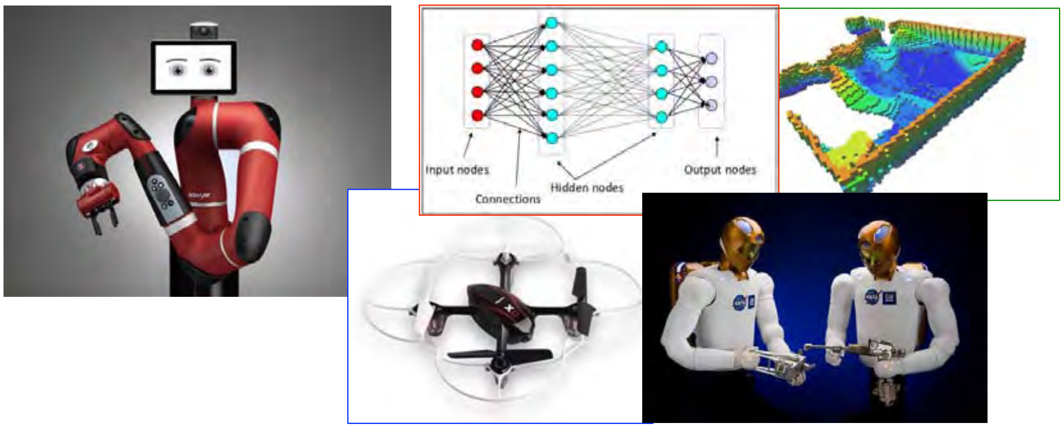
Robotics and Intelligent Systems

Robert Stengel

Robotics and Intelligent Systems
MAE 345 Princeton University, 2017

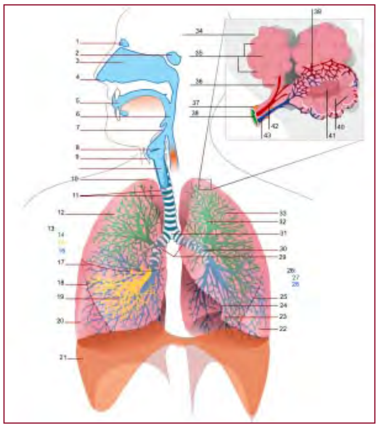


www.princeton.edu/~stengel/MAE345.html

Robots and Robotics

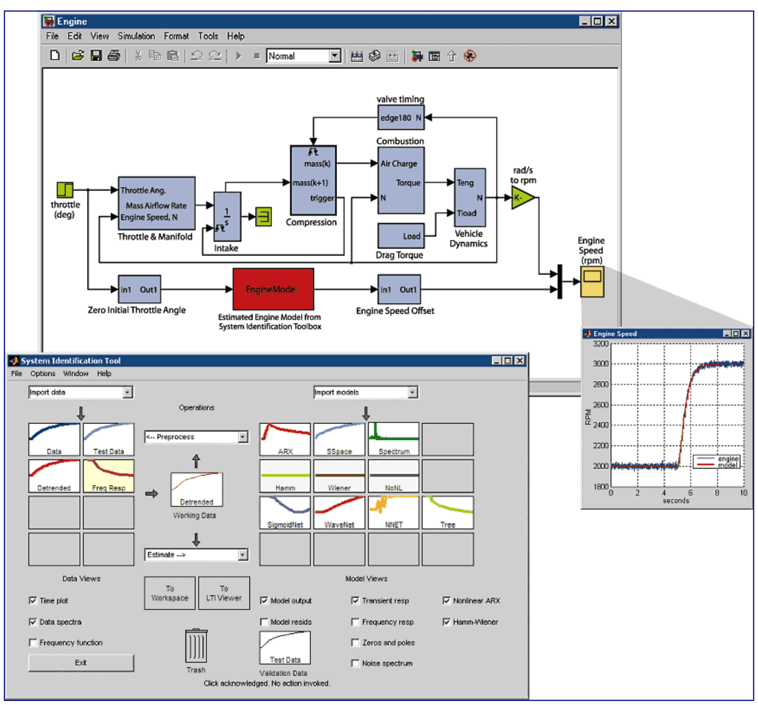
- Design, manufacture, control, and programming of robots
- Use of robots to solve problems
- Study of control processes, sensors, and algorithms used in humans, animals, and machines
- Application of control processes and algorithms to designing robots

What are Systems?

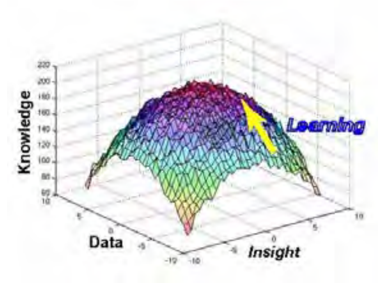


- Assemblages of parts with structure, connectivity, and behavior
- Modules that relate to each other
- Interacting entities with common goals
- Objects with defined boundaries within some environment
- Objects that respond to inputs from externalities
- Objects that create outputs to externalities

Representing Dynamic Systems and Their Performance



Intelligent Systems



- Systems that
  - perform useful functions driven by desired goals and current knowledge
  - emulate biological and cognitive processes
  - process information to achieve objectives
  - learn by example or from experience
  - adapt functions to a changing environment
- Learning: Data + Insight ➔ Knowledge

Biomimetics (Bionics)

- Understanding biological principles and applying them to system design
  - Configuration
  - Structure
  - Behavior
  - Dynamics
  - Control

Syllabus

- Overview and Preliminaries
- Coordinates and Kinematics
- Mobile Robots
- Path Planning
- Articulated Robots
- Rigid-Body Dynamics
- Dynamic Effects of Feedback Control
- Control Systems
- Sensors and Actuators
- Introduction to Optimization
- Numerical Optimization
- Dynamic Optimal Control
- Formal Logic, Algorithms, and Incompleteness
- Computers, Computing, and Sets
- Probability and Statistics
- Classification of Data Sets
- Neural Networks
- Machine Learning, Communication, and Information
- Expert Systems
- State and Parameter Estimation
- Stochastic and Adaptive Control
- Task Planning and Multi-Agent Systems

Preliminaries

- ***Office Hours***
  - *Mon Wed, 1:30-3pm*
- ***Assistant in Instruction:***
- ***MATLAB / SimuLink / SimMechanics***
- ***Course Home Page, Syllabus, and Links***
  - *www.princeton.edu/~stengel/MAE345.html*
- ***On-Line Resources***
  - ***Blackboard: https://blackboard.princeton.edu/webapps/login***
    - *Lecture Slides*
    - *Suggested Reading (E-Reserves, E-Journals, and Web Pages)*
    - *Virtual Reference Book*

- ~GRADING
  - Class participation: 15%
  - Quick Quizzes: 10%
  - Assignments: 45%
  - Term Paper: 30%
  - Late policy: 10% reduction/day

Electronic Devices in Class

- *Silence all cellphones and computer alarms*
- *Don't check e-mail or send text, tweets, etc.*
- *If you must make a call or send a message, you may leave the room to do so*
- *Tablets/laptops for class-related material ONLY (unrelated surfing is negative participation)*

Collaborative Learning

- **Randomly assigned teams for some assignments**
  - **Single grade for each team**
- **Significant student participation in most classes, Q&A**
- **Slides will be available before each class**
- **Discussion of slides by students**

Background Reading

- Chapters, sections, and pages from various books and papers
  - Electronic Reserves: 'E-Reserves' on Blackboard sidebar
  - Hard copies on Engineering Library Reserve Shelf
- Technical journal papers
  - E-Journals:
    - http://getit.princeton.edu/

Additional Information: Virtual Reference Book

Links to web pages describing material related to the course

Entries marked by asterisks (*) are especially relevant

Arranged to correspond to course lectures

Predominantly Wikipedia entries

http://www.princeton.edu/~stengel/RISVirText.html

Written Assignment Reporting Format

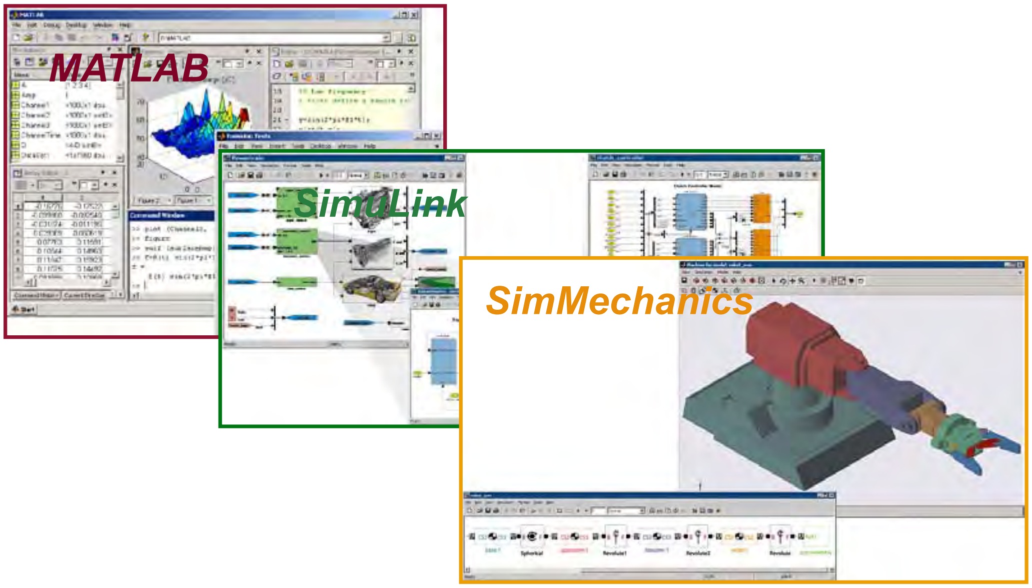
- *Assignments will evolve toward Technical Reports*
- *Write-ups should present explanations, not just numbers, graphs, or computer code*
- *Orderliness and neatness count*
- *Don't forget your name, date, and assignment title or number*

Assignment # 1
due: September 22, 2017

1) **Describe a specific, existing robot or robotic system in about 500 words.**
2) **Describe an existing or hypothetical intelligent system in about 500 words.**

Submit via Blackboard

Computational Tools



A Little Historical Background

Robotic Antecedents: Antiquity

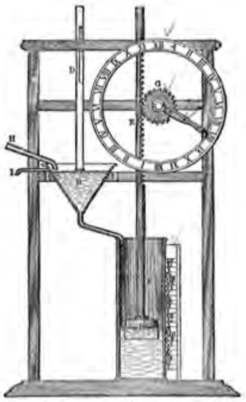


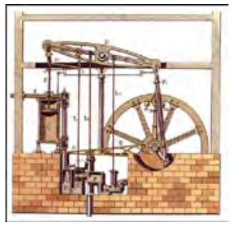
FIG. 29. — A COMMON FORM OF CLEPSYDRA IN GREEK AND ROMAN TIMES.

- Aristotle, 4th c. BC
  - "If every instrument could accomplish its own work, obeying or anticipating the will of others … chief workmen would not need servants."
- Toys, gadgets, and clocks
  - Puppets, various cultures, BC
  - Water-driven clock, 2nd c. BC
  - Automata, clock works, *et al* (da Vinci's Lion, 15th c. BC ; Zytgloggeturm, Bern, 12th and 16th c.)
- Elektro, 1939 NY World's Fair

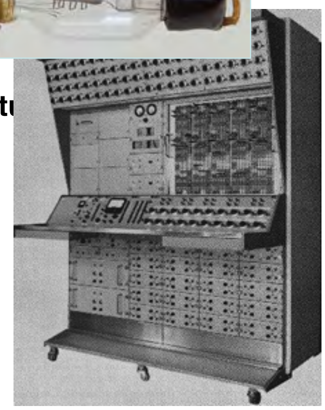
Robotic Antecedents: Science Fiction

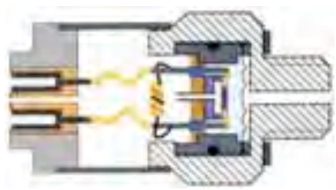
- "Robot" = "worker" in Slavic
  - Karel Capek's 1921 play, *RUR (Rossum's Universal Robots)*, in which machines took over the world
- Short story in collection, *I, Robot*, Isaac Asimov, 1942
  - Code of ethics for robots
- Victorian pulp fiction (Frank Reade's *Electric Man*, the *Electric Horse*)

Robotic Antecedents: Industry



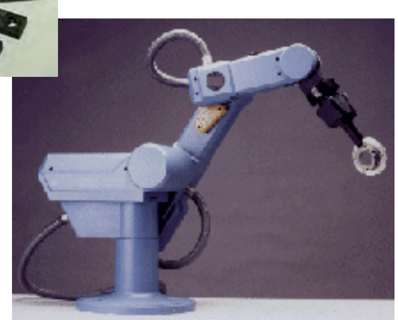
- 18th c.: Industrial Revolution
  - Jacquard loom (punched cards)
  - Watt steam engine (regulator)
- 1900-30s: Enabling Technologies
  - Vacuum tubes
  - Electric motors
  - Hydraulic/pneumatic actu
  - Sensors
  - Analog computation
  - Control theory





Toward Autonomous Robots

- 1940s: World War II
  - Teleoperators
  - Fire control systems
  - Aerial drones
  - Numerically controlled machines
  - Chemical process control
- 1947: Transistor invented
- 1950s: Cold War
  - Guided multi-stage missiles
- 1960s: Space Age
  - Uninhabited spacecraft
  - Industrial robots
  - "Boston Arm" (Mann, MIT)
- 1970s: Energy and the Environment
  - Computer-machine integration
  - Entertainment

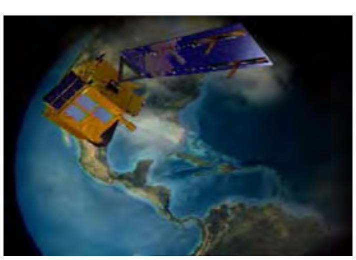


Elements of Robotic Devices

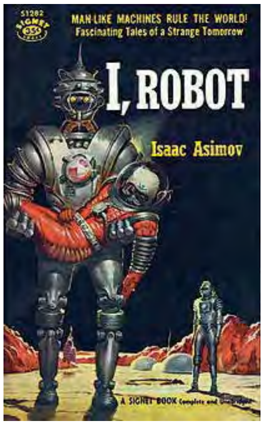
- Structure
- Power source
- Actuation
- Sensing
- Locomotion
- Environmental Interaction
- Human-machine interaction
- Guidance
- Navigation
- Control

Autonomous Robots

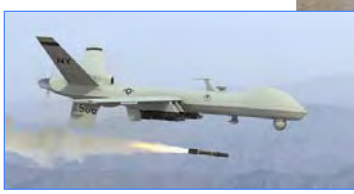
- Self control
- Self maintenance
- Awareness of environment
- Task orientation
- Mission specificity
- Power source
- Cooperation and collaboration
- = Intelligence?
- Self replication?
- Ethical issues



Ethics of Robotics



- **Three Laws of Robotics** (Asimov, *"Runaround"*, in *Astounding Science Fiction*, 1942)
  - **1: A robot may not injure a human being or, through inaction, allow a human being to come to harm.**
  - **2: A robot must obey any orders given to it by human beings, except where orders conflict with the First Law.**
  - **3: A robot must protect its own existence as long as protection does not conflict with First or Second Law.**



- **RoboEthics = Human-Centered Ethics?**
  - Human dignity, respect, privacy, and rights
  - Equality and justice
  - Benefit and harm
  - Discrimination and diversity
  - Individual autonomy and social responsibility

Ethics of Robotics

RoboEthics = Human-Centered Ethics?

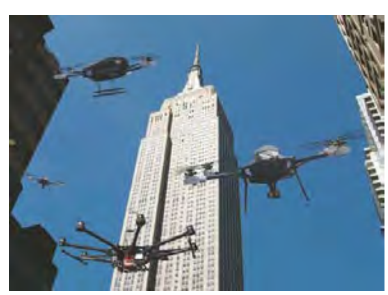
Human dignity, respect, privacy, and rights

Equality and justice

Benefit and harm

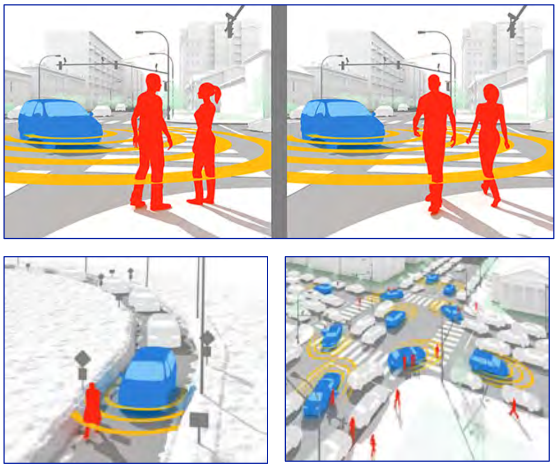
Discrimination and diversity

Individual autonomy and social responsibility



http://www.sciencemag.org/cgi/content/full/322/5909/1800

Human-Robot Interaction:
Signaling Intent



The Big Problem With Self-Driving Cars Is People, Rodney Brooks, *IEEE Spectrum*, Jul/Aug 2017

- **What should the autonomous car do in uncertain situations?**
- **What should pedestrians do to preserve safety and efficient travel?**
- **How can the mix between human and computer drivers be handled?**
- **What takes the place of *eye contact*?**

Intelligent System Antecedents: Language and Communication

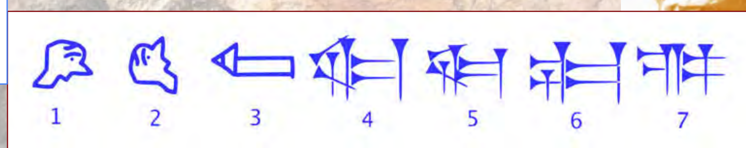
- **Information to communicate**
  - **Meaningful utterances (proto-languages, 100,000-200,000 years ago, ~age of *homo sapiens*)**
  - **Music and mimicry (e.g., talking drum: "the tones of the syllables of conventional phrases"*)**
  - **Culturally distinct oral languages**
  - **Subject-Object-Verb order**
  - **Storytelling**

* Roger Clarke, missionary, ~1840, in *The Information*, J. Gleick

Intelligent System Antecedents:
Drawing, Symbols, and Writing

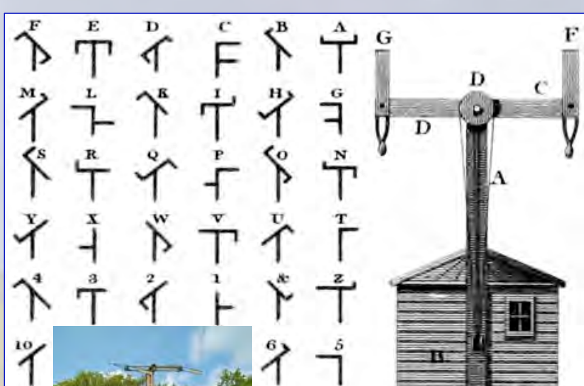
- Pictures -> pictographs -> cuneiform
- Alphabets, written words, and grammar
- Numbers, logic, and mathematics
- Books -> dictionaries -> encyclopedias



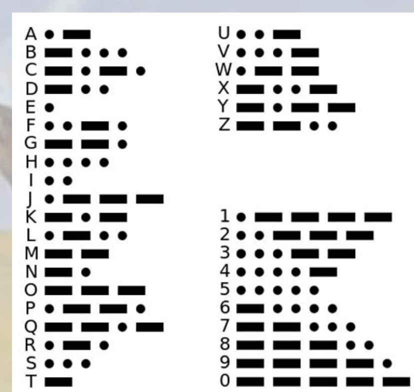



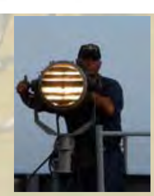
Intelligent System Antecedents:
Codes and Long-Distance Signaling

Semaphore Line Code



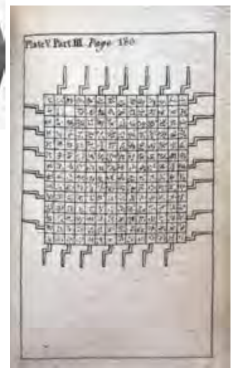
Morse Code

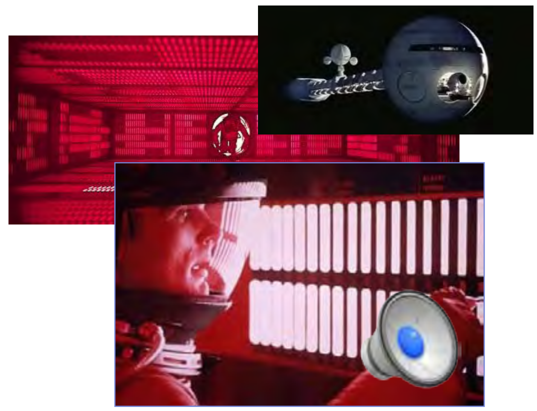




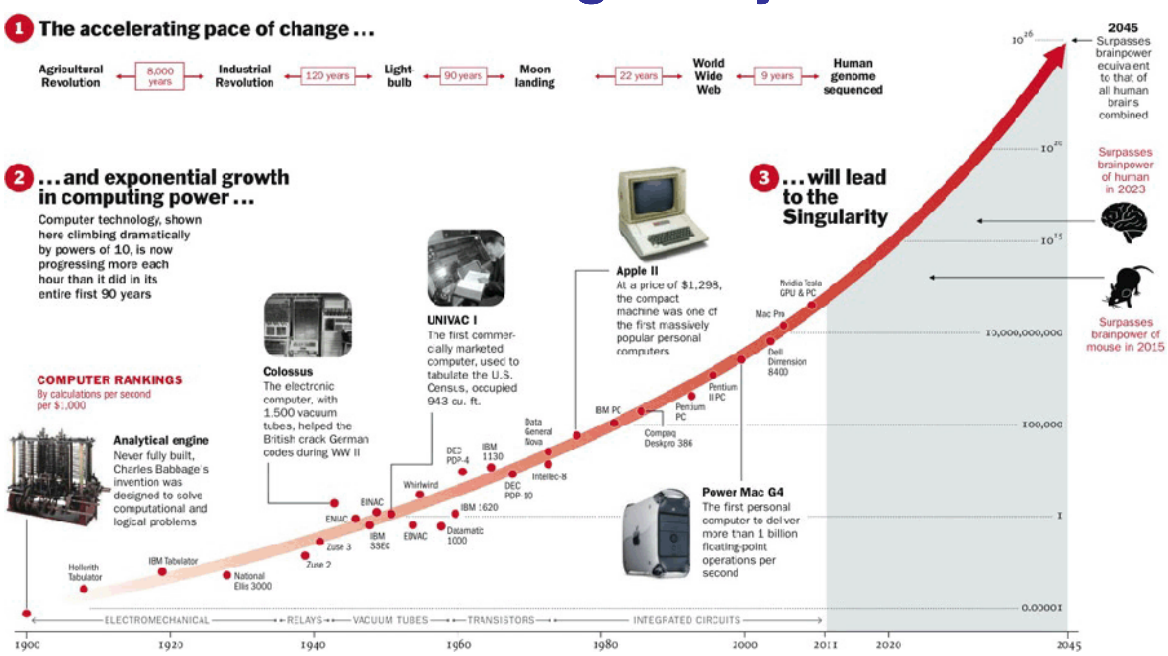
Intelligent System Antecedents: Science Fiction

- Greek myths, drama, and poetry
- "The Engine", *Gulliver's Travels* (1726), Jonathan Swift
- *Dr. Frankenstein's "Creature"* (1818), Mary Shelley: the first artificial human
- HAL 9000, in 2001: *A Space Odyssey* (1968), Arthur C. Clarke





The Singularity*

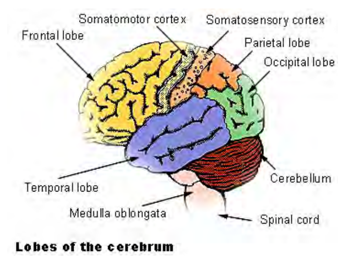


* *Ray Kurzweil, futurist*

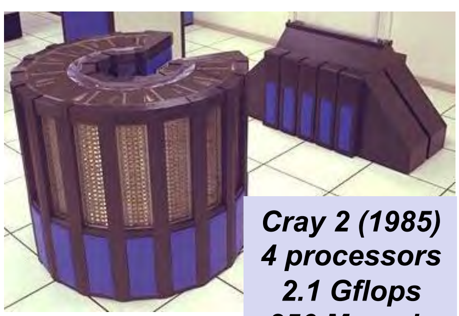
Will autonomous robots rule the world?

The Brain vs. The Supercomputer

- **Human brain**
  - 38 x 10^{15} ops/s
  - 3.5 x 10^{15} bytes
  - 100 watts
- **Supercomputer**
  - NUDT Tienhe-2: 33 x 10^{15} flops (2012)
  - ~10 Mwatts
  - ~2,000 Gigaflops/kW
- **Singularity: plausible?**



But Wait ….



Cray 2 (1985)
4 processors
2.1 Gflops
256 Mwords

=

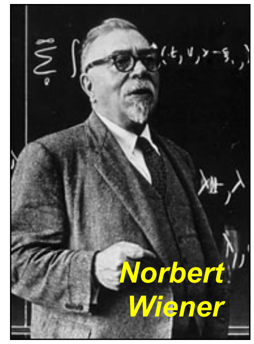
iPad Air 2 (2014)
Dual core
Triple-processor: 1.3-8 Gflops
128 Gbytes

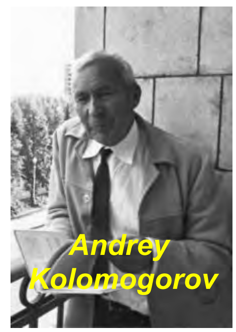
iPad Air 2 speed comparable to Top 500 List supercomputer in1998

iPhone 8 (2017)
Dual core
5-20 Gflops
256 Gbytes
0.5-2.5 watts

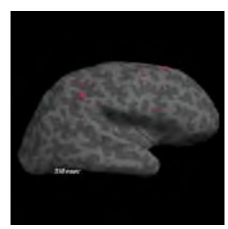
Intelligent System Antecedents: Cybernetics

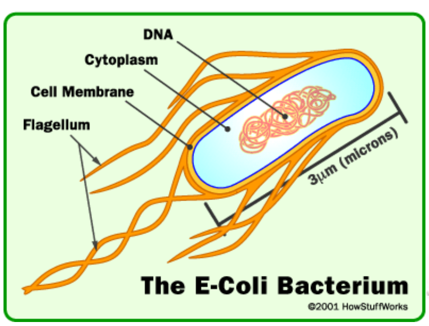
- **Early definitions of what we call "intelligent systems"**
  - **"Scientific study of control and communication in the animal and the machine." (Norbert Wiener, 1948)**
  - **"Science concerned with the study of systems of any nature which are capable of receiving, storing and processing information so as to use it for control." (Andrey Kolmogorov, -)**
  - **"Art and science of manipulating defensible metaphors." (Gordon Pask, 1961)**
- **Other figures in cybernetics**
  - **Jay Forrester, Urban and world dynamics**
  - **Warren McCullough, neural networks**
  - **Walter Pitts, neural networks**





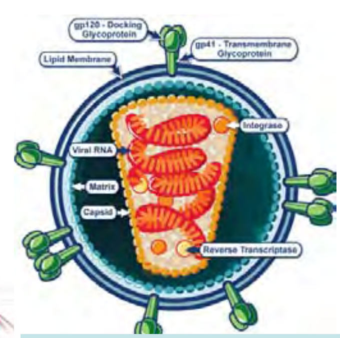
What Makes A System "Intelligent"?





~1-2 μm
Genome: 5 million base pairs
No brain

Copepod, 1-2 mm
Genome: 5 billion base pairs
Brain: ~100 μm



HIV
Genome: 10,000 base pairs
No brain

Human Genome: 3.2 billion base pairs

Some "Artificially Intelligent Systems"

- *Eliza*, Weizenbaum, 1976
  - http://www.manifestation.com/neurotoys/eliza.php3
- *SIRI, Alexa, Echo,* voice response systems
- Statistical decision theory
- Symbolic computation (*Mathematica, Maple*)
- Theorem-proving s/w
- Chess, checkers, computer games
- Health/Financial Planning s/w
- *MapQuest, Google, Wikipedia, Alpha*
- GPS navigation

Ethics of Intelligent Systems

- "Big Data", data mining
- Intellectual property
- Commercial Entities
  - Google
  - Facebook
  - Sqrrl
  - Credit card industry
  - Violent video games
- Government Entities
  - NSA
    - Accumulo
    - PRISM

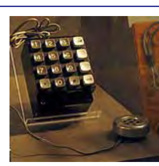
http://en.wikipedia.org/wiki/PRISM_(surveillance_program)

http://en.wikipedia.org/wiki/Intellectual_property

http://en.wikipedia.org/wiki/Blue_box

http://en.wikipedia.org/wiki/Anonymous_(group)

- Whistle-Blowing
- WikiLeaks.org
- Private vs. Public Domain
- Privacy vs. security
- Encryption
- Hacking
  - Blue box
  - Anonymous



http://en.wikipedia.org/wiki/Nineteen_Eighty-Four

Intelligent System Structures

Essential Abilities for Intelligence

(*Gödel, Escher, Bach*, D. Hofstadter, 1979)

- **Respond flexibly to unforeseen situations**
  - **Take advantage of fortuitous circumstances**
  - **Make sense of ambiguity or contradiction**
- **Recognize relative importance of information**
- **Find similarities and differences among things**
- **Generate novel ideas**
  - **Synthesize new ideas from old concepts**
  - **"Think different"**

Cognitive and Biological Paradigms

Thinking

- Syntax (form) and Semantics (meaning)
- Algorithmic vs. Non-Algorithmic Behavior
- Consistency, Emotion, "The Collective Subconscious"
- Generating Alternatives
- Randomized Search

Consciousness

- Self-Awareness and Perception
- Creativity, Wisdom, and Imagination
- Common Sense, Understanding, and Judgment of Truth
- Learning by Example

Qualities of Thought

Conscious Thought

- Awareness
- Focus
- Reflection
- Rehearsal
- *Declarative* Processing of Knowledge or Beliefs

Unconscious Thought

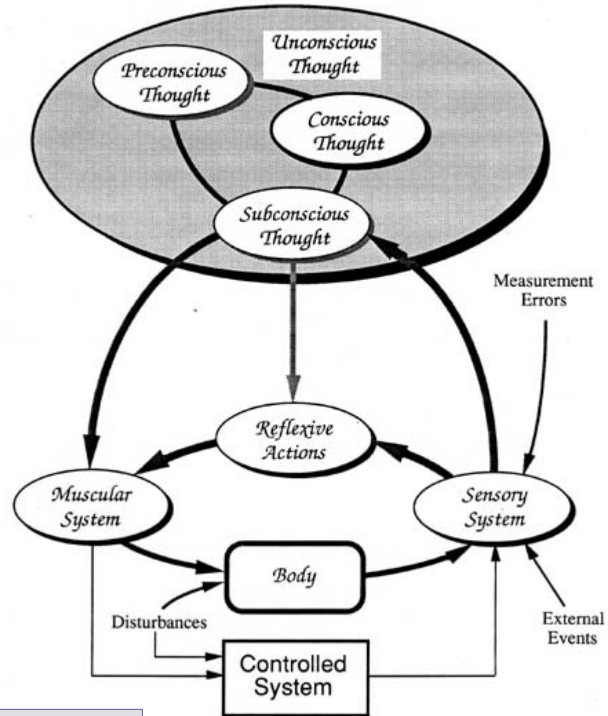
- Subconscious Thought
  - . *Procedural* Processing
  - . Communication
  - . Learned Skills
  - . Subliminal Knowledge Acquisition
- Preconscious Thought
  - . Pre-attentive *Declarative* Processing
  - . Subject Selection for Conscious Thought
  - . Learning and Concept Development
  - . Information Pathway to Memory
  - . Intuition

***Reflexive* Behavior**

- Instantaneous Response to Stimuli
- Elementary, Forceful Actions
- Stabilizing Influence
- Simple Goals

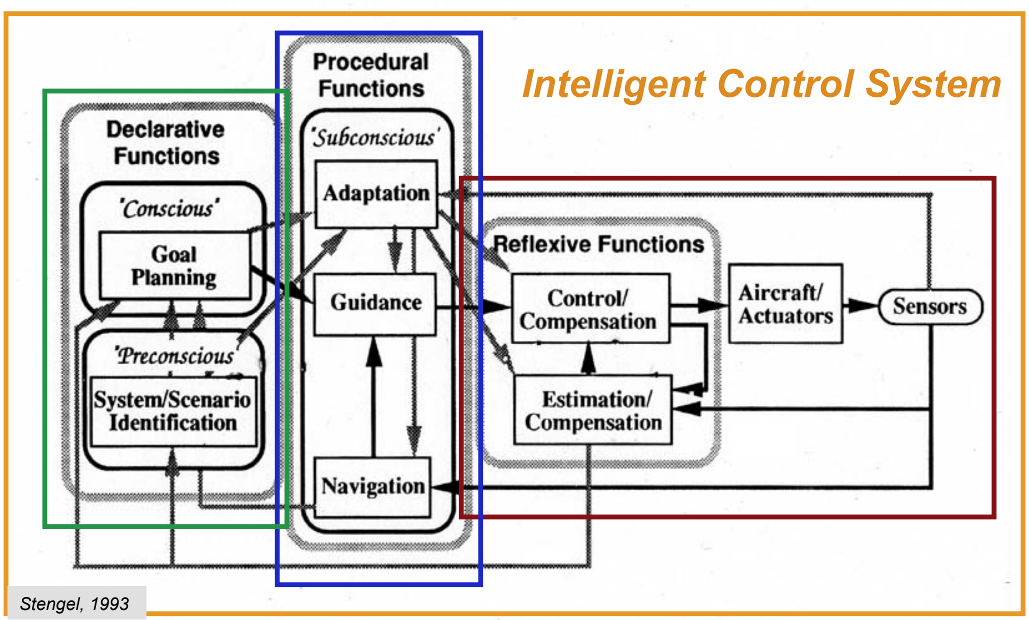
Hierarchy of Declarative, Procedural, and Reflexive Actions

- Conscious Thought
- Unconscious Thought
  - Subconscious Thought
  - Preconscious Thought
- Reflexive Behavior



http://www.princeton.edu/~stengel/TIFC.pdf

Elements of Intelligent Control



Declarative Functions		*Expert Systems, Decision Trees*
Procedural Functions	*modeled by*	*Estimation and Control "Circuits"*
Reflexive Functions		*Control Laws, Neural Networks*

Biological Paradigms for Control

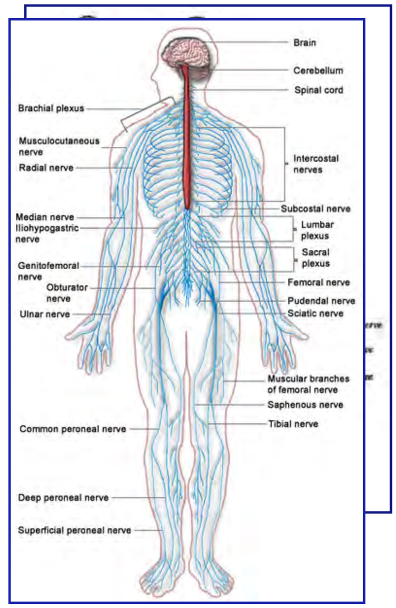
Short, Dedicated, Parallel Channels for High-Bandwidth, High-Resolution Information (vision, sound, and balance)

Dissimilar but Related Sensory Inputs

Hierarchical and Redundant Structures

Pairing Allows Graceful Degradation of Sensors and Effectors

Richness of Sensory Information



Math Review

- *Scalars and Vectors*
- *Sums and Multiplication*
- *Inner Product*
- *Derivatives and Integrals*

Scalars and Vectors

- **Scalar: usually lower case:** ***a, b, c, …, x, y, z***
- **Vector: usually bold or with underbar: x or x**
  - **Ordered set**
  - **Column of scalars**
  - **Dimension = *n* x 1**

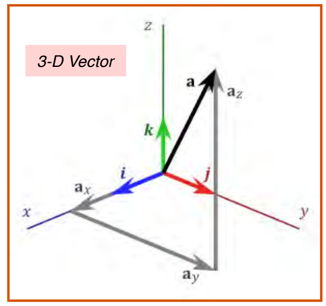
$$\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} \quad ; \quad \mathbf{y} = \begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix}$$

3 x 1 *4 x 1*

Transpose: interchange rows and columns

$$\mathbf{x}^T = \begin{bmatrix} x_1 & x_2 & x_3 \end{bmatrix}$$

1 x 3



Multiplication of Vector by Scalar

Multiplication of vector by scalar is associative, commutative, and distributive

$$a\mathbf{x} = \mathbf{x}a = \begin{bmatrix} ax_1 \\ ax_2 \\ ax_3 \end{bmatrix}$$

$$a(\mathbf{x}+\mathbf{y}) = (\mathbf{x}+\mathbf{y})a = (a\mathbf{x}+a\mathbf{y})$$

$\dim(\mathbf{x}) = \dim(\mathbf{y})$

$$a\mathbf{x}^T = \begin{bmatrix} ax_1 & ax_2 & ax_3 \end{bmatrix}$$

- **Could we add** $(\mathbf{x}+a)$ **?**
- **Only if** $\dim(\mathbf{x}) = (1 \times 1)$

MATLAB allows it as an "overloaded function"
https://en.wikipedia.org/wiki/Function_overloading

Addition

Conformable vectors and matrices are added term by term

$$\mathbf{x} = \begin{bmatrix} a \\ b \end{bmatrix} \quad ; \quad \mathbf{z} = \begin{bmatrix} c \\ d \end{bmatrix}$$

$$\mathbf{x} + \mathbf{z} = \begin{bmatrix} a+c \\ b+d \end{bmatrix}$$

Inner (Dot) Product

Inner (dot) product of vectors produces a scalar result

$$\mathbf{x}^T\mathbf{x} = \mathbf{x} \bullet \mathbf{x} = \begin{bmatrix} x_1 & x_2 & x_3 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$$

$$(1 \times m)(m \times 1) = (1 \times 1)$$

$$= (x_1^2 + x_2^2 + x_3^2)$$

Derivatives and Integrals of Vectors

Derivatives and integrals of vectors are vectors of derivatives and integrals

$$\frac{d\mathbf{x}}{dt} = \begin{bmatrix} dx_1/dt \\ dx_2/dt \\ dx_3/dt \end{bmatrix}$$

$$\int \mathbf{x}\,dt = \begin{bmatrix} \int x_1\,dt \\ \int x_2\,dt \\ \int x_3\,dt \end{bmatrix}$$

$$\mathbf{x}(t) = \begin{bmatrix} 7 \\ 8t \\ 9t^2 \end{bmatrix}; \quad \frac{d\mathbf{x}(t)}{dt} = \begin{bmatrix} 0 \\ 8 \\ 18t \end{bmatrix}$$

$$\mathbf{x}(t) = \begin{bmatrix} 7 \\ 8t \\ 9t^2 \end{bmatrix}; \quad \int \mathbf{x}(t)\,dt = \begin{bmatrix} 7t + x_1(0) \\ 8t^2/2 + x_2(0) \\ 9t^3/3 + x_3(0) \end{bmatrix}$$

MATLAB Code for Math Review

```
%   MAE 345 Lecture 1 Math Review
%   Rob Stengel

    clear
    disp('   ')
    disp('======================================')
    disp('>>>MAE 345 Lecture 1 Math Review<<<')
    disp('======================================')
    disp('   ')
    disp(['Date and Time are ', num2str(datestr(now))]);
    disp('   ')

%   Scalars and Vectors
    a   =   4               %   Scalar
    x   =   [1; 2; 3]       %   Column Vector
    y   =   [4; 5; 6; 7]    %   Column Vector

%   Vector Transpose
    xT  =   x'
    yT  =   y'

%   Multiplication by Scalar
    w   =   a * x
    v   =   x * a
    wT  =   a * xT
```

MATLAB Code for Math Review

```
%   Vector Addition
    zz  =   [8; 9; 10]
    u   =   x + zz

%   Inner (Dot) Product
    zzz =   x' * x

%   Symbolic Toolbox
    disp(' ')
    disp('Symbolic Toolbox')
    disp(' ')
    syms x y z z1 z2 z3 z4

    y   =   x * x       %   Define Function
    z   =   diff(y)     %   Differentiate Function
    z1  =   int(y)      %   Integrate Function

    z2  =   [x; y; z]   %   Column Vector

    z3  =   diff(z2)    %   Derivative of Column Vector
    z4  =   int(z2)     %   Integral of Column Vector
```


MATLAB Command Window Output for Math Review

```
======================================
>>>MAE 345 Lecture 1 Math Review<<<
======================================
Date and Time are 24-May-2013 12:31:13

a =  4

x =
     1
     2
     3

y =
     4
     5
     6
     7

xT = 1     2     3

yT = 4     5     6     7
```

```
w =
     4
     8
    12

v =
     4
     8
    12

wT = 4     8     12

zz =
     8
     9
    10

u =
     9
    11
    13

zzz = 14
```

```
Symbolic Toolbox

y = x^2

z = 2*x

z1 = x^3/3

z2 =
   x
  x^2
  2*x

z3 =
   1
  2*x
   2

z4 =
 x^2/2
 x^3/3
  x^2
```

Next Time: Mobile Robots, Position, and Orientation

Supplemental Material

MAE 345 Course Learning Objectives

- Understanding of the dynamics and control of robotic devices.
- Understanding of cognitive and biological paradigms for system design.
- Ability to estimate quantitatively the behavior of dynamic systems.
- Facility in the application of decision-making concepts, including neural networks, expert systems, and genetic algorithms.
- Familiarity with the components of systems for decision-making and control, such as sensors, actuators, and computers.
- Ability to apply a systems-engineering approach to the analysis, design, and testing of robotic devices.
- Demonstration of computational problem-solving, through thorough knowledge, application, and development of analytical software.
- Appreciation of the historical context within which robotics and intelligent systems have evolved.
- Appreciation of the global and ethical impact of robotics and intelligent systems in the context of contemporary society.
- Competence in presenting ideas orally and in writing.

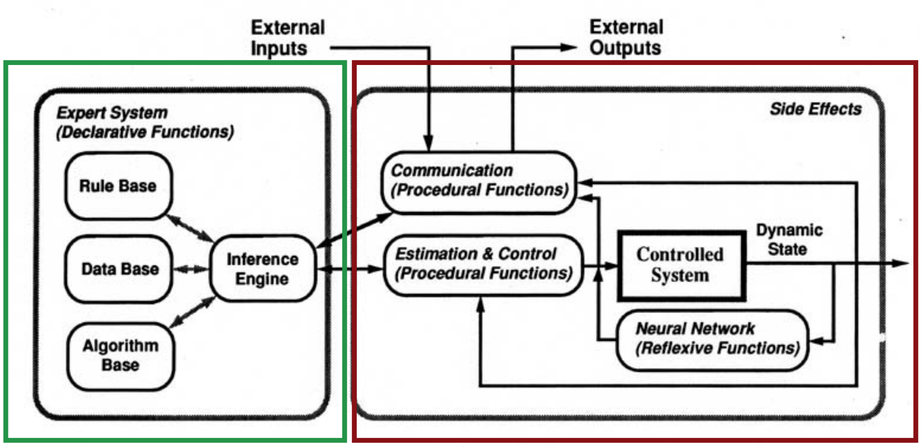
Philosophical Questions about Machine-Intelligent Control

- Must intelligent machines be better than humans?
- Can machines make decisions without human supervision?
- What information should machines display to human operators?
- May machine-intelligent systems make mistakes?
- May intelligent systems gamble when uncertain?
- Can (or Should) intelligent systems exhibit "personality"?
- Can (or Should) intelligent systems express "emotion"?
- Is on-line learning necessary or desirable for machine intelligence?

Knowledge Acquisition, Behavior, Aging, and Control

- Learning Requires Error or Incompleteness
- Biological Adaptation is a Slow Process
- Rest is an Essential Feature
- REM Sleep: Learning, Consolidating, and Pruning Knowledge
- Birth-Life-Death Cycle
- Central Nervous System Does Not Regenerate
- Short-Term Memory Recedes into Long-Term Memory or is Forgotten
- Humans Form Chords of Actions
- "Knee-Jerk" Reactions

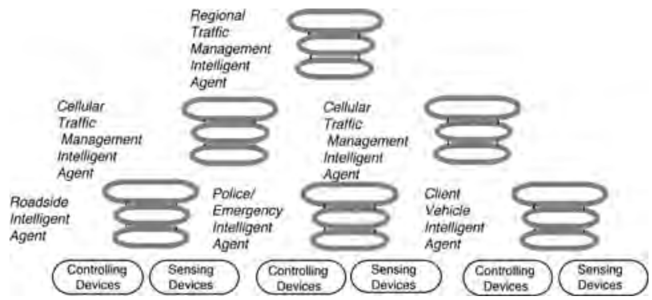
An *Artificial Intelligence* View of Intelligent Control



Declarative Functions		*Expert Systems, Decision Trees*
Procedural Functions	*modeled by*	*Estimation and Control "Circuits"*
Reflexive Functions		*Control Laws, Neural Networks*

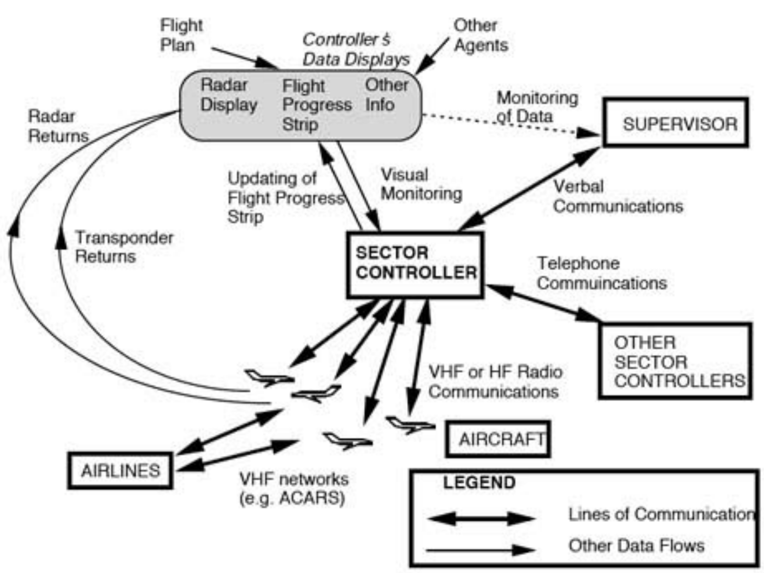
Intelligent Vehicle/ Highway System

- **Taxonomies of Declarative, Procedural, and Reflexive Functions (Chao, 1993)**

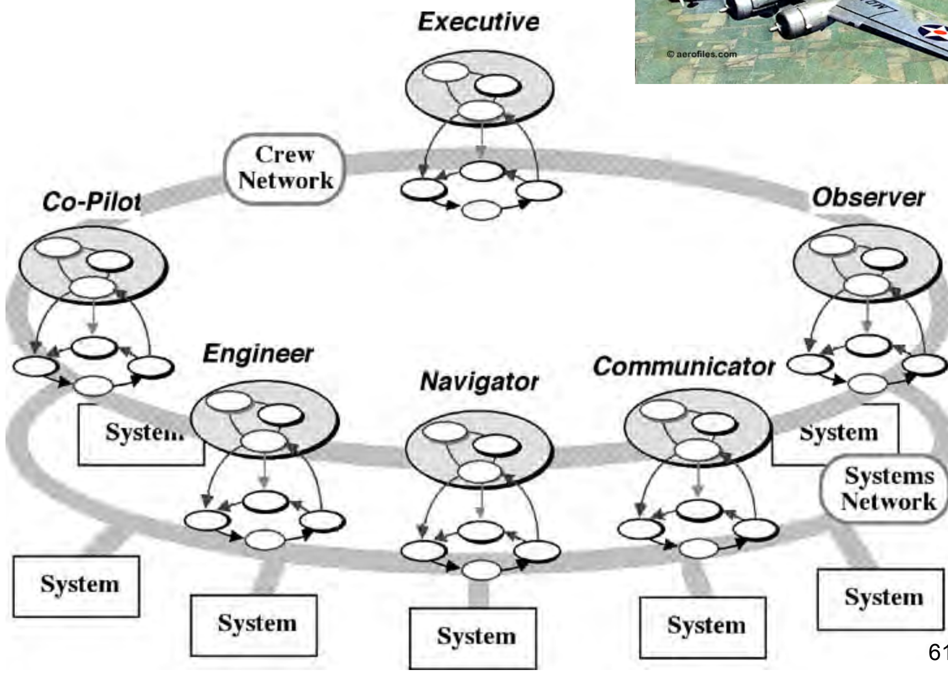


- **Automobile**
  - **Declarative**
    - **Determine Destination**
    - **Traffic Management Advice**
  - **Procedural**
    - **Lane Change**
    - **Transmit Information**
  - **Reflexive**
    - **Steering**
    - **Speed Control**
- **Emergency Management System**
  - **Declarative**
    - **Predict Emergency Scenarios**
    - **Optimize Situation Handling**
  - **Procedural**
    - **Dispatch Emergency Services**
    - **Resolve Specific Incidents**
  - **Reflexive**
    - **Provide Medical Treatment**
    - **Control Traffic at Scene**

Intelligent Aircraft/ Airspace System



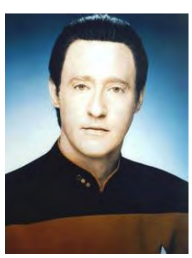
System of Systems



Superheroes, Androids, Gynoids, and Cyborgs

Superman

Androids



Gynoids

Cyborgs

Bionic man and woman