Introduction to Civil Information Systems

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Overview

Modern Civil Infrastructure Systems

Modern Civil Infrastructure Systems

Various Sources (Google, ScienceDirect):

- Civil Infrastructure Systems provide for human activity, ranging in scale from buildings to cities.
- Includes supporting infrastructure: water supply networks; energy networks; transportation systems, communication systems.

Support Human Needs:

- Basic: Access to clean air and clean water.
- Health: Access to good medical services.
- Economic: Affordable low maintenance housing.
- Security: Protections against crime, environmental attack.

Modern Civil Infrastructure Systems

- Transportation: Good roads; parking; fast access to work.
- Educational: Access to good schools.
- Green Spaces: Access to parks, bike paths, etc.
- Retail: Access to shopping; reliable supply chains.
- Lifestyle: Access to social and recreational spaces.

Urban Planning and Engineering Concerns:

- Understand short- and long-term planning needs.
- Efficiency in design – aesthetically pleasing design.
- Efficiency in operations – better use of limited resources.
- Improved response to unexpected events.

Framing the Opportunity

We seek:

- Data-driven approaches to measurement of performance in the building environment and identification of trends and patterns in behavior.
- Solutions that account for unique physical, economic, social and cultural characteristics of individual cities.

Sources of Complication:

- Multiple domains; multiple types of data and information.
- Network structures that are spatial and interwoven.
- Behaviors that are distributed and concurrent.
- Many interdependencies among coupled urban subsystems.

Framing the Opportunity

Systems Perspective:

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

Decision makers use behavior modeling to understand:

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

Framing the Opportunity

Premises of ENCE688R:

- Modern civil infrastructure systems can be modeled as graphs and networks – sometimes they are intertwined networks of networks – that will dynamically respond to events.
- These systems grow and fourish based on societal and economic stimulus, and fall into decay when stimulus is absent.
- Advances in computer software, sensing, and networking technologies can work together to expand the functionality and performance of systems.

Long-Term Need:

- To understand and manage interactions among infrastructure networks and organizational and societal factors.

A Little History

Pathway Forward $\rightarrow$ Look to the Past

What is Civil Engineering?

Civil Engineering deals with (Civil Engineering, Wikipedia) ...

.

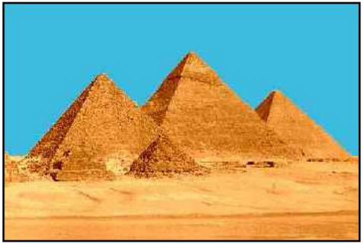
.. the design, construction, and maintenance of the physical and naturally built environment, including roads, bridges, canals, dams, and buildings.

After military engineering, civil engineering is the oldest engineering profession.

Goals during Early Civilization (4000 BC – 6000 BC)

- Problems of survival and basic systems were solved.
- Design and construction methods evolved.

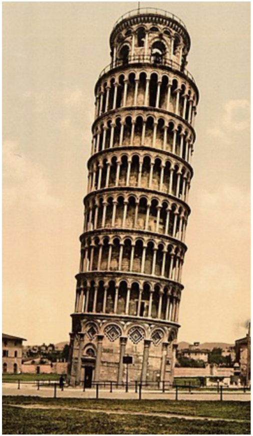
Exemplars of Early Work



- Great Pyramid of Giza, Egypt (20 year construction; finished 2556 BC).
- The Parthenon in Ancient Greece (447-438 BC).
- Construction of the Great Wall of China (220 BC).
- The Romans developed civil structures throughout their empire, including especially aqueducts, insulae,

Exemplars of Early Work

Leaning Tower of Pisa (12th Century)



- Designed to be the tallest bell tower in Europe.
- Construction: Three stages over 199 years (1173-1372).
- Constructed from white marble.
- Tower leans because of weak unstable subsoil.
- It once leaned at 5.5 degrees.
- Currently leans at 3.99 degrees.
- Has survived 4 earthquakes –ironically, weak subsoil conditions work to protect Pisa from ground accelerations.

Industrial Revolution

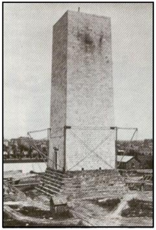
Fast forward to the Industrial Revolution: (1760 – 1840).

Year	Milestone
1692	Languedoc Canal. 240 miles long. 100 locks.
1708	Tull's mechanical seed sower → large-scale planting.
1765	Spinning jenny/wheel automates weaving of cloth.
1775	Watt's first efficient steam engine.
1801	Robert Trevithick demonstrates a steam locomotive.
1821	Faraday, electro-magnetic rotation → electric motor.
1834	Babbage analytic engine → forerunner of the computer.
1903	Wright brothers make first powered flight.
1908	Henry Ford mass-produces the Model T.

Industrial Revolution

Advances in Civil Engineering

Year	Milestone
1854	Bessemer invents steel converter.
1849	Monier develops reinforced concrete.
1863	Siemens-Martin makes steel available in bulk.



The Eiffel Tower - April 1888

Industrial Revolution

Industrial Revolution Actually Changed the World!

Characteristics	**Stage 1 Mechanical Era**	**Stage 2 Electrical Era**
Onset in the U.S.	Late 1700s.	Late 1800s.
Economic Focus	Agriculture/Mining	**Manufacturing**
Productivity Focus	Farming	Factory
Underlying Technologies	**Mechanical Tools**	**ElectroMechanical**
Product Lifecycle	Decades	Years
Human Contribution	Muscle Power	Muscle/Brain Power
Living Standard	Subsistence	**Quality of Goods**
Geographical	Family/Locale	Regional/National

Skyscrapers

- New materials → design of tall structures having large open interior spaces.
- Elevators (1857) → vertical transportation building occupants.
- Mechanical systems → delivery of water, heating and cooling.
- Collections of skyscrapers → high-density CBDs/commuter society.

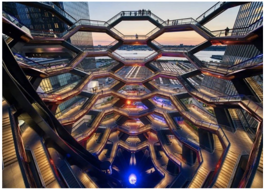
Skyscrapers → High-Density Urban Development

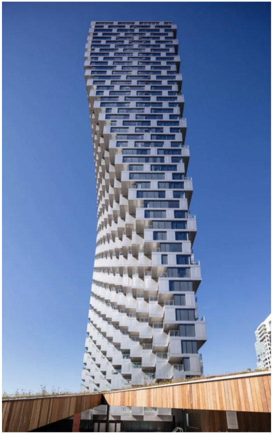
Urban Development in NYC

Urban Development in Shanghai

Advances in Computing and Analysis

Emergence of New Architectural Forms





Advances in Computing and Analysis

Parametric Architectural Design

Advances in Computing and Analysis

Convergence: Engineering-Architecture-AI

AI-generated art ...

AI-generated building architecture

Near-Term Challenges

Civil Engineers need to create the infrastructure for citizens of the Information Era

Crisis in US Infrastructure Investment

Exemplars of Work from the 1800s and 1900s

From the 1800s	From the 1900s
Erie Canal (1825)	New York City Subway (1904)
Transcontinental Railroad (1869)	The Panama Canal (1914)
Brooklyn Bridge (1883)	Holland Tunnel (1927)
Washington Monument (1884)	Empire State Building (1931).
	Hoover Dam (1936).
	Golden Gate Bridge (1937)
	Interstate Highway System (1956)

Source: Celebrating the Greatest Profession, Magazine of the American Society of Civil Engineers, Vol. 72, No. 11, 2002.

Crisis in US Infrastructure Investment

Universal Observations:

- Aging infrastructure becomes expensive to maintain.
- New (replacement) infrastructure is very expensive.
- Politicians are eager to talk up Infrastructure Investment , but slow to deliver ….

Bottom line:

- Critical infrastructure is taken for granted and not a national priority (ASCE, IEEE).

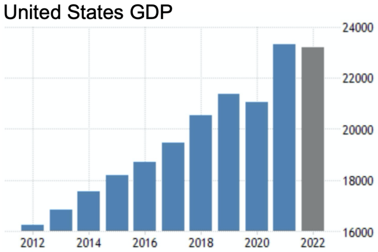
Delay, delay, delay ….

Bangkok, Thailand

Crisis in US Infrastructure Investment

Statistics:

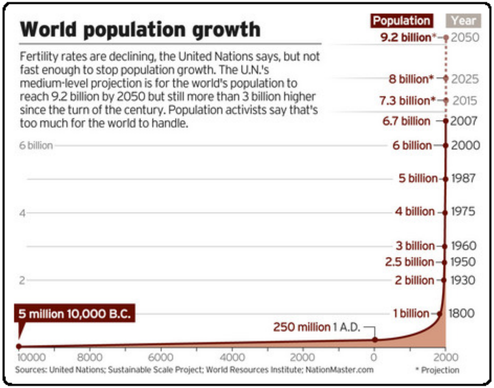
- US: Post World-War II (1950-1970): 3% of Gross Domestic Product (GDP)
- US: 1980-present: 2% of GDP.
- China: 5% GDP.
- India: 9% GDP.



Infrastructure Investment and Jobs Act (2021).

- Invest $1.2T over 10 years.
- Sounds like a lot – but is it too low, too high?
- Increases investment by 0.5% of GDP.

World Population Forecasts



Increasing Population → Increased Demand on Limited Resources
→ Increasing need for Improvements to System Efficiency.

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:

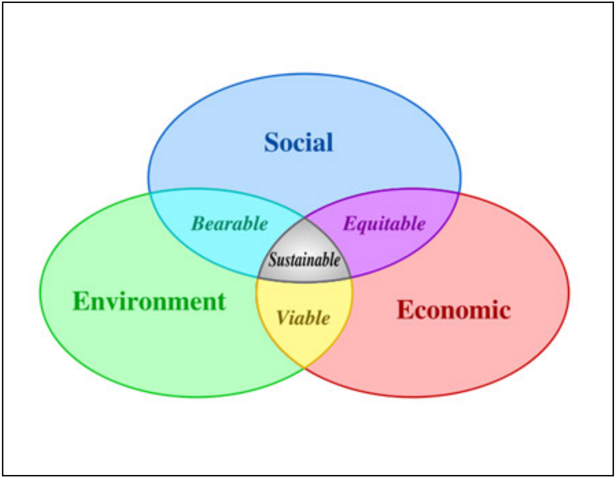
- Two thirds of the energy used,
- 60 percent of all water consumed, and
- 70 percent of all greenhouse gases produced worldwide.

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 ⇔ New York City Skyline).
- Cities grow and fourish 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.

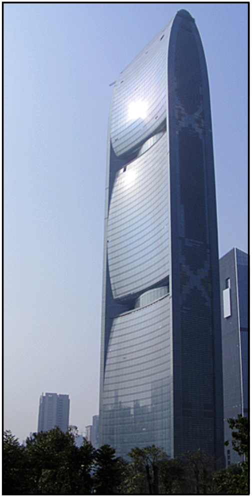
Cities are system of systems:

- Subsystems have a preference to operate as independently as possible from the other subsystems.
- Strategic collaborations needed to raise levels of attainable performance and limit cascading failures.

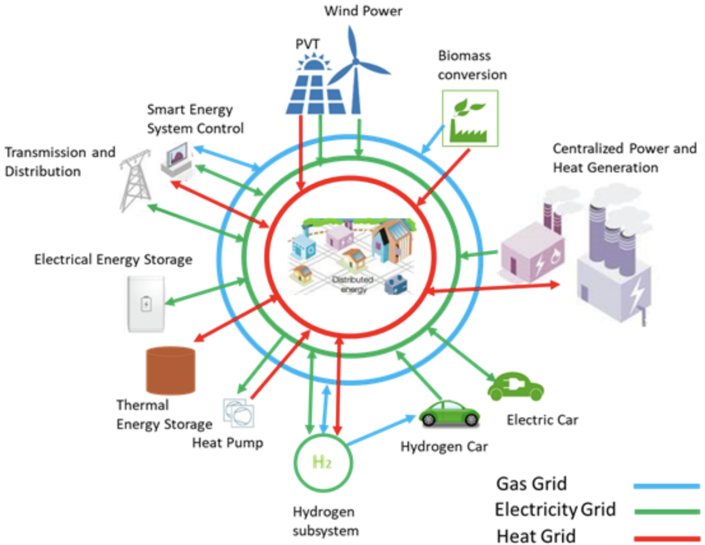
Integrated Energy Systems

Pearl River Tower (2010):

- High performance structure designed to produce as much energy as it consumes.
- Guides wind to a pair of openings at its mechanical floors.
- Wind drives turbines that generate energy for the heating, ventilation and air conditioning systems.
- Openings provide structural relief, by allowing wind to pass through the building.



Integrated Energy Systems (Proposed)



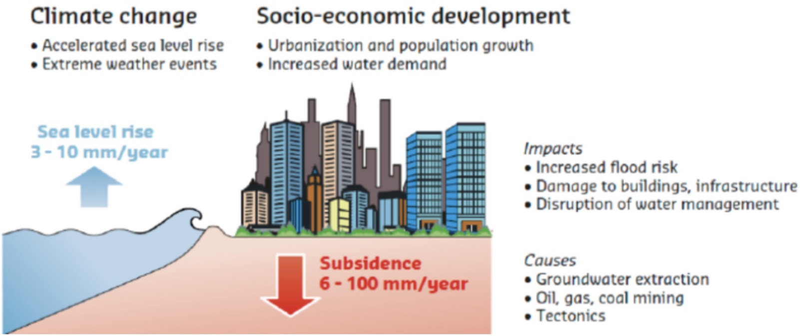
Infrastructure Protection and Recovery

New Threats to Urban Infrastructure

Coastal Cities are Sinking: (St. Mark's Square, Venice, Italy)

New Threats to Urban Infrastructure

Coastal Cities are Sinking: (within the US too ...)



Statistics: New Orleans, 2 inches per year; Houston, 0.8 inches per year; Miami, 12 inches in the past 100 years. Virginia Beach, 12 inches in the past 50 years.

Resilience of Urban Infrastructure

Example. Cascading Failures in Hurricane Katrina

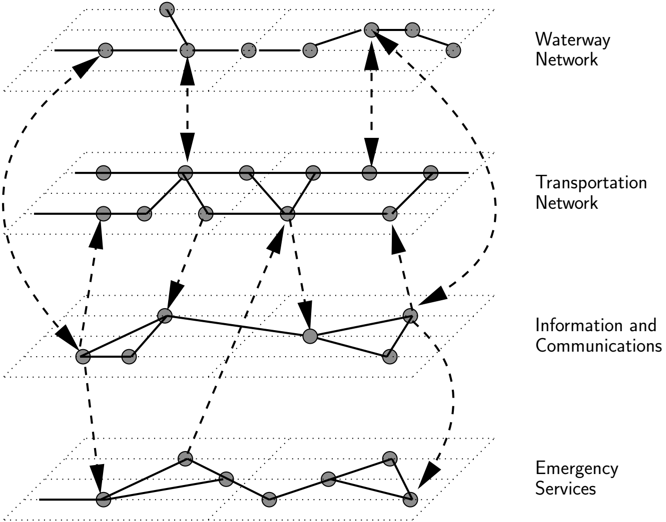
- Hurricane Katrina caused a storm surge which, in turn, resulted in the failure of levees around New Orleans.
- This is a failure in the waterway network.
- A more conservative (expensive) design might have prevented this failure.
- But the failure didn't stop there.

Resilience of Urban Infrastructure

Cascading Failures in Hurricane Katrina:

- **Waterway system failure.** The levees were insufficint 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.** Inhabits 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.** ...

Dependencies Among Urban Networks



Planning for Disaster Relief and Recovery

Lessons Learned

Cascading failures of this type indicate that:

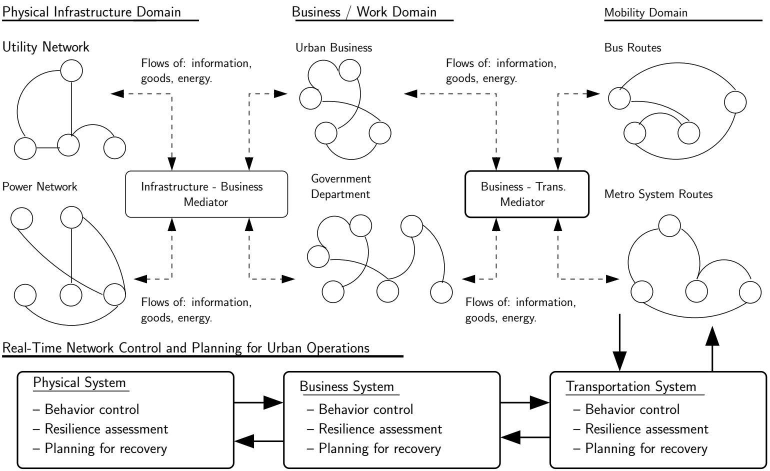
- There is a need to understand and manage interactions among infrastructure networks and organizational and societal factors.

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.

Near-Term View of Assessment & Planning for Recovery



Near-Term View of Assessment & Planning for Recovery

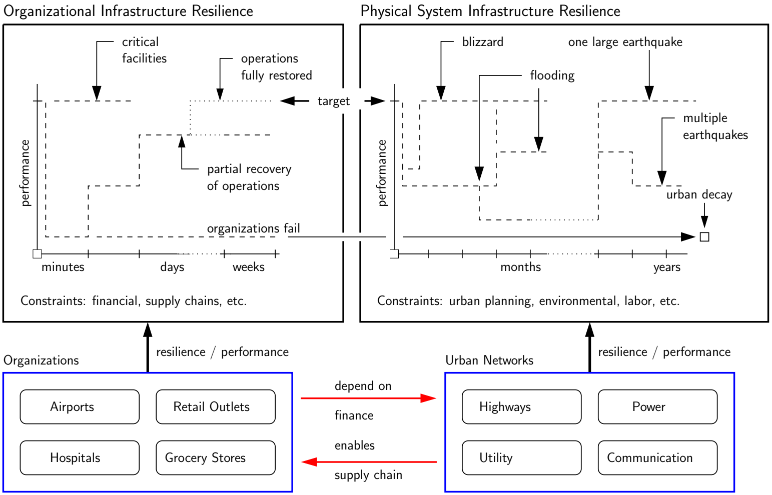
Key Characteristics

1. Networks are heterogeneous, interwoven, dynamic.
2. Disciplines want to operate independently in their domain.
3. Achieving target levels of performance and correctness of functionality requires that disciplines coordinate activities at key points in the system operation.
4. Disturbance in one system can impact other networks in ways that are unexpected.
5. Information exchange establishes common knowledge among the decision making agents. Better system management!

Key Challenge in Distributed System Control

1. How should decision makers cooperate to achieve system-wide performance and management objectives?

Longer-Term View of Infrastructure Resilience



Planning for Protection and Recovery

Critical Role of Sensing:

- Need situational awareness to understand what is actually happening (or about to happen) in a city.
- Sense 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).

Goal and Approach:

- Connect measurements and behavior modeling to planning of protection mechanisms and relief actions.
- Create warning systems that can look ahead and predict likely future states of the urban system.
- Use ML to identify events and cause-and-effect relationships. Use AI for distributed system behavior modeling.

Transition to Information Era

Post- Industrial Revolution (Mid-1900s)

New types of systems – planes, trains and automobiles – rely on human involvement as a means for sensing and controlling behavior, e.g.,

- Driving a car,
- Manual collection of road tolls,
- Traffic controllers at an airport,
- Manual focus of a camera.

Systems work, but:

- Humans are slow.
- Humans make mistakes.
- They also easily tire.

Transition to Information Era

Since 1990 we have been in an Information Era

Characteristics	**Stage 2 Electrical Era**	**Stage 3 Information Era**
Onset in the U.S.	Late 1800s.	**Late 1900s.**
Economic Focus	Manufacturing	Services
Technologies	ElectroMechanical	**Information**
Product Lifecycle	Years	Months
Living Standard	Quality of Goods	**Quality of Life**
Geographical Impact	Regional/National	**Global**

Design of Information-Age Systems

Premise of Information-Age System Design:

- Advances in computer software, sensing, and wireless networking technologies can work together to expand the functionality and performance of systems.

Trend toward Automation:

- New types of systems where human involvement for management of system functionality is replaced (or partially replaced) by software automation.

Civil Engineering Applications:

- Automated road toll collection (Rt. 200).
- Automated baggage handling systems at airports.

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.

Features of Modern Computing

Key Question: How can we use modern computing technologies to improve Civil Engineering Systems?

Man and Machine (Traditional View)

Man	Machine
• Good at formulating solutions to problems. • Can work with incomplete data and information. • Creative. • Reasons logically, but very slow. • Performance is static. • Humans break the rules.	• Manipulates Os and 1s. • Very specific abilities. • Requires precise decriptions of problem solving procedures. • Dumb, but very fast. • Performance doubles every 18-24 months. • Machines will follow the rules.

Sensible Problem Solving Strategy

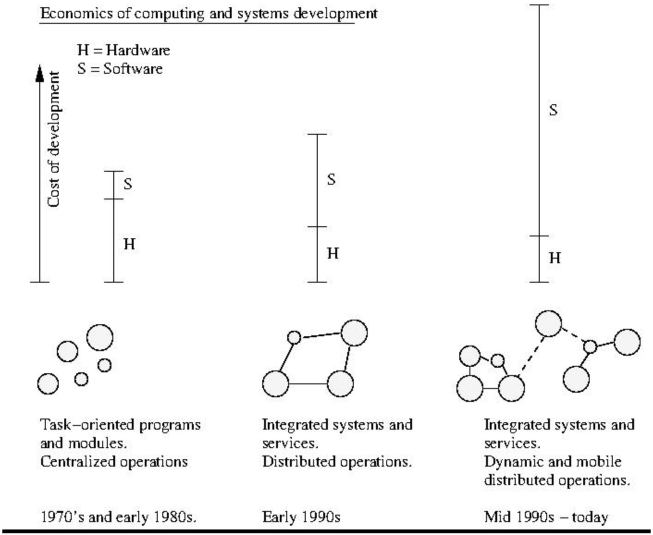
Let engineers and computers play to their strengths:

- 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:

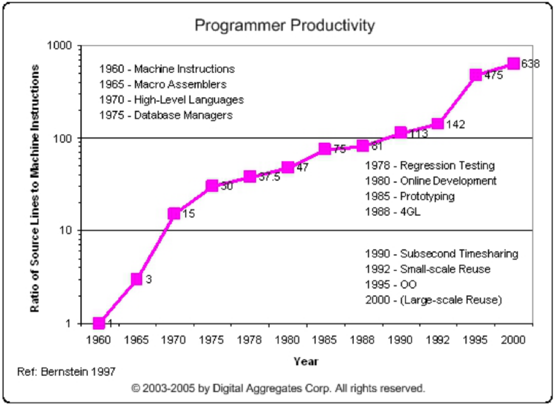
- Describe to the computer solution procedures that are completely unambiguous.
- Look at data, organization and manipulation of data, and formal languages.

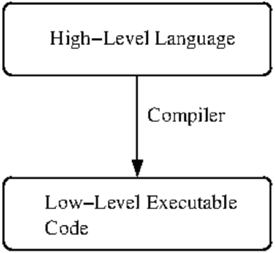
Expanding Expectations of Computing



Pathway to Improved Programmer Productivity

Increasing System Complexity: Software programmers need to find ways to solve problems at high levels of abstraction.





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	HTML, 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). A great 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 $\rightarrow$ App development on iPhone/iPad.
- Many new types of sensors and methods of data collection.

Post- 2000 Era

New Computing Infrastructure → New Architectures, Languages, ...

Capability	2000-present	2020-2030
Users	Groups of people, sensors and computers.	Integration of the cyber and physical worlds.
Usage	Mobile computing. Control of physical systems. Social networking.	Embedded real-time control of physical systems.
Interaction	Touch, multi-touch, proximity.	....
Languages	XML, RDF, OWL.	New languages to support time-precise computations.

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:

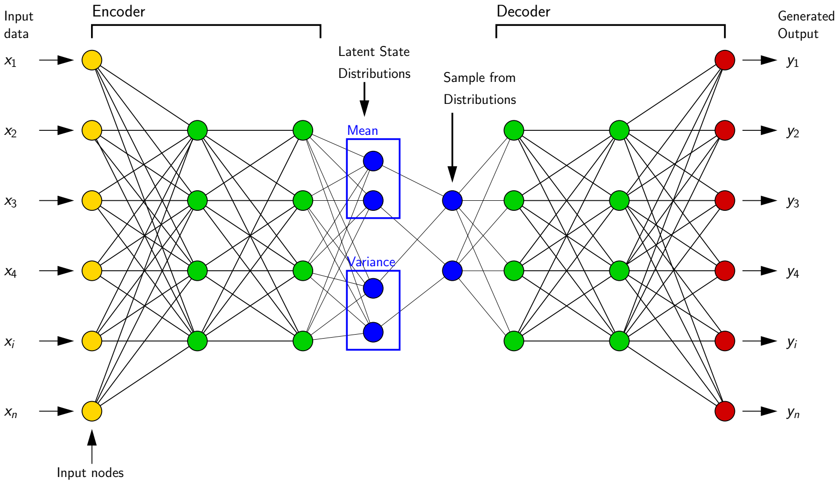
- Knowledge representation and reasoning with ontologies and rules. Semantic graphs. Executable event-based processing.

Machine Learning:

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

Post-2010 Era → Generative AI

Variational AutoEncoders (Generative Models)



Post-2010 Era → AI Generated Architecture

Convergence: Engineering-Architecture-AI

AI-generated art …

AI-generated building architecture

Cyber-Physical Systems

New Computing Infrastructure $\rightarrow$ New System Abstractions

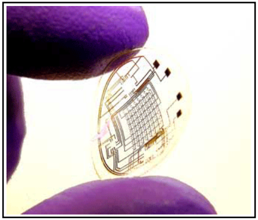
Cyber-Physical Systems

General Idea

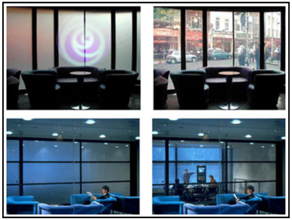
Embedded computers and networks monitor and control the physical processes, usually with feedback loops where computation affects physical processes, and vice versa.

Two Examples

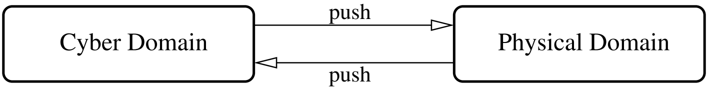
Programmable Contact Lens



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

Physical System Concerns

- Design success corresponds to notions of resilience and reliability.
- Behavior is constrained by conservation laws (e.g., conservation of mass, conservation of momentum, conservation of energy, etc..).
- Behavior often described by families of differential equations.
- Behavior tends to be continuous – usually there will be warning of imminent failure.
- Behavior may not be deterministic – this aspect of physical systems leads to the need for reliability analysis.
- For design purposes, uncertainties in behavior are often handled through the use of safety factors.

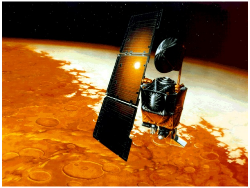
Cyber-Physical Systems

Software System Concerns

- Design success corresponds to notions of correctness of functionality and timeliness of computation.
- Computational systems are discrete and inherently logical. Notions of energy conservation ...etc... and differential equations do not apply.
- Does not make sense to apply a safety factor. If a computational strategy is logically incorrect, then "saying it louder" will not fix anything.
- The main benefit of software is that functionality can be programmed and then re-programmed at a later date.
- A small logical error can result in a system-wide failure.

Cyber-Physical Systems (Notable Failures)

Example 1. NASA's Mars Climate Orbiter, September 1999.



NASA's systems engineering process did not specify the system of measurement. One of the development teams used Imperial measurement; the other metric.

When parameters from one module were passed to another during orbit navigation correct, no conversion was performed, resulting in $125m loss.

Cyber-Physical Systems (Notable Failures)

Example 2. Denver Airport Baggage Handling System

1995. Baggage handling system is 26 miles of conveyors; 300 computers. Fixing the incredibly buggy system requires additional 50 percent of the original budget - nearly $200m.

2005. System still does not work. Airport managers revert to baggage carts with human drivers.

Source: Jackson, Scientific American, June 2006.

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.

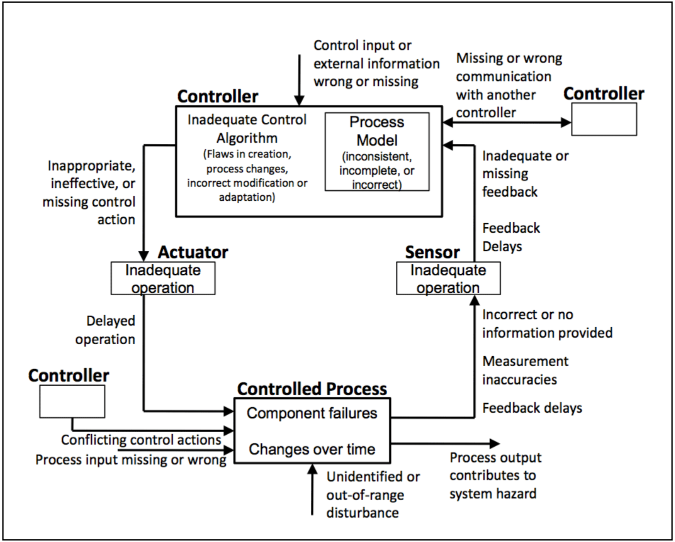
Software Accidents

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)

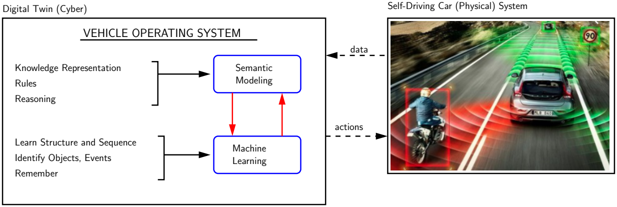


Digital Twin Systems

New Computing Infrastructure → New System Abstractions

Digital Twins (2000-today)

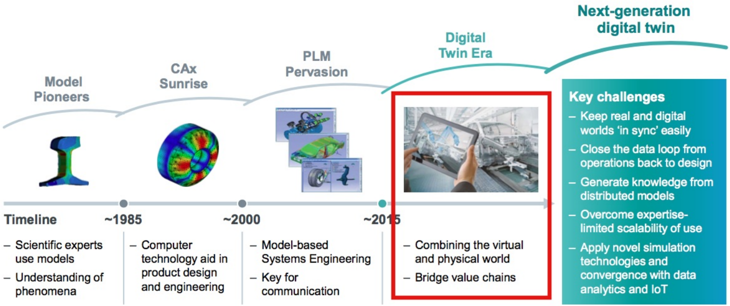
Definition. Virtual representation of a physical object or system that operates across the system lifecycle (not just the front end).



Required Functionality

- Mirror implementation of physical world through real-time monitoring and synchronization of data with events.
- Provide algorithms and software for observation, reasoning, and physical systems control.

Digital Twins (Business Case + Applications)



Many Applications

- NASA Spacecraft
- Manufacturing processes
- Building operations
- Personalized medicine
- Smart Cities
- ... etc.

Digital Twins (Technical Implementation)

Technical Implementation (2023, Google, Siemens, IBM)

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

Artificial Intelligence:

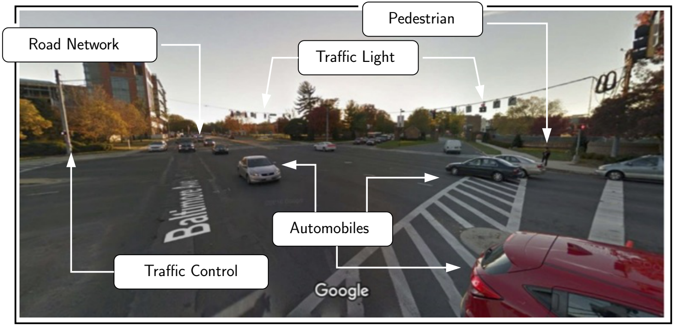
- Knowledge representation and reasoning with ontologies and rules. Semantic graphs. Executable event-based processing.

Machine Learning:

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

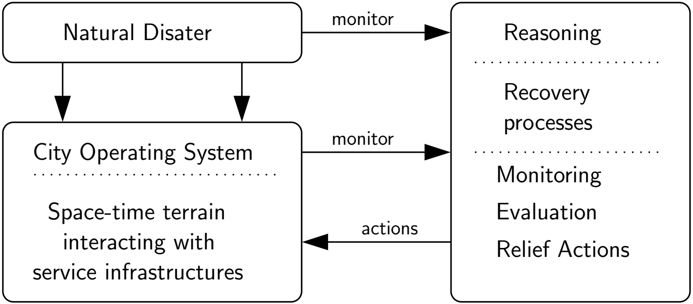
Digital Twin Application (Self-Drivng Car)

Goal. How to traverse traffic intersection safely and without causing an accident?



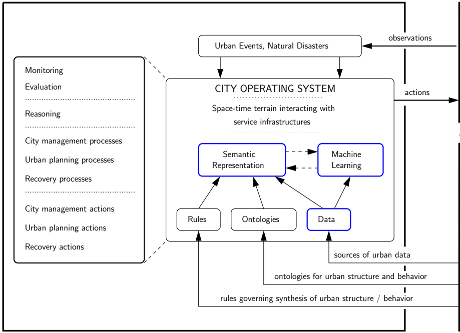
Required Capability. Observe, evaluate, reason, take actions.
Challenges. Multiple domains, multiple streams of heterogeneous data, event-driven behavior, dynamic, time critical.

Digital Twin: City Operating Systems



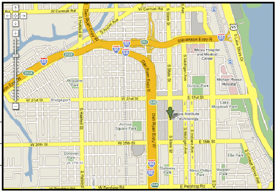
Smart City Digital Twins (2018-2019)

Smart City Digital Twin Architecture



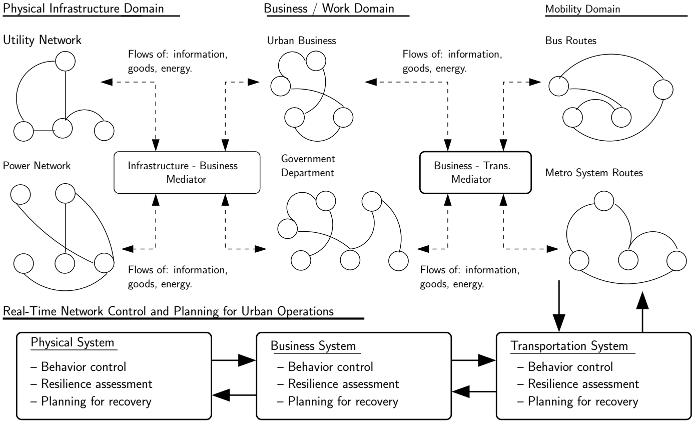
Downtown, Chicago, USA

Geo-informatics: Urban data, ontologies and rules.



Required Capability. Monitoring and control of urban processes.
Complications. Potentially, a very large number of digital twins. Distributed decision making.

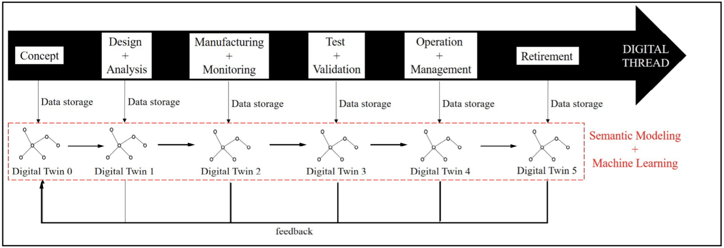
Smart City Digital Twins (2018-2019)



Requirements. Support for digital twin individuals and digital twin communities.

Digital Thread Systems

Digital Threads: (Cradle-to-Grave Lifecycle Support) ...

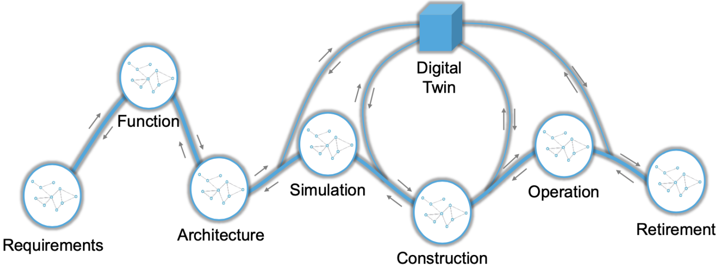


Graph-based Approach

A lot of model-centric engineering boils down to representation of systems as graphs and sequences of graph transformations punctuated by decision making and work/actions.

Digital Thread Systems

Digital Thread System at INL: (Conceptual Model) ...



Def'n: A digital thread is an interconnected software data exchange used to enable digital engineering and digital twinning systems ...

Source: Coelho and Browning, INL, 2022.

Engineering Sensor Systems

Engineering Sensor Systems

General Opportunities for Sensing

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

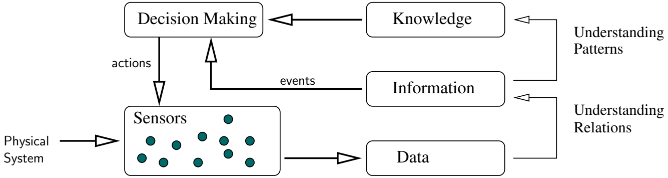
Sensing in the Built Environment

- 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

Human-in-the-Loop Systems

Pros and Cons of Human Control:

- Human machine comes with five sensor types and reasoning capability builtin!
- Humans have slow response; sub-optimal performance; capabilities degrade with age. Approach isn't scalable.

Engineering Sensor Systems

Instrumented Systems:

Basic premise:

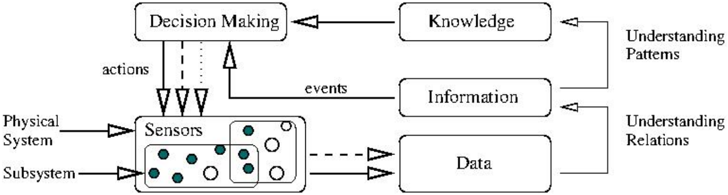
- Advances in computing, sensing, and communications technologies will allow for new types of systems where human involvement is replaced (or partially replaced) by automation.

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:

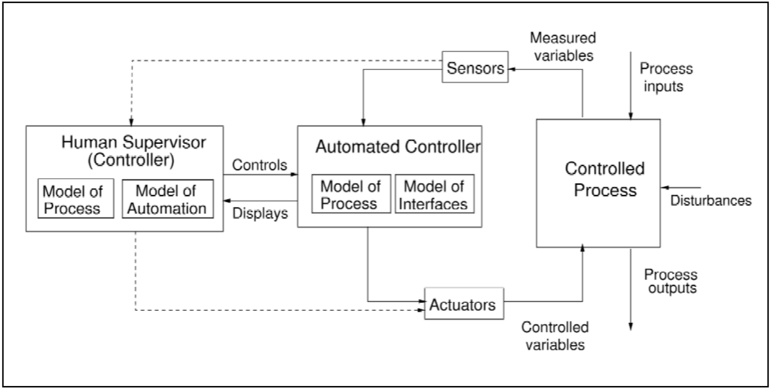


Chain of dependency relationships:

```
1.  improved performance <-- actions
2.  actions              <-- ability to identify events.
3.  identify events      <-- data processing
4.  data processing      <-- types and quality of data
5.  types and quality of data <-- sensor design and placement.
```

Engineering Sensor Systems

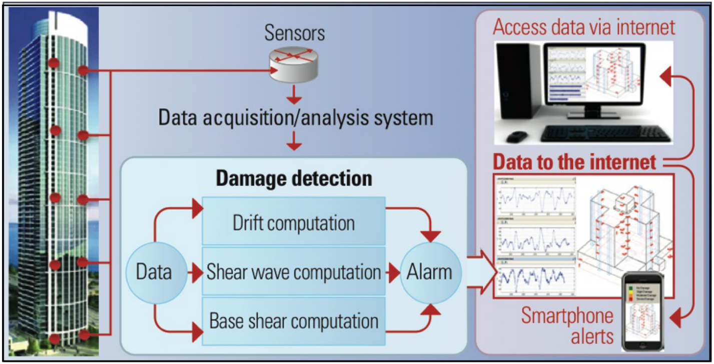
Human-in-the-Loop and Automated Control:



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/

Real-World Application (Modern Aircraft)

During the past three decades aerospace systems have seen increased use of electrical systems to achieve functionality.

Example 1. Boeing 777 → Boeing 787 (more electric aircraft).

Example 2. F-16 and F-35 Military Jets

F-16

F-35

Real-World Application (Modern Aircraft)

F-16 (production began 1974):

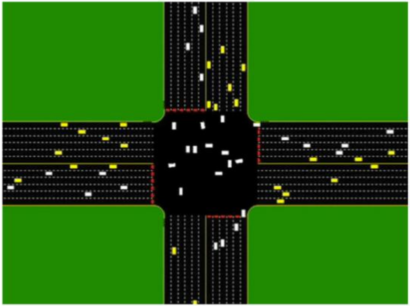
- 15 subsystems; $O(10^3)$ interfaces.
- Less than 40% of the functions managed by software.

F-35 (production began in 2006):

- 3-8 times the operational capability of previous aircraft.
- New sensor systems to support: situational awareness and targeting; sensor integration and data fusion.
- 130 subsystems; $O(10^5)$ interfaces.
- 90% of its functions are managed by software.

Real-World Application (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.

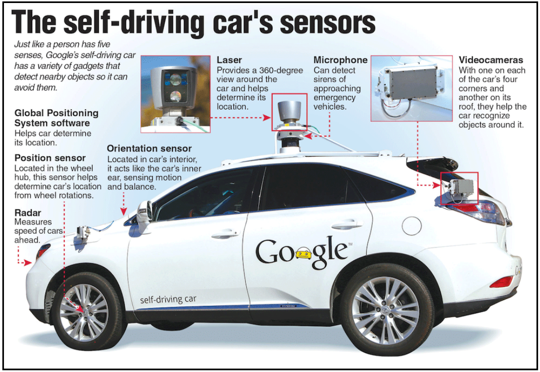
Source: ISR visitor from GM Research.

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).

Real-World Application (Self-Driving Cars)



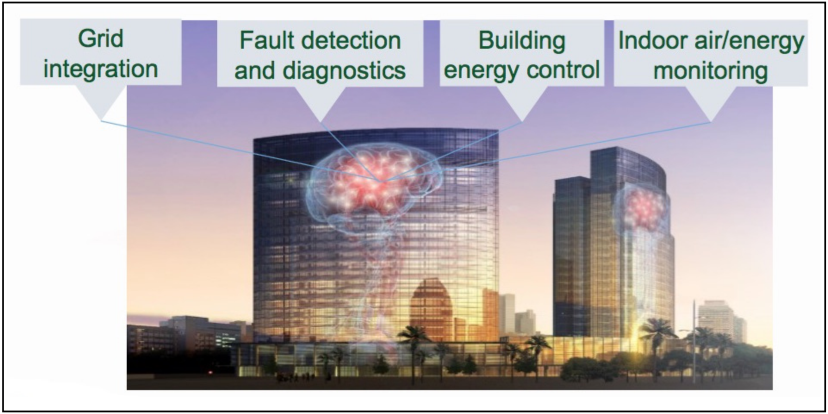
Today: Modern automobiles → 100 million lines of software.
Tomorrow: Self-Driving automobiles → 200-300 million lines of software.

Urban Applications

How do buildings and cities work?

Modern Buildings (Vision for Future)

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



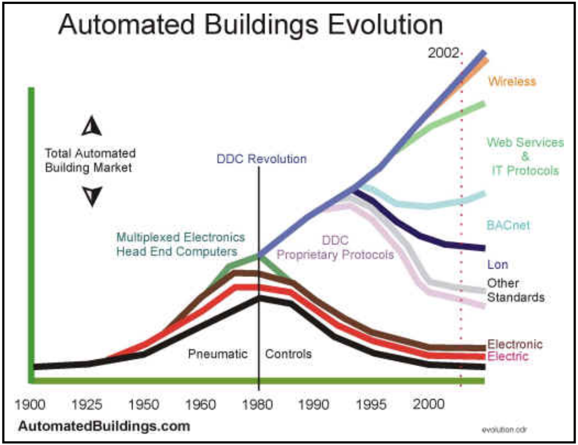
Modern Buildings (Key Features)

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.
- Building 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!

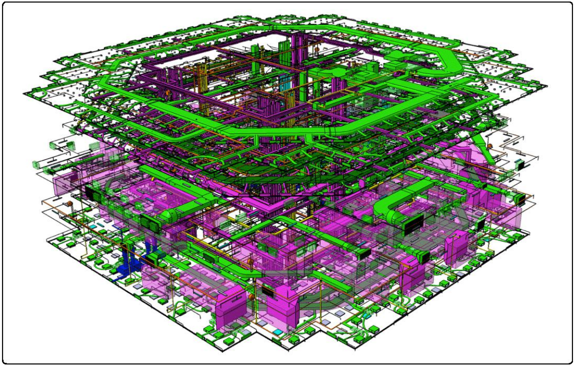
Modern Buildings (Key Features)

Large-scale building systems are packed with automation:



Modern Buildings (Key Features)

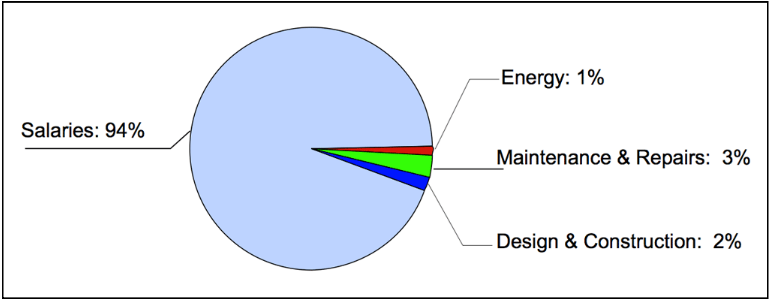
Large-scale building systems are intertwined networks of networks:



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.

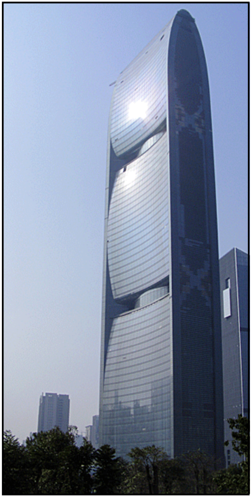
Examples:

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

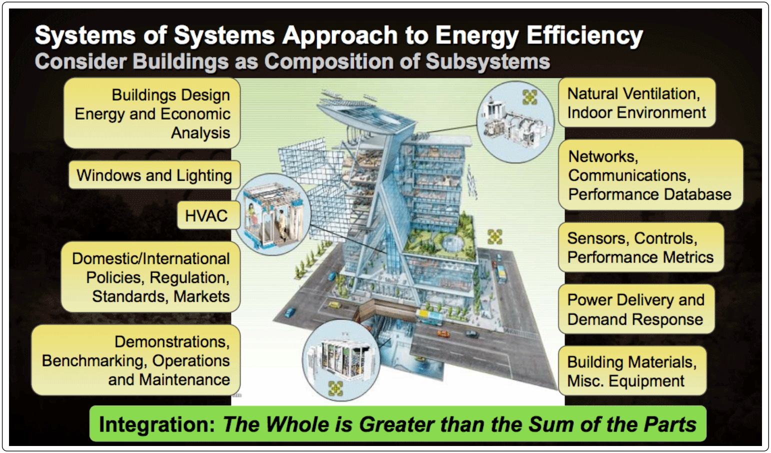
Modern Buildings (Integrated Energy Systems)

Pearl River Tower (2010):

- High performance structure designed to produce as much energy as it consumes.
- Guides wind to a pair of openings at its mechanical floors.
- Wind drives turbines that generate energy for the heating, ventilation and air conditioning systems.
- Openings provide structural relief, by allowing wind to pass through the building.

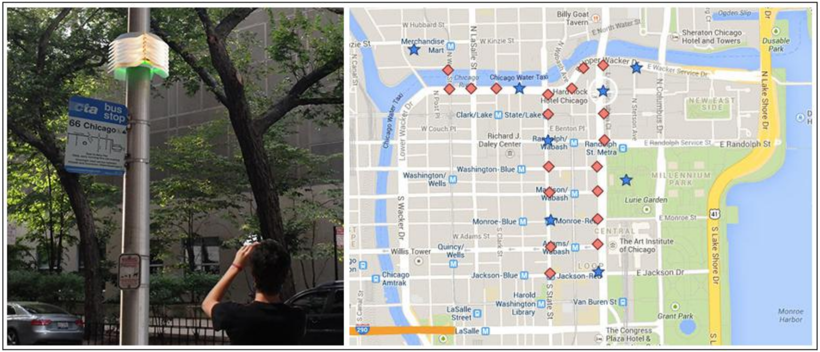


Modern Buildings (Automation Systems Design)



Smart Cities: Urban Sensing in Chicago

Array of Things, Chicago. Modular sensor boxes will collect real-time data on the city's environment, infrastructure and activity.



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

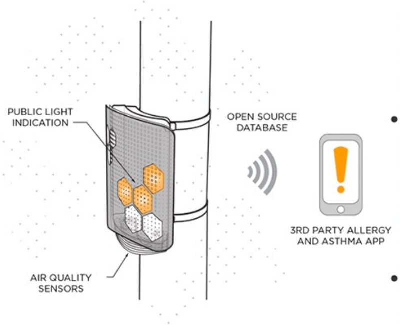
Smart Cities: Urban Sensing in Chicago

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.

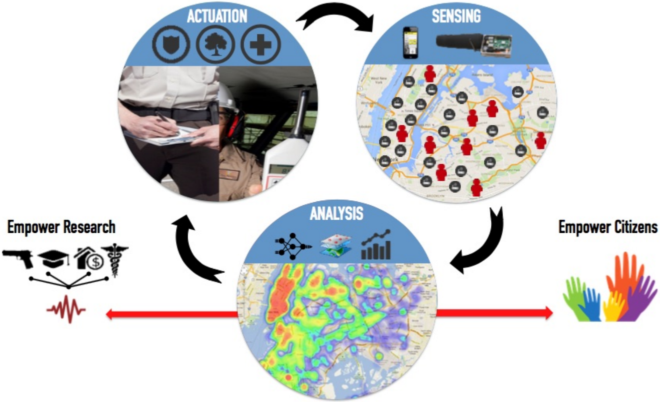
Motivation. Over 70 million people in US are exposed to noise levels beyond the limit of EPA considers to be harmful.

Short-term Problems. Sleep disruption.

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

SONYC: Sounds of New York City

Complaints. NYC authorities receive more than 800 noise-related complaints per day!



SONYC: Sounds of New York City

Noise Analytics. Analyze and understand noise pollution at a city-scale.

Global Applications

Answering Big Science Questions

NASA's Earth Observing System

NASA'S EOSDIS PROGRAM

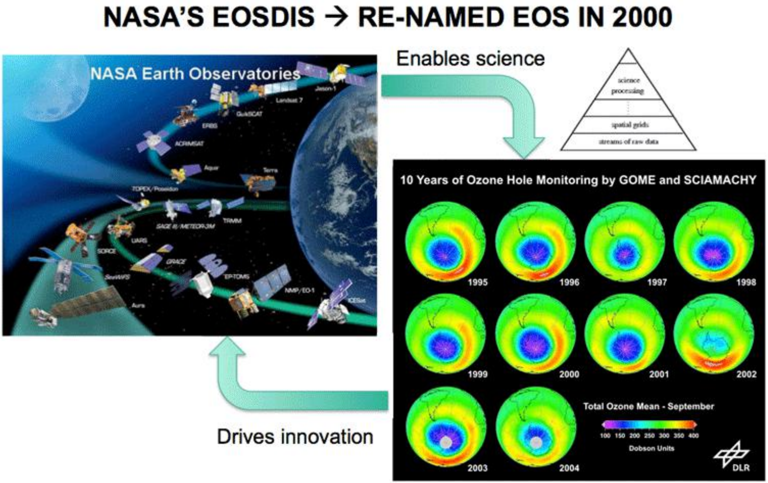
NASA / Hughes Contract in 1993

- 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:

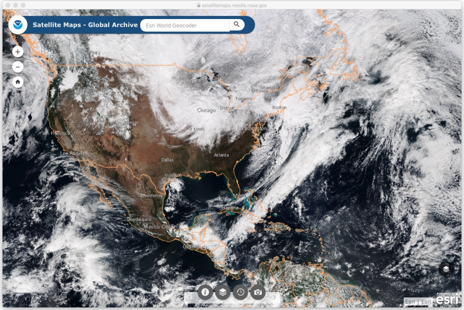
- How is the Global Earth System changing?
- What are the primary factors that influence change?
- How does the Earth System respond to natural and human-induced actions?
- What are the consequences of change in the Earth Systems for humans?
- How will the Earth System change in the future?

NASA's Earth Observing System



Satellite Imagery and Measurements

Understanding Climate Change

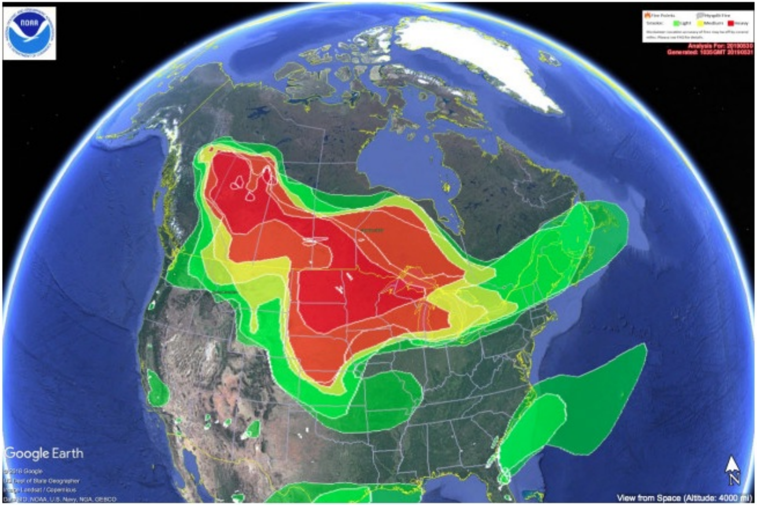


Example. Measure spatial and temporal extent of annual Snow Pack → Estimate water resources available for agriculture and urban consumption.

California Wildfires force Evacuations

Canadian Wildfires impact US

Wildfires in Alberta: Smoke covers millions of square miles:



Canadian Wildfires impact US Health/Food Chain

Poor Air Quality (Summer, 2018):

- Hundreds of wildfires in BC and WA.
- Smoke in BC drifts south to Washington State.
- Air quality in Seattle is very poor.

Wildfires impact Food Chain:

- Blankets of smoke obsure direct sunlight over orchards.
- Apples cannot grow to full size.
- Price of apples at Safeway goes up!

Summary

Recurring Themes and Key Points

Recurring Themes

- Information-age systems offer enhanced functionality and better performance, but their design is more difficult than in the past.
- Physical systems and computational systems fail in completely different ways.
- Sensor networks will form the eyes and ears of complex control and information systems.
- As system complexity increases, more and more of the functionality will be managed by software!

Key Points for Building Better Systems

Looking Forward

Use sensing and software to build better systems:

- Improve situational awareness – to understand what is actually happending 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?

References

- Array of Things: See https://arrayofthings.github.io
- Austin M.A., Delgoshaei P., Coelho M. and Heidarinejad M. , Architecting Smart City Digital Twins: Combined Semantic Model and Machine Learning Approach, Journal of Management in Engineering, ASCE, Volume 36, Issue 4, July, 2020.
- Bello J.P. et al., SONYC: A System for Monitoring, Analyzing, and Mitigating Urban Noise Pollution, Communications of the ACM, 62, 2, 2019, pp. 68-77.
- Coelho M., and Browning L.S., INL Digital Engineering: Model-Based Design, Digital Threads, Digital Twins, Artificial Intelligence, and Extended Reality for Complex Energy Systems, INL/CON-22-69247, Idaho National Laboratory, Idaho Falls, Idaho 83415, September, 2022.
- Leveson N.G., A New Approach to Software Systems Safety Engineering, System Safety Engineering: Back to the Future, MIT, 2006.
- Tien J.M., Toward a Decision Informatics Paradigm: A Real-Time Information-Based Approach, to Decision Making, IEEE Transactions on Systems, Man, and Cybernetics – Part C: Applications and Reviews, Vol. 33, No. 1, February, 2003.