



# Overview

- 1 Definition and A Little History
- 2 Near-Term Challenges (2020-2060)
- 3 Features of Modern Computing
- 4 Urban and Global Applications
- 5 Appendix A: Cyber-Physical Systems
- 6 Appendix B: Engineering Sensor Systems

# Getting Started







# Framing the Opportunity

Systems Perspective:

- Entities in the built environment have both **system structure** and **system behavior** ....

Decision makers use **behavior modeling** to **understand**:

- Sensitivity of systems to model parameter choices.
- Influence of **resource constraints**.
- Potential **emergent** interactions and **propagation** of **cause-and-effect relationships**.
- Identification of parts of the systems that are **vulnerable**.

Cannot play with a real building/city – so a reasonable **first step** is **data-driven building science** in **gaming environments** ...



























# Transition to Information Era

## Metrics of Good Engineering Design:

- A good engineering design **works correctly**, has **good performance**, and is **economical**.
- Functionality and performance are resilient to uncertainties.
- System can be **easily upgraded** to take advantage of **new technologies**.

## Metrics of Good Systems Operation:

A well-run system has “situational awareness” and handles unexpected events:

- **Sense** the **system state** and **surrounding environment**,
- **Look ahead** and anticipate **events**, and
- Take action to control **system behavior**.





# Urbanization and Sustainable Cities

## Urbanization in America:

- In 2010, 82 percent of Americans lived in cities.
- By 2050 it will be 90 percent.

## Cities are responsible for:

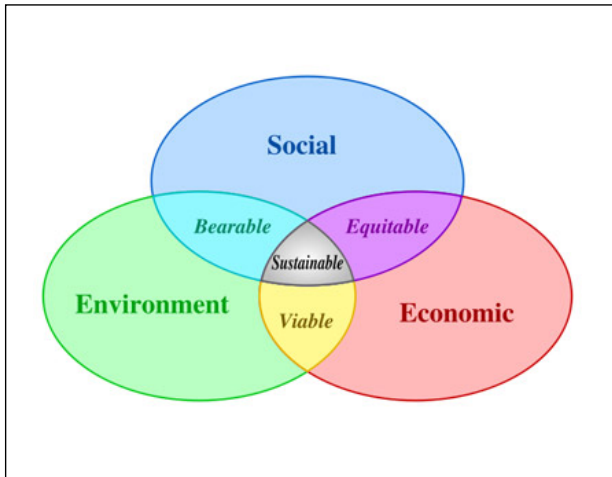
- Two thirds of the energy used,
- 60 percent of all water consumed, and
- 70 percent of all greenhouse gases produced worldwide.

## Sustainable cities (SIEMENS, Sustainable Cities, USA):

- Environmentally friendly infrastructures;
- Improved quality of life for residents;
- Good economics.

# Sustainable Urban Systems

Sustainability involves **physical**, **organizational** and **social** systems.



# Sustainable Urban Systems

Urban systems are like plants in your garden:

- Cities are defined by their **emergent properties** (e.g., beautiful flower  $\Leftrightarrow$  New York City Skyline).
- Cities **grow and flourish** based on societal and economic stimulus, and **fall into decay** when stimulus is absent.

But sustainability is a tough problem:

- Many of the world's large urban areas – so-called **mega-cities** – are in **poor economic shape**.

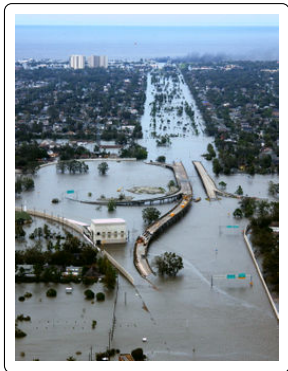
Cities are **system of systems**:

- Subsystems have a preference to **operate** as **independently as possible** from the other subsystems.
- Strategic **collaborations needed** to **limit cascading failures**.

# Resilience of Urban Infrastructure

## **Example.** Cascading Failures in Hurricane Katrina

- Hurricane Katrina caused a storm surge which, in turn, resulted in the failure of levees around New Orleans.
- This is a failure in the waterway network.
- A more conservative (expensive) design might have prevented this failure.
- But the failure didn't stop there.



# Resilience of Urban Infrastructure

## Cascading Failures in Hurricane Katrina:

- **Waterway system failure.** The levees were insufficient to resist the storm surge.
- **Highway and electrical power system failures.** Flooding resulted in failure of the electrical power and highway systems.
- **Federal emergency failures.** Inhabitants had to flee their homes, but few plans were in place for their orderly evacuation.
- **Social network failures.** After the inhabitants left their homes, looters stole property from evacuated properties.
- **Political system failures.** ...



# Planning for Disaster Relief and Recovery

## Lessons Learned

Cascading failures of this type indicate that:

- There is a need to **understand** and **manage interactions** among **infrastructure networks** and **organizational** and **societal factors**.

## Basic Questions

- What kinds of dependencies exist between the networks?
- How will a failure in one network impact other networks?  
These are so-called **cascading failures**.
- What parts of a system are most vulnerable?

We need to look at **interactions between network models**.

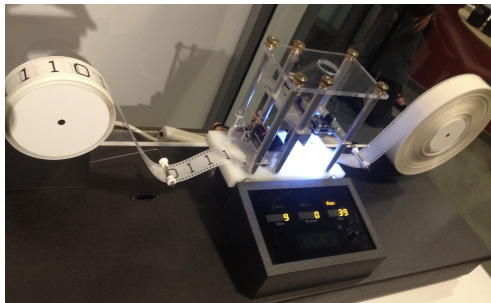




# Early Models of Computing

## Turing Machine Model: 1930s ...

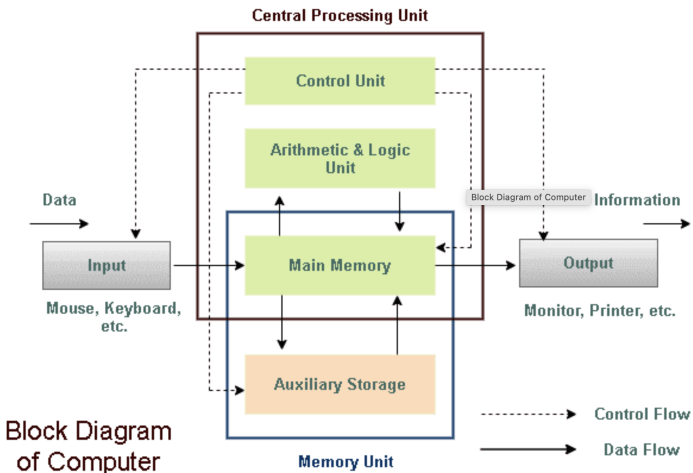
- Alan Turing (1936) created the **Turing machine** that included the **idea** of a **computer program**.



- Turing showed that you can **compute anything** using only **6 primitives**: right, left, print, scan, erase, nothing.

# Early Models of Computing

## Block Diagram of a Computer: 1980s ...



# State-of-the-Art Computing

## What does a modern computer do?

- Performs calculations – **billions** (sometimes even trillions) of **calculations per second**.
- Remembers results – **gigabytes** and terabytes of **storage**.

## Modern Programming Languages

- **Modern programming languages** have a **more convenient set of primitives**.
- Can abstract methods to create new primitives (e.g., user-defined objects).
- **Anything computable in one language** is **computable** in **any other programming language**.

# Man and Machine (Traditional View)

Man	Machine
<ul style="list-style-type: none"><li>● Good at formulating solutions to problems.</li><li>● Can work with incomplete data and information.</li><li>● Creative.</li><li>● Reasons logically, but very slow.</li><li>● Performance is static.</li><li>● Humans break the rules.</li></ul>	<ul style="list-style-type: none"><li>● Manipulates Os and 1s.</li><li>● Very specific abilities.</li><li>● Requires precise descriptions of problem solving procedures.</li><li>● Dumb, but very fast.</li><li>● Performance doubles every 18-24 months.</li><li>● Machines will follow the rules.</li></ul>

# Sensible Problem Solving Strategy

Let engineers and computers play to their strengths:

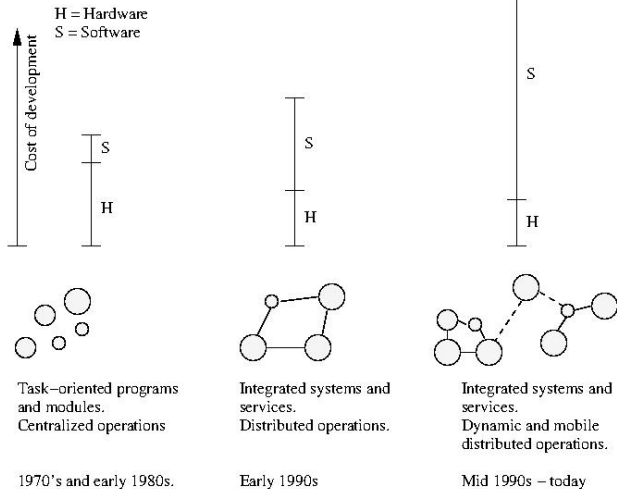
- Accelerates the solution procedure.
- Enables the analysis of problems having size and complexity beyond manual examination.
- Adds value in areas that will lead to long-term economic growth.

**Getting things to work** We need to:

- Describe to the computer solution procedures that are completely unambiguous.
- Look at data, organization and manipulation of data, and formal languages.

# Expanding Expectations of Computing

## Economics of computing and systems development





# Evolution of Computer Languages

**Computer Languages.** Formal description – **precise grammar** – for how a problem can be solved.

**Evolution.** It takes about a decade for significant advances in computing to occur:

Capability	1970s	1980s	1990s
Users	Specialists	Individuals	Groups
Usage	Numerical computations	Desktop computing	E-mail, web, file transfer.
Interaction	Type at keyboard	Screen and mouse	audio/voice.
Languages	Fortran, C	MATLAB	Python, Java

# Popular Computer Languages

Tend to be **designed** for a **specific set of purposes**:

- FORTRAN (1950s – today). Stands for formula translation.
- C (early 1970s – today). New operating systems.
- C++ (early 1970s – today). Object-oriented version of C.
- MATLAB (mid 1980s – today). Stands for matrix laboratory.
- Python (1990s – today). Object-oriented scripting language.
- HTML (1990s – today). Layout of web-page content.
- Java (1994 – today). Object-Oriented language for network-based computing.
- XML (late 1990s – today). Description of data on the Web.

# Post- 2000 Era

**Imagine:** What if COVID-19 had arrived in 2000?

- No iPhone, No iPad, No iTunes.
- No Facebook, No Instagram, No WhatsApp.
- No Google Maps, No Google Streetview.
- No Dropbox, No Zoom.

**Recent Advances in Technology:**

- Average internet speeds: In 2000, 0.07 Mbs; In 2009, 5-7 Mbs; In 2020, 100-200 Mbs; 5G, 1000-2000 Mbs.
- Cloud-based data storage and computational services (AWS).
- New languages: [Swift](#) → App development on [iPhone/iPad](#).
- Many new types of [sensors](#) and [methods of data collection](#).

# Post-2010 Era → Emergence of AI

State-of-the-Art Implementation (2020, Google, Siemens, IBM)

- AI and ML will be **deeply embedded** in new **software and algorithms**.

Artificial Intelligence:

- **Knowledge representation** and **reasoning** with ontologies and rules. Semantic graphs. Executable **event-based processing**.

Machine Learning:

- Modern neural networks. Input-to-output prediction.
- Data mining.
- Identify **objects**, **events**, and **anomalies**.
- Learn structure and sequence. **Remember stuff**.

# Man and Machine (AI-ML View)

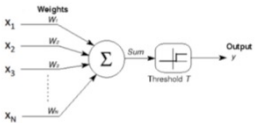
Man	AI-ML Machine
<ul style="list-style-type: none"><li>● Good at formulating solutions to problems.</li><li>● Can work with incomplete data and information.</li><li>● Creative.</li><li>● Reasons logically, but very slow. Forgetful.</li><li>● Performance is static.</li><li>● Humans make the rules, then they break them.</li></ul>	<ul style="list-style-type: none"><li>● Manipulates 0s and 1s.</li><li>● Can work with incomplete data and information.</li><li>● Creative.</li><li>● Fast logical reasoning.</li><li>● Performance doubles every 18-24 months.</li><li>● Data mining can discover the rules.</li></ul>





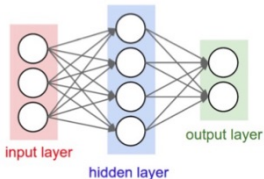
# Machine Learning Capabilities (1980-1990)

## Expressive Power of a Neural Network

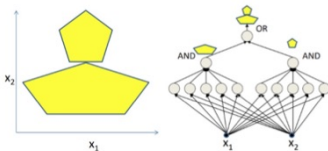
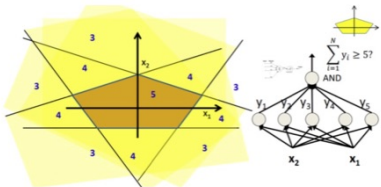


$$y = \begin{cases} 1 & \text{if } \sum_{i=1}^d w_i x_i \geq T \\ 0 & \text{else} \end{cases}$$

## Neural Network with Single Hidden Layer



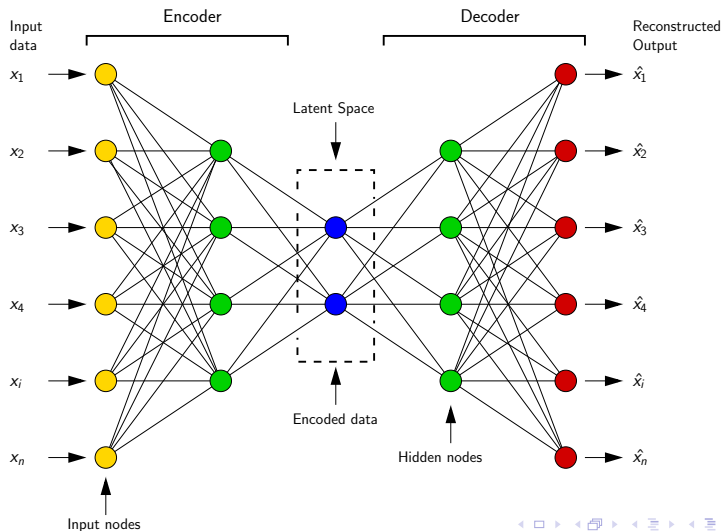
## Approximation of Functions / Boolean Logic





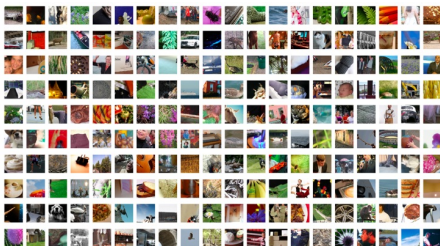
# Classification of Machine Learning Problems

## AutoEncoder (Encoder-Decoder-Reconstruction)



# Classification of Machine Learning Problems

## ImageNet and Deep Learning (2009-present)



## Indexed Database of 14.2 million Images

- Project initiated by Fei Fei Li in 2006
- Image annotation process crowd sourced via Amazon's Mechanical Turk. Categories derived from WordNet.
- Well organized → supervised machine learning.

# Classification of Machine Learning Problems

## ImageNet and Deep Learning Capabilities:

- Identify objects in an image.
- 27 high-level categories; 21,800 sub-categories.



# ImageNet and Deep Learning

## Capabilities (2018):

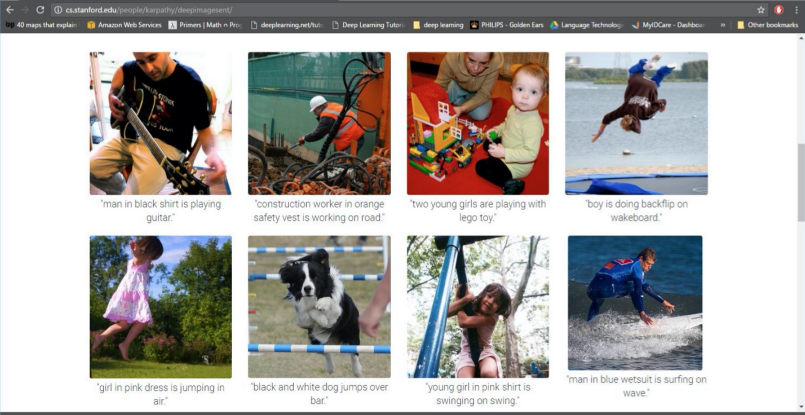
- Identify relationship among multiple objects in a image.

**Example.** Dog riding skateboard



# ImageNet and Deep Learning

## Captions generated by a neural network:



The screenshot shows a web browser window with the address bar displaying 'cs.stanford.edu/people/karpathy/deeplearning/'. The browser tabs include '40 maps that explain...', 'Amazon Web Services', 'Primer | Math - Pro...', 'deeplearning.net/tu...', 'Deep Learning Tutor...', 'deep learning', 'PHILIPS - Golden Ears', 'Language Technology', 'MyiCare - Dashbo...', and 'Other bookmarks'. The main content area displays a 2x4 grid of images with captions generated by a neural network:

- Image 1: A man in a black shirt playing a guitar. Caption: "man in black shirt is playing guitar."
- Image 2: A construction worker in an orange safety vest working on a road. Caption: "construction worker in orange safety vest is working on road."
- Image 3: Two young girls playing with lego toys. Caption: "two young girls are playing with lego toy."
- Image 4: A boy performing a backflip on a wakeboard. Caption: "boy is doing backflip on wakeboard."
- Image 5: A girl in a pink dress jumping in the air. Caption: "girl in pink dress is jumping in air."
- Image 6: A black and white dog jumping over a bar. Caption: "black and white dog jumps over bar."
- Image 7: A young girl in a pink shirt swinging on a swing. Caption: "young girl in pink shirt is swinging on swing."
- Image 8: A man in a blue wetsuit surfing on a wave. Caption: "man in blue wetsuit is surfing on wave."

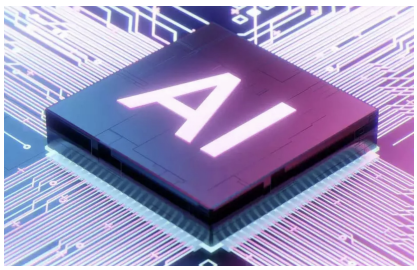
# Machine Learning at Scale

Object-recognition module:

- 24 million nodes; 140 million parameters; 15 billion connections.

Source: Fei Fei Li, TEDTalk, YouTube 2015.

**AI Chips:** Nvidia, Google TPUs, etc ...



# Machine Learning at Scale (Transformers)

## Input

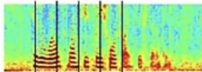
## Output

Pixels:



“leopard”

Audio:



“How cold is it outside?”

“Hello, how are you?”



“Bonjour, comment allez-vous?”

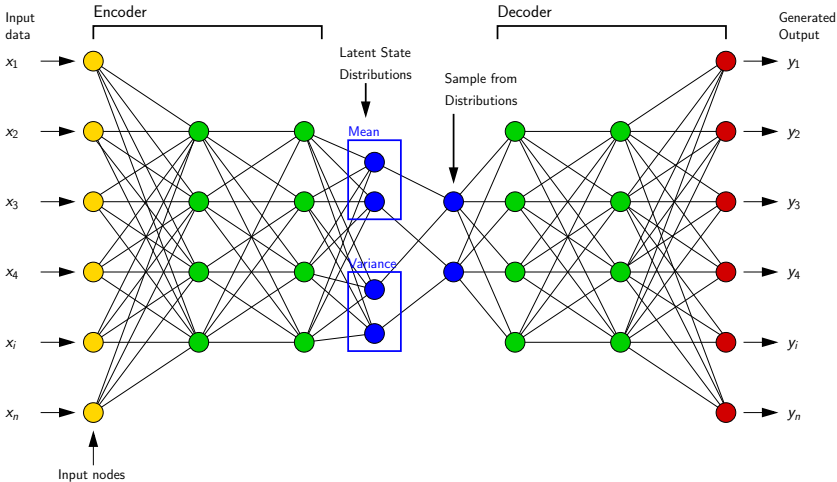
Pixels:



“A cheetah lying on top of a car”

# Post-2020 Era → Explosion of Generative AI

## Variational AutoEncoders (Generative Models)

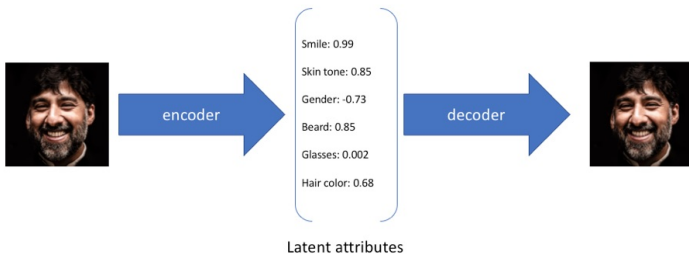


# Post-2020 Era → Explosion of Generative AI

Standard Autoencoders vs. Variational Autoencoders:

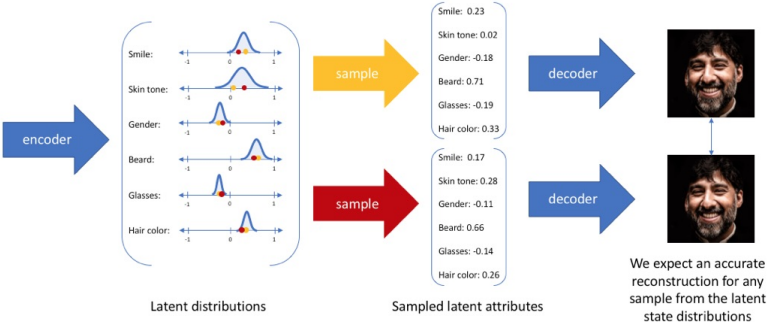
- A **standard autoencoder** outputs a **single value** for each **encoding dimension**.
- **Variational autoencoders** provide a **probability distribution** for each latent attribute.

**Example:** Single value representations for latent attributes:



# Post-2020 Era → Explosion of Generative AI

**Image Reconstruction:** sampled from latent distributions ...



We expect an accurate reconstruction for any sample from the latent state distributions

Source: Jordan J., Variational Autoencoders, Data Science, March 2018.

# Post-2020 Era → ChatGPT

## ChatGPT: Generative Pre-Trained Transformer

AU

write paragraph on civil engineering



Civil engineering is a fundamental discipline that shapes and transforms the physical infrastructure of our modern world. It encompasses the design, construction, and maintenance of a vast array of structures and systems, ranging from buildings, bridges, and roads to water supply networks, sewage systems, and environmental protection facilities. Civil engineers are responsible for ensuring the safety, functionality, and sustainability of these essential structures that support and enhance our daily lives. Their work involves a deep understanding of materials, mechanics, geotechnical engineering, structural analysis, and urban planning. By integrating scientific principles with innovative technologies, civil engineers address societal needs, address challenges posed by urbanization, and contribute to the creation of resilient and efficient urban environments. Whether it's developing eco-friendly infrastructure, earthquake-resistant buildings, or efficient transportation systems, civil engineering remains at the forefront of shaping a better and more connected world.



Regenerate

Send a message



Free Research Preview. ChatGPT may produce inaccurate information about people, places, or facts. [ChatGPT August 3 Version](#)

# Post-2020 Era → ChatGPT

 integrate  $\sin(3x)\sin(2x)$  dx



To integrate the expression  $\int \sin(3x) \sin(2x) dx$ , we can use the product-to-sum trigonometric identity, which states that:



$$\sin(A) \sin(B) = (1/2) [\cos(A - B) - \cos(A + B)].$$

Using this identity, we can rewrite the integral as:

$$\begin{aligned} \int \sin(3x) \sin(2x) dx &= (1/2) \int [\cos(3x - 2x) - \cos(3x + 2x)] dx \\ &= (1/2) \int [\cos(x) - \cos(5x)] dx. \end{aligned}$$

Now, we can integrate each term separately:

$$\int \cos(x) dx = \sin(x) + C_1,$$

$$\int \cos(5x) dx = (1/5)\sin(5x) + C_2.$$

Putting it all together:

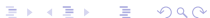
$$\begin{aligned} \int \sin(3x) \sin(2x) dx &= (1/2) [\sin(x) + C_1 - (1/5)\sin(5x) - C_2] \\ &= (1/2) [\sin(x) - (1/5)\sin(5x)] + (C_1/2 - C_2). \end{aligned}$$

So, the integral of  $\sin(3x) \sin(2x)$  with respect to  $x$  is:

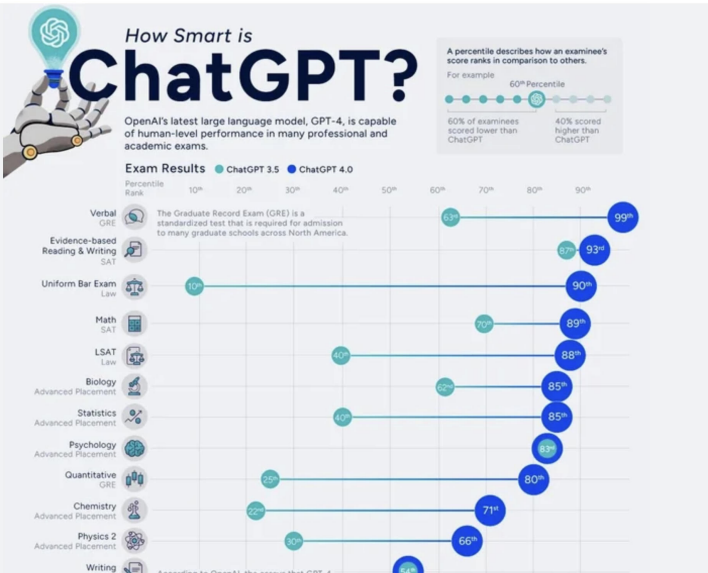
$$\int \sin(3x) \sin(2x) dx = (1/2) [\sin(x) - (1/5)\sin(5x)] + C,$$

where  $C = C_1/2 - C_2$  is the constant of integration.

 Regenerate



# Post-2020 Era → ChatGPT



# Post-2020 Era → AI Generated Architecture

## Convergence of AI and Architecture: (Microsoft Co-Pilot)

Generate beautiful building:



Generate ugly building:



Source: ...

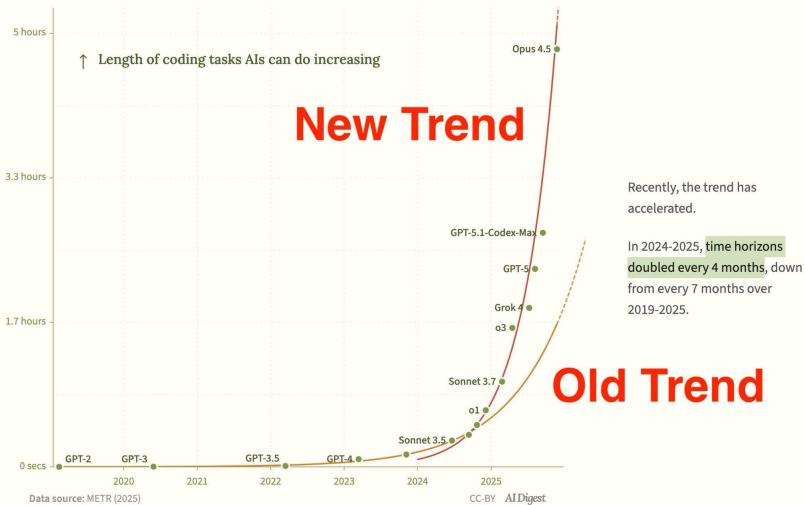
# Post-2020 Era → AI Generated Architecture

## Generate Iconic Building: (Microsoft Co-Pilot)



Source: ...

# Post-2020 Era → AI Code Generation





# Machine Learning in CEE

## Opportunities for Machine Learning in CEE:

- Predicting system response and performance.
- Interpreting data and formulating models to predict component and subsystem-level properties.
- Information retrieval from images and text.
- Recognizing patterns in streams of sensed data.

## Economic Considerations (CS Perspective):

- Urban infrastructure is permanent/semi-permanent and very expensive to build and maintain.
- Prioritize improvements to efficiency by identifying and removing bottlenecks in performance.
- Use AI-ML to identify events, cause-and-effect relationships, and design of actions that enhance system performance.

# AI-ML Enabled Decision Making

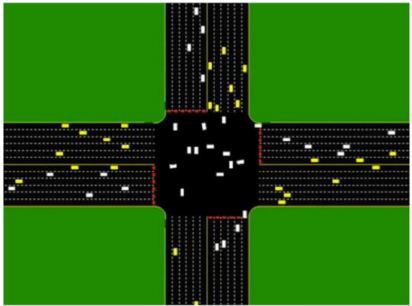
AI Road Maintenance: Detection of cracks in infrastructure:





# AI-ML Enabled Decision Making (Self-Driving Cars)

**Goal.** Improve performance by removing bottlenecks → no human driver; no traffic lights.



**Remark:** 95% of the requirements are for the system software.

**Source:** ISR visitor from GM Research.

**Remark:** Tesla will produce self-driving cars by 2016.

**Source:** Elon Musk.

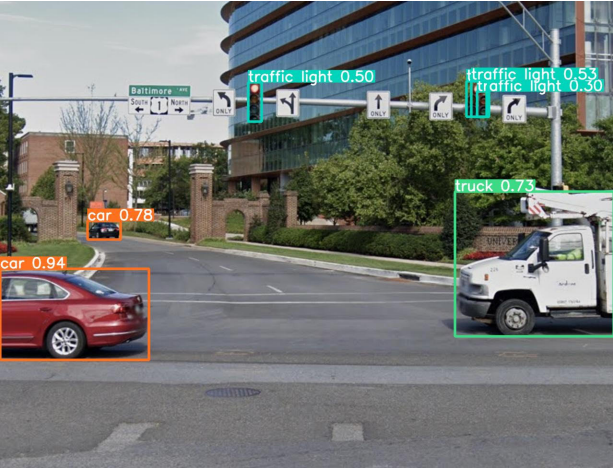
Stop signs and traffic lights are replaced by mechanisms for vehicle-to-vehicle communication (Adapted from <http://citylab.com>).



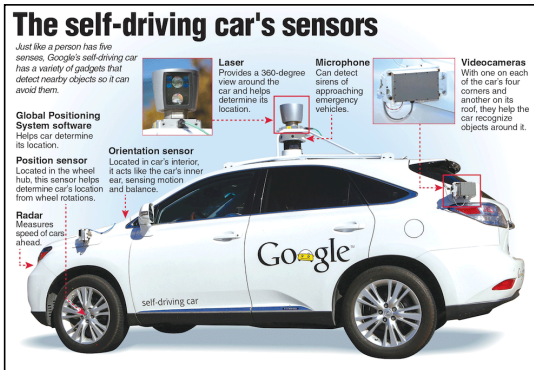


# AI-ML Enabled Decision Making (Self-Driving Cars)

Ainur's Experiments with Computer Vision (OpenCV):



# AI-ML Enabled Decision Making (Self-Driving Cars)



**Today:** Modern automobiles → 100 million lines of software.

**Tomorrow:** Self-Driving automobiles → 200-300 million lines of software.

# AI-ML Enabled Decision Making (Self-Driving Cars)

## Navigating a Busy Traffic Intersection:

<p><b>How the car operates</b></p>		<p><b>How the car sees the world</b></p>
<p>1 Any object the vehicle's sensors spot is interpreted by software to determine if it's a pedestrian, cyclist, vehicle or something else.</p> <p>2 Using what it's learned from previous driving, the software makes predictions about what objects will do next.</p> <p>3 The software analyzes the information to decide whether it is safe to accelerate, turn or hit the brakes.</p>		<p>This computerized image is what Google researchers monitoring sensor data see as they ride in the vehicle.</p> <ul style="list-style-type: none"> <li> Other vehicle</li> <li> Pedestrian</li> <li> Cyclist</li> <li> Objects that warrant caution</li> <li> A crosswalk, indicating the car needs to stop</li> <li> A traffic signal, warning of upcoming railroad tracks</li> <li> Path where Google's car intends to go</li> </ul>
<p>Source: Google Graphic: Tribune News Service</p>		

- Identify various kinds of objects (e.g., vehicles, crosswalk).
- Predict what objects will do next.
- Conduct safety assessment.
- Take action.

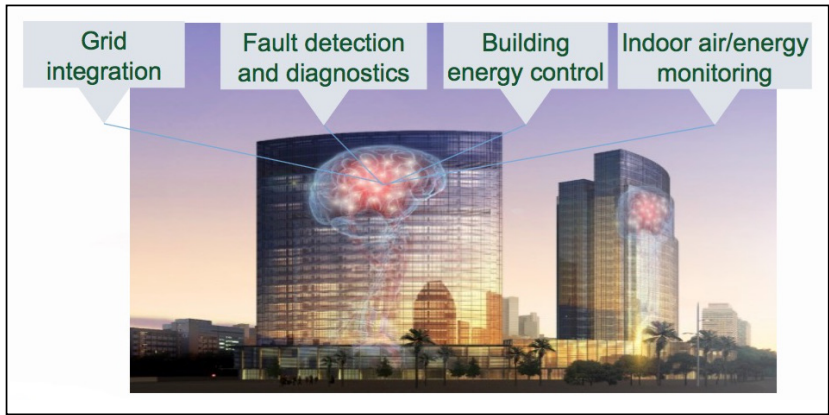


# Urban Applications

How do buildings and cities work?

# Modern Buildings (Vision for Future)

## Buildings that Think! (Work at NIST/UMD 2017)



# Modern Buildings (Key Features)

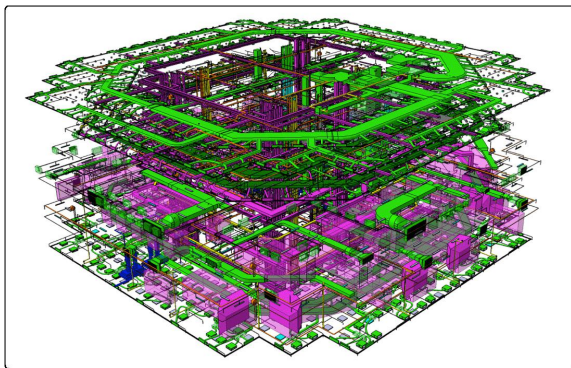
Modern buildings are:

- Advanced, self-contained and tightly controlled environments design to provide services (e.g., transportation, lighting, etc).
- Large size (e.g., 30,000 occupants, thousands of points of sensing and control for air quality and fire protection).
- Many stakeholders; highly multi-disciplinary.
- Buildings have networks for: arrangement of spaces; fixed circulatory systems (power, hvac); dynamic circulatory systems (flows of energy).
- Many sources of heterogeneous data.
- Necessity of performance-based design and real-time management.
- System functionality controlled by software!



# Modern Buildings (Key Features)

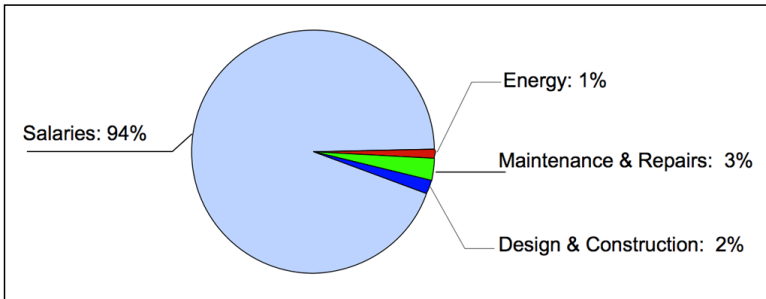
Large-scale building systems are intertwined networks of networks:



Understanding the **relationships among the networks** and their combined behaviors can be **very challenging**.

## Modern Buildings (Economics)

Lifecycle costs in office buildings over a 30-Year period:



Energy systems have a huge impact on building occupant comfort and indoor air quality which, in turn, affects salary performance.

**Source:** United Technologies Research Center, 2009.

## Modern Buildings (Integrated Energy Systems)

Trend toward Integrated Energy Systems:

- Commercial and residential buildings consume 1/3 of the world's energy.
- And by 2025, buildings will consume more energy than the transportation and industrial sectors combined.
- **Standard models** of building operation rely on **centrally produced power** as a source of high-grade energy.
- Advances in technology allow for consideration of alternatives, such as **local production of power**.

Examples:

- Solar power; small-scale combined heat and power systems.
- **Electricity production** through use of **ducted wind turbines**.



# Modern Buildings (Automation Systems Design)

## Systems of Systems Approach to Energy Efficiency Consider Buildings as Composition of Subsystems

Buildings Design  
Energy and Economic  
Analysis

Windows and Lighting

HVAC

Domestic/International  
Policies, Regulation,  
Standards, Markets

Demonstrations,  
Benchmarking, Operations  
and Maintenance



Natural Ventilation,  
Indoor Environment

Networks,  
Communications,  
Performance Database

Sensors, Controls,  
Performance Metrics

Power Delivery and  
Demand Response

Building Materials,  
Misc. Equipment

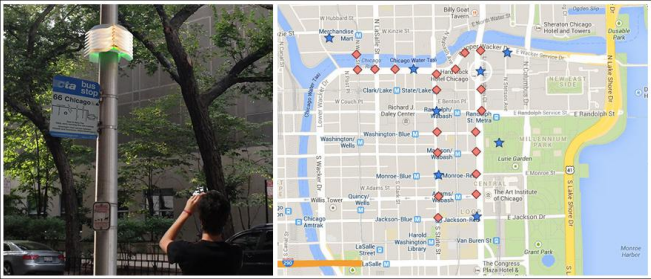
**Integration: The Whole is Greater than the Sum of the Parts**





# Smart Cities: Urban Sensing in Chicago

**Array of Things, Chicago (EOL 2022).** Modular sensor boxes collect real-time data on the environment, infrastructure and activity.



**Basic Questions.** How is the city used? What is going on?

Source: <https://arrayofthings.github.io>

# Smart Cities: Urban Sensing in Chicago

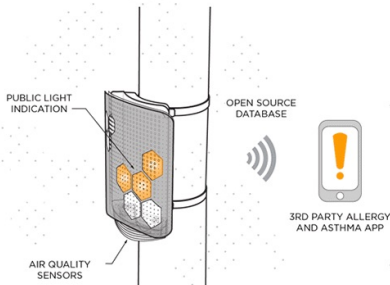
## What Data is Collected?

The nodes will initially measure temperature, barometric pressure, light, vibration, carbon monoxide, nitrogen dioxide, sulfur dioxide, ozone, ambient sound intensity, pedestrian and vehicle traffic, and surface temperature. Continued research and development will help create sensors to monitor other urban factors of interest such as flooding and standing water, precipitation, wind, and pollutants.

Array of Things is interested in monitoring the city's environment and activity, not individuals. In fact, the technology and policy have been designed to specifically avoid any potential collection of data about individuals, so privacy protection is built into the design of the sensors and into the operating policies. Array of Things will not collect any personal or private information.



# Smart Cities: Urban Sensing in Chicago



## What Can be Done with this Data?

Potential applications of data collected by the Array of Things include:

- Sensors monitoring air quality, sound and vibration (to detect heavy vehicle traffic), and temperature can be used to suggest the healthiest and unhealthiest walking times and routes through the city, or to study the relationship between diseases and the urban environment.
- Real-time detection of urban flooding can improve city services and infrastructure to prevent property damage and illness.
- Measurements of micro-climate in different

areas of the city, so that residents can get up-to-date, high-resolution "block-by-block" weather and climate information.

- Observe which areas of the city are heavily populated by pedestrians at different times of day to suggest safe and efficient routes for walking late at night or for timing traffic lights during peak traffic hours to improve pedestrian safety and reduce congestion-related pollution.

# SONYC: Sounds of New York City

**SONYC.** A system for monitoring, analysis and mitigation of urban noise pollution.



**Motivation.** Over 70 million people in US are exposed to noise levels beyond the limit of EPA considers to be harmful.

**Short-term Problems.** Sleep disruption.

**Long-term Problems.** Hypertension, heart disease, hearing loss.







# NASA's Earth Observing System

## NASA'S EOSDIS PROGRAM

### NASA / Hughes Contract in 1993

- Project planning begins in 1989.
- Proposal submitted July 1, 1991.
- Contract awarded 1992.
- \$600 million to design and building the infrastructure for a global data and information system that can handle petabytes ( $2^{50}$  bytes) of data.
- 13 participating countries: USA, Canada, Japan, etc.
- Data collection and information processing: 1995 – 2015.



### Big Science Questions:

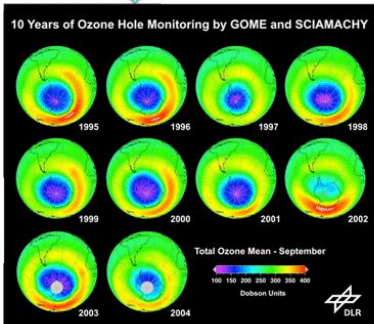
- How is the Global Earth System changing?
- What are the primary factors that influence change?
- How does the Earth System respond to natural and human-induced actions?
- What are the consequences of change in the Earth Systems for humans?
- How will the Earth System change in the future?

# NASA's Earth Observing System

## NASA'S EOSDIS → RE-NAMED EOS IN 2000



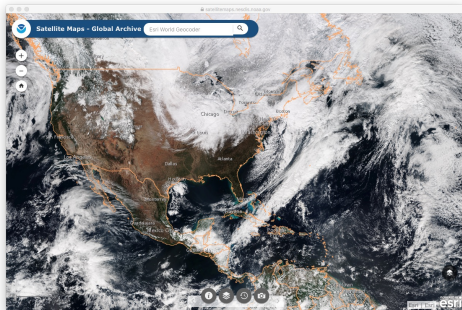
Enables science



Drives innovation

# Satellite Imagery and Measurements

## Understanding Climate Change



**Example.** Measure spatial and temporal extent of annual Snow Pack → Estimate water resources available for agriculture and urban consumption.

# California Wildfires force Evacuations







# Summary



# Key Points for Building Better Systems

## Looking Forward

Use sensing and software to build better systems:

- Improve **situational awareness** – to understand what is actually happening a building or city?
- Connect **sensor measurements** to short- and long-term **urban needs** (e.g., decisions on a bus stop; longer term urban planning).
- Capture the **spatial**, **temporal**, and **intensity** aspects of environmental phenomena (e.g., fires, flooding) and their **impact** on natural (e.g., air quality) and **man-made systems** (e.g., transportation networks, food chains).
- **Look ahead** and **forecast future states** of the system?

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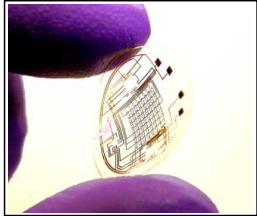
# Appendix A: Cyber-Physical Systems

## General Idea

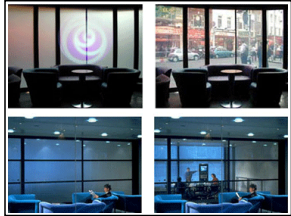
Embedded **computers** and networks **monitor and control** the **physical processes**, usually with **feedback loops** where **computation affects physical processes**, and vice versa.

## Two Examples

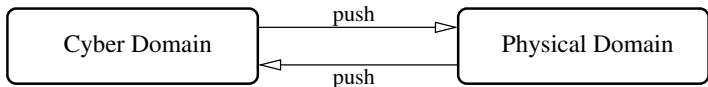
Programmable Contact Lens



Programmable Windows



# Cyber-Physical Systems Overview



## C-P Structure

Cyber capability in every  
physical component  
Executable code  
Networks of computation  
Heterogeneous implementations

Spatial and network abstractions  
-- physical spaces  
-- networks of networks  
Sensors and actuators.

## C-P Behavior

Dominated by logic  
Control, communications  
Stringent requirements on timing  
Needs to be fault tolerant

Physics from multiple domains.  
Combined logic and differential equations.  
Not entirely predictable.  
Multiple spatial- and temporal- resolutions.









# Cyber-Physical Systems (Error-Free Software)

Embedded computer systems and software need to deliver functionality that is **correct** and **works with no errors**.

CPS Design Requirements:

- **Reactivity**: System response need to occur within a known **bounded range and delay**.
- **Autonomy**: Systems need to provide **continuous service** without human intervention.
- **Dependability**: Systems need to be **resilient to attack** and **hardware/software failures**.
- **Scaleability**: System **performance** needs to **scale** with supplied **resources**.

Software for **smart electronic devices** is how **Java got started !!!**

# Causes of Software-Related Accidents

## Modern Software

Modern software is simply the **design of a machine** abstracted from its physical realization.

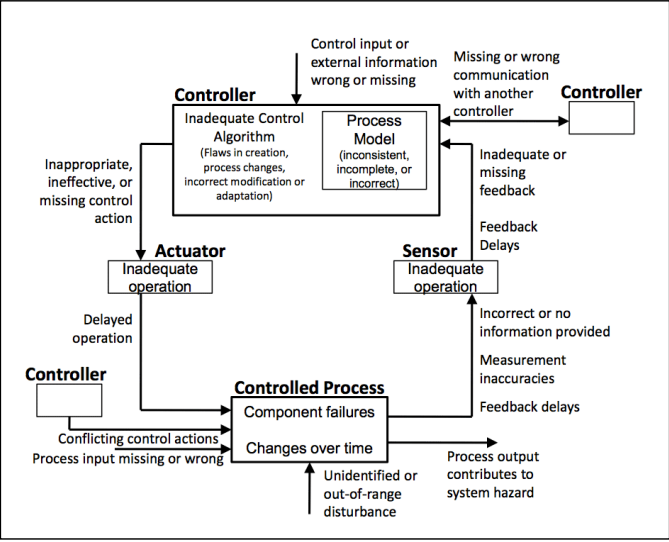
## Software Accidents

**Software accidents** are usually **caused** by **flawed requirements** and **not** standard **wear-out failures**.

This includes:

- Incomplete (or wrong) assumptions about the operation of the controlled system or required operation of the software.
- Unhandled control system states and environmental conditions.

# Engineering Sensor Systems (Error-Free Software)





# Appendix B: Engineering Sensor Systems

## General Opportunities for Sensing

- Enhanced levels of **attainable performance** ...
- Create **new** forms of **functionality** ...
- Improved **economics** and **operational efficiency** (energy consumption).
- Improved **resilience** and **agility** ...

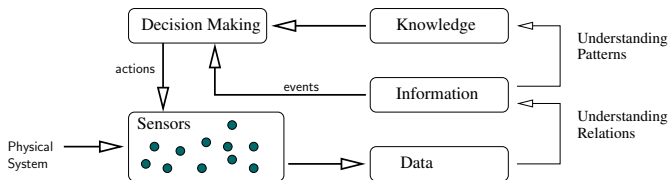
## Sensing in the Built Environment

- We need sensors to serve as the **eyes** and **ears** of **control and information systems** designed to make buildings and cities more efficient and environmentally sensitive.

But how will such a system work?

# Engineering Sensor Systems

## Abstract Model for Sensor System Operations (Simplified!)



## Implementation Options

- **Human** responsible for sensing and control.
- **Automation** (hardware and software) responsible for sensing and control.
- **Human and automation systems cooperate** in sensing and control.



# Engineering Sensor Systems

## Instrumented Systems:

Basic premise:

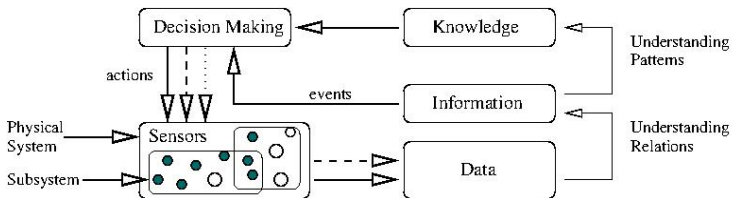
- Advances in **computing, sensing, and communications** technologies will allow for **new types of systems** where **human involvement** is **replaced** (or partially replaced) by **automation**.

## Examples:

- Autofocus camera,
- Electronic systems in automobiles and planes → self-driving cars.
- Structural health monitoring / building automation systems.

# Engineering Sensor Systems

Sensor networks and frameworks for decision making:

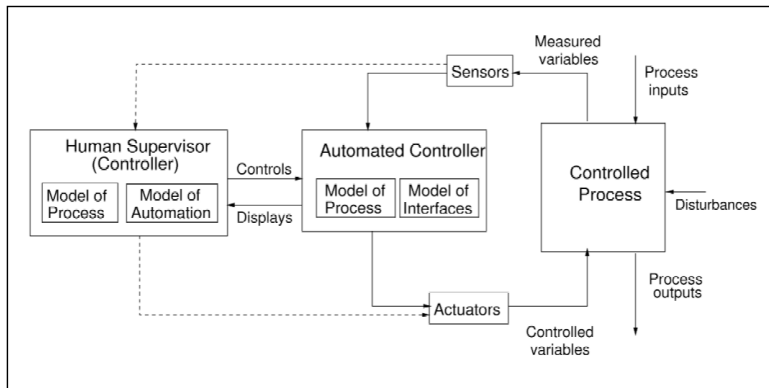


Chain of dependency relationships:

1. improved performance  $\leftarrow$  actions
2. actions  $\leftarrow$  ability to identify events.
3. identify events  $\leftarrow$  data processing
4. data processing  $\leftarrow$  types and quality of data
5. types and quality of data  $\leftarrow$  sensor design and placement.

# Engineering Sensor Systems

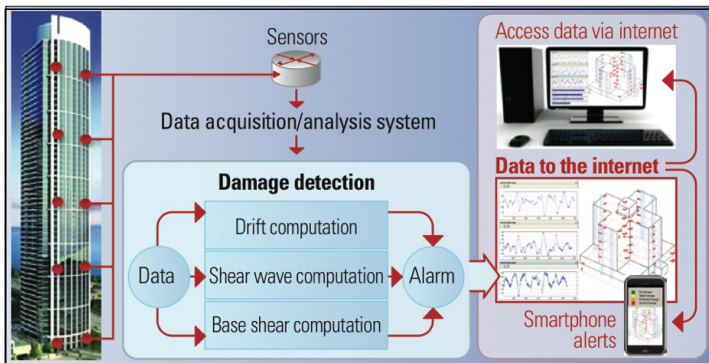
## Human-in-the-Loop and Automated Control:



Source: Leveson, 2006.

# Real-World Application (Structural Health Monitoring)

Flowchart of activities for real-time monitoring of instrumented buildings.



Source: <http://earthquake.usgs.gov/monitoring/buildings/>



