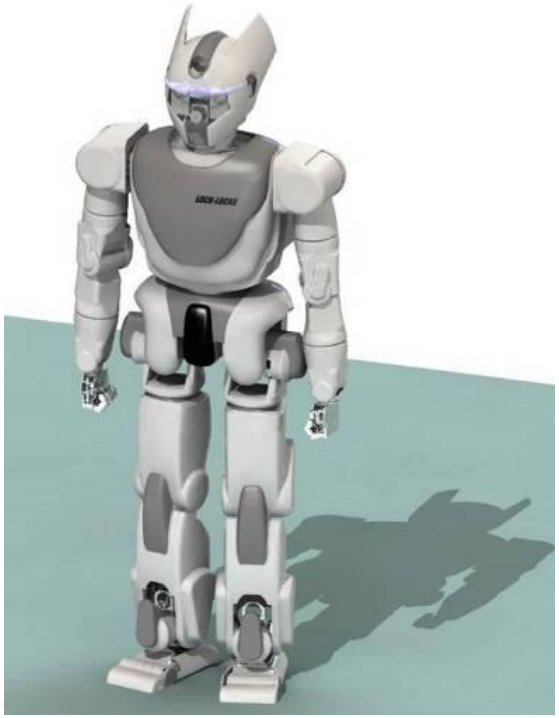
## Electronic Brain

- Which is a network of neurons or transistors
- Neurons or transistors create logic gates
- Logic gates create CPUs
- Logic gates also create memory devices

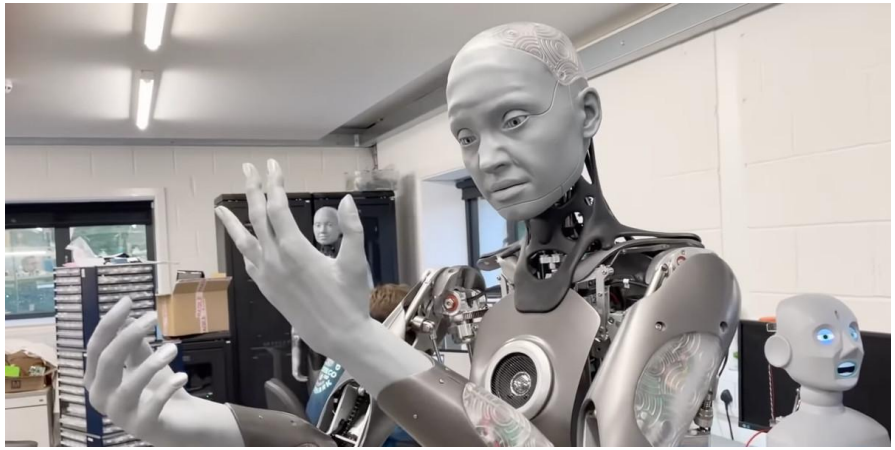
# Our Example of Designed Appearance

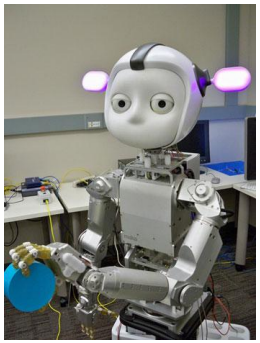


# Our Example of Designed Appearance (continued)

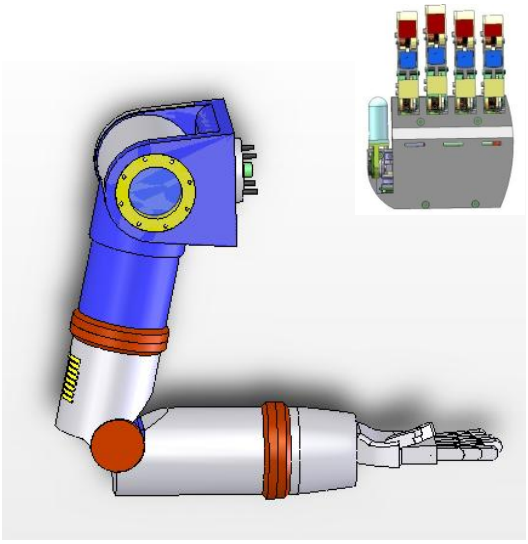


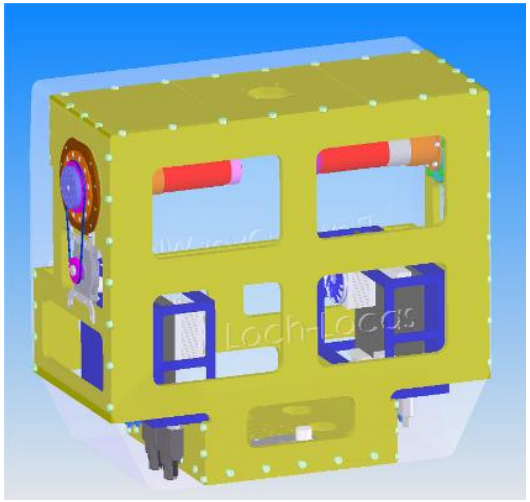
# Others' Examples of Designed Appearance …

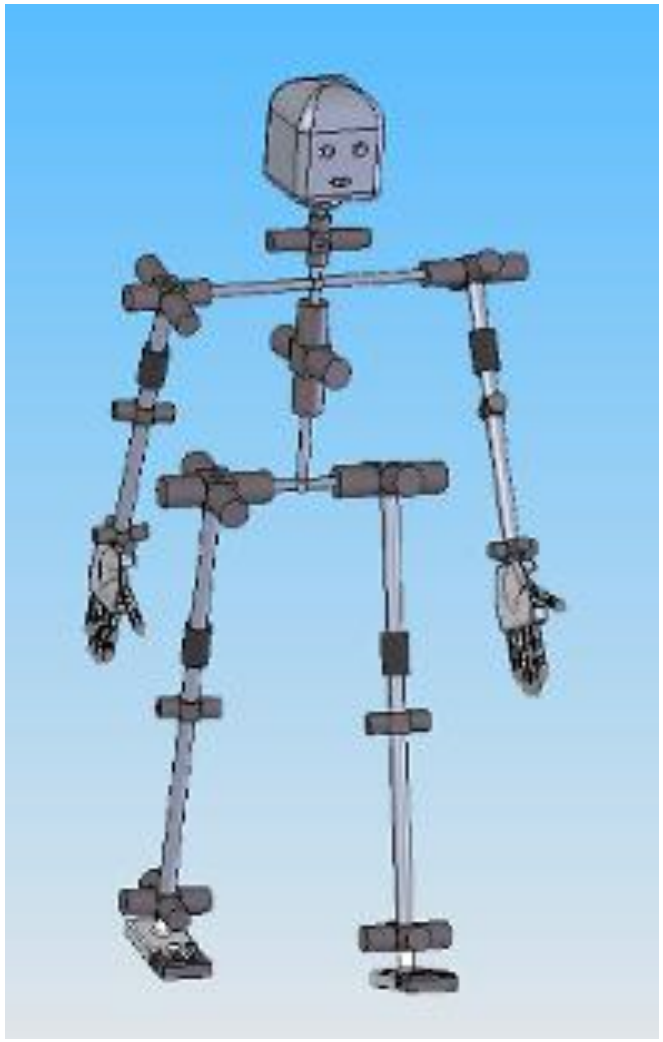


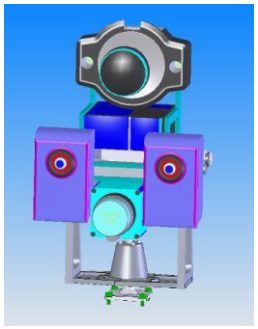



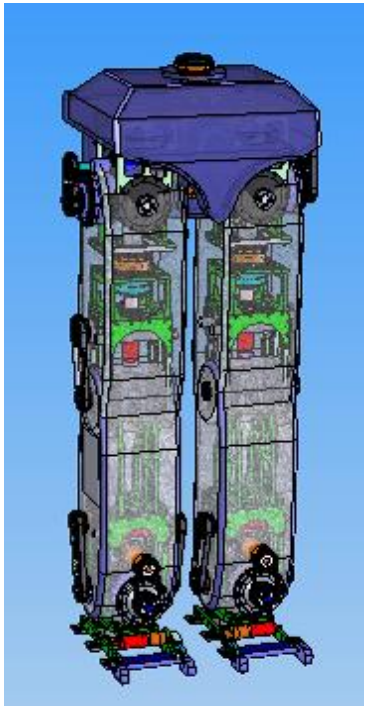
# Our Example of Designed Mechanism







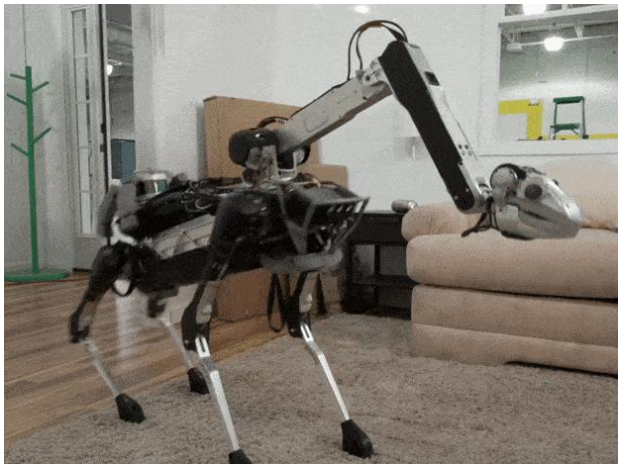


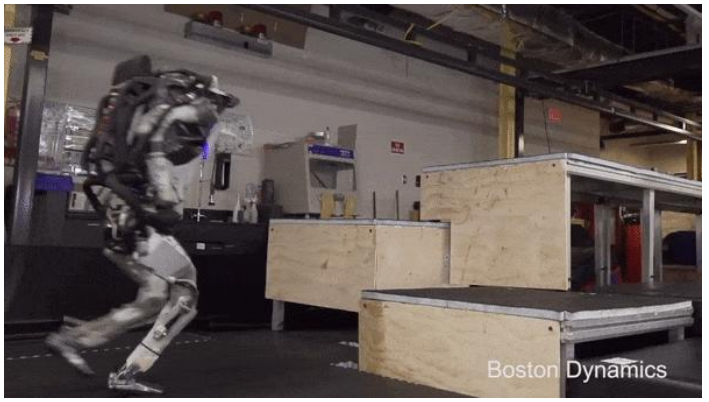


# Early 1990s

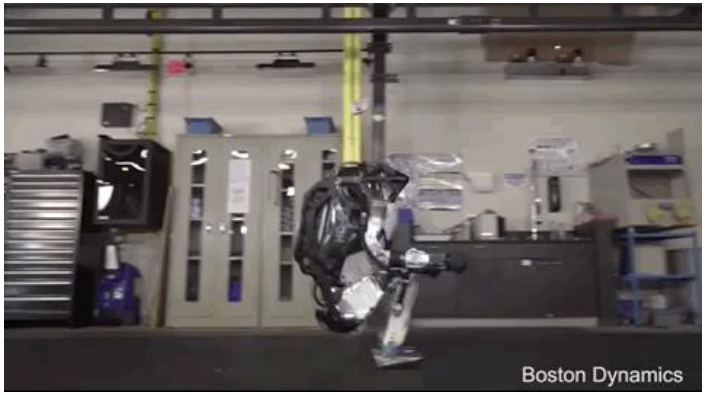
(Modular 2-DOF Links)

# Others' Examples of Designed Mechanism ...

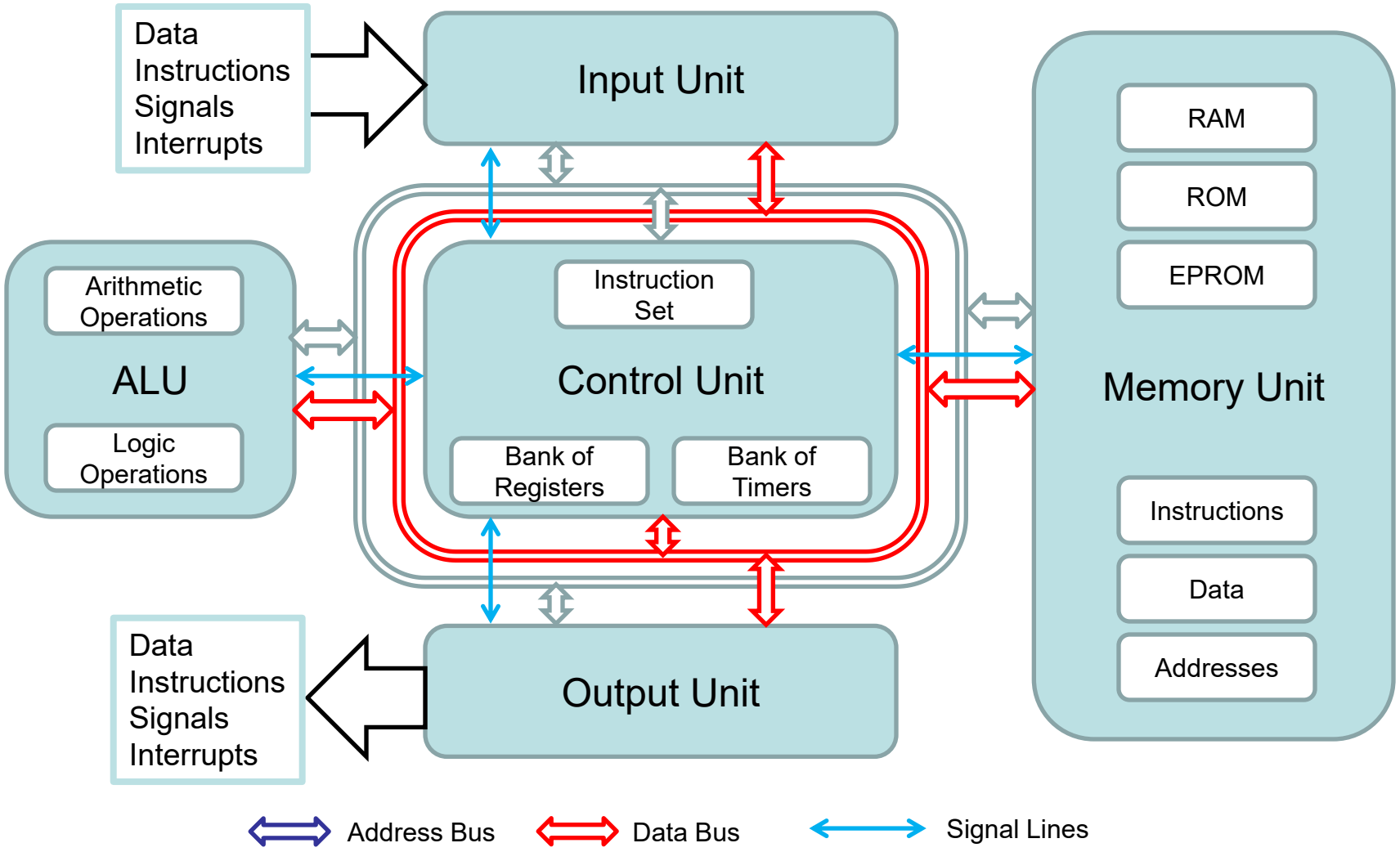




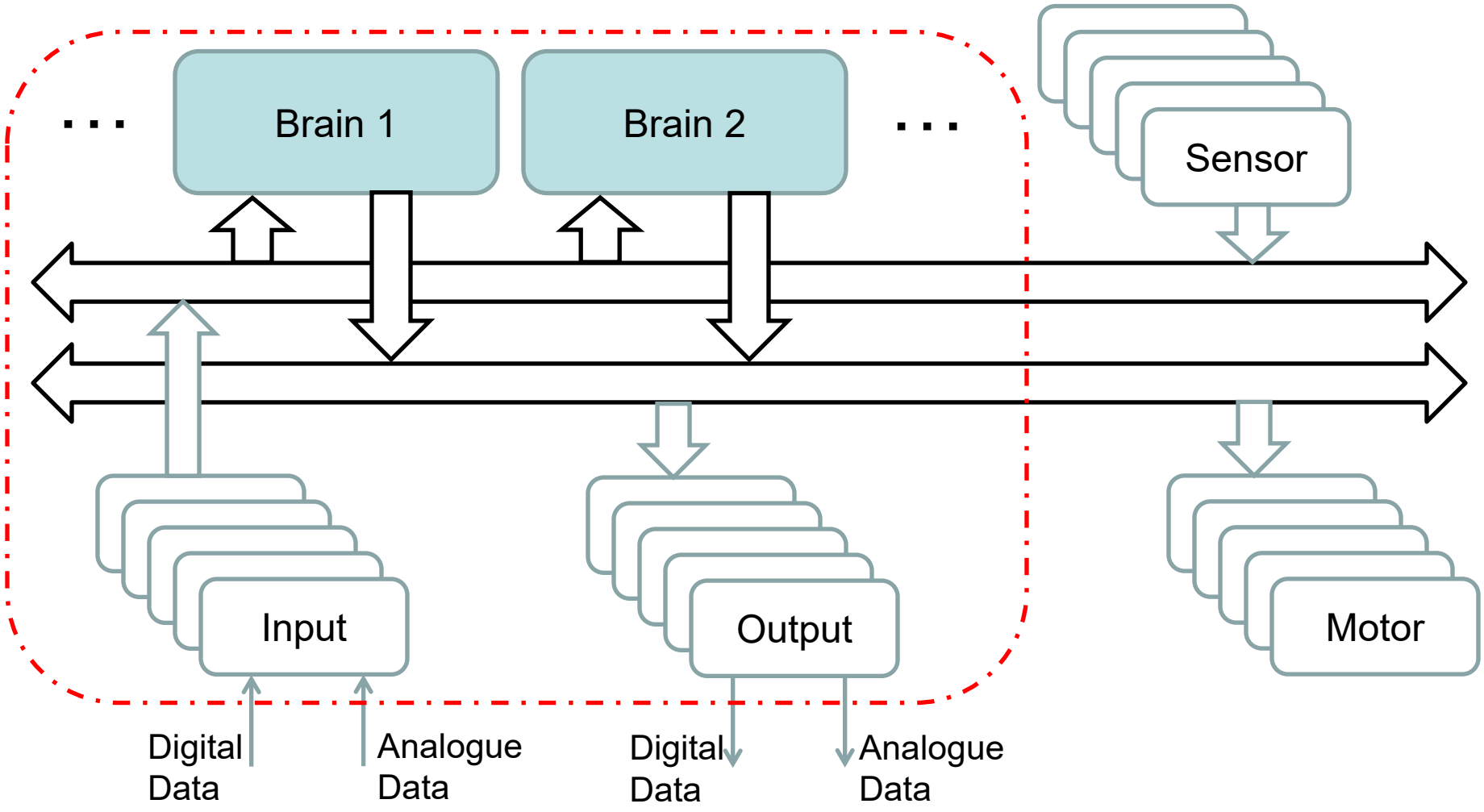




# Electronic brains are made of logic gate devices which creates CPUs and memory units ...

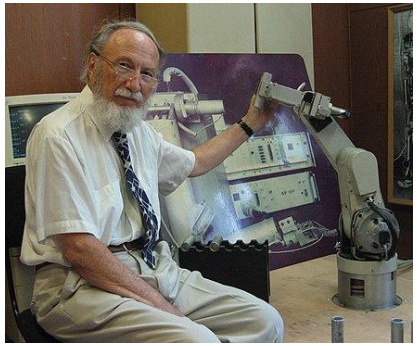


# Example of Using Electronic Brains ...



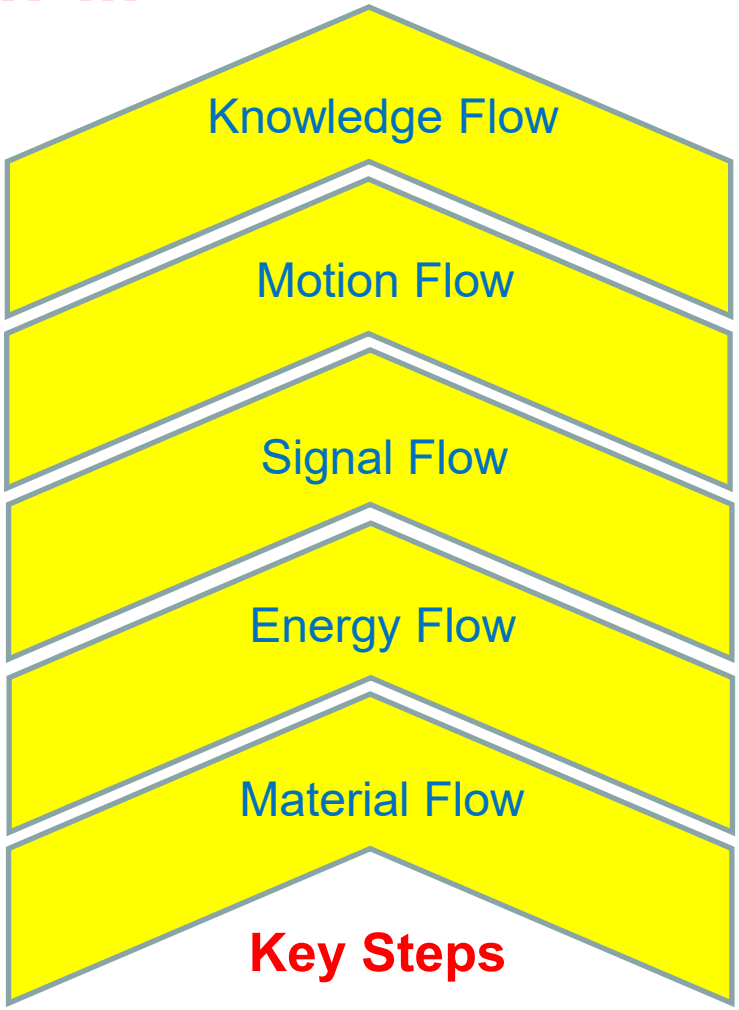

To support mental processes of doing: Signals → Knowledge → Knowledge → Signals

# The key solutions underlying the development of humanoid robot could be grouped into these five layers of flow …



Miomir Vukobratovic
(1931-2012)
Discovery of ZMP

Any smart dynamic system consumes energy




- Cognition
- Recognition
- Interaction

- Perception
- Planning
- Control

- Motion Kinematics
- Motion Dynamics

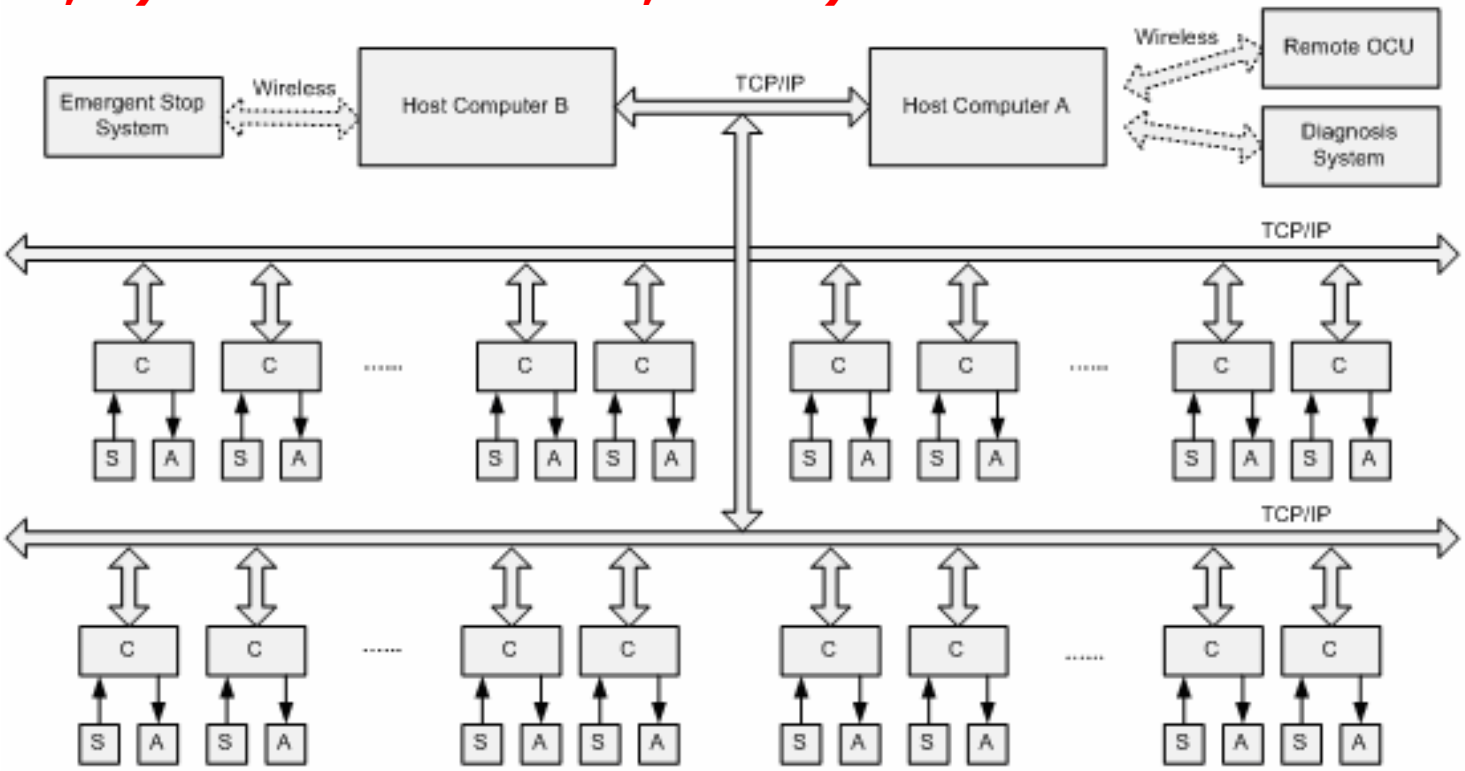
- Position Sensors
- Velocity Sensors
- Force/Torque Sensors
- Visual/Acoustic Sensors

- Power Suppliers
- Actuators and Controllers

- Appearance
- Structure
- Mechanism

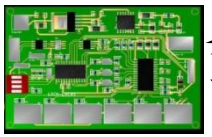
- Computing
- Memory

**A humanoid robot's body consumes energy because it is a mini-version of IoT (Internet of Things) which includes: a) sensor network, b) actuator network, and c) controller network.**




PC104

Micro Controller

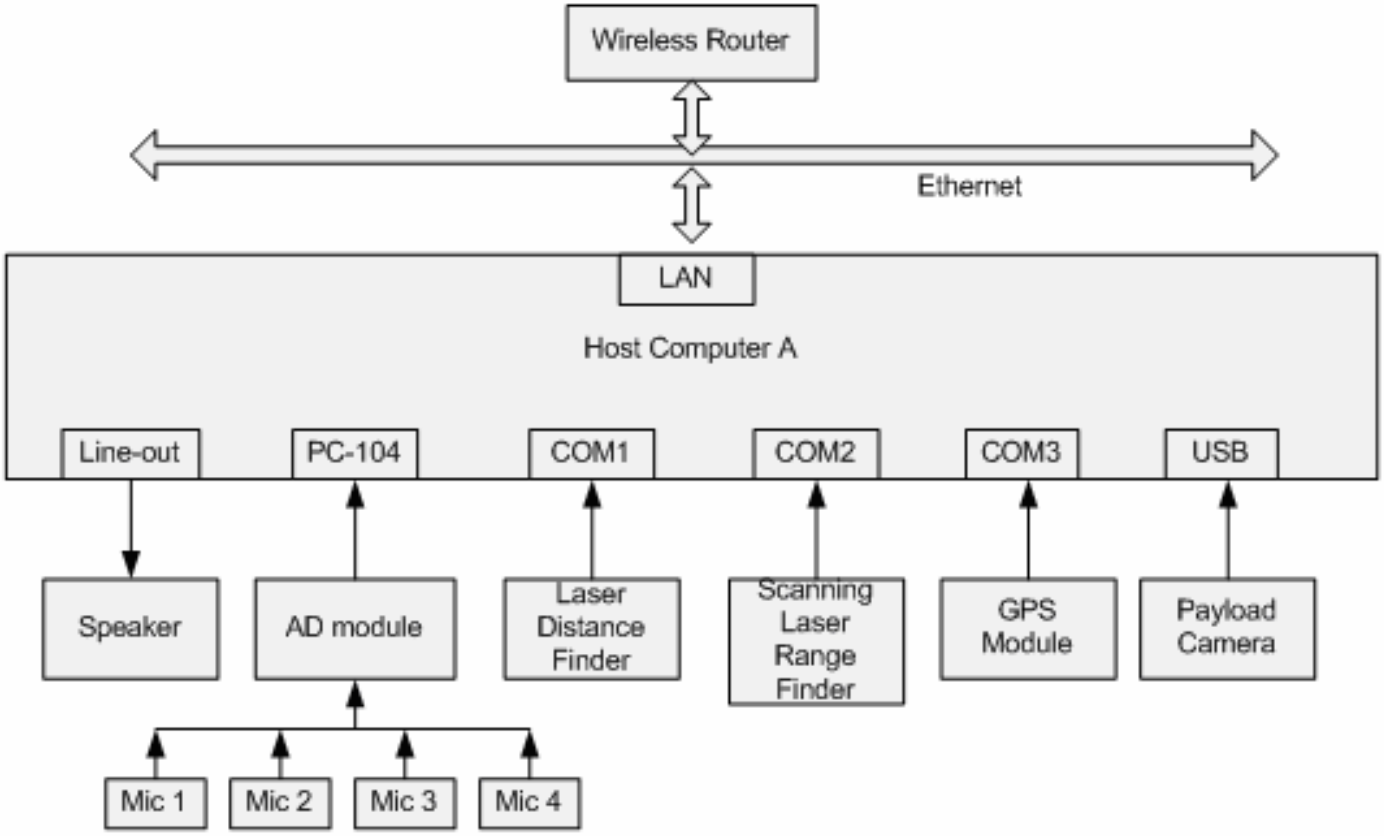


Motor Driver

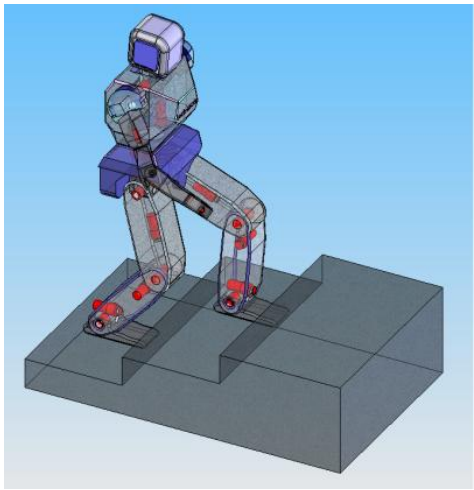
Brushless DC Motor

Encoder

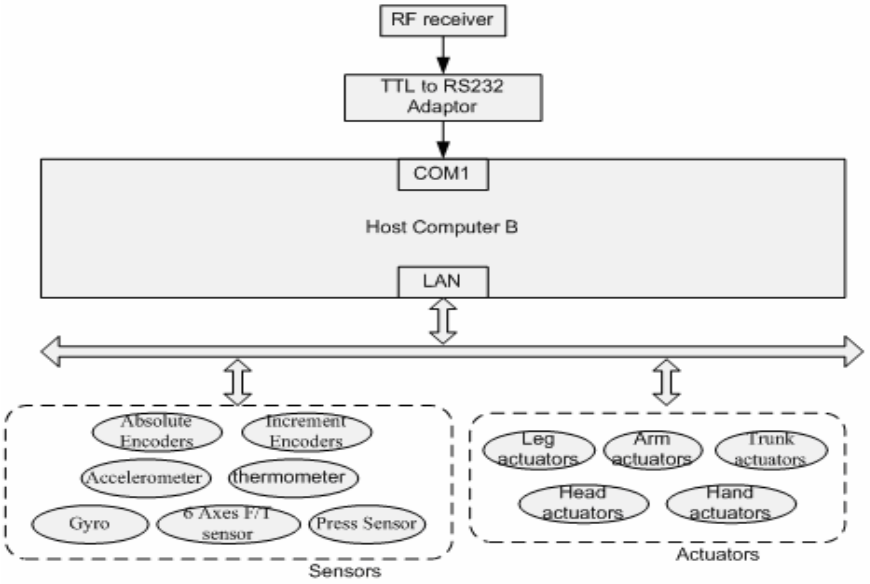
# Humanoid Robot's Cerebrum Consumes Energy …

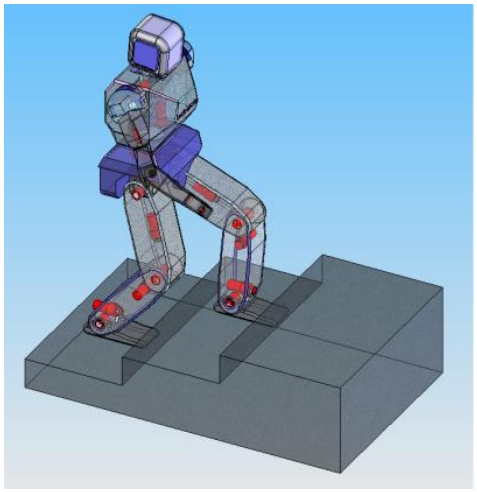



Cerebrum + Sensory Systems

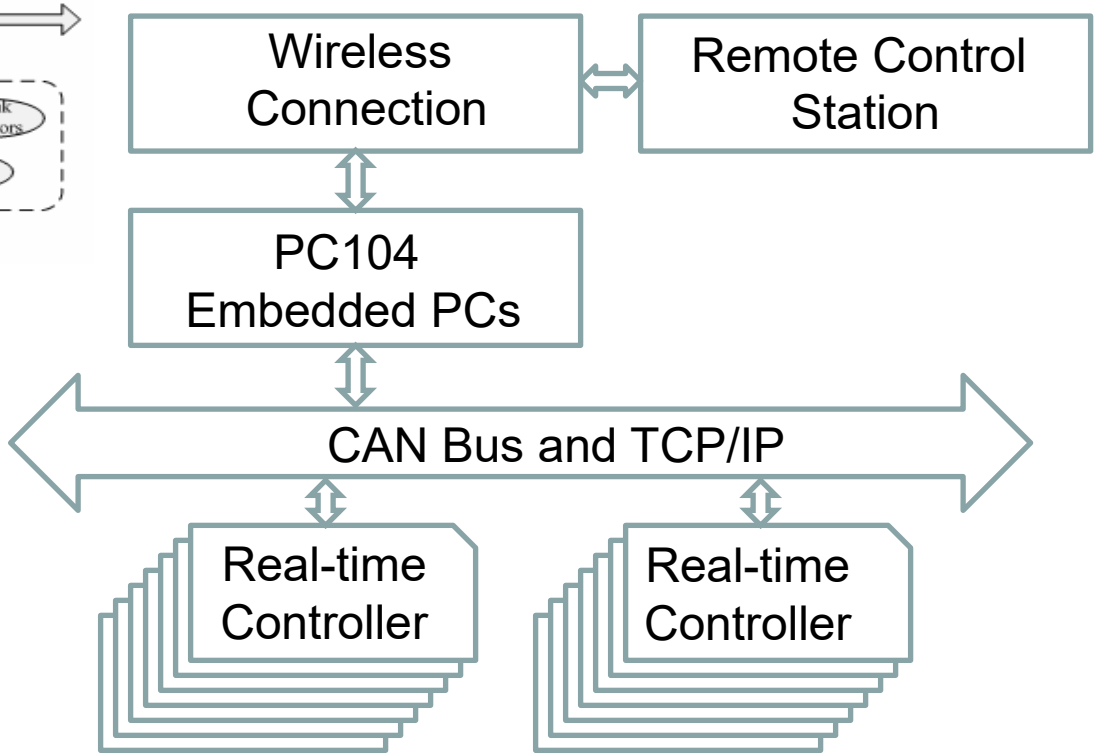


# Humanoid Robot's Cerebellum Also Consumes Energy …

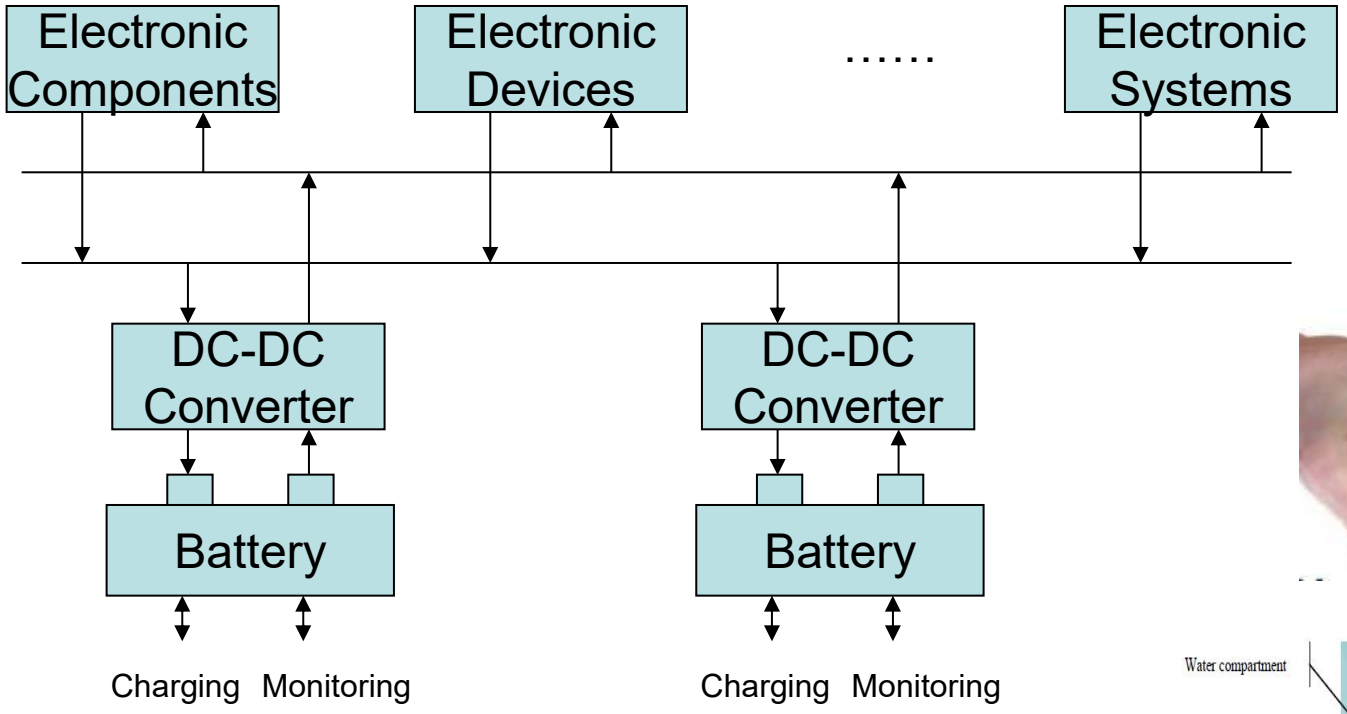


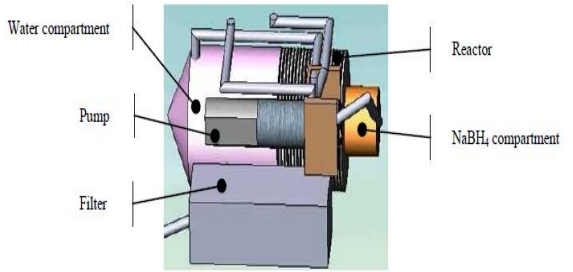



Cerebellum + Controllers



# Our Example of Distributed Power Supply System …




Hybrid Power Unit:
1. Fuel-cell
2. Battery

# Example of Prototypes Powered by Single Actuator

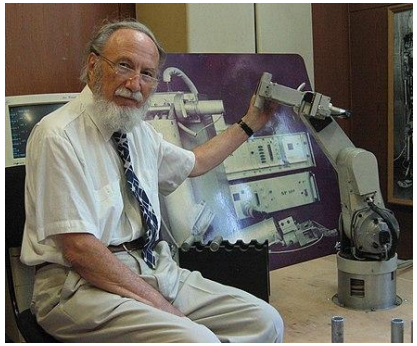


(Results Achieved in Late 1990s)

# Example of Prototype Powered by Multiple Actuators

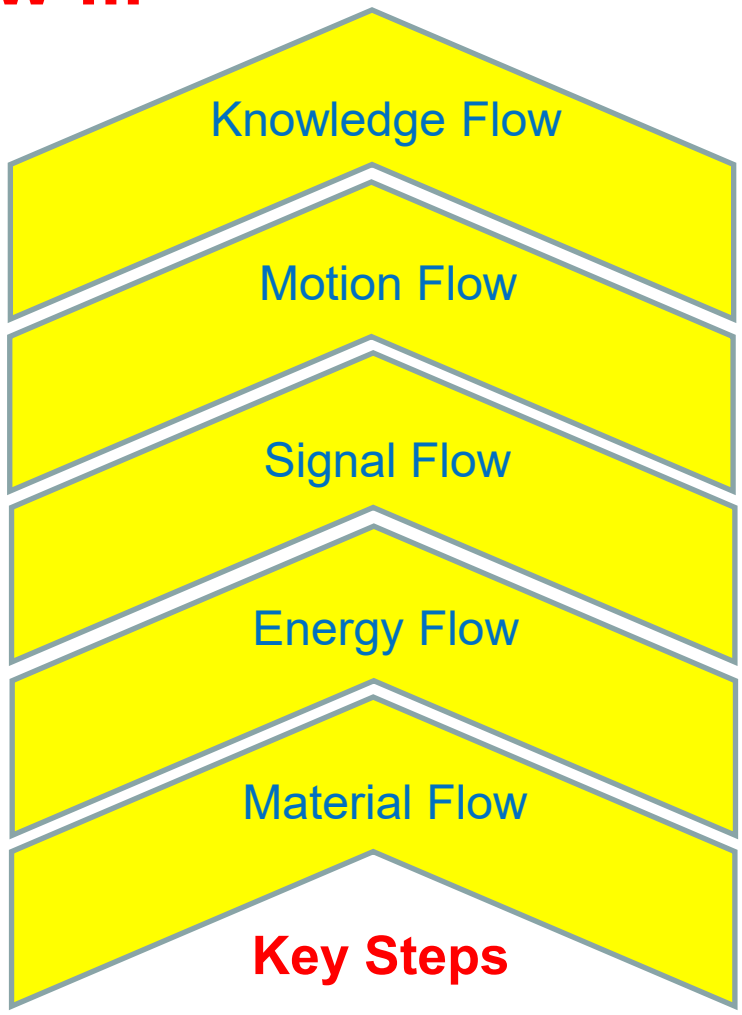
# Other's Example of Prototype Powered by Multiple Actuators

# The key solutions underlying the development of humanoid robot could be grouped into these five layers of flow …



Miomir Vukobratovic
(1931-2012)
Discovery of ZMP

Any dynamic system has properties and constraints which could be manifested in the form of signals

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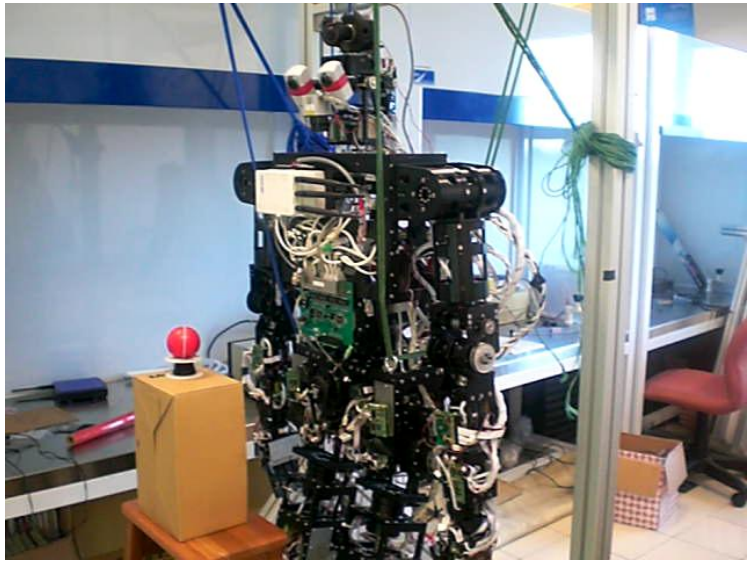
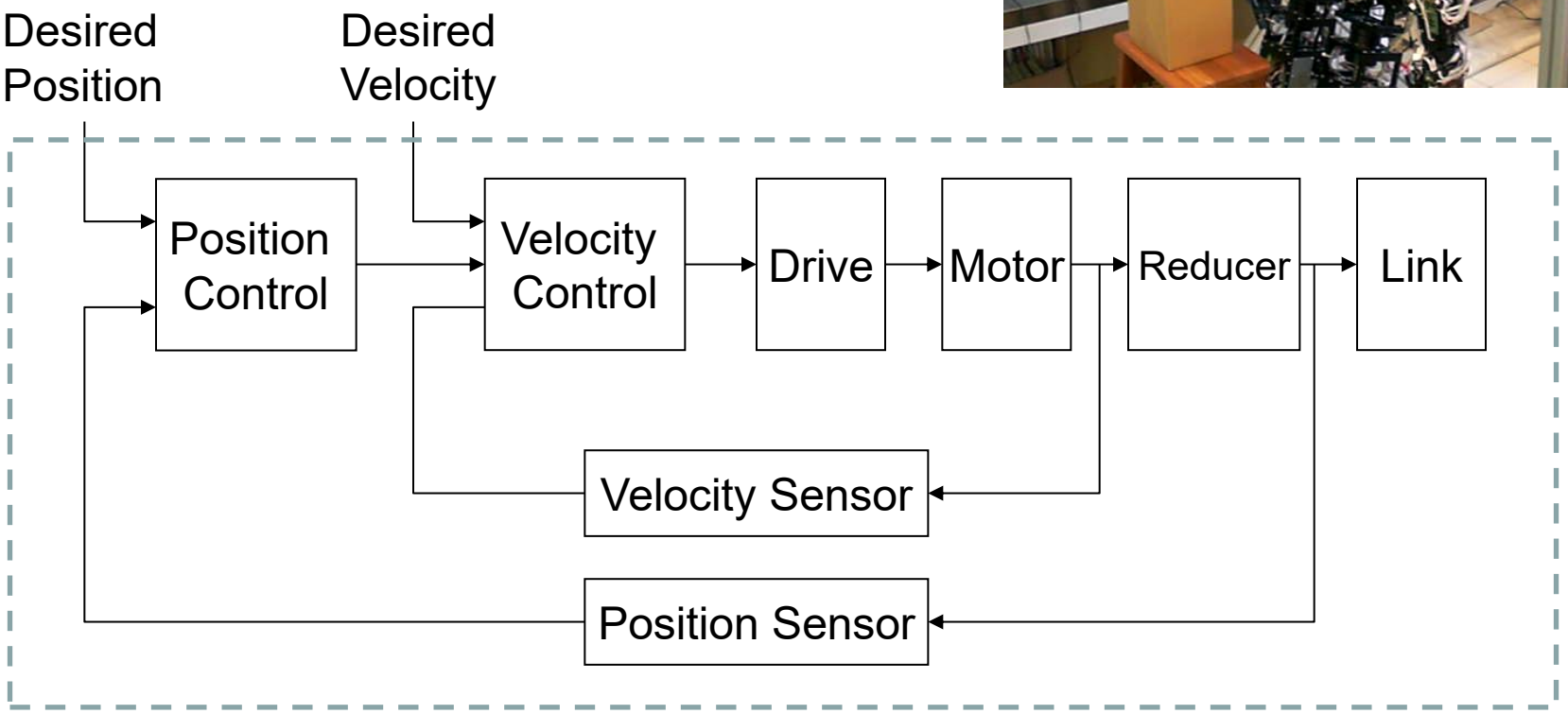
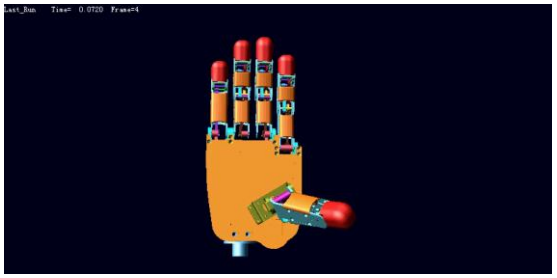
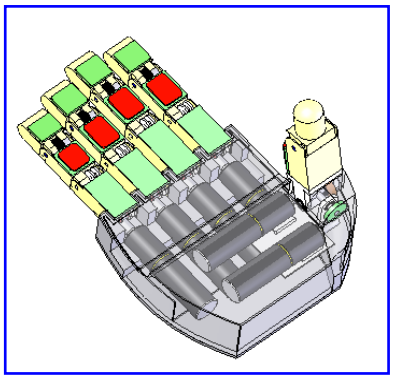
**A humanoid robot lives inside an ocean of signals.**
**It must be sensitive to: Signal Flows of Position, Velocity, Force, Torque, etc.**

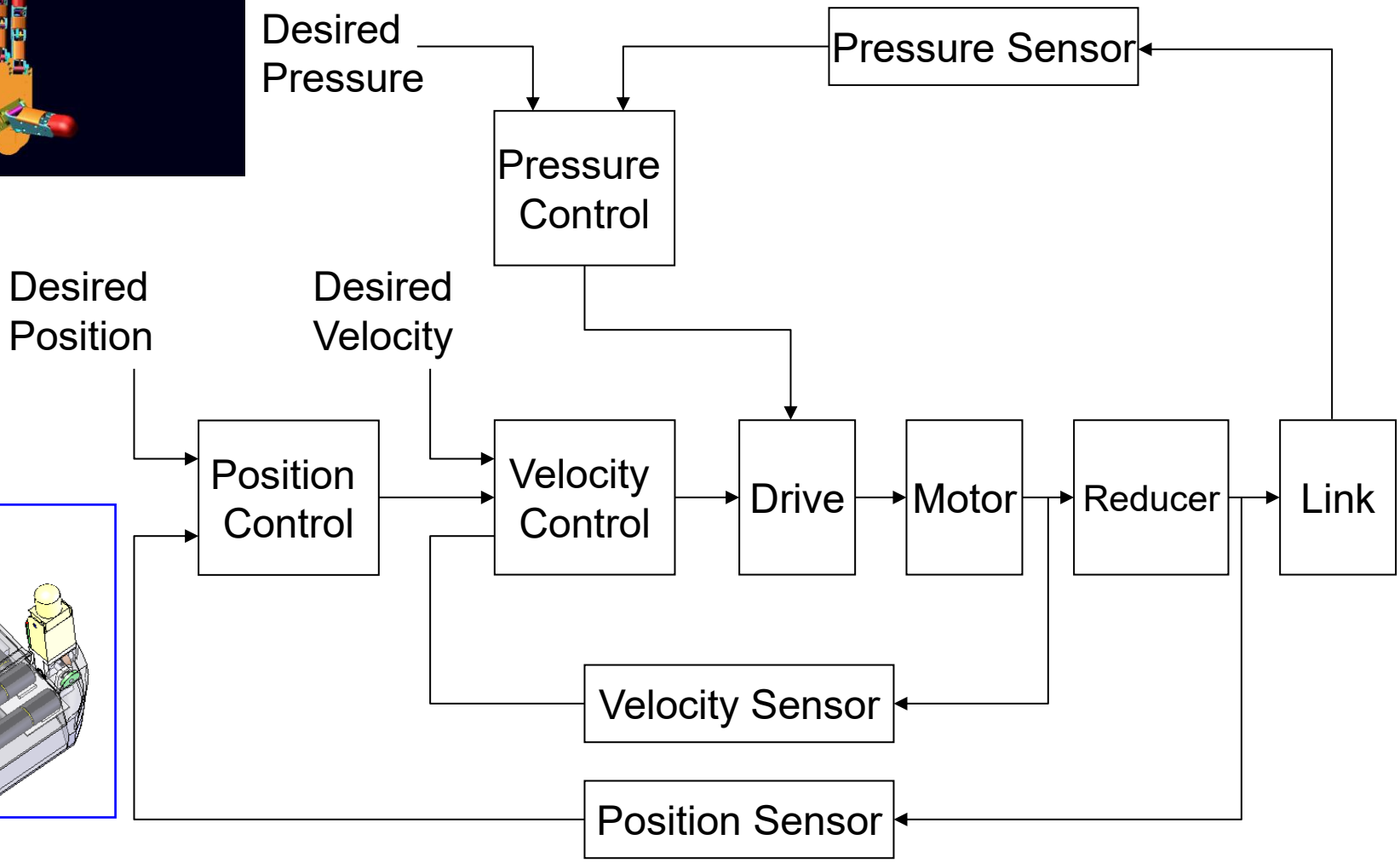




# Example of Using Signals of Pressure, Position and Velocity to Enable Humanoid Robots to Do Control of Grasping ...

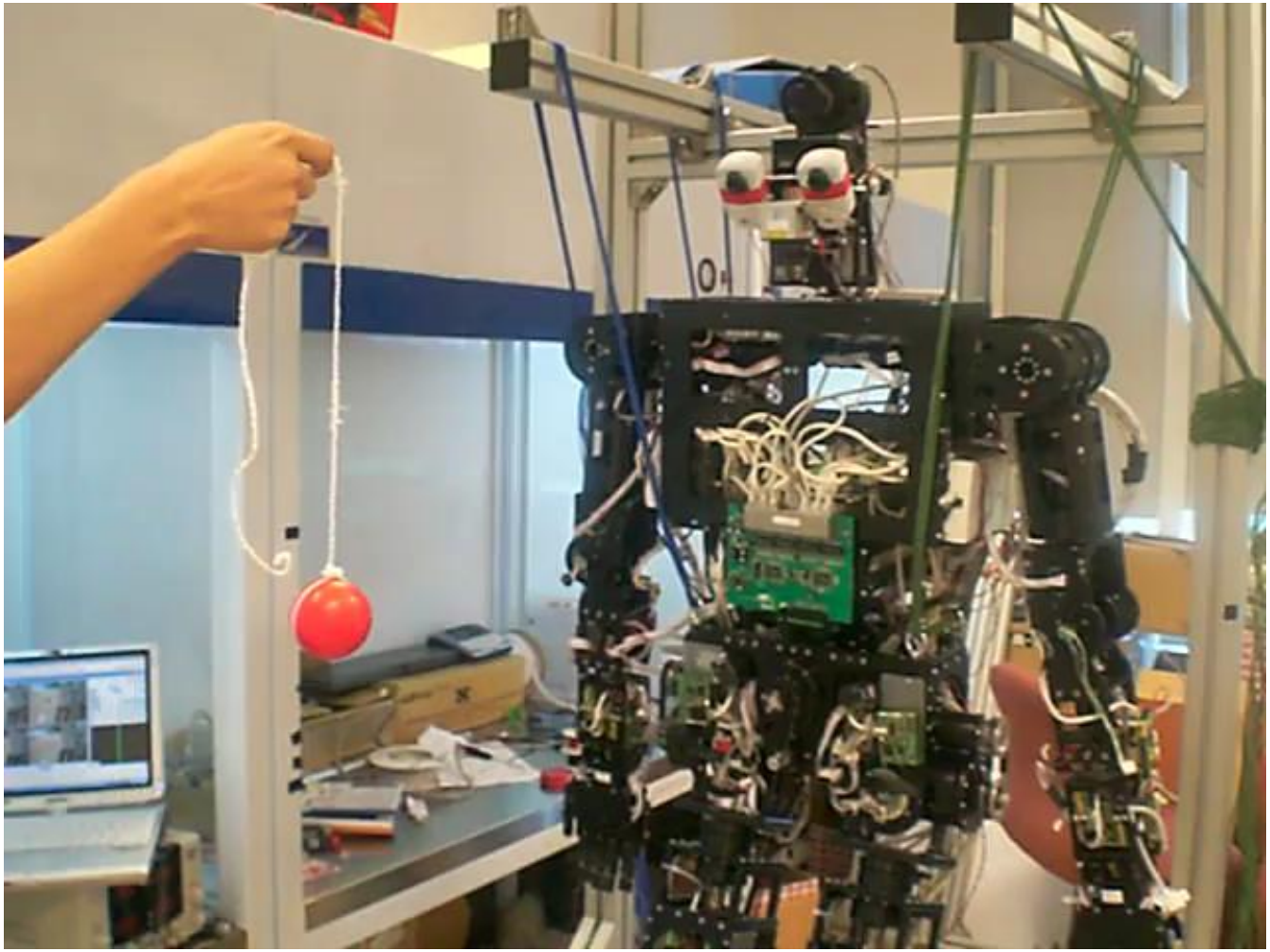






# Example of Using Force/Torque Signals to Enable Human-Robot Interaction …

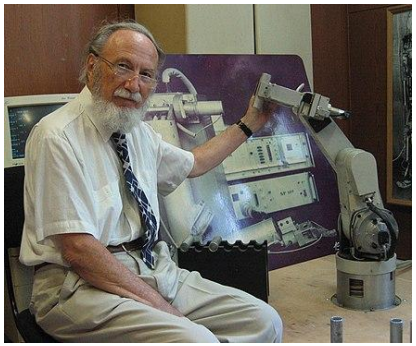
# Example of Using Visual Signals to Enable Human-Robot Interaction …



# Example of Using Acoustic Signals to Enable Human-Robot Interaction …

# The key solutions underlying the development of humanoid robot could be grouped into these five layers of flow …

Motion is the manifestation of kinetic energy



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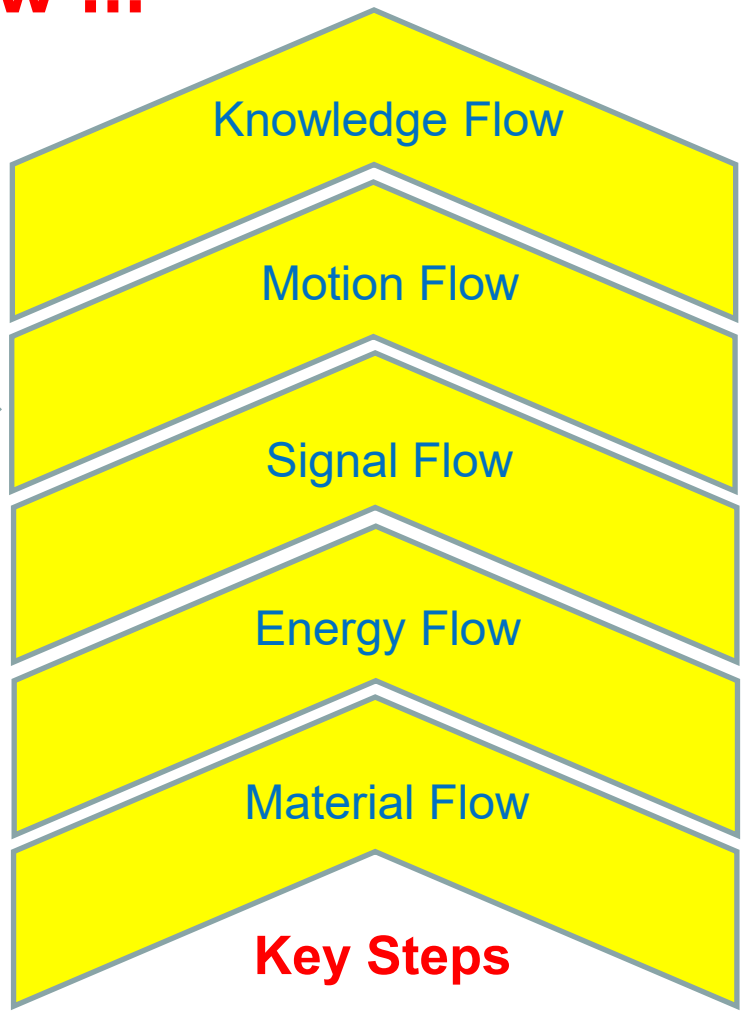


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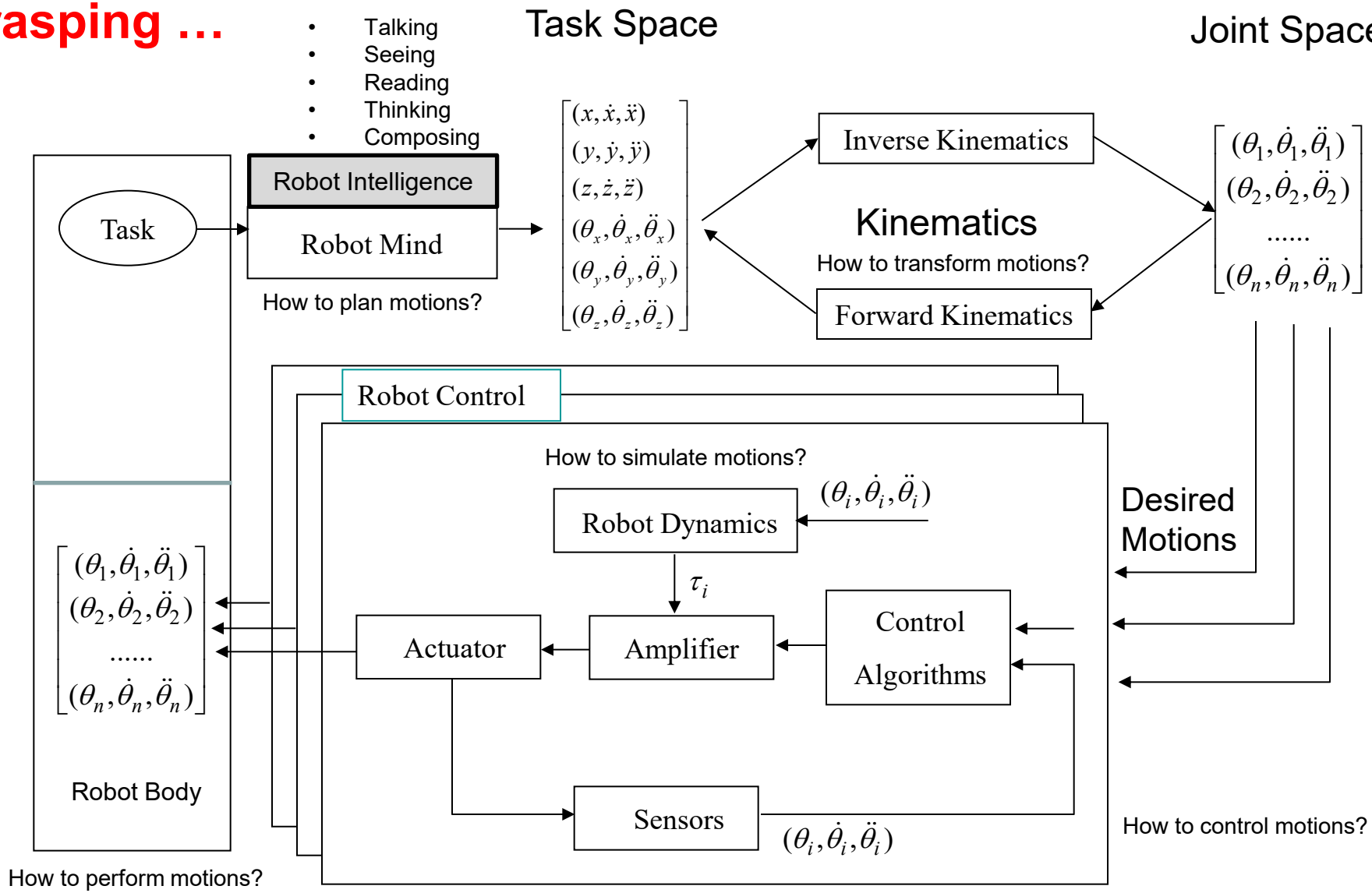
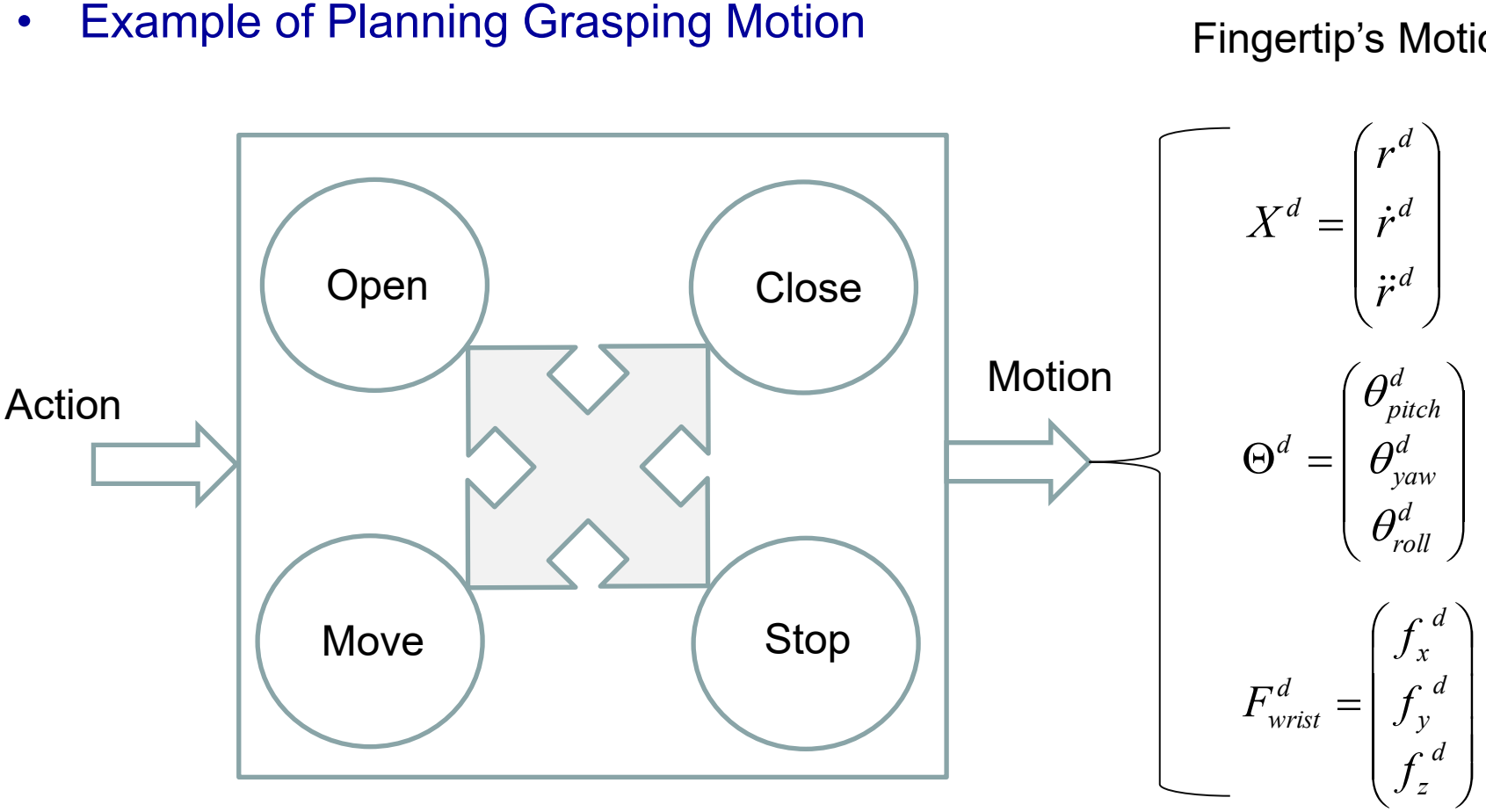
# Motion Flows Are Related to Locomotion, Manipulation, and Grasping …

- Talking
- Seeing
- Reading
- Thinking
- Composing



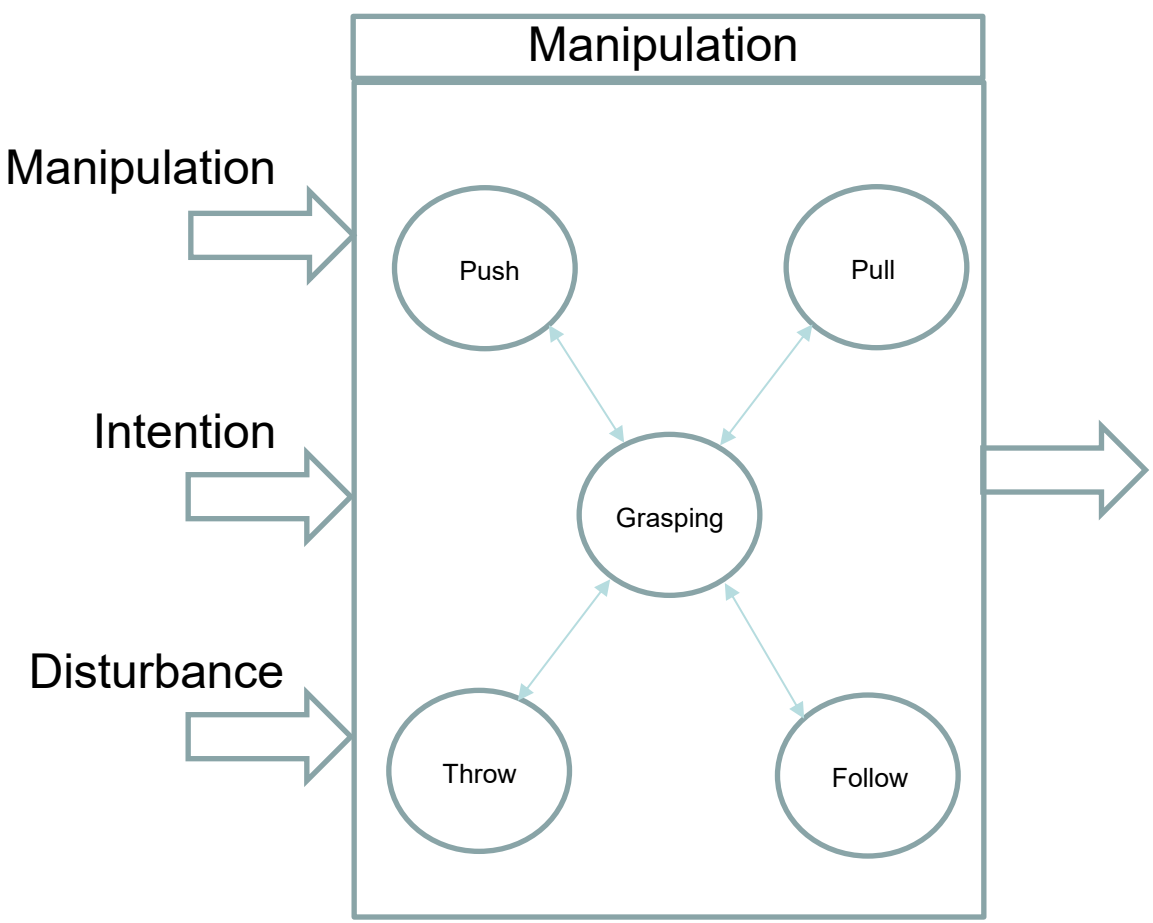
# Motion Flows Are Planned …

- Example of Planning Grasping Motion



# Motion Flows Are Planning …

- Example of Planning Manipulation Motion




Hand's Motion

Motion

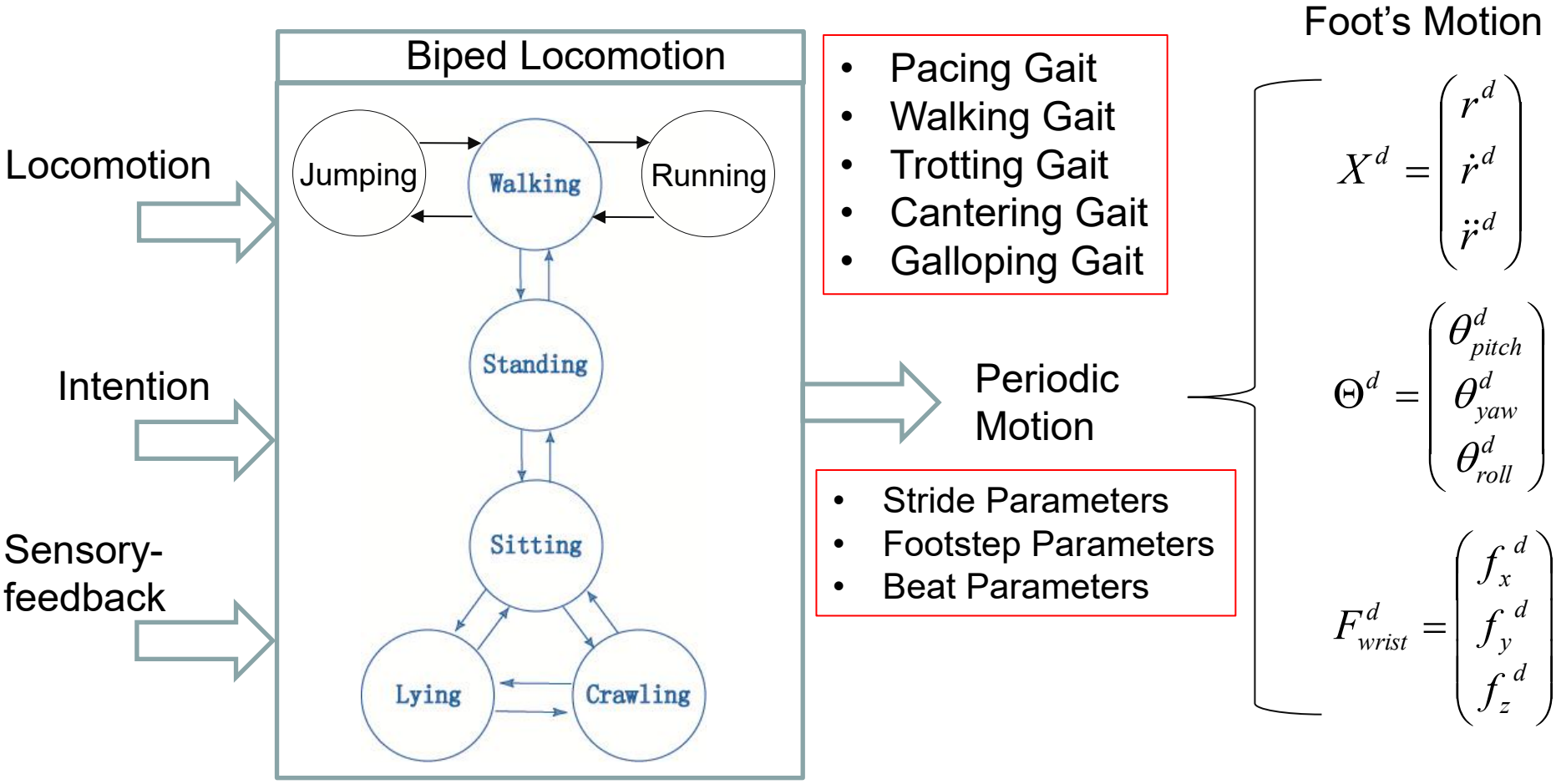
$$X^d = \begin{pmatrix} r^d \\ \dot{r}^d \\ \ddot{r}^d \end{pmatrix}$$

$$\Theta^d = \begin{pmatrix} \theta^d_{pitch} \\ \theta^d_{yaw} \\ \theta^d_{roll} \end{pmatrix}$$

$$F^d_{wrist} = \begin{pmatrix} f_x^{\,d} \\ f_y^{\,d} \\ f_z^{\,d} \end{pmatrix}$$

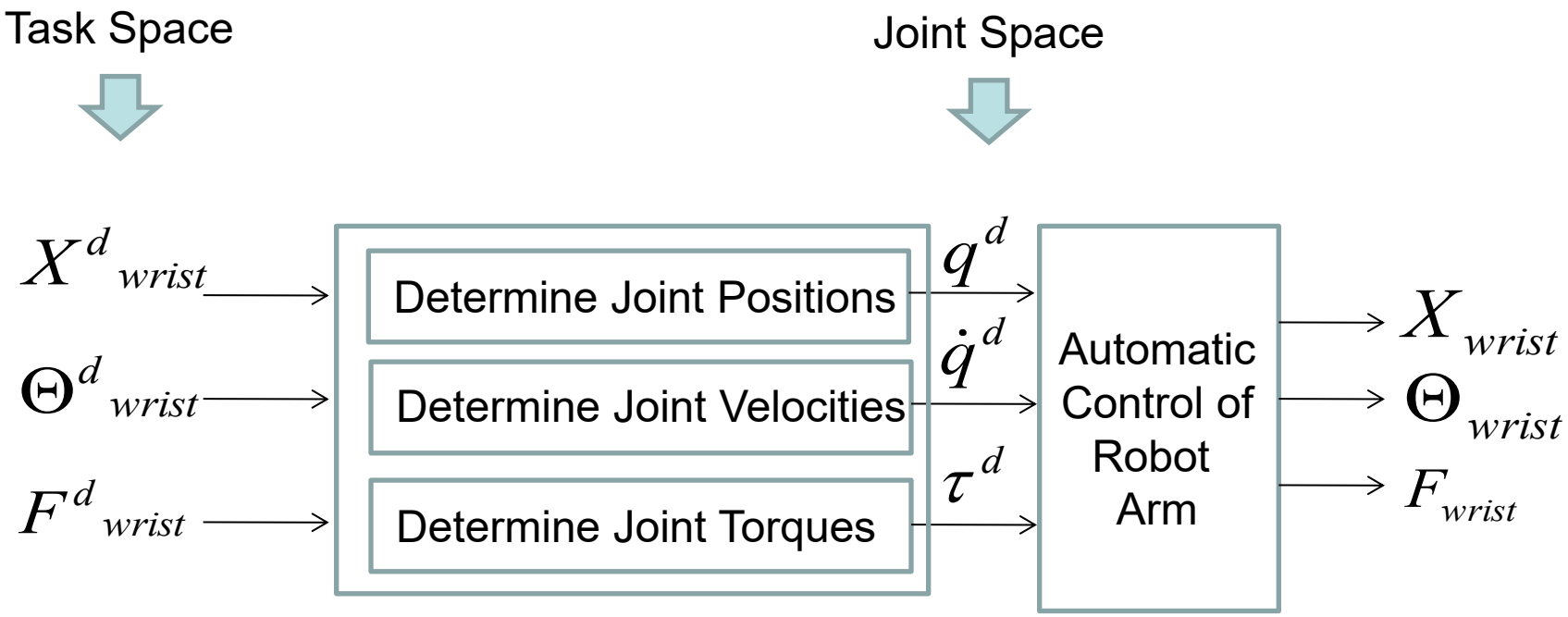
# Motion Flows Are Planned …

- Example of Planning Biped Walking Motion

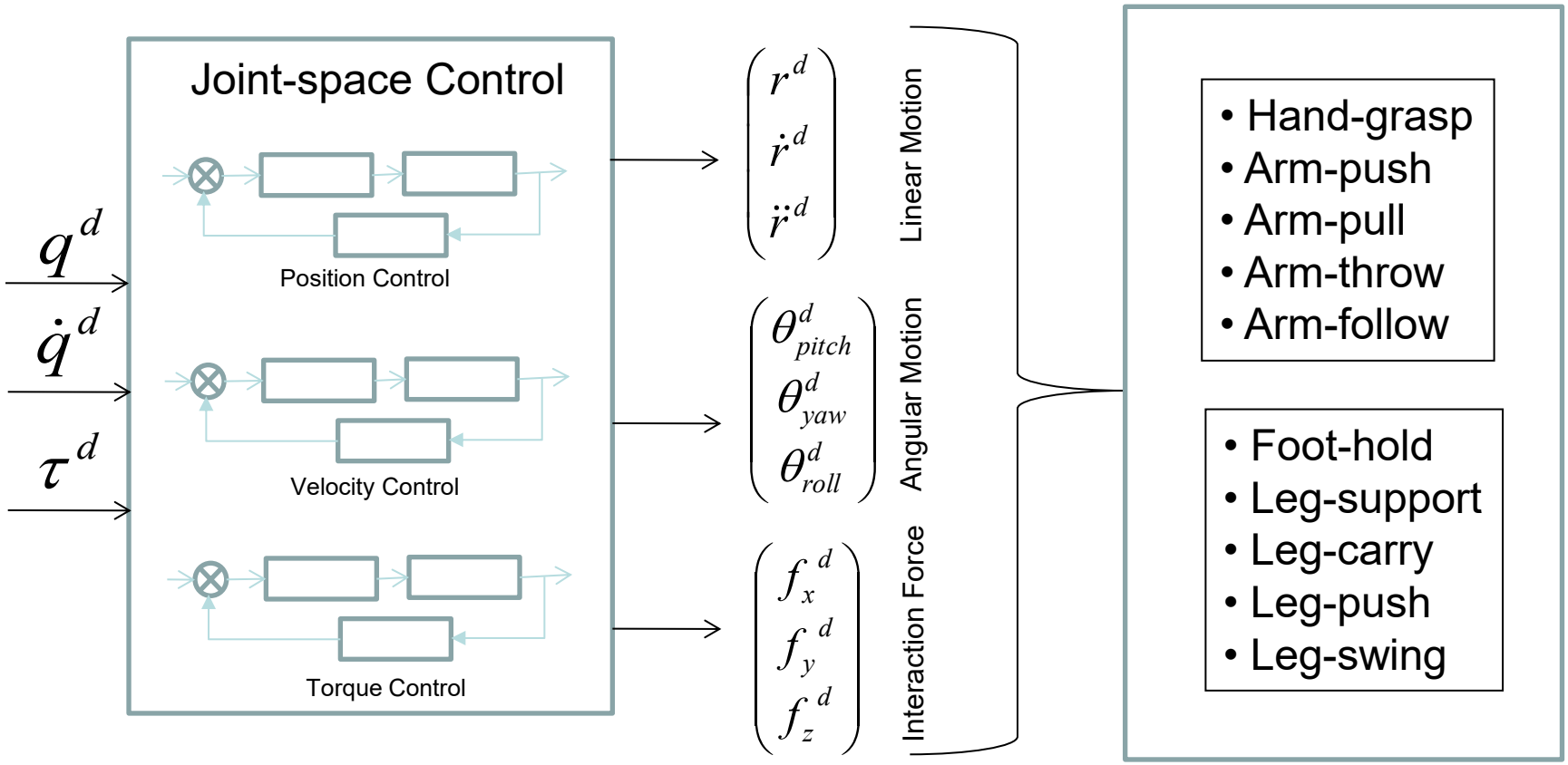


# Motion Flows Could Be Transformed from Task Space to Joint Space

- Example of Transforming Manipulation Motion

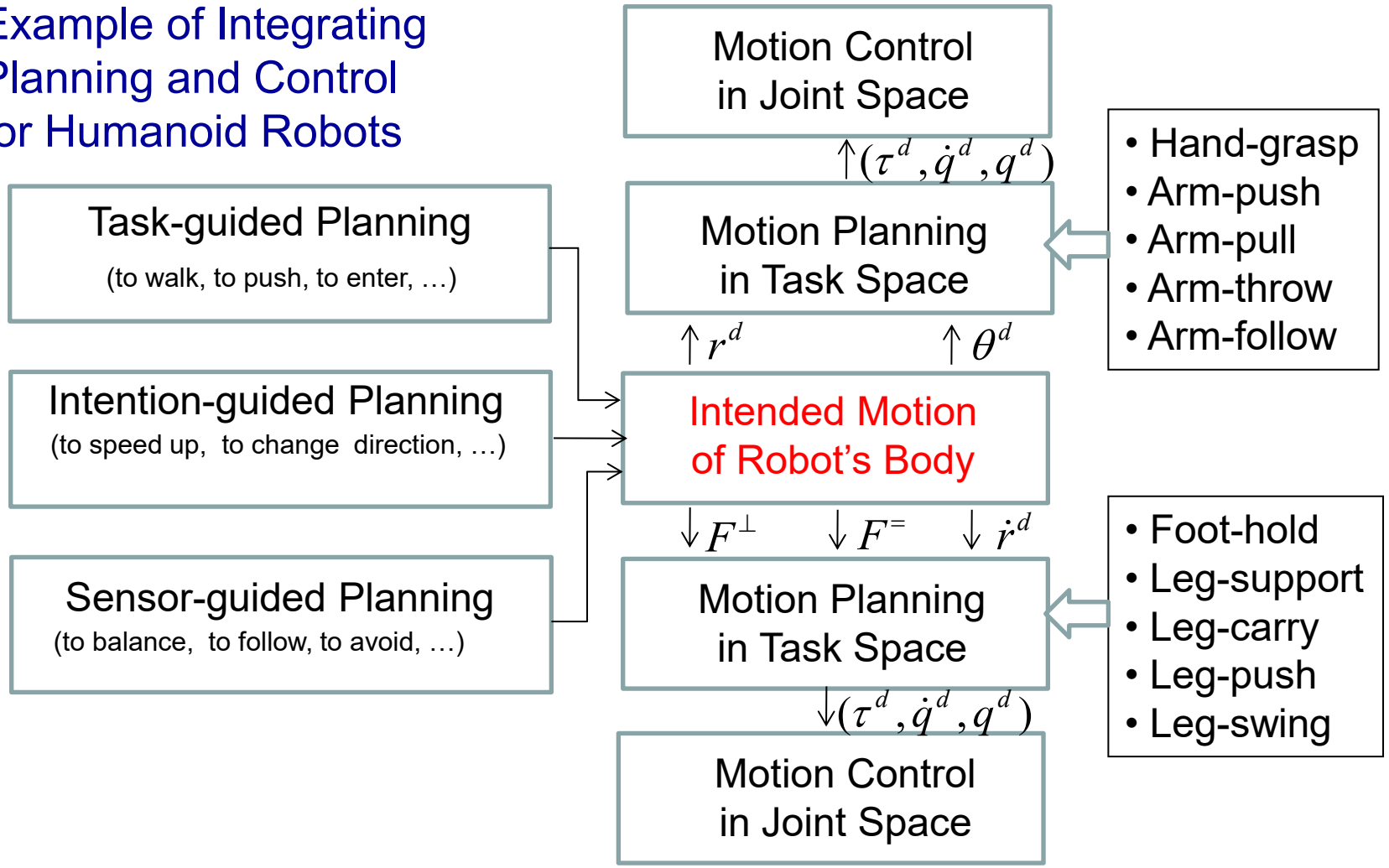


# Planned Motion Flows Are Achieved By Motion Control Systems …

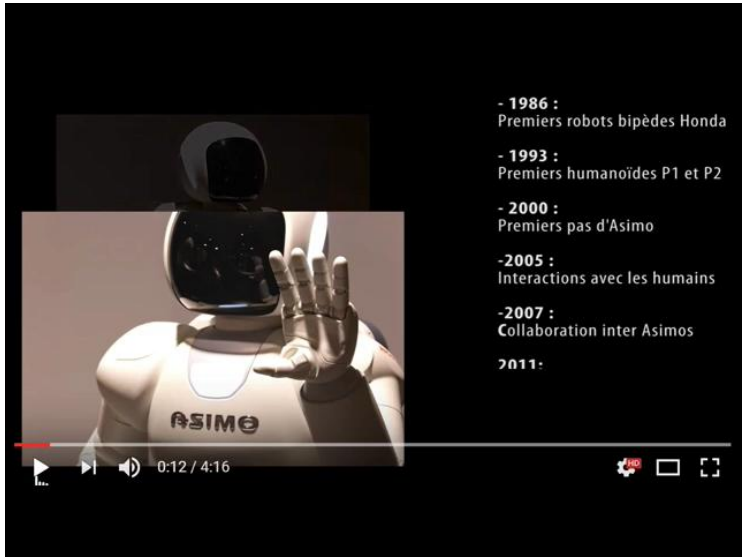


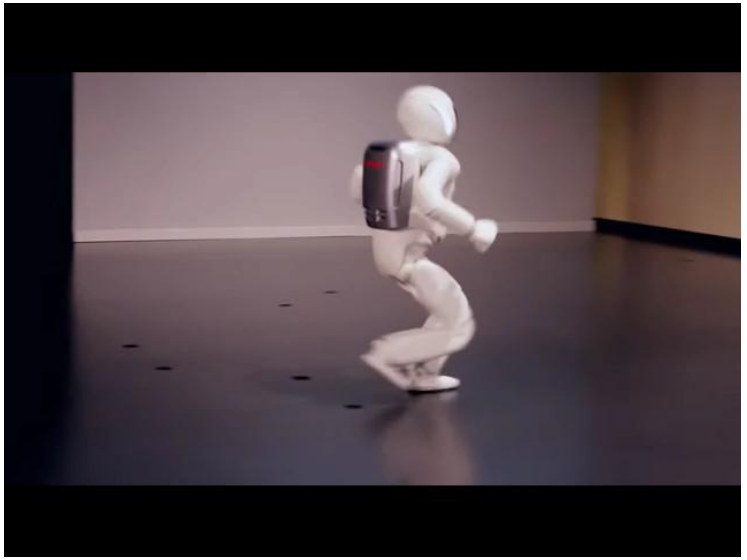
# Planning and Control of Motion Flows Could Be Integrated Together …

- Example of Integrating Planning and Control for Humanoid Robots



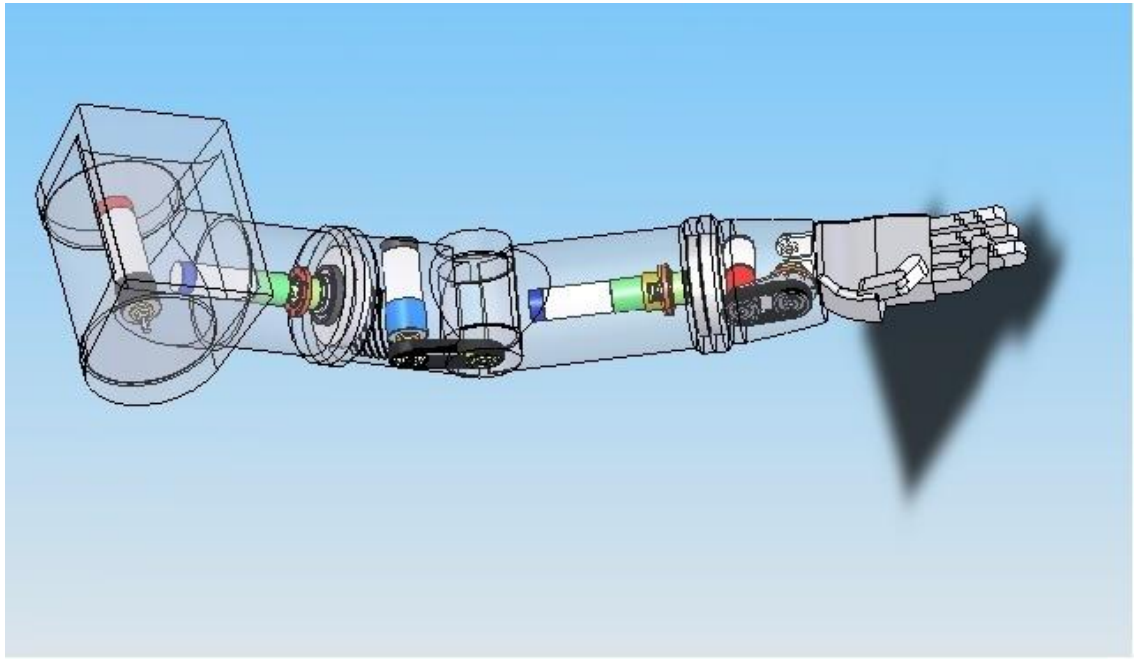
# Example of Implementation Done by Honda Co.




# Motion Flows Could Be Described by Equations …

- Motion Equations of Manipulator in Static States



$$\begin{pmatrix} \tau_1 \\ \tau_2 \\ \dots \\ \tau_k \end{pmatrix} = J_k^T \bullet \begin{pmatrix} F_{x,k} \\ F_{y,k} \\ F_{z,k} \\ M_{x,k} \\ M_{y,k} \\ M_{z,k} \end{pmatrix}$$

$$\tau = J^T \bullet h$$

# Motion Flows Could Be Described by Equations ...

- Motion Equations of Manipulator in Dynamic States

$$B(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) = \tau - k_v\dot{q} - J^T \bullet h$$

Inertial Force

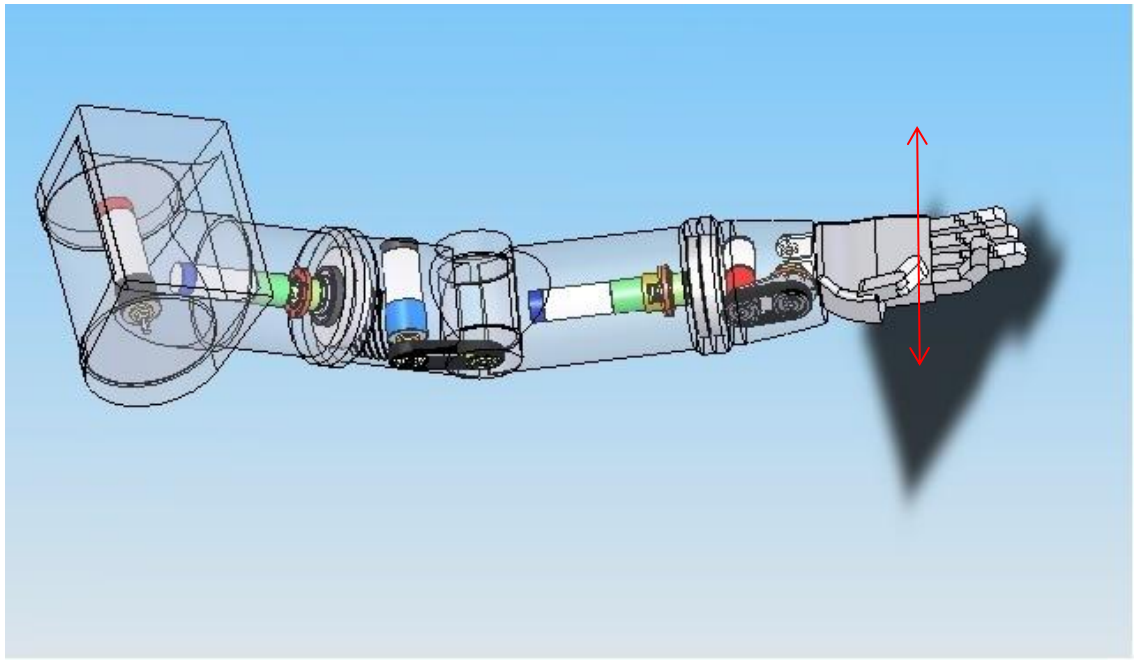
Coriolis Force
Centrifugal Force

Gravity

Torque

Friction

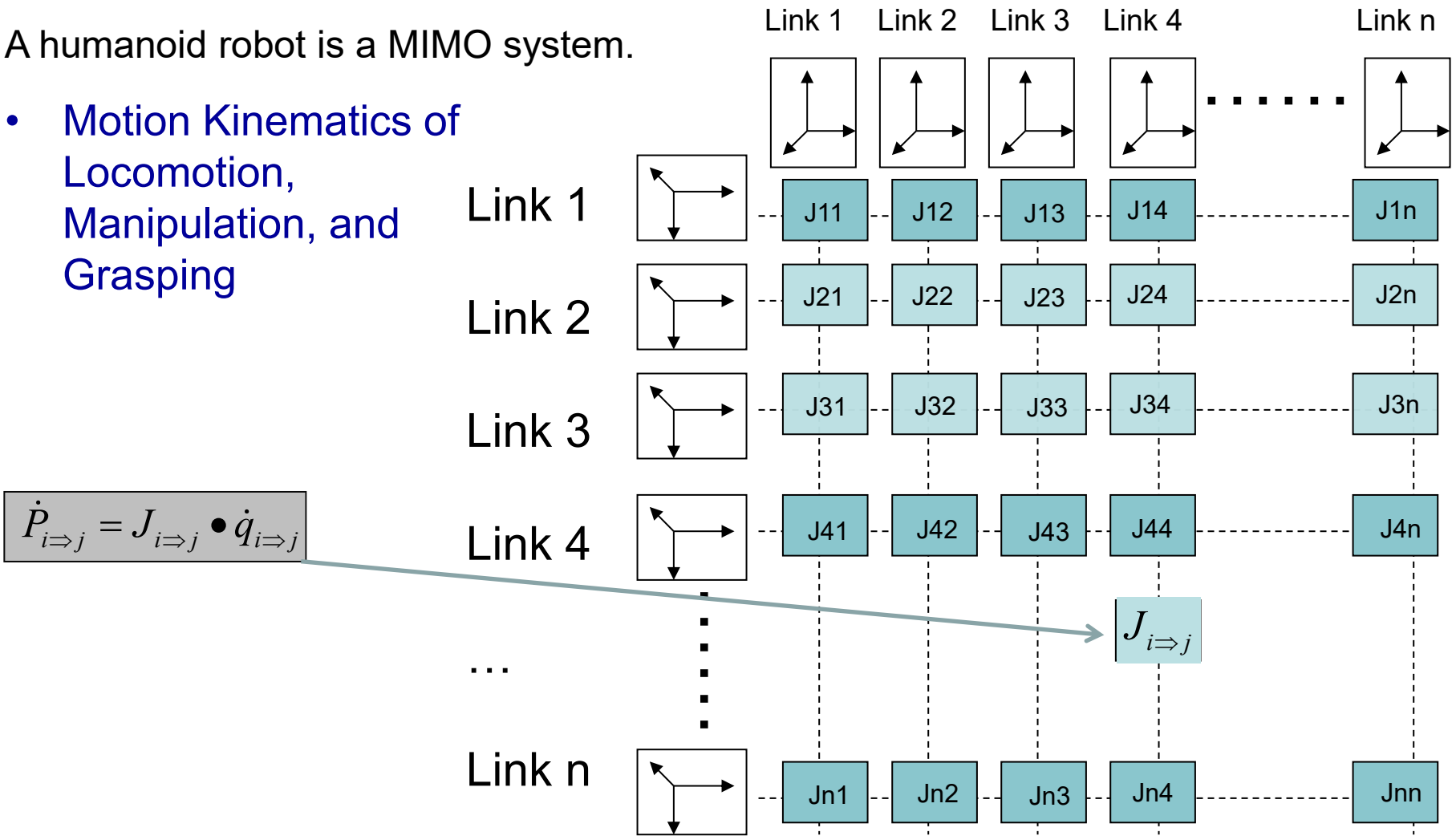
Interaction Force



# Motion Flows Could Be Described by Equations …

A humanoid robot is a MIMO system.

- Motion Kinematics of Locomotion, Manipulation, and Grasping



# Motion Flows Could Be Described by Equations …

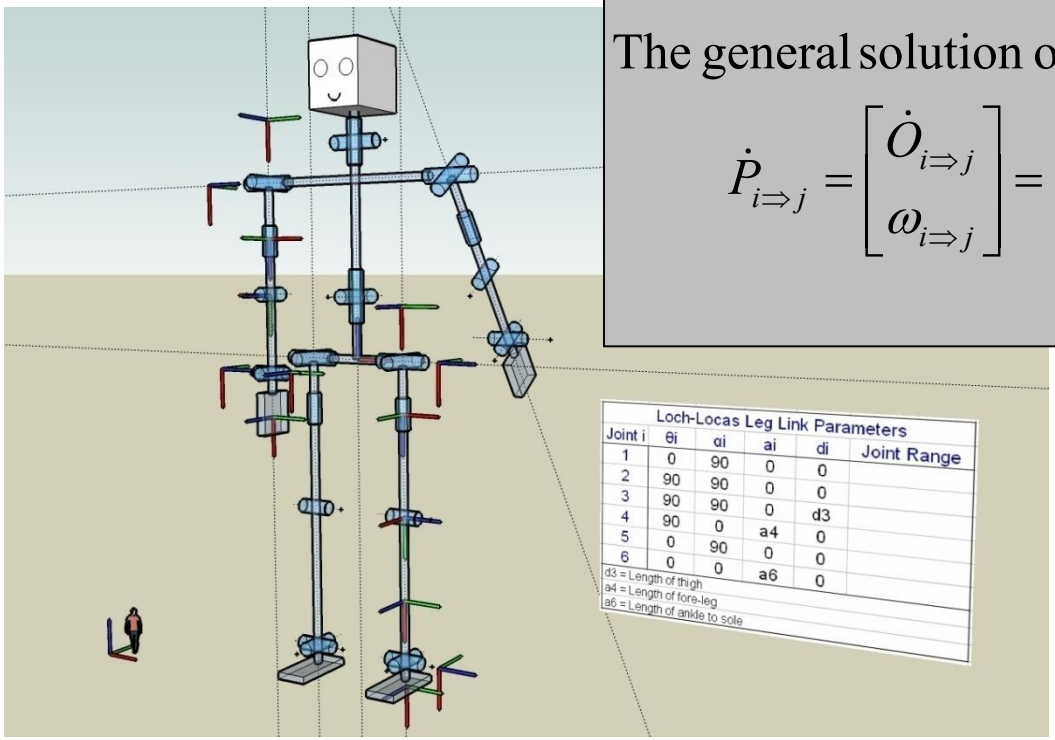
- Motion Kinematics of Locomotion, Manipulation and Grasping (continued)

The velocity vector of the end-effector's pose:

$$\dot{P}_{i\Rightarrow j} = \begin{bmatrix} \dot{O}_{i\Rightarrow j} \\ \omega_{i\Rightarrow j} \end{bmatrix}$$

The general solution of differential kinematics:

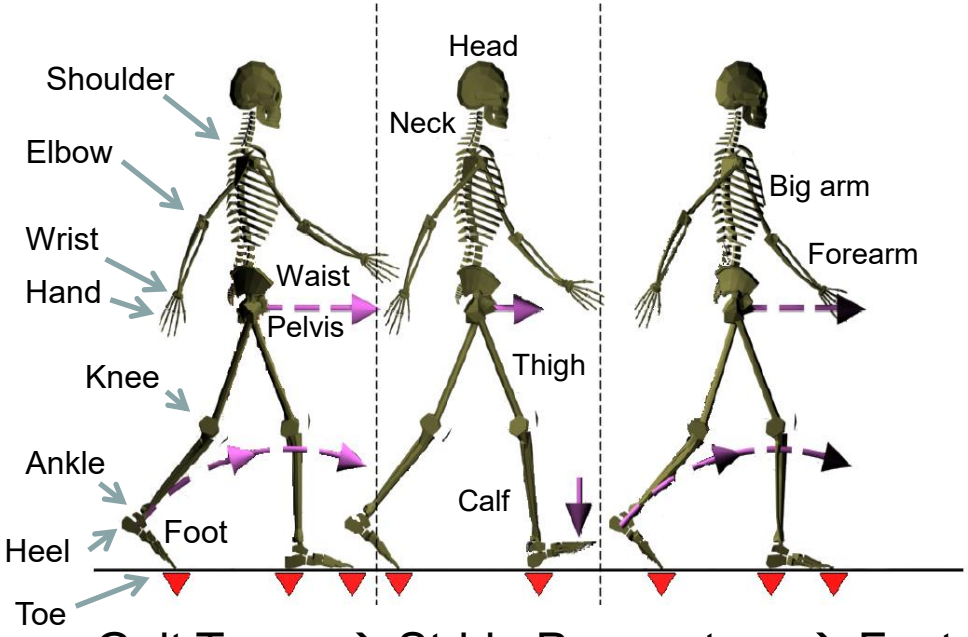
$$\dot{P}_{i\Rightarrow j} = \begin{bmatrix} \dot{O}_{i\Rightarrow j} \\ \omega_{i\Rightarrow j} \end{bmatrix} = \begin{bmatrix} J_{o1} & J_{o2} & \cdots & J_{on} \\ J_{\omega 1} & J_{\omega 2} & \cdots & J_{\omega n} \end{bmatrix} \bullet \dot{q}_{i\Rightarrow j} = J_{i\Rightarrow j} \bullet \dot{q}_{i\Rightarrow j}$$

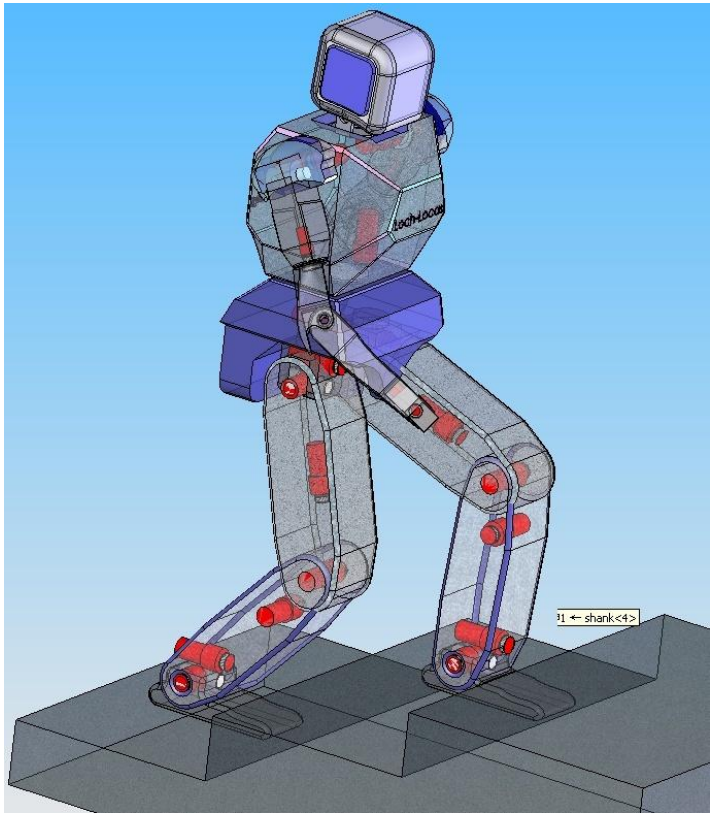


# Motion Flows Could Be Described by Equations …

- Motion Dynamics of Biped Walking

  It refers to the relationships among legs' forces, legs' motions and body's stability.

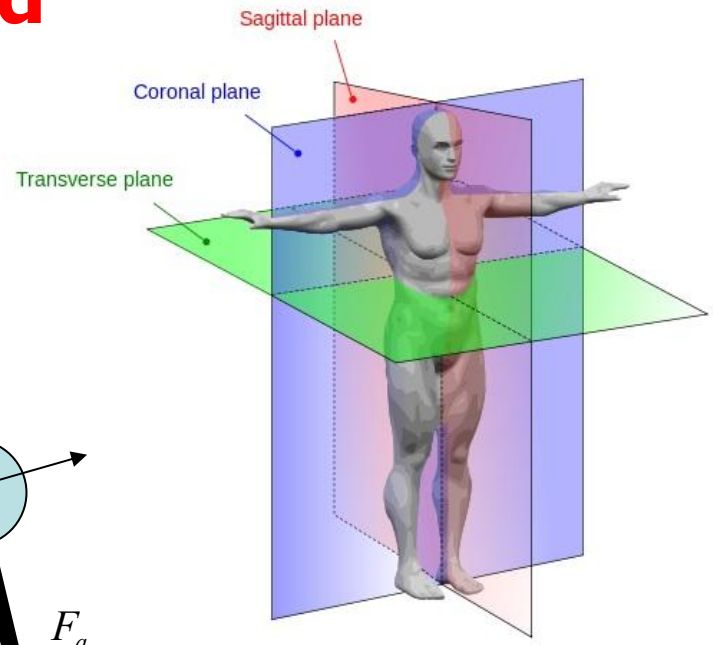


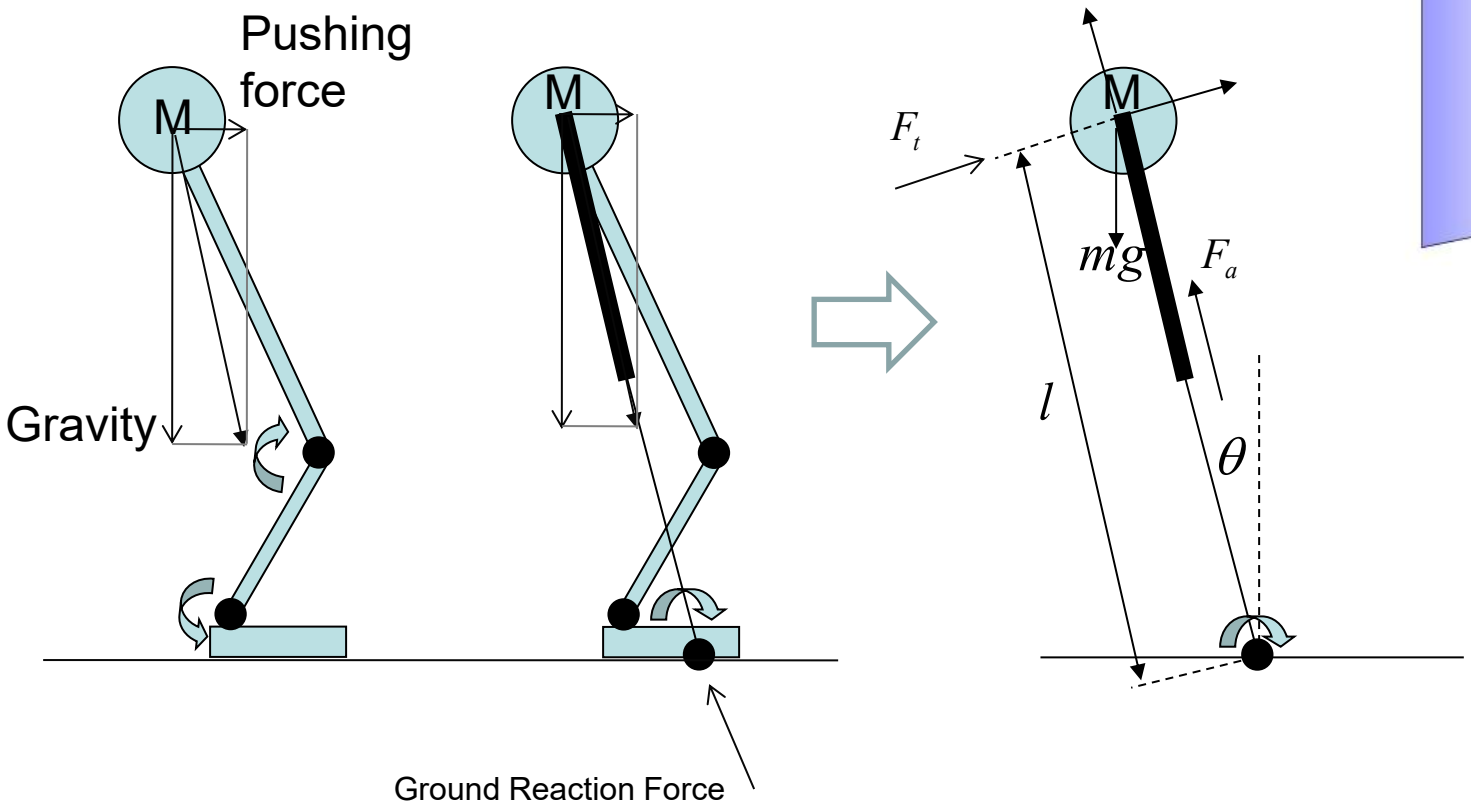



Gait Types → Stride Parameters → Footstep Parameters → Beat Parameters

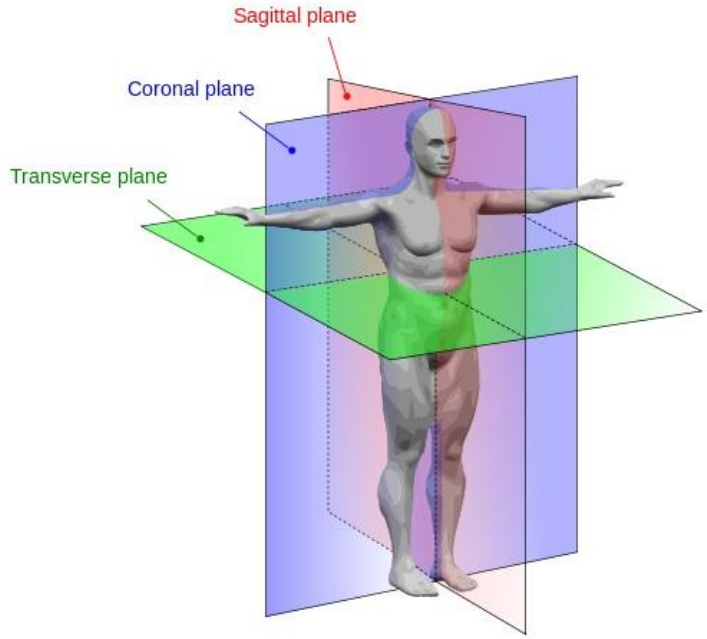
# Motion Dynamics of Inverted Pendulum …

- Illustration



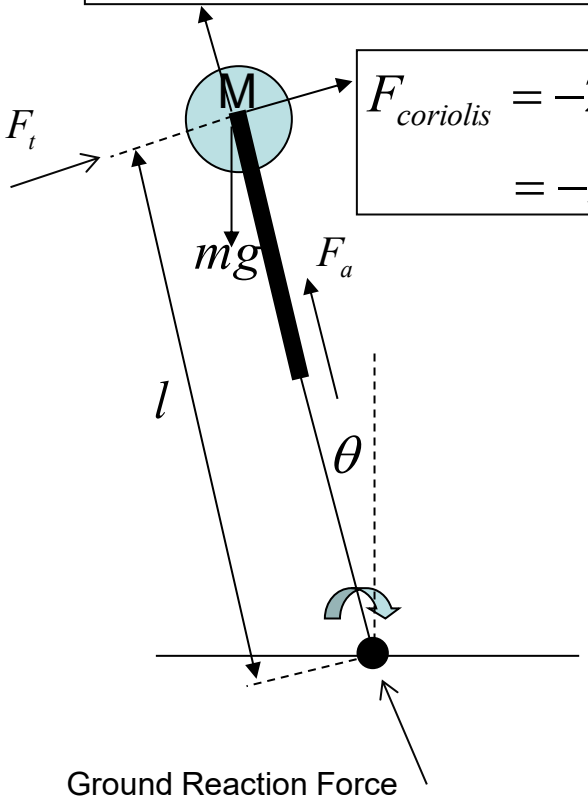
# Motion Dynamics of Inverted Pendulum …




- Equations

$$F_{centrifugal} = m\frac{v^2}{l} = m\frac{(l\dot{\theta})^2}{l} = ml\dot{\theta}^2$$

$$F_{coriolis} = -2m(\dot{\theta} \bullet \dot{l}) = -2m\dot{l}\dot{\theta}$$




Axial Dynamics:

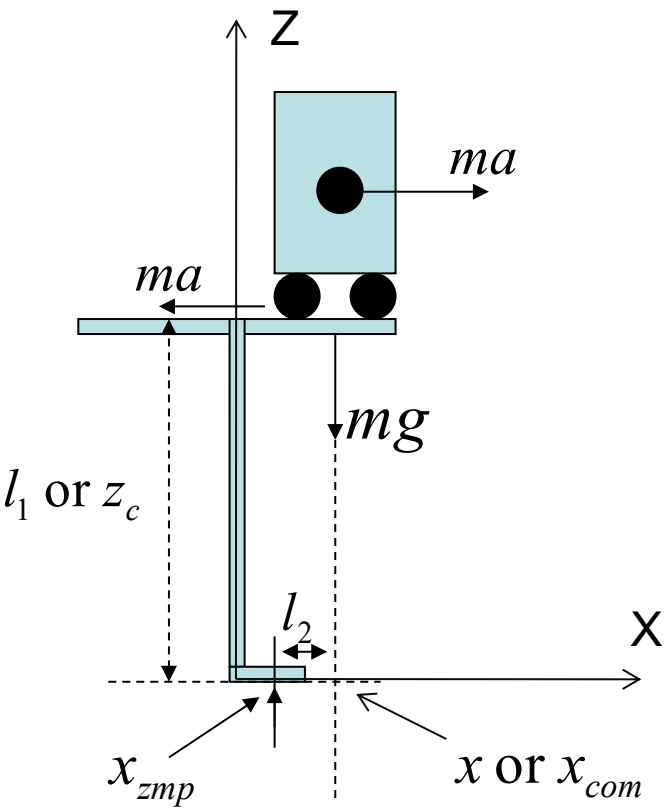
$$F_a - mg\cos(\theta) + ml\dot{\theta}^2 = m\ddot{l}$$

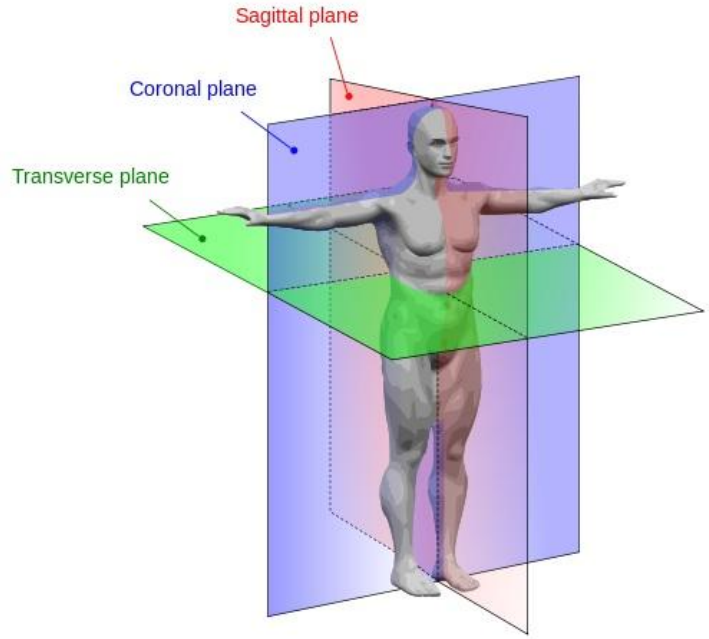
Tangential Dynamics:

$$l \bullet F_t - mgl\sin(\theta) - 2ml\dot{l}\dot{\theta} = ml^2\ddot{\theta}$$

# Motion Dynamics of Cart on Table …

- Illustration



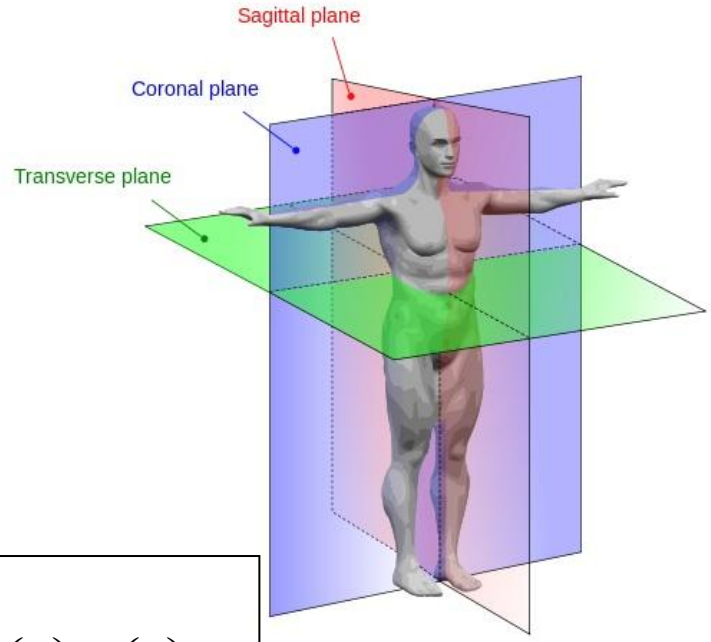



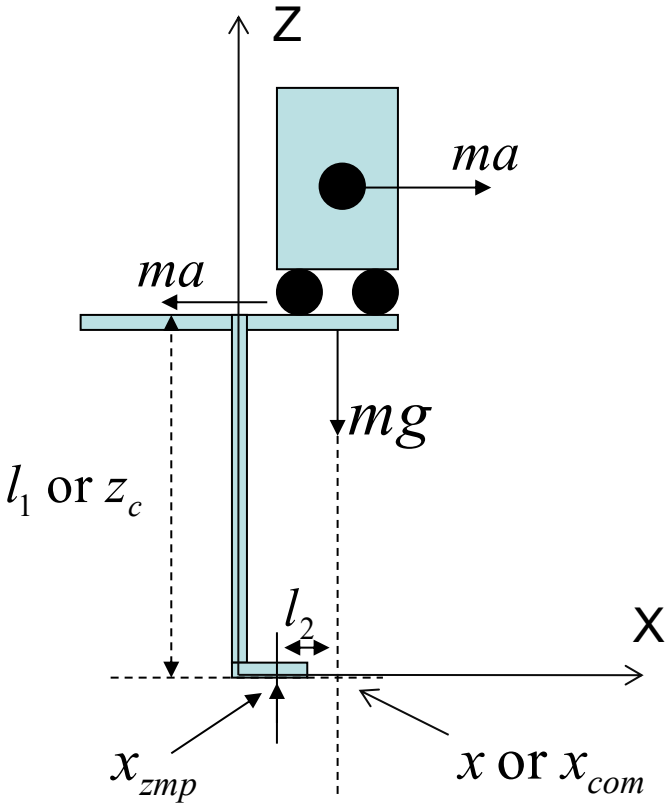

$$m \bullet a \bullet z_c = m \bullet g \bullet (x - x_{zmp})$$

$$x_{zmp} = x - \frac{z_c}{g}\ddot{x}$$

# Motion Equations of Cart on Table …

- Equations




State Vector:

$$X = \begin{pmatrix} x \\ \dot{x} \\ \ddot{x} \end{pmatrix}$$

State Equation:

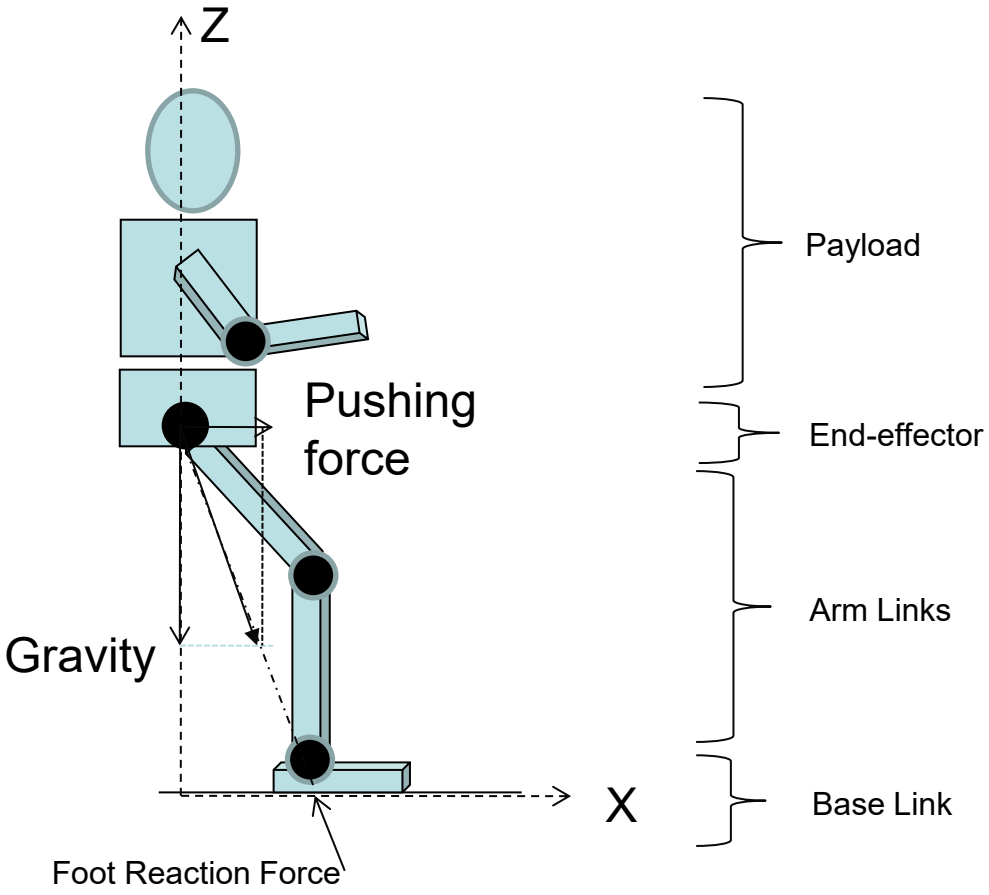
$$\dot{X} = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix} \bullet \begin{pmatrix} x \\ \dot{x} \\ \ddot{x} \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \bullet u$$

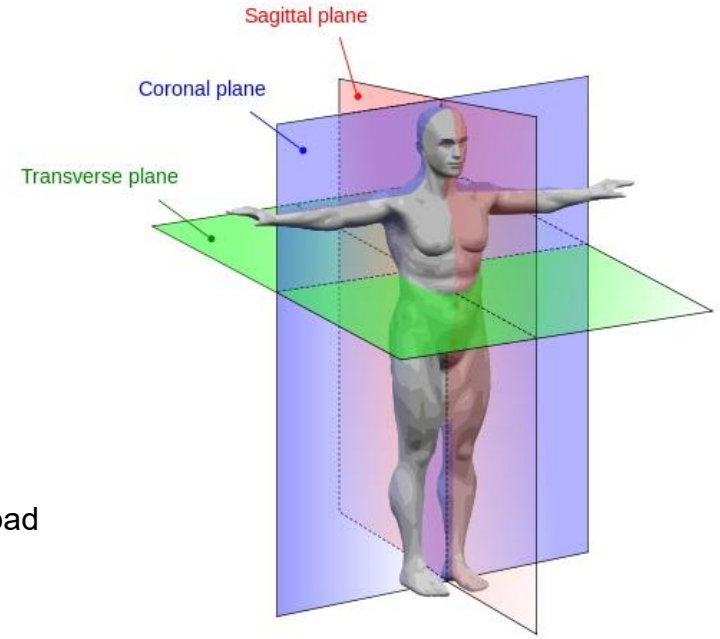
Output Equation:

$$x_{zmp} = x - \frac{z_c}{g}\ddot{x} = \begin{pmatrix} 1 & 0 & -\frac{z_c}{g} \end{pmatrix} \bullet \begin{pmatrix} x \\ \dot{x} \\ \ddot{x} \end{pmatrix}$$

# Motion Dynamics of Inverted Arm …

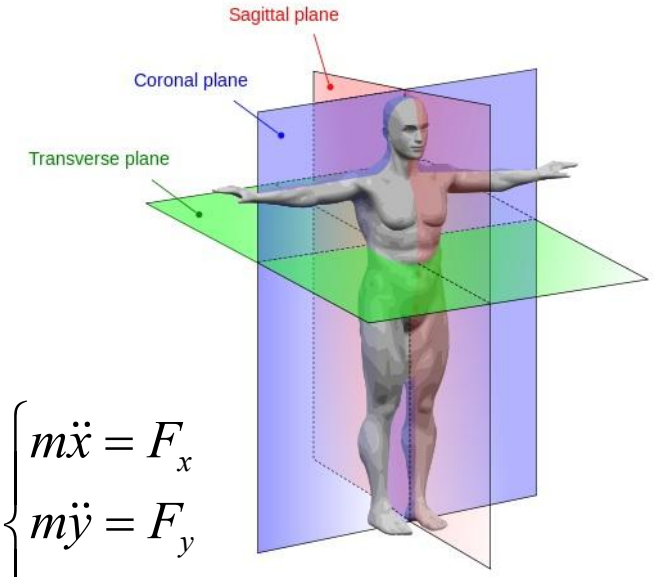
- Illustration

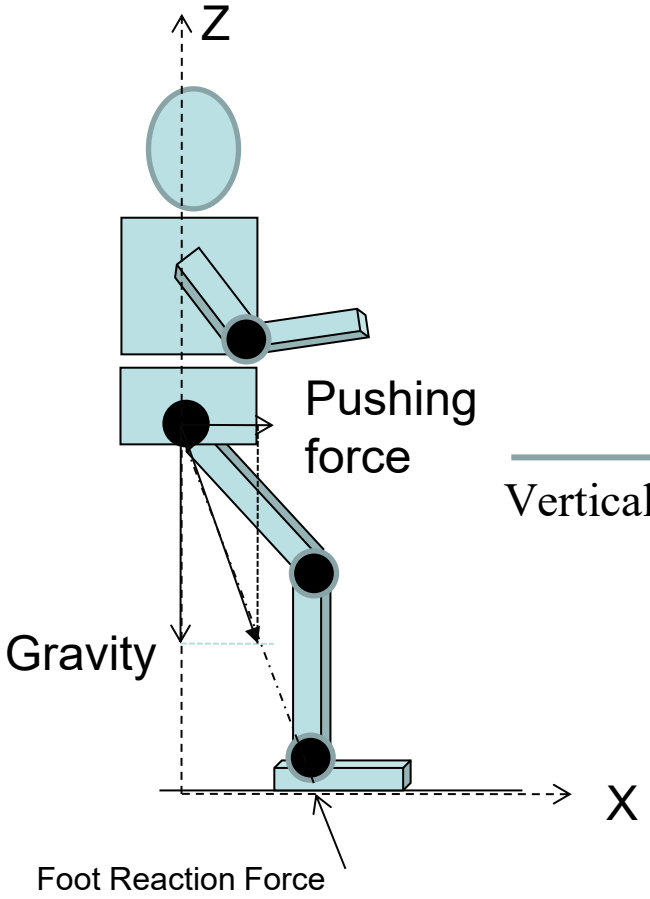


# Motion Dynamics of Inverted Arm …

- Equations



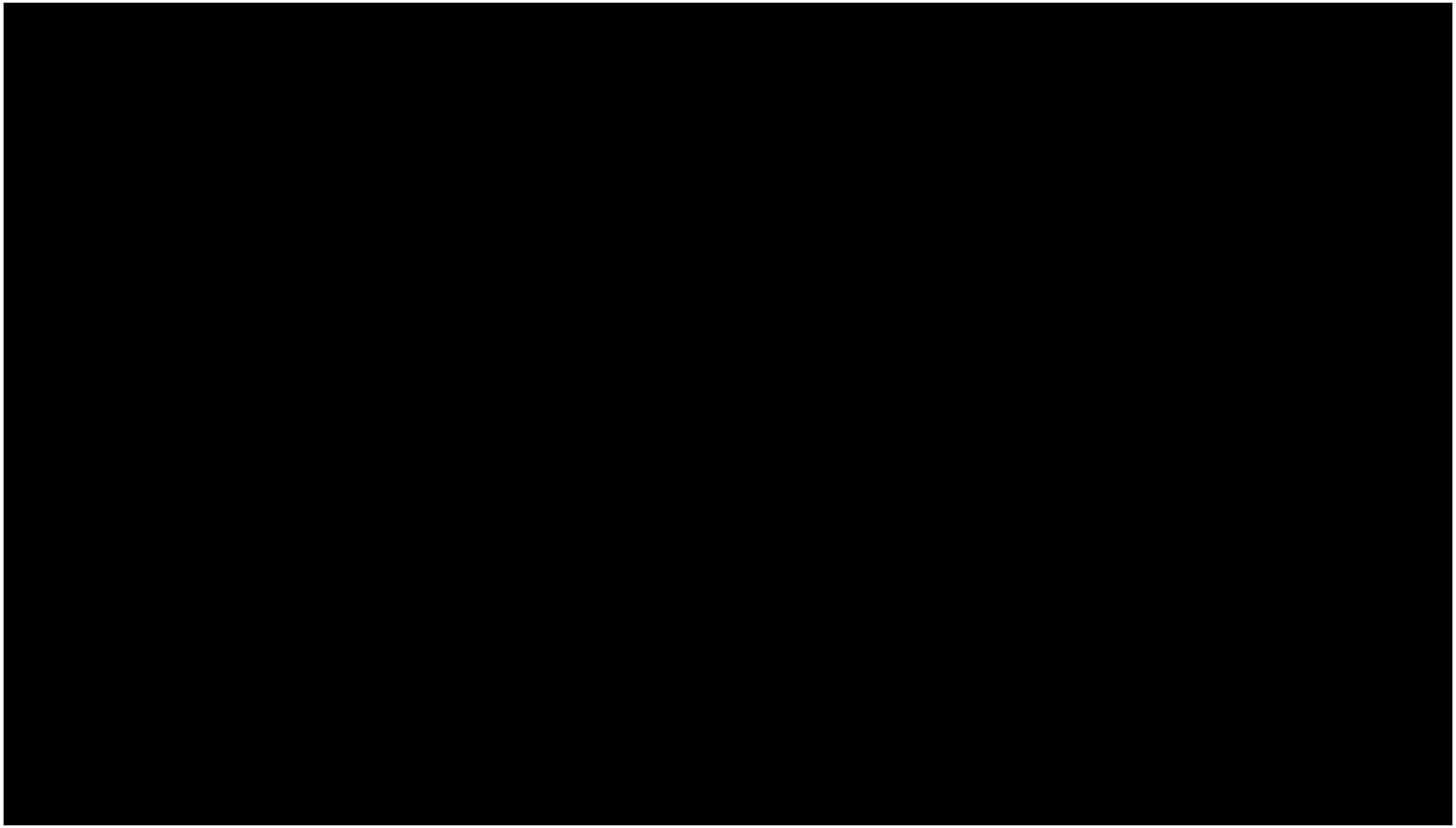

Horizontal Dynamics :

$$\begin{pmatrix}\tau_1\\ \tau_2\\ \tau_3\\ \tau_4\\ \tau_5\\ \tau_6\end{pmatrix} = J^T \bullet \begin{pmatrix}F_x\\ F_y\\ 0\\ 0\\ 0\\ 0\end{pmatrix} \Rightarrow \begin{cases} m\ddot{x} = F_x \\ m\ddot{y} = F_y \\ \dot{P} = J \bullet \dot{q} \end{cases}$$

Vertical Dynamics :

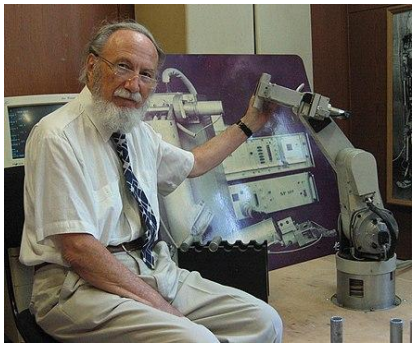
$$\begin{pmatrix}\tau_1\\ \tau_2\\ \tau_3\\ \tau_4\\ \tau_5\\ \tau_6\end{pmatrix} = J^T \bullet \begin{pmatrix}0\\ 0\\ mg\\ 0\\ 0\\ 0\end{pmatrix} \Rightarrow \begin{cases} m\ddot{z} = 0 \\ \dot{P} = J \bullet \dot{q} \end{cases}$$

# Example of Implementation Done by Boston Dynamics Co. …

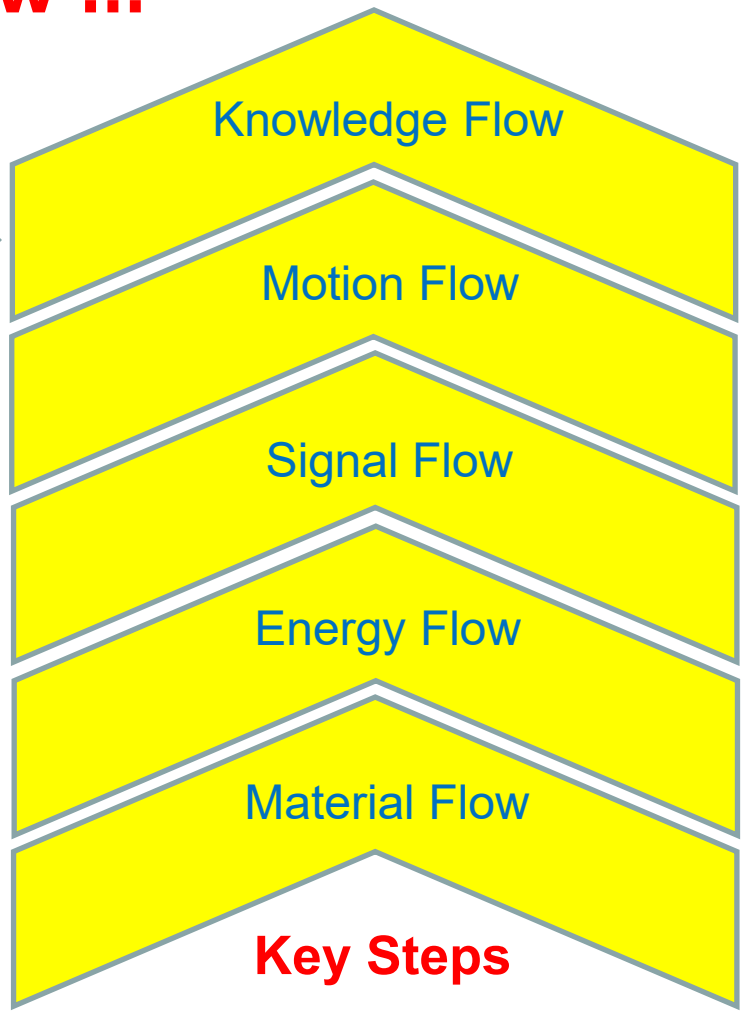


# The key solutions underlying the development of humanoid robot could be grouped into these five layers of flow …

Sensory signals could be transformed into knowledge, which could in return be transformed into motor signals



Miomir Vukobratovic
(1931-2012)
Discovery of ZMP




- Cognition
- Recognition
- Interaction

- Perception
- Planning
- Control

- Motion Kinematics
- Motion Dynamics

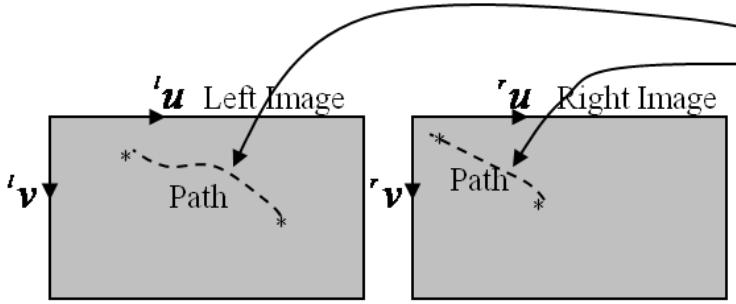
- Position Sensors
- Velocity Sensors
- Force/Torque Sensors
- Visual/Acoustic Sensors

- Power Suppliers
- Actuators and Controllers

- Appearance
- Structure
- Mechanism

- Computing
- Memory

# On-fly Motion Planning with X-Eye Coordination Algorithm Developed in 1997



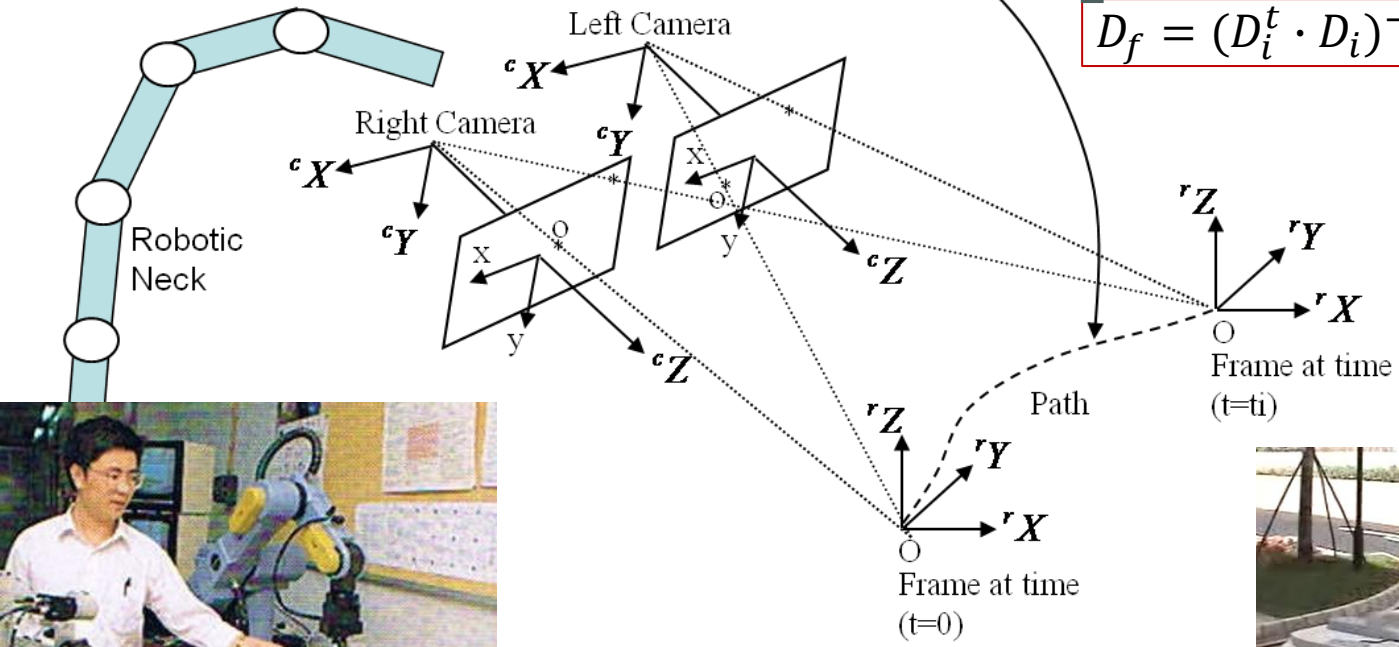

**3D Forward Projection**

$$\begin{bmatrix}\Delta u_l \\ \Delta v_l \\ \Delta u_r \\ \Delta v_r\end{bmatrix} = D_f \cdot \begin{bmatrix}\Delta X \\ \Delta Y \\ \Delta Z\end{bmatrix}$$

**3D Inverse Projection**

$$\begin{bmatrix}\Delta X \\ \Delta Y \\ \Delta Z\end{bmatrix} = D_i \cdot \begin{bmatrix}\Delta u_l \\ \Delta v_l \\ \Delta u_r \\ \Delta v_r\end{bmatrix}$$

$$D_f = (D_i^t \cdot D_i)^{-1} \cdot D_i^t$$






Hand-Eye Coordination

Head-Eye Coordination

# Validation with Robot (1997)

## RESEARCH OPPORTUNITIES IN SINGAPORE

**Be in the right place! Come to Singapore, the gateway to the Asia Pacific Region. Come to the School of Mechanical and Production Engineering, Nanyang Technological University, the premier university in the region.**

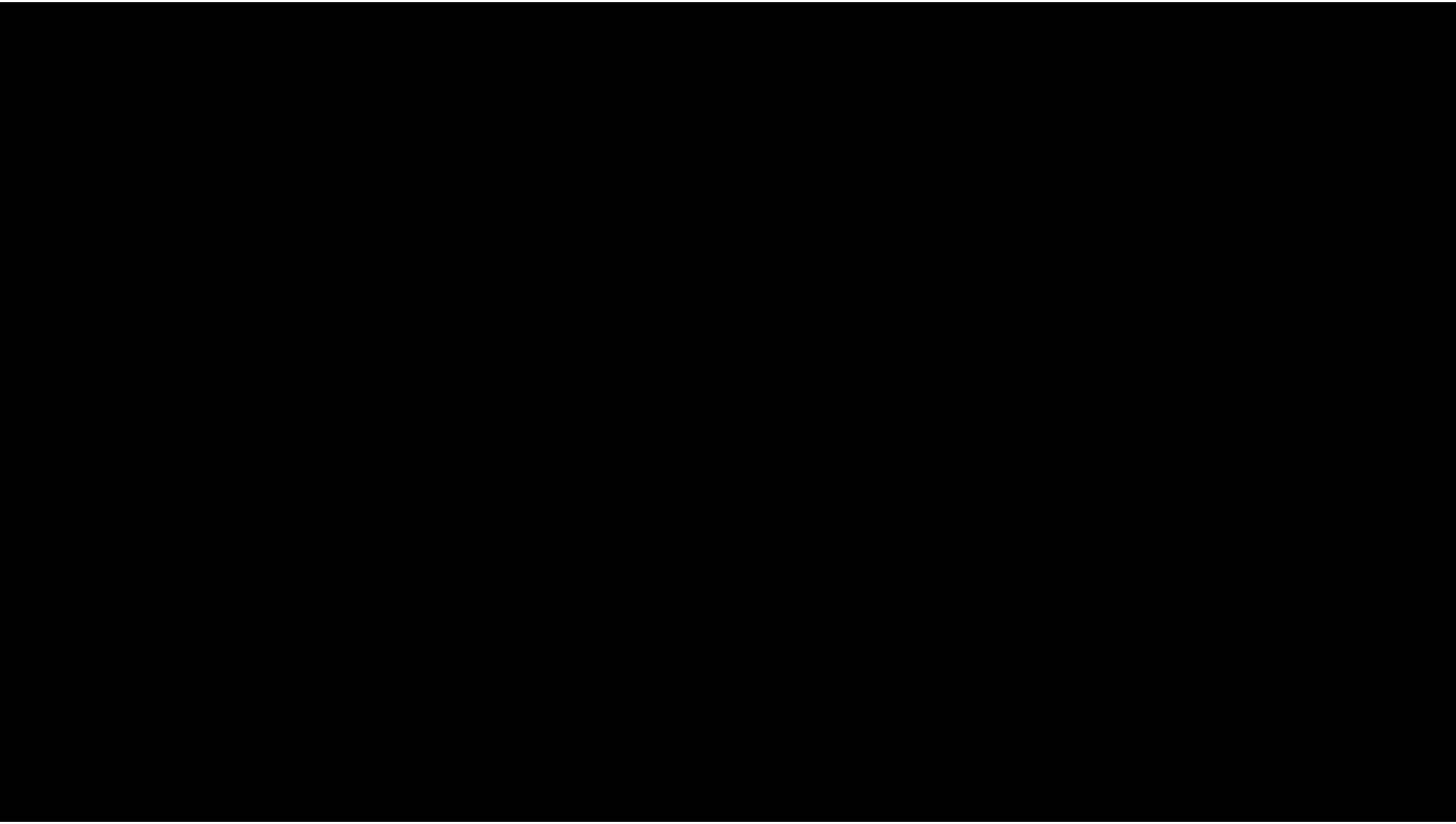
**We have excellent infra-structures, state-of-the-art facilities, conducive work environment, and pleasant surroundings for you to realize your potential.**

***RESEARCH AREAS:***

Product Design
Intelligent Manufacturing Systems
Precision Engineering
Rapid Prototyping
Robotics and Vision Systems

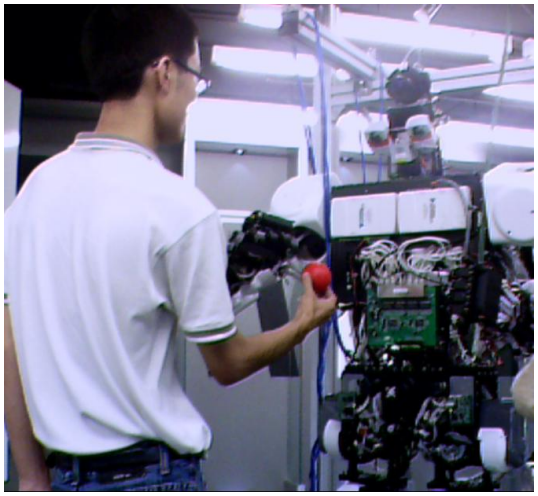
Hand-Eye Coordination

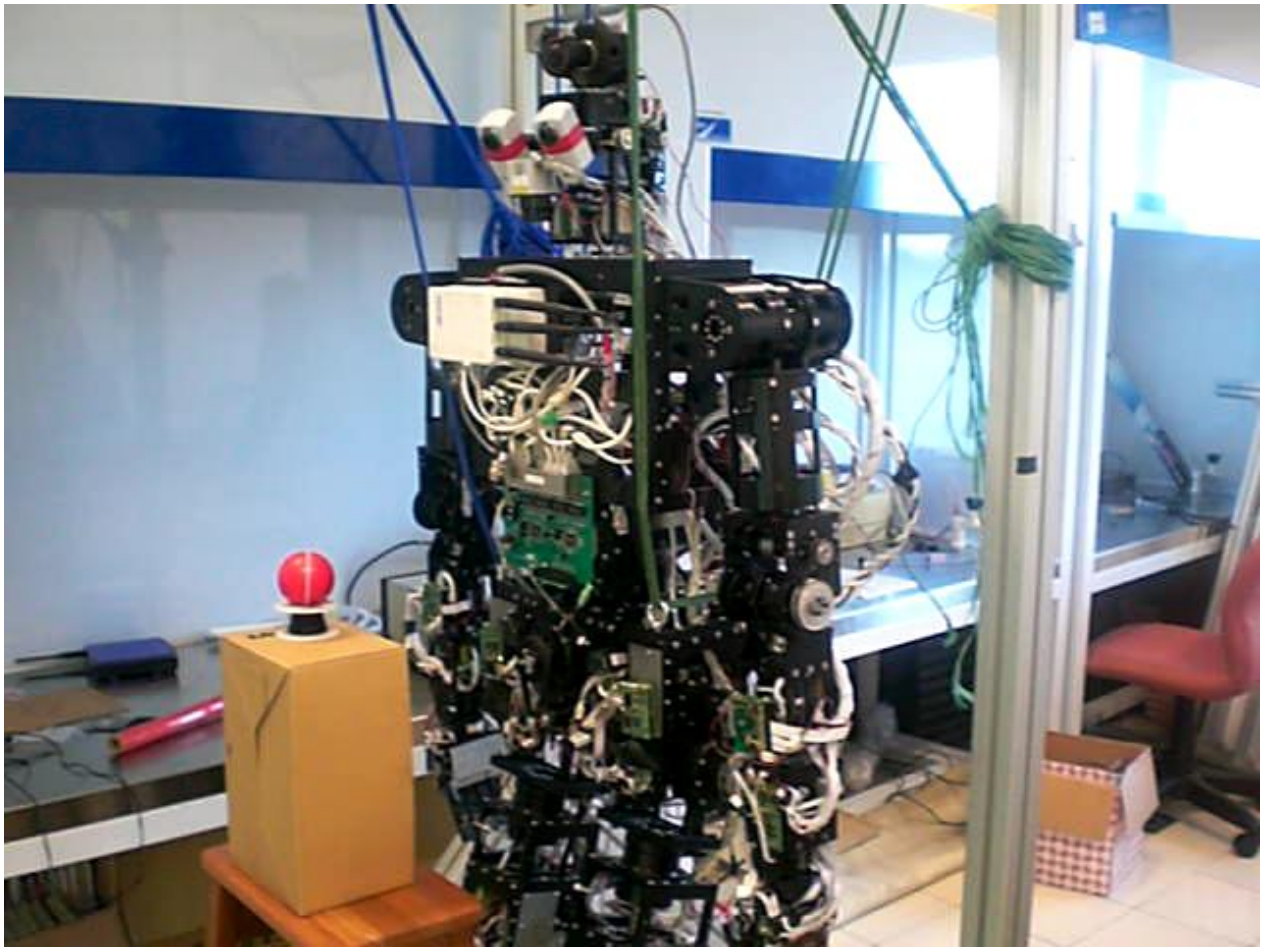
# Validation with Simulation (2000)



# Validation with Monkey (2007)

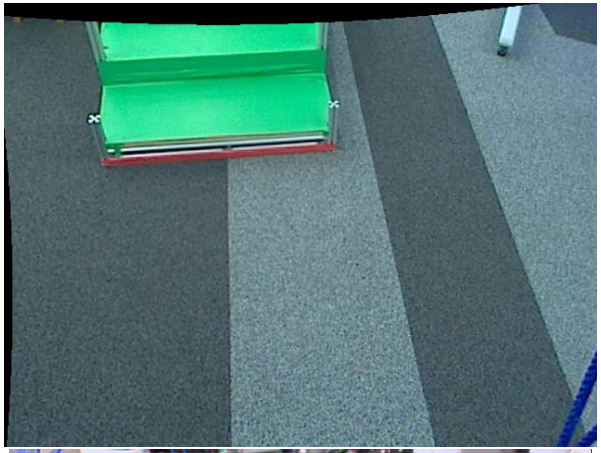
# Example of Cognitively-Intelligent Humanoid Robot in Doing Hand-Eye Coordination (2008)

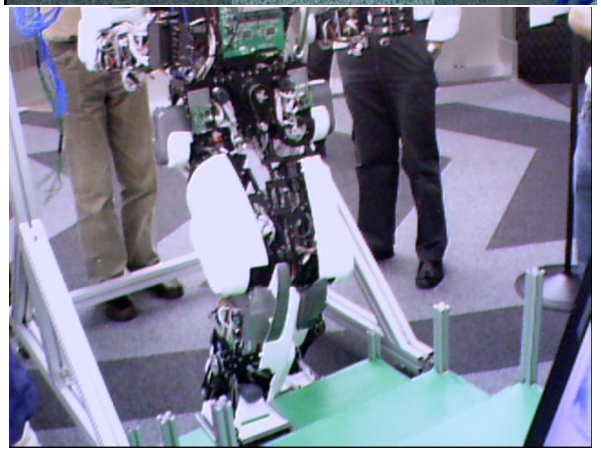


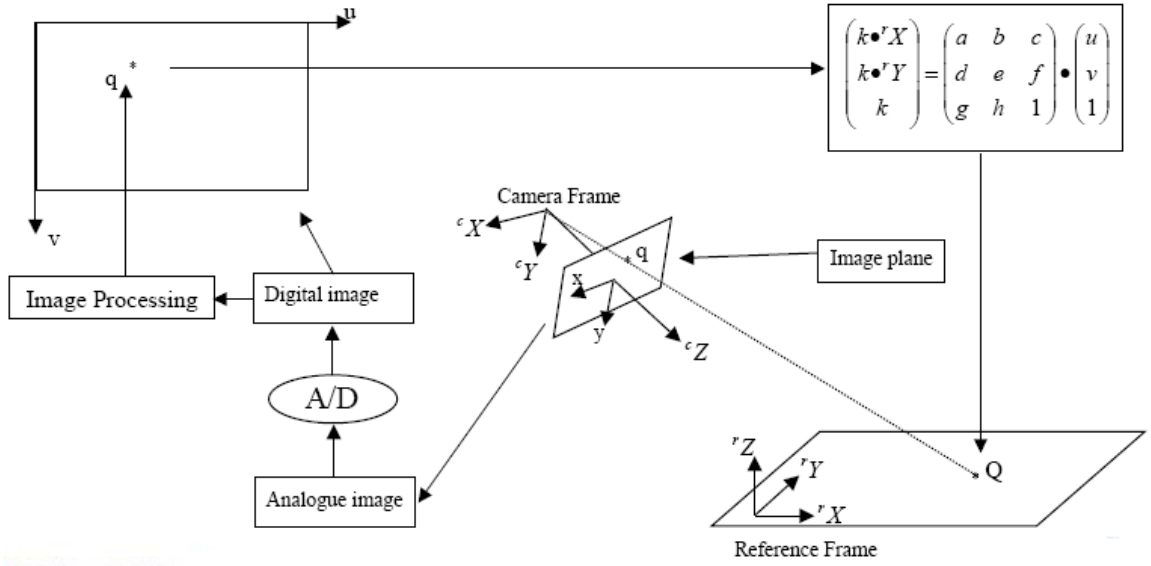


- Signal to Knowledge
- Knowledge to Knowledge
- Knowledge to Signal

# Example of Cognitively-Intelligent Humanoid Robot in Doing Leg-Eye Coordination (2008)







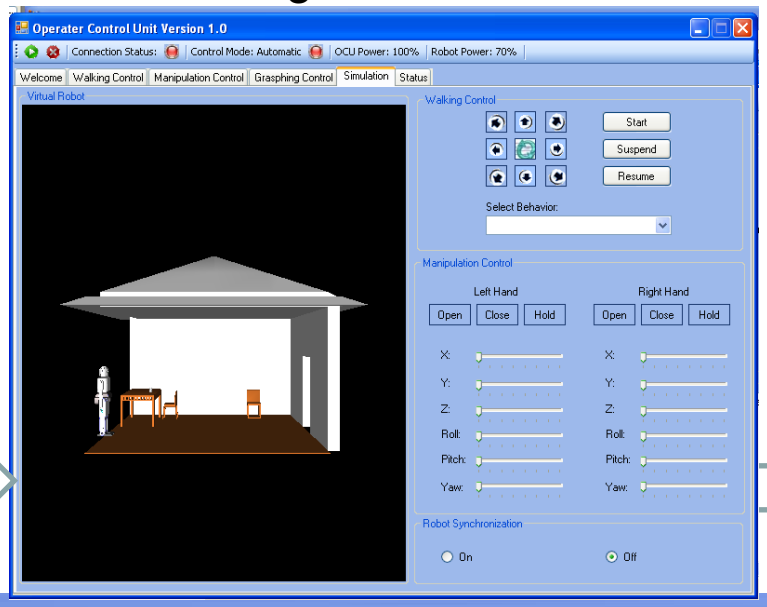

- Signal to Knowledge
- Knowledge to Knowledge
- Knowledge to Signal

# Human-Robot Interaction Could Occur At ...

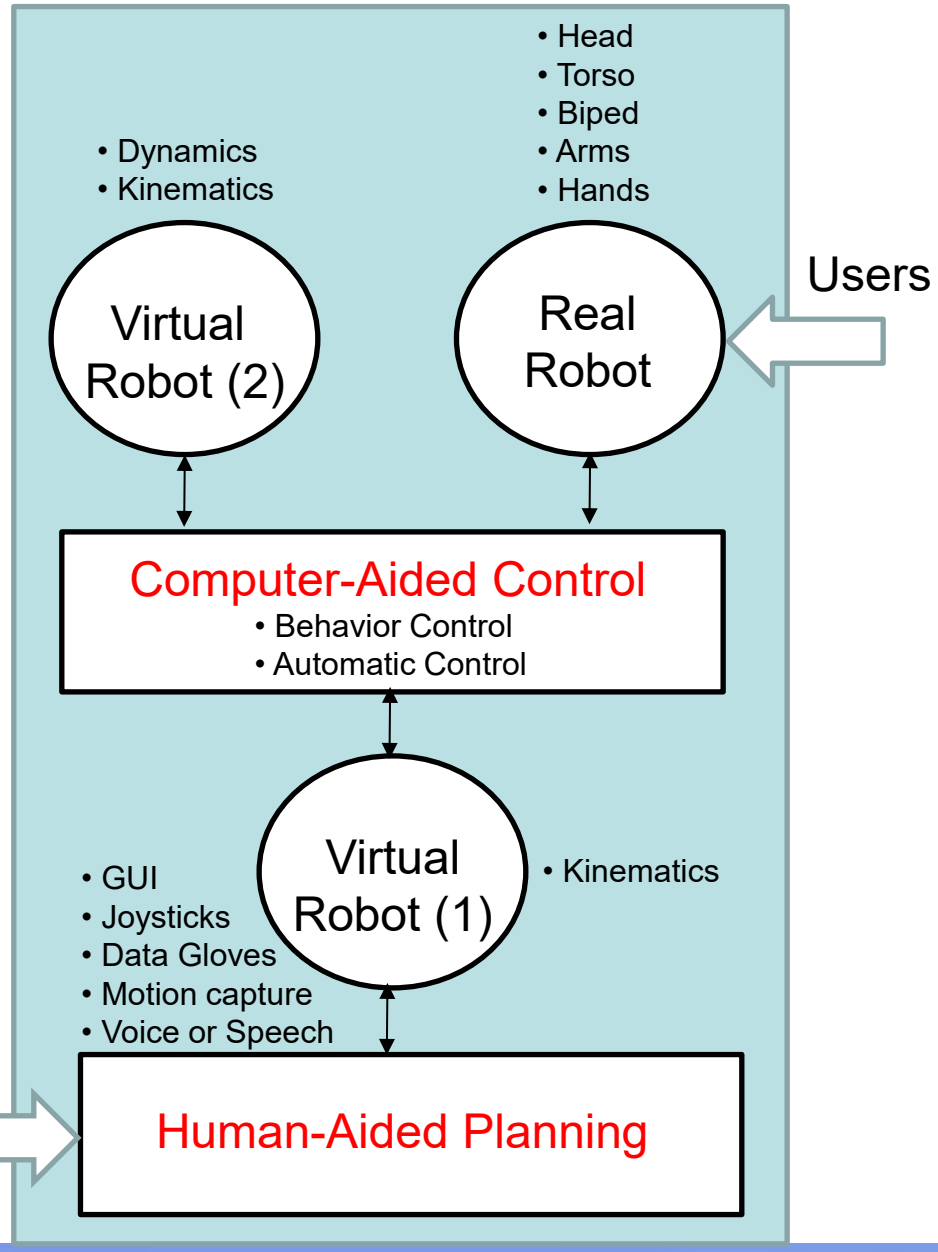
- Signal Level, and
- Cognitive Level

Cognitively-Intelligent Humanoid Robots

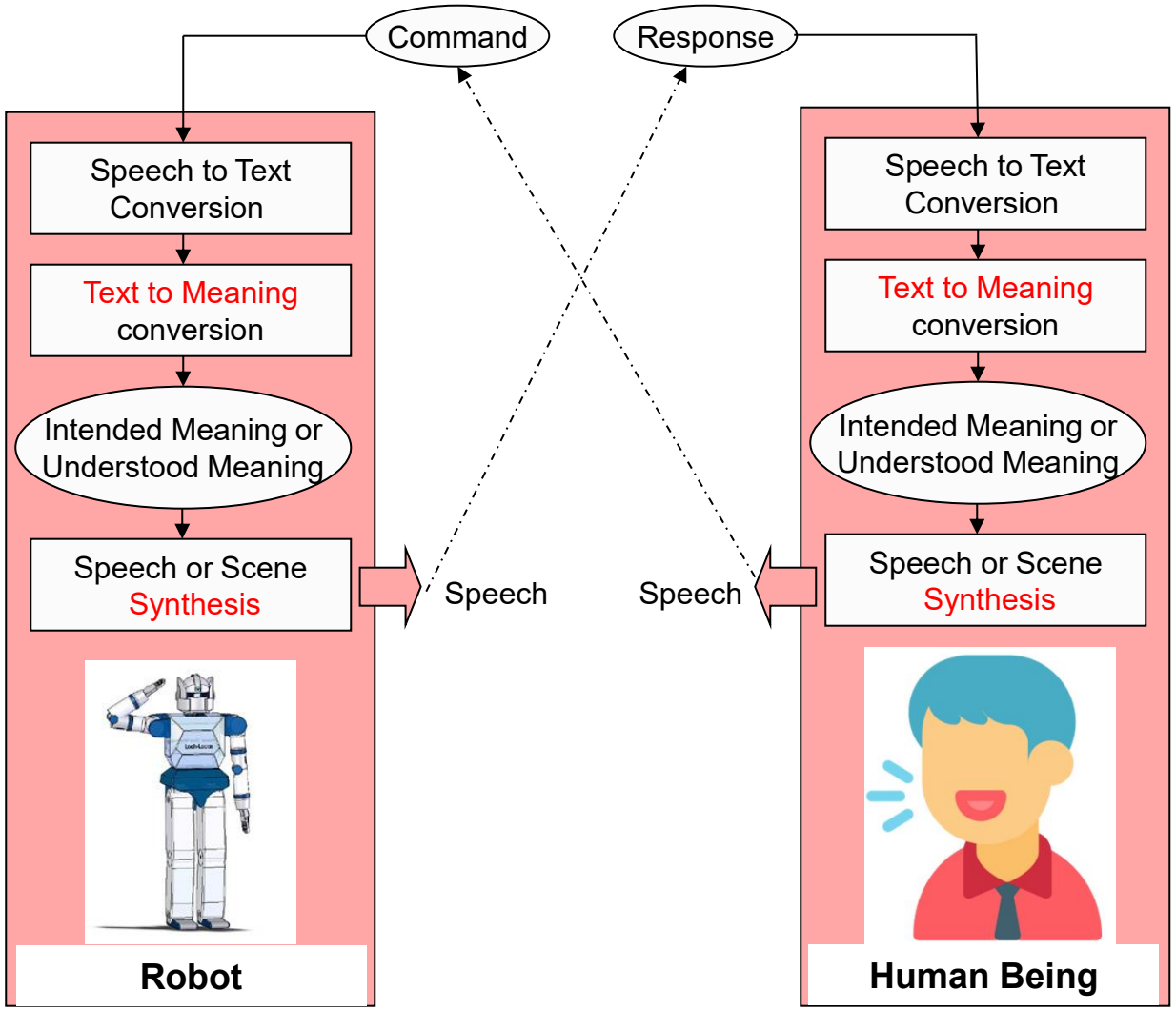
Digital Twin




Users



# Scenario of Human-Robot Interaction at Cognitive Level …




Seven Specific Skills

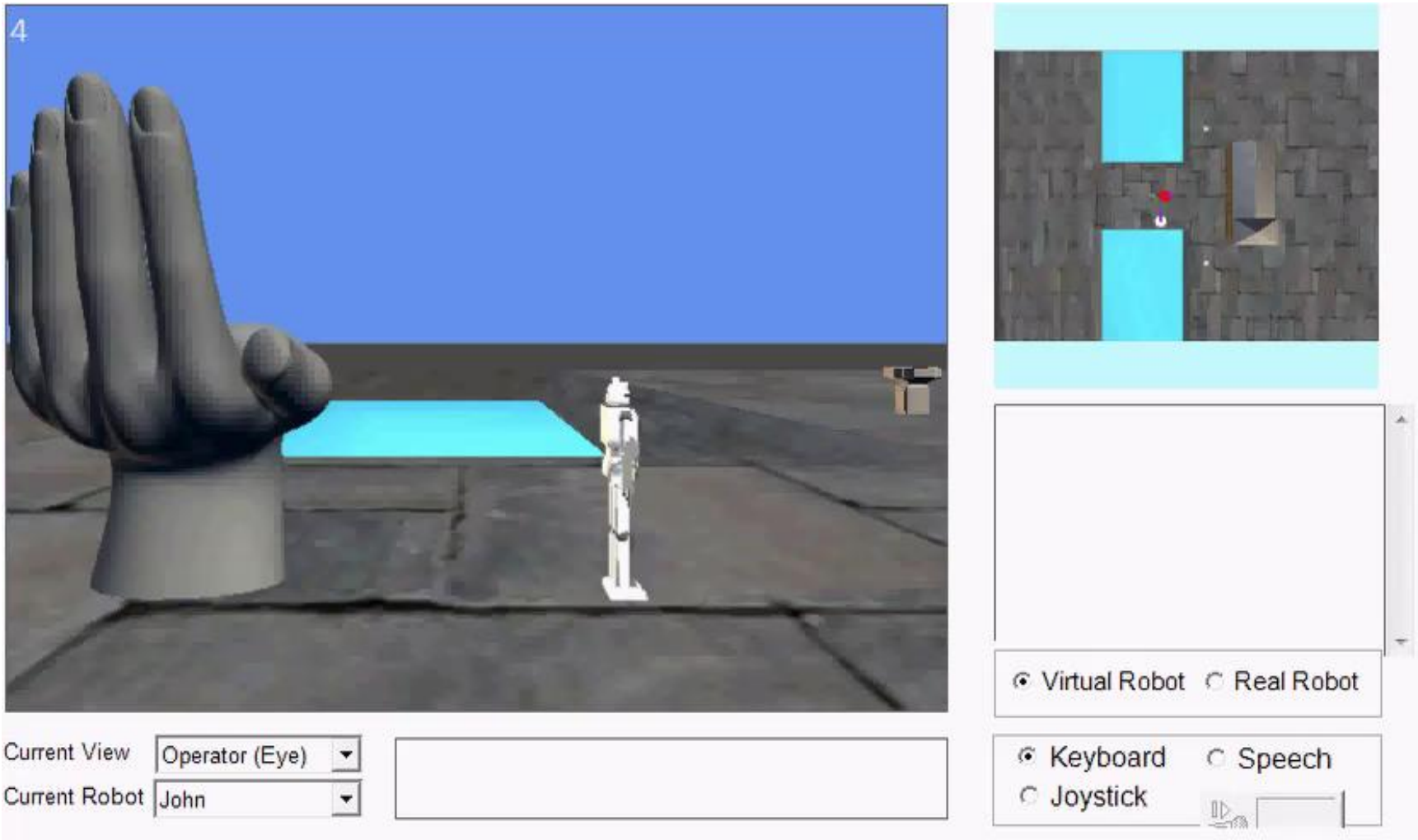
1. To hear
2. To speak
3. To see
4. To read
5. To write
6. To do
7. To walk

Four Domain Knowledge

1. Speech-centric knowledge
2. Vision-centric knowledge
3. Motion-centric knowledge
4. Task-centric knowledge

# Example of Human-Robot Interaction at Cognitive Level ...

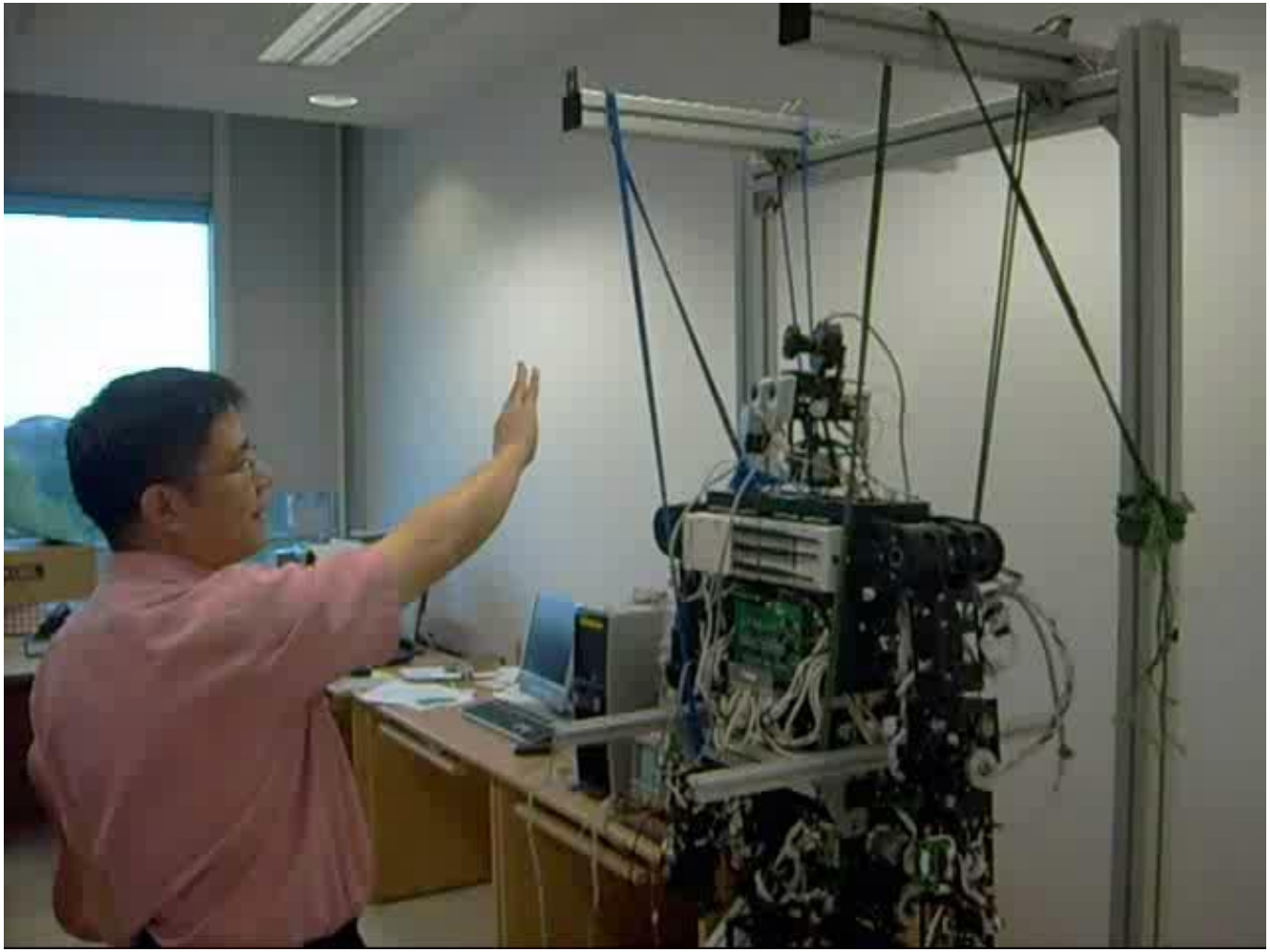
Signal (voice/text) → Knowledge → Knowledge → Signal




Results in 2010

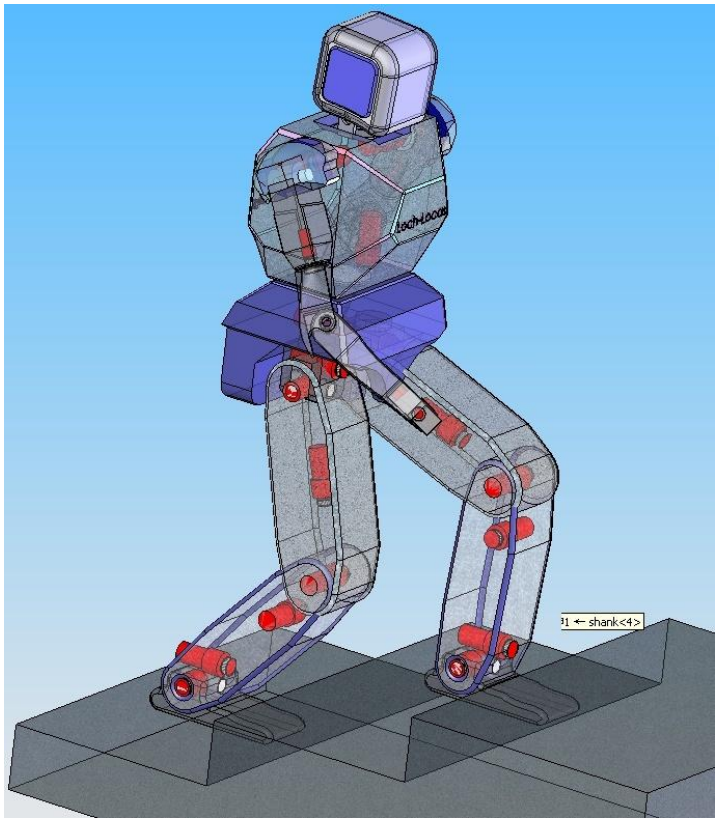
# Example of Human-Robot Interaction at Cognitive Level ...

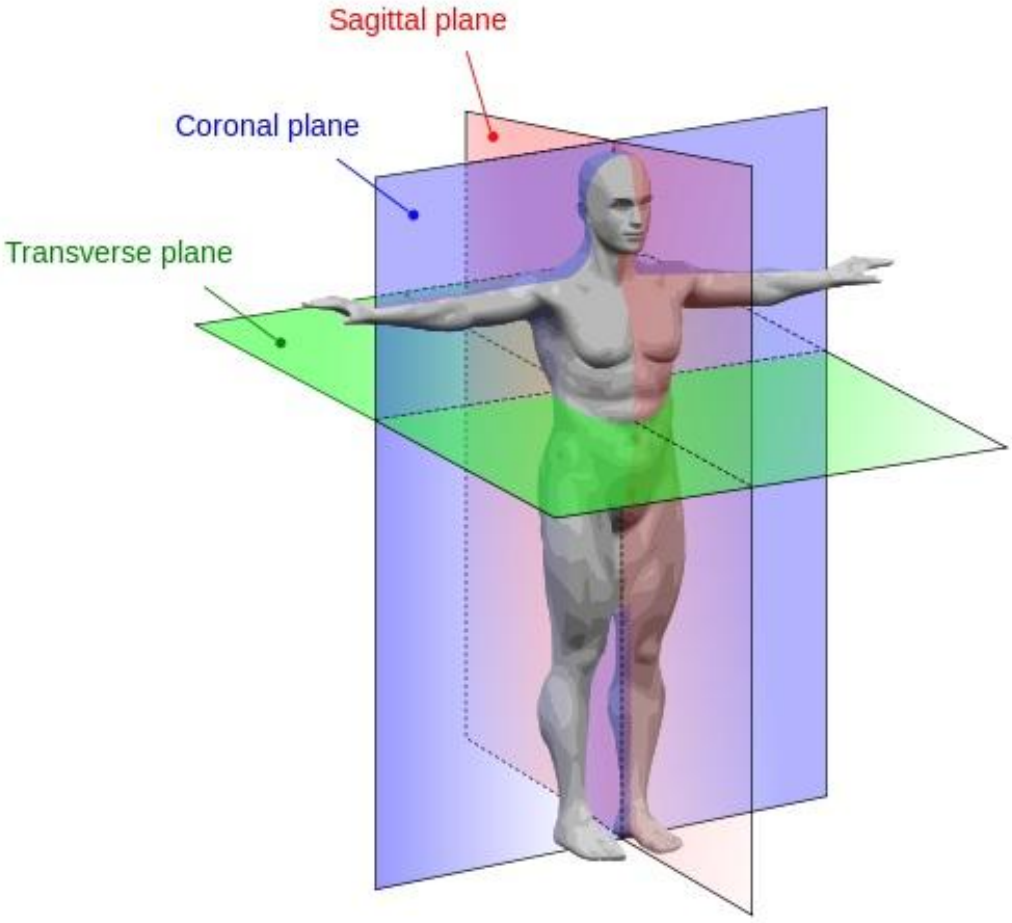
Visual Signal → Knowledge → Knowledge → Signal



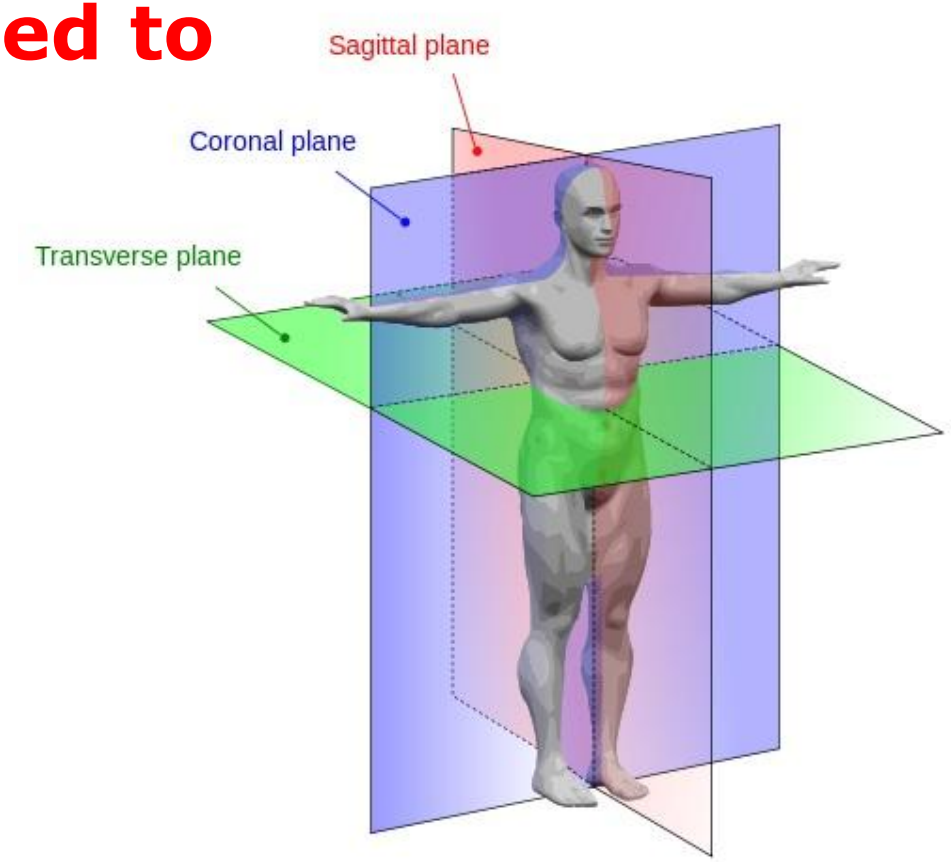
# Knowledge Flow Related to Biped Walking

- Physical Space and Definitions of Planes

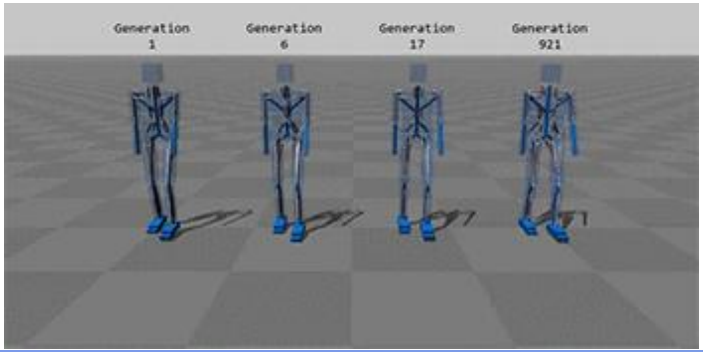




# Knowledge Flow Related to Biped Walking

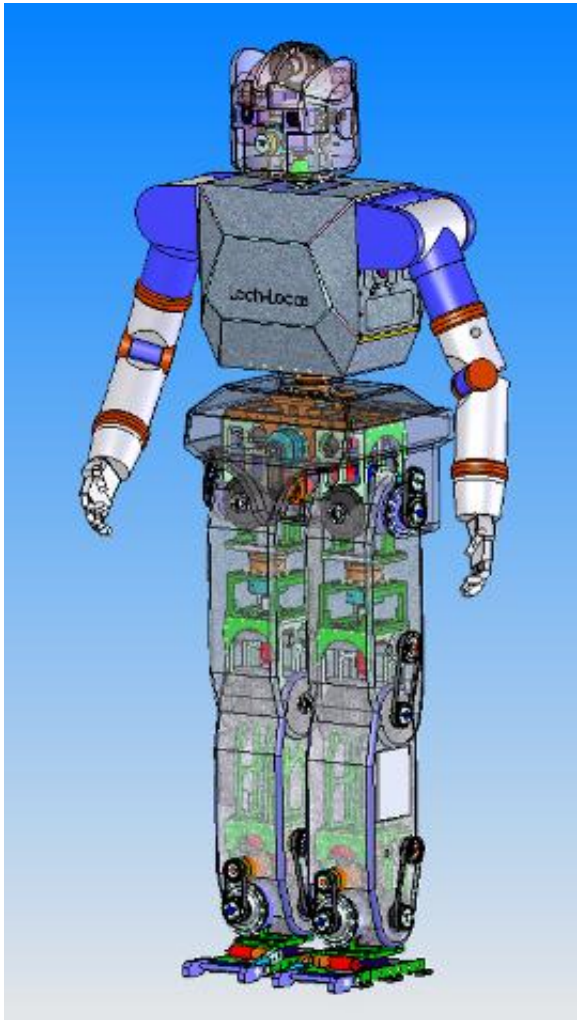



- Stability of Walking:
  - If a humanoid robot can sustain its walking, then the walking is stable.
- Stability of Static Walking
  - If a humanoid robot can sustain its walking in which accelerations are not influential factors, then the walking is statically stable.
- Stability of Dynamic Walking
  - If a humanoid robot can sustain its walking in which accelerations are influential factors, then the walking is dynamically stable.

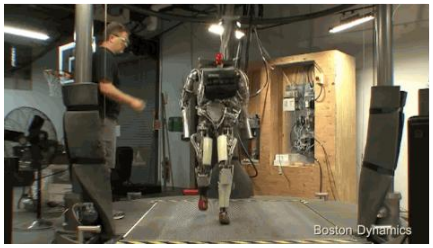


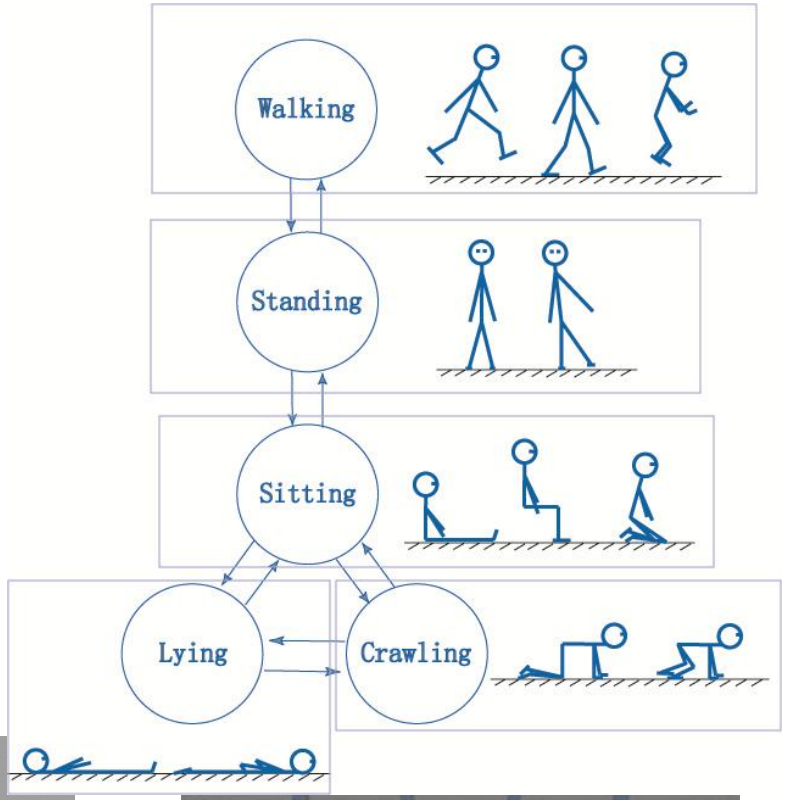
# Knowledge Flow Related to Biped Walking

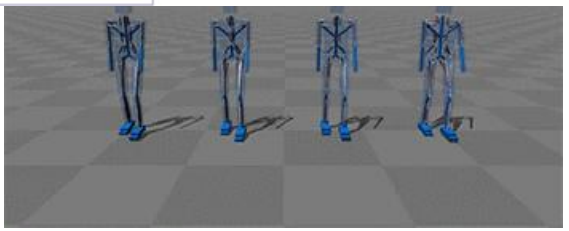
- Walking Behavior Types



- Pacing Gait
- Walking Gait
- Trotting Gait
- Cantering Gait
- Galloping Gait



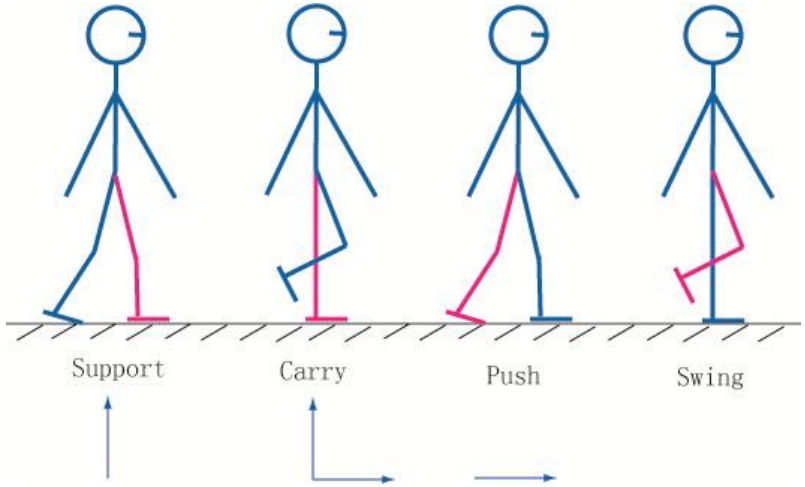



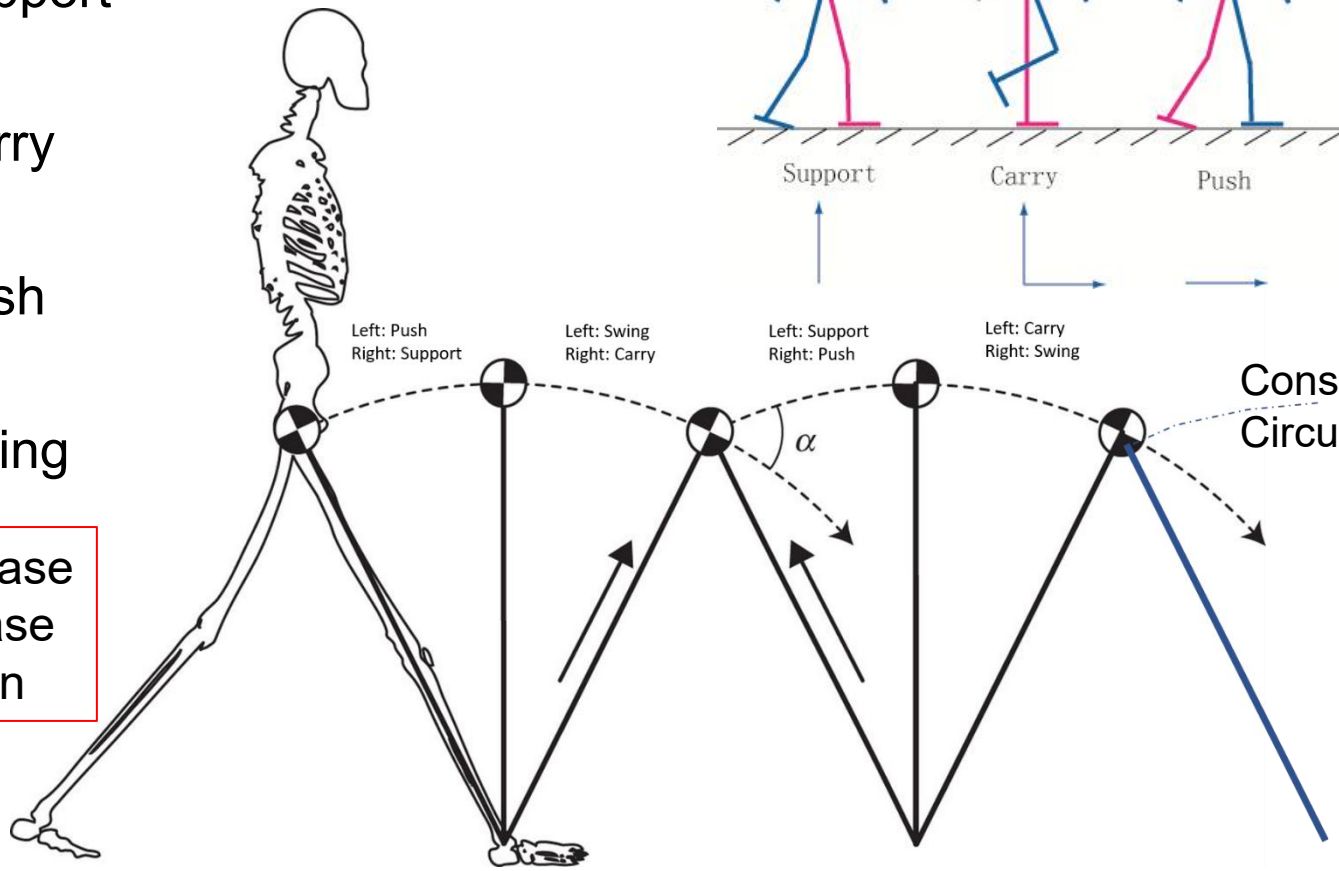
# Knowledge Flow Related to Biped Walking

- Four basic actions by each leg:

Stance Phase
- Support
- Carry
- Push

- Swing




- Stance Phase
- Swing Phase
- Suspension

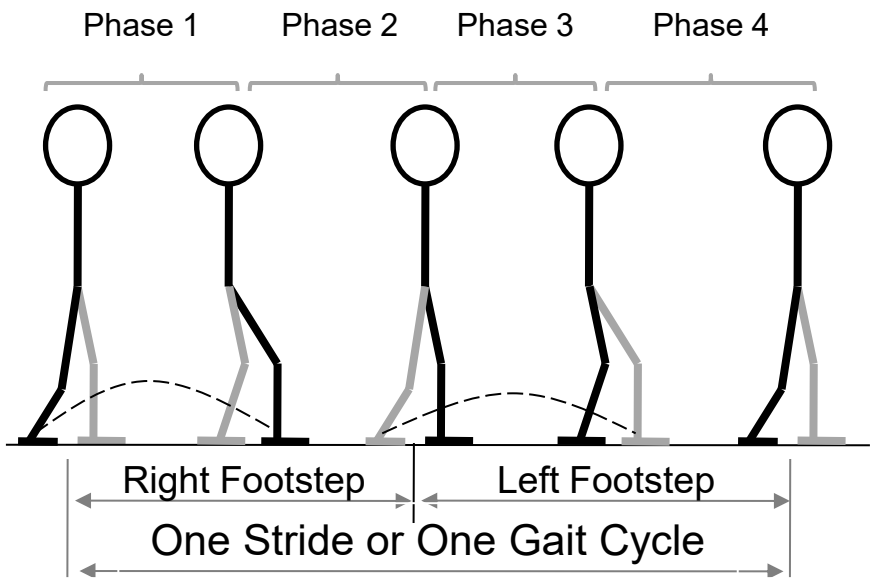
All the feet are off the ground.

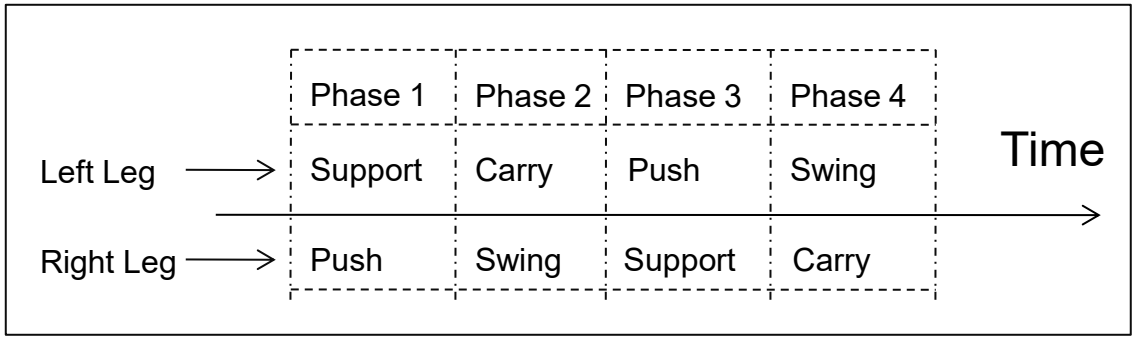
# Knowledge Flow Related to Biped Walking

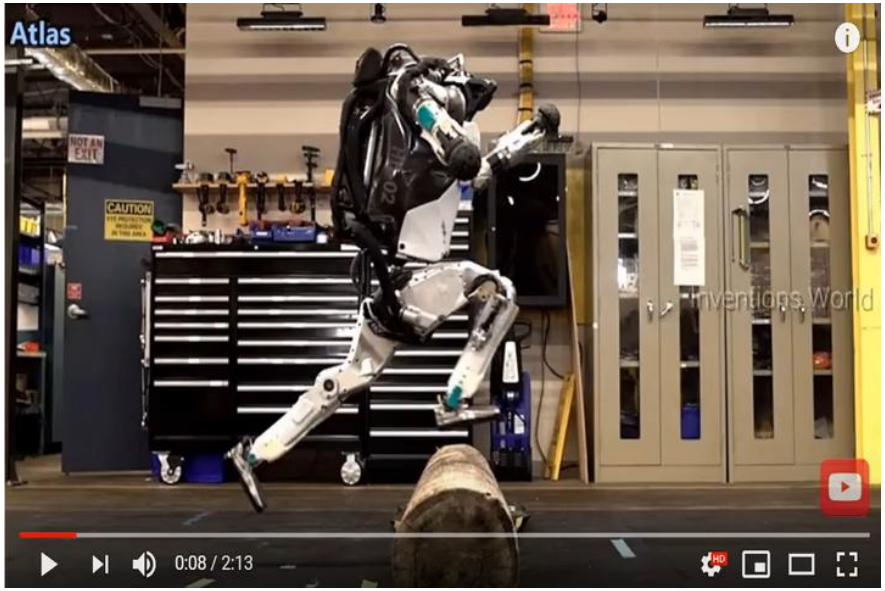
- Four basic walking phases:
  - Support-Push
  - Carry-Swing
  - Push-Support
  - Swing-Carry

by adding suspension phase

- Pacing Gait
- Walking Gait
- Trotting Gait
- Cantering Gait
- Galloping Gait




Atlas
0:08 / 2:13


6km/hの走行
Running at 6km/h


Humanoid
5/10/2009


HUMANOID ROBOT
& VTOL MICRO UAV


RSAF
AVIATION


RADAR TECHNOLOGY
FOR FIGHTERS


TARGETING PODS IN THE RSAF
AERONAUTICS RESEARCH & DEVELOPMENT
RADAR TECHNOLOGY FOR FIGHTERS
29/5/2011 11:43


AERONAUTICS RESEARCH & DEVELOPMENT
RADAR TECHNOLOGY FOR FIGHTERS

# Mid-2010s

# Outline of Today's Talk

- What is humanoid robot?
- What are the domain knowledge behind humanoid robot?
- What are the key steps toward development of humanoid robot?
  - Material Flow Inside Humanoid Robots
  - Energy Flow Inside Humanoid Robots
  - Signal Flow Inside Humanoid Robots
  - Motion Flow Inside Humanoid Robots
  - Knowledge Flow Inside Humanoid Robots
- Concluding Remarks

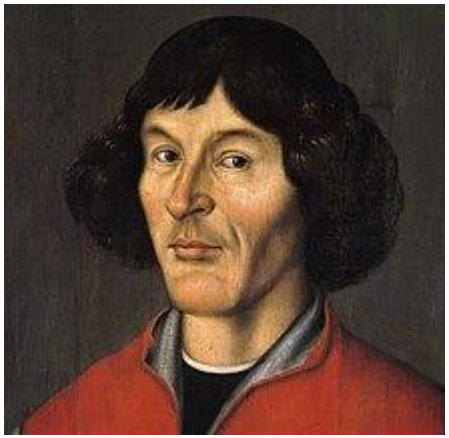
# Dilemma before 15th Century

In the study of astronomy, one of the biggest dilemma was about the center of the solar system:

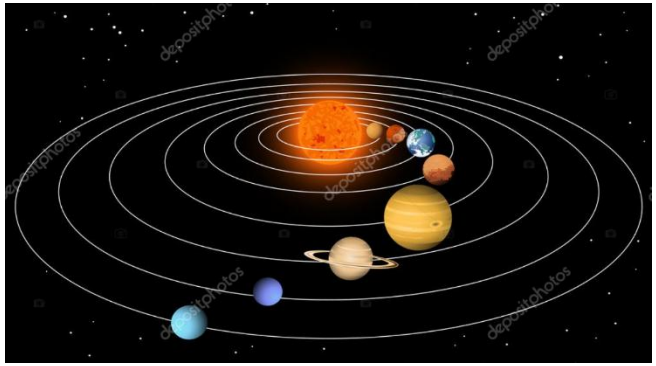
- Hypothesis 1 (Geo-centrism): Earth is the center of the solar system.

  (e.g., What is 昆仑? Point of Sunrise? Point of Sunset?)

- Hypothesis 2 (Helio-centrism): Sun is the center of the solar system.



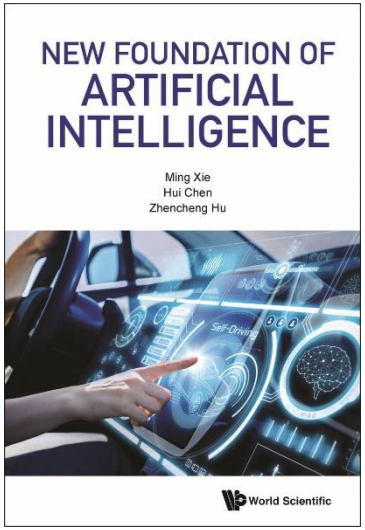
Nicolaus Copernicus
(1473 - 1543)



# Dilemma before 21th Century

In the study of artificial intelligence, one of the biggest dilemma was about the origin of intelligence:

- Hypothesis 1 (Brain-centrism): Brain is generator of intelligence.
- Hypothesis 2 (Mind-centrism): Mind is generator of intelligence.




2021

# It is an Interesting Parallel in History …

## Earth-Sun Relationship

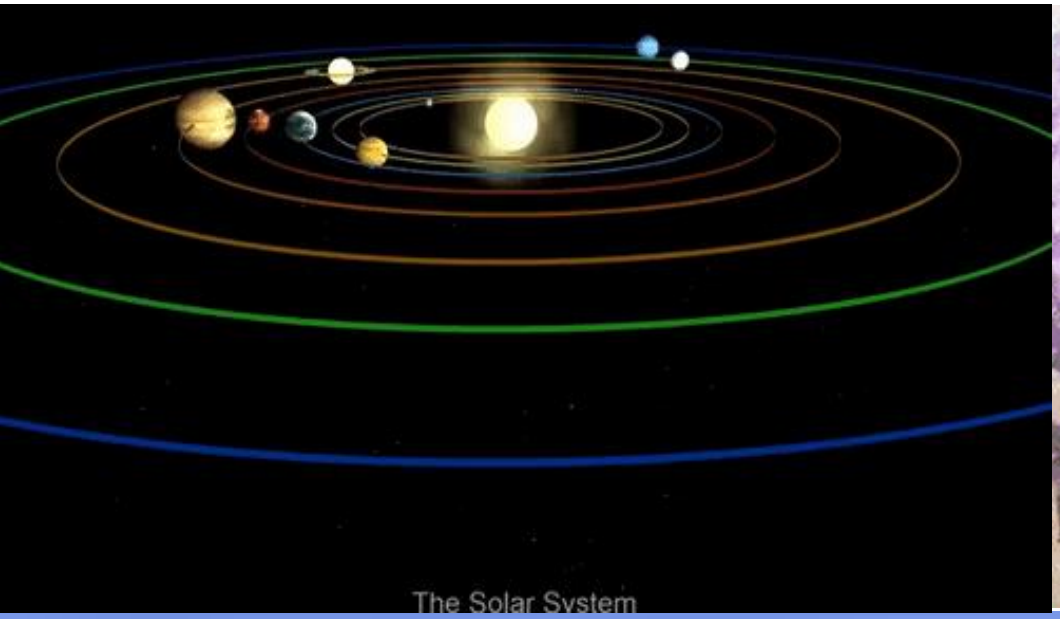
- Nicolaus Copernicus was an astronomer who proposed a heliocentric system, that the planets orbit around the Sun; that Earth is a planet which, besides orbiting the Sun annually, also self-rotates once daily on its own axis. Sun is at the center of the universe, but not Earth which orbits the Sun.

## Brain-Mind Relationship

- Brain provides hardware support to the functionalities of Mind. Brain's primary functions are computation and memorization (or storage), while Mind's primary functions are cognition and recognition. Mind is at the root of natural or artificial intelligence. Intelligence arises from Mind directly, but not Brain which supports Mind.

# What is our mission on Earth?

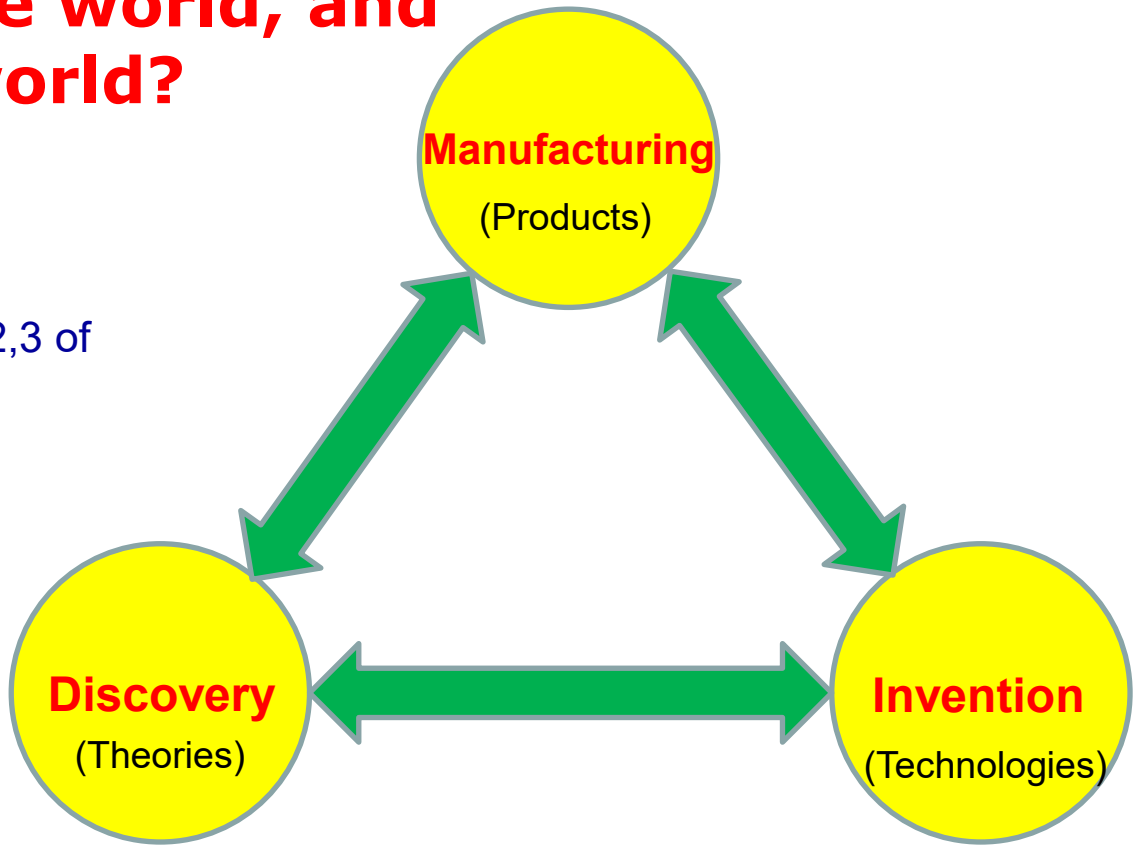
- (1) to understand the world, and
- (2) to improve the world?




# How to fulfill our missions on Earth, which include:
# (1) to understand the world, and
# (2) to improve the world?

## Research comes first:

- What is research? What are the 1,2,3 of research?



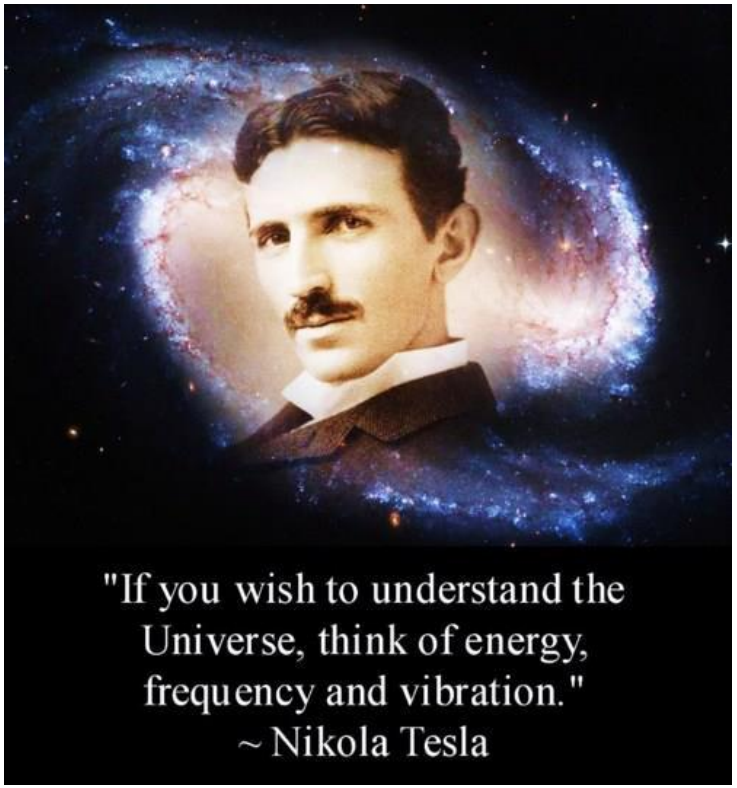

One Objective:
1. Research has one objective which is to create values by finding better ways of solving problems.

Two Driving Forces of Research
1. Scientific Problems
2. Social Needs

Three Outcomes:
1. Creation of Better Theories
2. Creation of Better Technologies
3. Creation of Better Products

# How to understand the universe?

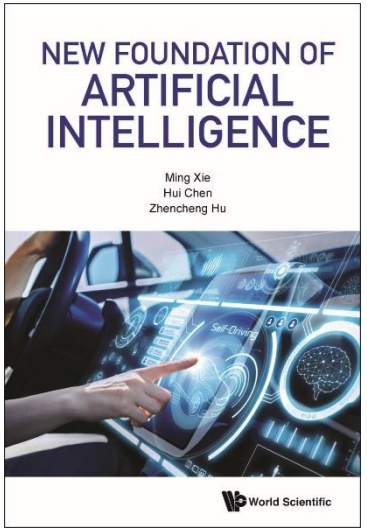
- If you wish to understand the secrets of the universe, think in terms of energy, frequency and vibration. – Nikola Tesla



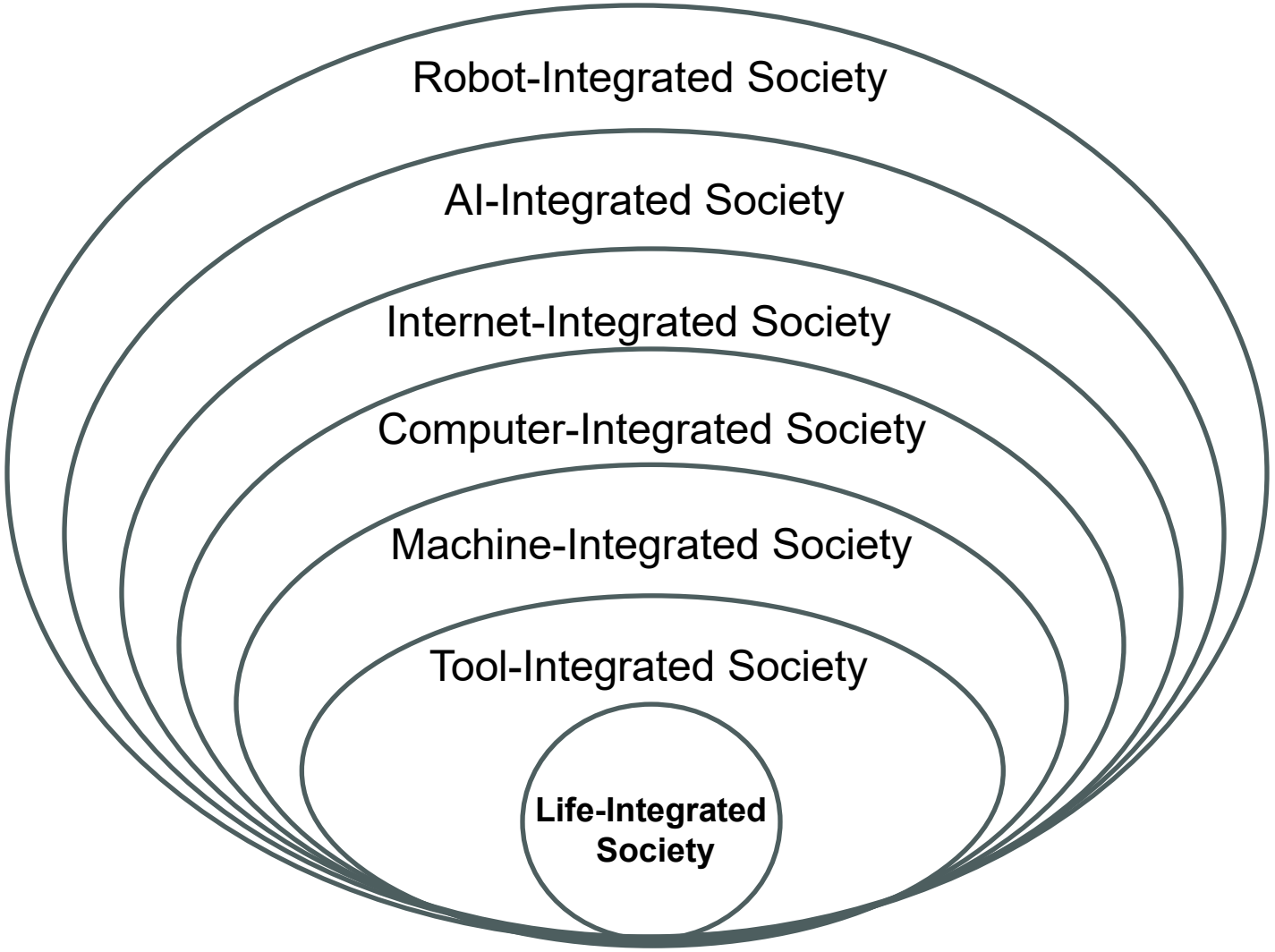
# How to understand the world?


- If you wish to understand the world, think in terms of systems, devices and materials – Ming XIE

- If you wish to understand the meanings of the world, think in terms of space (空), vector (色) and time (无常)? - Ming XIE

# How to improve the world?



# How to improve the world?

- To invent smarter products, smarter systems and smarter machines

# Advice 1: It is beneficial to compare Humanoid Robot's Intelligence with Human Being's Intelligence …

## Human Intelligence

- Signal to Knowledge Transformation
- Knowledge to Knowledge Transformation
- Knowledge to Signal Transformation

## Robot Intelligence

- Signal to Knowledge Transformation
- Knowledge to Knowledge Transformation
- Knowledge to Signal Transformation

# Advice 2: It is beneficial to compare Humanoid Robot's Learning with Human Being's Learning ...

## Human Learning

- Learning of Static Systems
- Learning of Dynamic Systems
- Learning of Properties
- Learning of Constraints

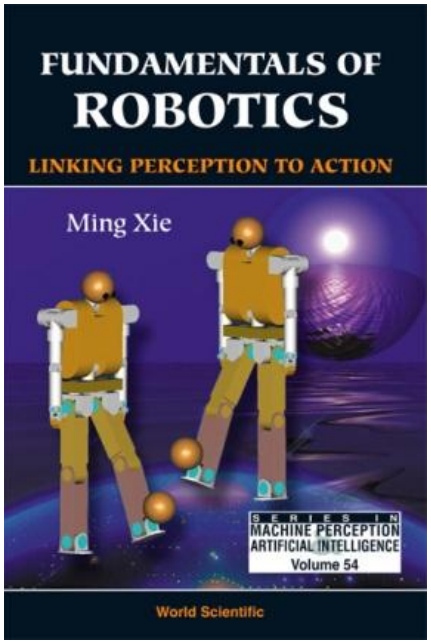
## Robot Learning

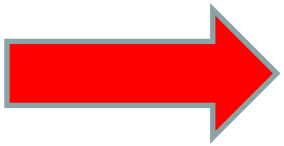
- Learning of Static Systems
- Learning of Dynamic Systems
- Learning of Properties
- Learning of Constraints

# Advice 3: We should not forget the prerequisite of learning …

- Human being's intelligence makes human beings educable or teachable. Educable human beings will greatly grow the knowledge and skills through learning.

- Similarly, humanoid robot's intelligence must make humanoid robots educable or teaachable. Educable humanoid robots will greatly grow the knowledge and skills through learning.



Educable Humanoid Robots

# Summary of Today's Talk

- What is humanoid robot?
- What are the domain knowledge behind humanoid robot?
- What are the key steps toward development of humanoid robot?
  - Material Flow Inside Humanoid Robots
  - Energy Flow Inside Humanoid Robots
  - Signal Flow Inside Humanoid Robots
  - Motion Flow Inside Humanoid Robots
  - Knowledge Flow Inside Humanoid Robots
- Concluding Remarks

# Key Takeaways: Understanding of …

- One Definition: Robot in Image of Human Being
- Three Domains of Knowledge: Body, Brain and Mind
- Five Key Steps of Development: They are the effective ways which translate the three domains of know-hows into the achievements of these five layers of:
  - Material Flow Inside Humanoid Robots
  - Energy Flow Inside Humanoid Robots
  - Signal Flow Inside Humanoid Robots
  - Motion Flow Inside Humanoid Robots
  - Knowledge Flow Inside Humanoid Robots

"Ask not what your country can do for you – ask what you can do for your country," - John F. Kennedy

"Do not think that you are needy – think that you are needed in the world", - Manis Friedman

"Study will make you knowledgeable, resourceful, and hence more needed", - Xie Ming

# Thank You for Listening!