ENCE 688R Civil Information Systems

Introduction, Motivation, and Drivers

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Lecture 1: Topics

Part 1: A Little History

- Early Civil Engineering, Industrial Revolution, Landmarks in American Civil Engineering

Part 2: Civil Engineering Today

- Areas of Concern and Challenges, Role of Computing, Engineering Modern Skyscrapers.

Part 3: Civil Systems Drivers

- Infrastructure Crisis, World Urbanization, Sustainable Systems Design, Cascading Network Failures, Automated Systems Safety.

Part 4: Information-Age Systems

- Capability, Cyberphysical Systems.

Part 5: Recurring Themes

Part 1. A Little History

What is Civil Engineering?

Here's what Wikipedia says

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.

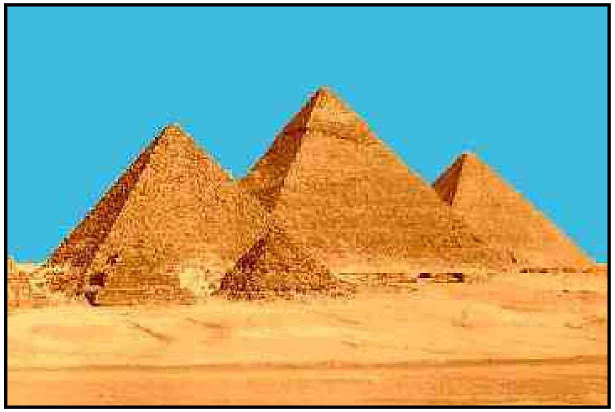
Goals during Early Civilization

The earliest examples of civil engineering occured during the period 4000 BC – 6000 BC.

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

What is Civil Engineering?

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, harbours, bridges, dams and roads.

The Industrial Revolution

Fast forward to the Industrial Revolution

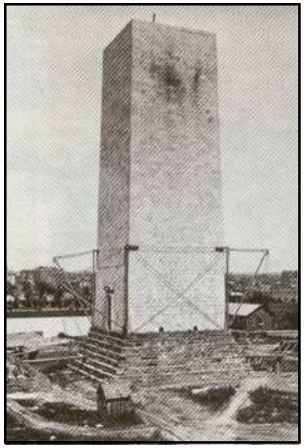
Year	Milestone
1692	Languedoc Canal. 240 miles long. 100 locks. 3 major aqueducts.
1708	Jethro Tull's mechanical seed sower $\rightarrow$ large-scale planting/cultivation.
1765	Invention of the spinning jenny/wheel automates weaving of cloth.
1775	Watt's first efficient steam engine.
1801	Robert Trevithick demonstrates a steam locomotive.
1821	Faraday demonstrates electro-magnetic rotation $\rightarrow$ electric motor.
1834	Charles Babbage analytic engine $\rightarrow$ forerunner of the computer.
1903	Wright brothers make first powered flight.
1908	Henry Ford mass-produces the Model T.

Source: The Industrial Revolution: A Timeline.

The Industrial Revolution

Advances in Civil Engineering during the Industrial Revolution

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



The Eiffel Tower - April 1888

Early Skyscrapers

Skyscrapers (1890s) create habitable spaces in tall buildings for office workers.

Enablers	Example: Empire State Building
• 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.	

Landmarks in American Civil Engineering

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.

The Industrial Revolution

The 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 Impact	Family/Locale	Regional/National

The Industrial Revolution

The Industrial Revolution Actually Changed the World!

During 1730 - 1749 ...

- 74.5% of children born in London who died before the age of five.

By 1810 - 1829 ...

- 31.8% of children born in London who died before the age of five.

Part 2. Civil Engineering Today

Civil Engineering Today

Areas of Concern – Not much change during past 200 years.

- Planning, design, construction and operation of buildings and bridges, highways, rapid transit and rail systems, ports and harbors, airports, tunnels and underground construction, and dams.
- Includes urban and city planning, water and land pollution and treatment problems, and disposal of hazardous wastes and chemicals.

Challenges

- Design and management problems are fraught with uncertain information, multiple objectives, conflicting objectives, numerous and conflicting constituencies.
- Solutions require consideration of human, social, economic, and technological systems.
- Solutions require multi-disciplinary expertise to design, maintain, manage and, eventually, retire systems.

Civil Engineering Today

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
Underlying Technologies	ElectroMechanical	**Information and Connectivity**
Product Lifecycle	Years	Months
Living Standard	Quality of Goods	**Quality of Life**
Geographical Impact	Regional/National	**Global**

Civil Engineers need to ...

... create the infrastructure for citizens of the Information Era.

Information Era: A Partnership between Man and Machine

The traditional role of man and machine is facilitated by complementary strengths and weaknesses.

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.

Civil Engineering Today

Sensible Problem Solving Strategy

Let engineers and computers do what they are best at. This strategy:

1. Accelerates the solution procedure.
2. Enables the analysis of problems having size and complexity beyond manual examination.

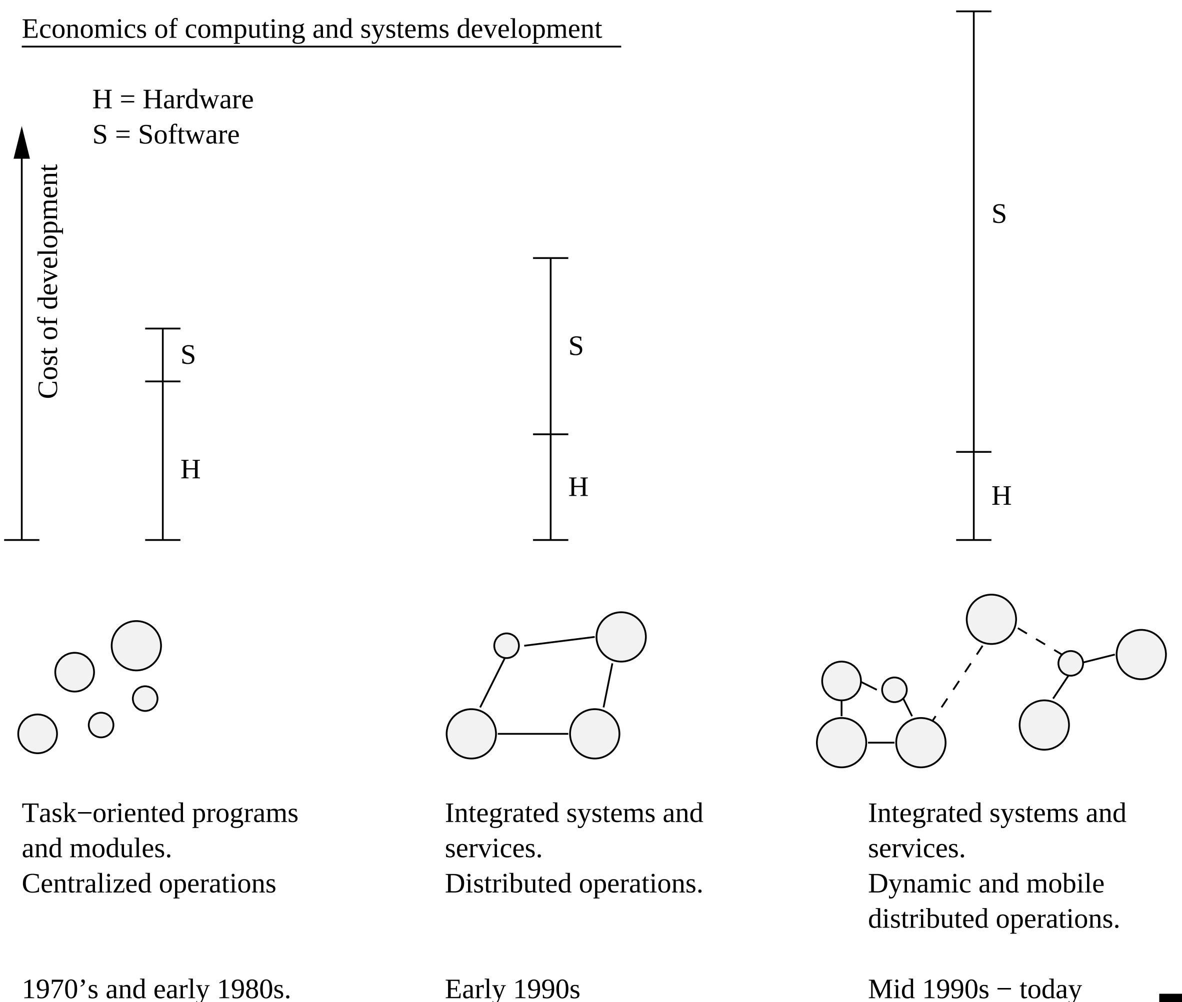
Getting things to work ...

> **... we need to describe to the computer solution procedures that are completely unambiguous.**

That is, we will need to look at data, organization and manipulation of data, and formal languages.

Civil Engineering Today

Expectations Expand to Improve Quality of Life.



Civil Engineering Today

History tells us that it takes about a decade for significant advances in computing capability to occur ...

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

Table 1: Decade-long stages in the evolution of computing focus and capability.

In the 1990s, mainstream computing capability expanded to take advantage of networking.

Civil Engineering Today

Example. Engineering Modern Skyscrapers

Modern buildings are:

> **... advanced, self-contained and tightly controlled environments designed to provide services (e.g., transportation, artificial lighting, ..etc.).**

The design of modern buildings is complicated by:

1. Necessity of performance-based design and real-time management.
2. Many stakeholders (owners, inhabitants), some with competing needs.
3. Large size (e.g., 30,000 occupants; thousands of points of sensing and controls for air quality and fire protection.)
4. Intertwined network structures for the arrangement of spaces, fixed circulatory systems (power, hvac, plumbing), dynamic circulatory systems (flows of energy through rooms).
5. System functionality is **controlled by software!**

Civil Engineering Today

The Case for Green Buildings

The National Science and Technology Council in the US estimates that ...

> **... commercial and residential buildings consume 1/3 of the world's energy.**

In North America, for example this translates to:

- 72% of the electricity generation, 12% of the water use, and 60% of non-industrial waste.

Looking Ahead

If worldwide energy use trends continue,

> **... buildings will become the largest consumer of global energy by 2025 - more than the transportation and industrial sectors combined.**

Without changes,

> **... up to 50% of the electricity and water in these buildings could be wasted.**

Source: IBM Smarter Planet Inititiave.

Civil Engineering Today

Green Buildings → Building-Integrated Energy Systems

Standard models of building construction rely on ...

> **... centrally produced power as a source of high-grade energy (i.e., can be readily converted into work).**

Advances in technology allow for reduced costs of energy consumption through ...

> **... replacement of power produced locally.**

Examples of building-integrated energy systems:

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

Example. Engineering Modern Skyscrapers

Enablers	Example: Pearl River Tower
• High performance structure designed to produce as much energy as it consumes. • Guides wind to a pair of openings at its mechanical floors. • Winds drive turbines that generate energy for the heating, ventilation and air conditioning systems. • Openings provide structural relief, by allowing wind to pass through the building.	

Part 3. Civil Systems Drivers

Issue 1. Infrastructure Crisis

The Problem

In America, ...

... civil infrastructure is not considered to be a national priority.

A few key statistics:

- From 1950-1970, the US devoted 3% of its gross domestic product (GDP) to infrastructure spending.
- Since 1980, spending on infrastructure has been cut to 2% of GDP.
- China spends 5% of GDP on infrastructure.
- India spends 9% of GDP on infrastructure.

Issue 1. Infrastructure Crisis

Key Problems

Two key problems:

- Much of America's infrastructure was built post World War II – it's now 50-60 years old, and being attacked by decay and neglect.
- The US Population is still growing! This puts additional demands on infrastructure.

Criticism

Quote from W.P. Henry, former president of ASCE:

Our infrastructure is in crisis mode ...

> **... how many more people must die needlessly because we do not take proper care of our infrastructure?**

Issue 1. Infrastructure Crisis

Poster Child: Collapse of the Minneapolis Bridge over Interstate 35W.

The 40-year old steel deck truss crossing had been considered ...

> **... structurally deficient since 1990, but engineers with the Minnesota Department of Transportation had not believed the bridge to be in danger of imminent collapse.**

Thirteen commuters were killed and more than 100 were injured on August 1, 2007.

Issue 1. Infrastructure Crisis

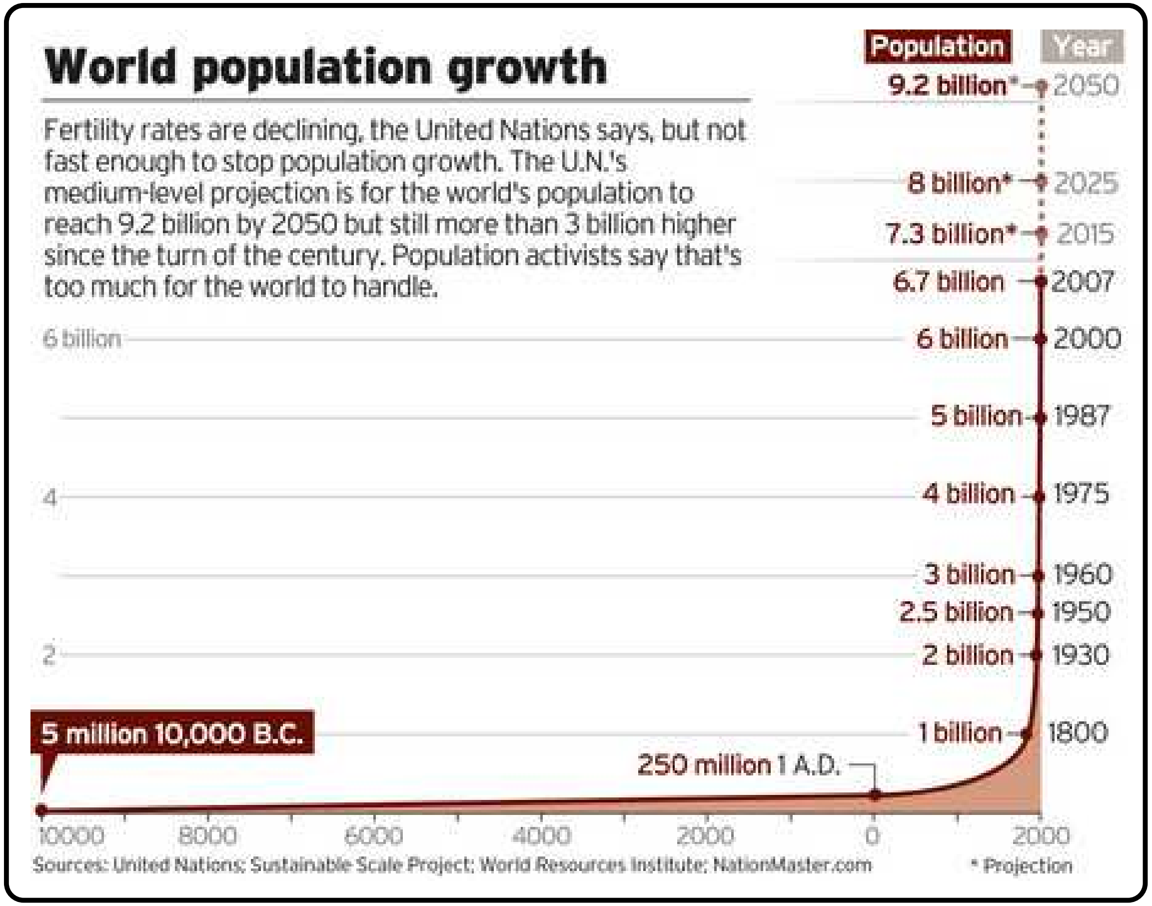
The Infrastructure Crisis extends beyond Bridges

Key quotes from ASCE's Infrastructure Crisis Report (Reid, 2008):

- Without "significant infrastructure investment" **aviation delays** are expected to cost this US economy $170 billion between 2000 and 2012.
- Improving the physical condition and service of the nation's **mass transit** systems will require between $30 billion and $45 billion a years, approximately 130 to 240 percent more than the total investment for 2004.
- More than 3,200 **dams** are currently classified as "unsafe" – meaning that their deficiencies leave them more susceptible to failure – a figure that has increase 80 percent since 1998.
- It took Congress eight years to pass the **water resources** bill, and then it was vetoed by President Bush!

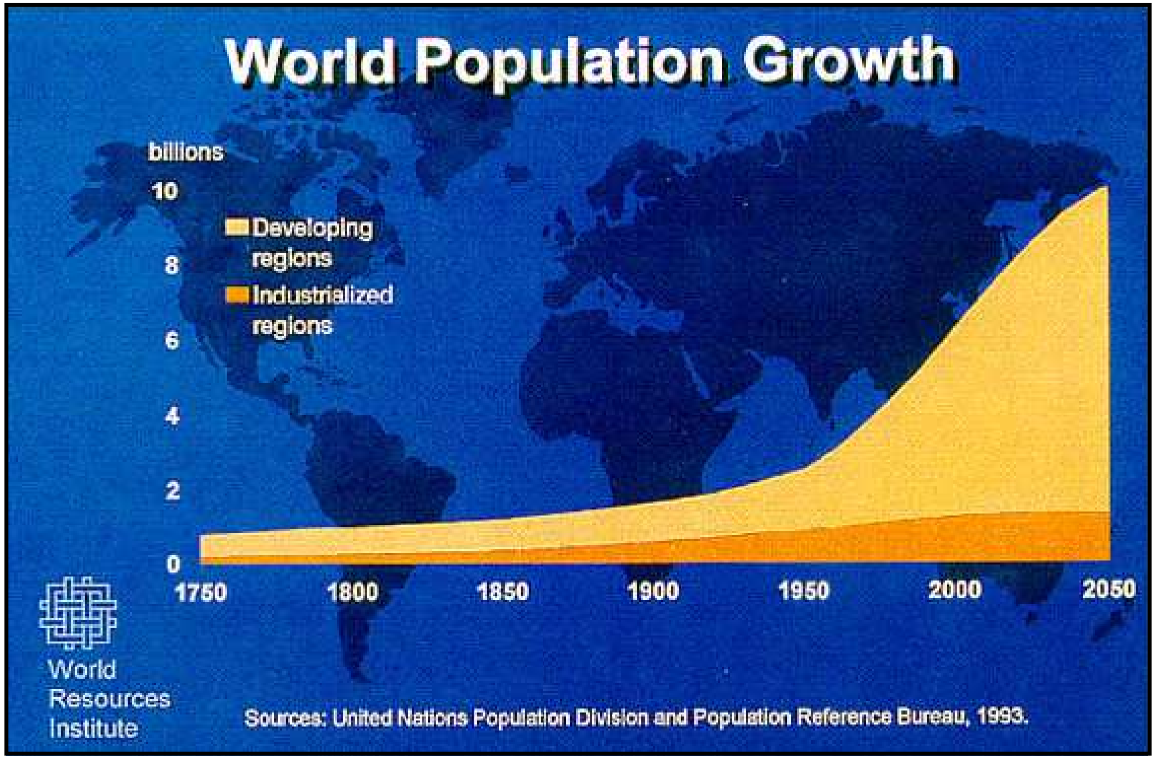
Issue 2. World Urbanization

Trends in World Population Growth



Issue 2. World Urbanization

Trends in World Population Growth



Global population is growing along with growing affluence. This creates additional system demands. **Are these trends sustainable?**

Issue 2. World Urbanization

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 are looking at ways to ...

> **... improve their infrastructures to become more environmentally friendly, increase the quality of life for their residents, and cut costs at the same time.**

Source: SEIMENS, Sustainable Cities, USA.

Issue 3. Sustainable Systems Design

Definition of Sustainability

The widely accepted definition of sustainability is ...

> **... the ability to provide for the needs of the current generation without compromising the ability of future generations to meet their needs.**

Why Care?

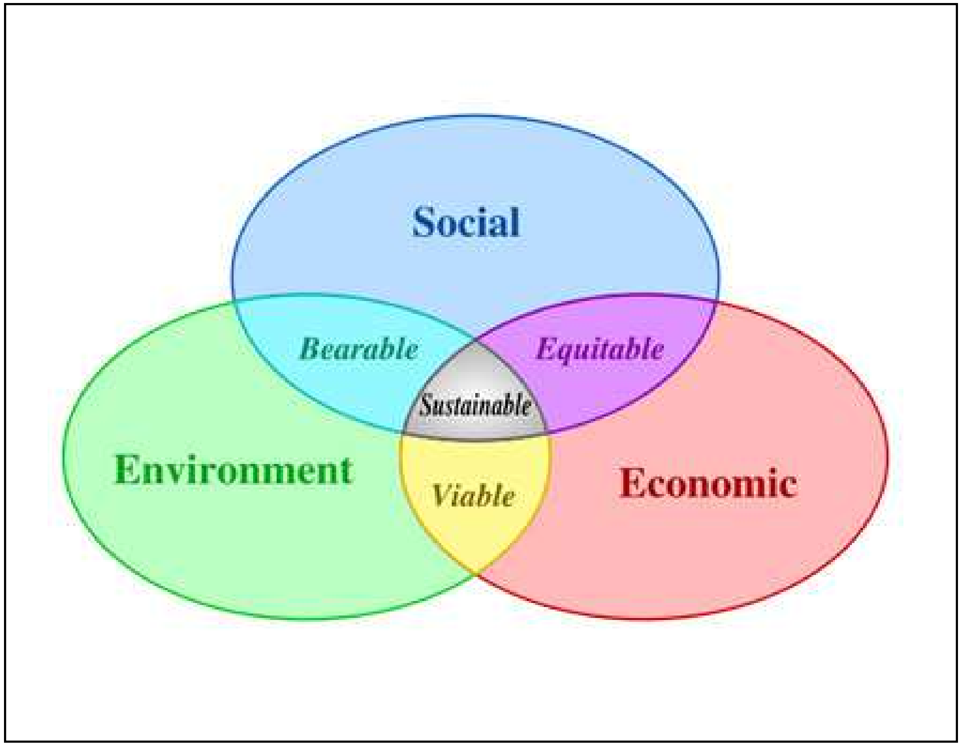
We must find ways of reducing consumption of resources if we are to avoid dramatic environmental degradation and the potential of global ecosystem collapse.

> **This is a particularly important challenge for Americans who consume more per person than any other people on the planet.**

If everyone on Earth (just the current population) consumed as much as the average American, we would need four more Earths just to harvest for resources!

Issue 3. Sustainable Systems Design

Elements of Sustainability



Sustainability involves physical systems, organizational systems, social systems, etc ...

Issue 3. Sustainable Systems Design

Sensor Networks - Integrating Urban Operation into the City Fabric

Sensor network will form the ....

> **... eyes, ears, and fingers of a complex control and information system that will facilitate broad, pervasive, and continuous use of sensor data and intelligence, making buildings and cities more efficient and environmentally sensitive.**

Sensors will monitor:

- Ambient conditions,
- Movement of people and traffic,
- Building and transportation system performance.

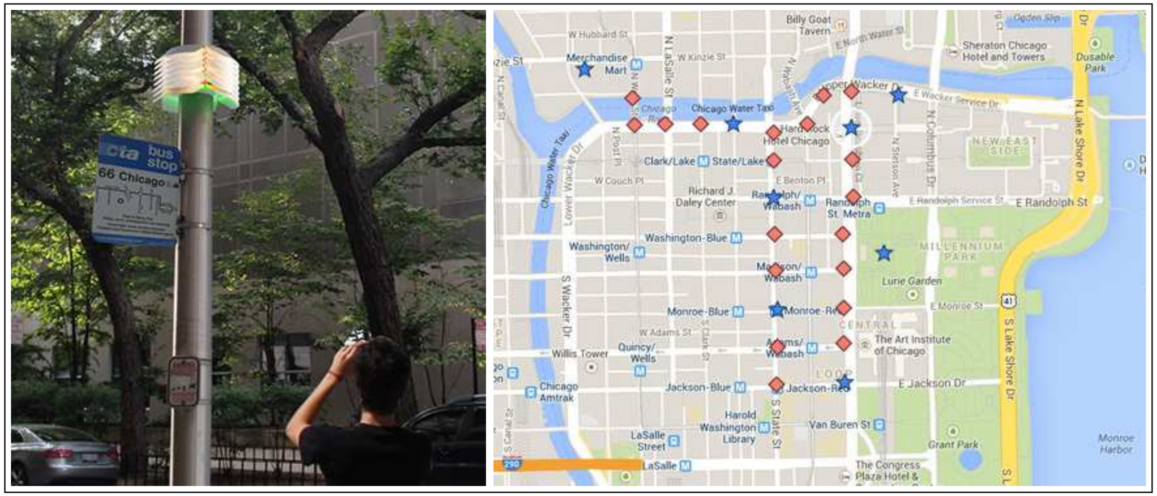
Source:Living PlanetIT. http://living-planetit.com

Issue 3. Sustainable Systems Design

Smart Cities: (Array of Things in Chicago)

Array of Things is an **urban sensing project**, ...

> **... a network of interactive, modular sensor boxes that will be installed around Chicago to collect real-time data on the citys environment, infrastructure, and activity for research and public use.**



Sensing Network: 50 nodes in early 2016. 500 nodes by Dec. 2017.

Source: https://arrayofthings.github.io

Issue 3. Sustainable Systems Design

Case Study C: Smart Cities (Array of Things in Chicago)

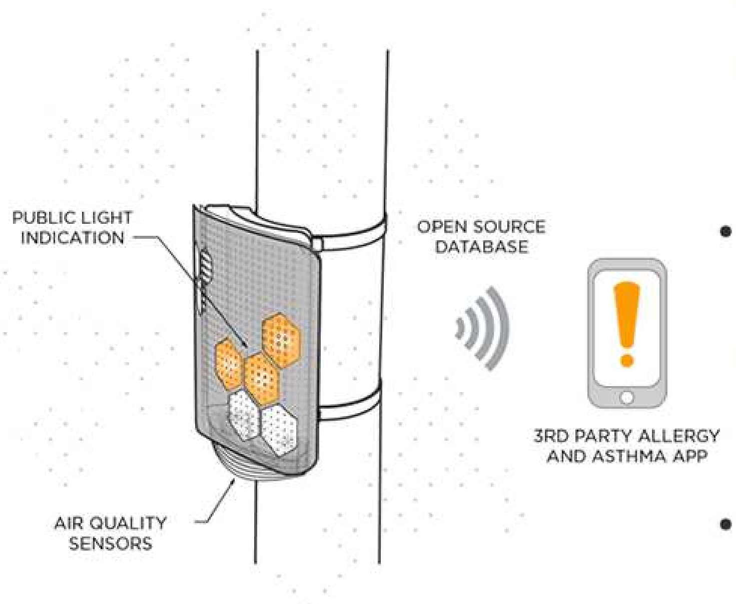
What Data is Collected?

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.

Issue 3. Sustainable Systems Design

Case Study C: Smart Cities (Array of Things 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.

Issue 4. Cascading Network Failures

Example 4. 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.

The waterway network failure ...

... set in motion a chain of events that highlighted weaknesses in civil infrastructure, electrical power, state and federal emergency, social and political networks/systems.

Issue 4. Cascading Network Failures

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 localised failure of the electrical power and highway systems.

- **Federal emergency failures**

  Flooding meant that inhabits had to flee their homes, but few plans were in place for their orderly evaculation.

- **Social network failures**

  After the inhabitants left their homes (and a degree of desparation sets in), looters stole property from evacuated properties.

- **Political system failures**

  The inability of politicians to coordinate activities from the top just confirmed everyone's worst fears!

Issue 4. Cascading Network Failures

Lessons Learned

Cascading failures of this type indicate that:

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

Long-Term Plan

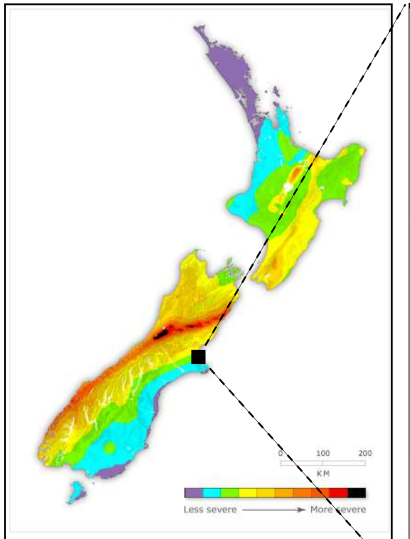
The ultimate goal is to ...

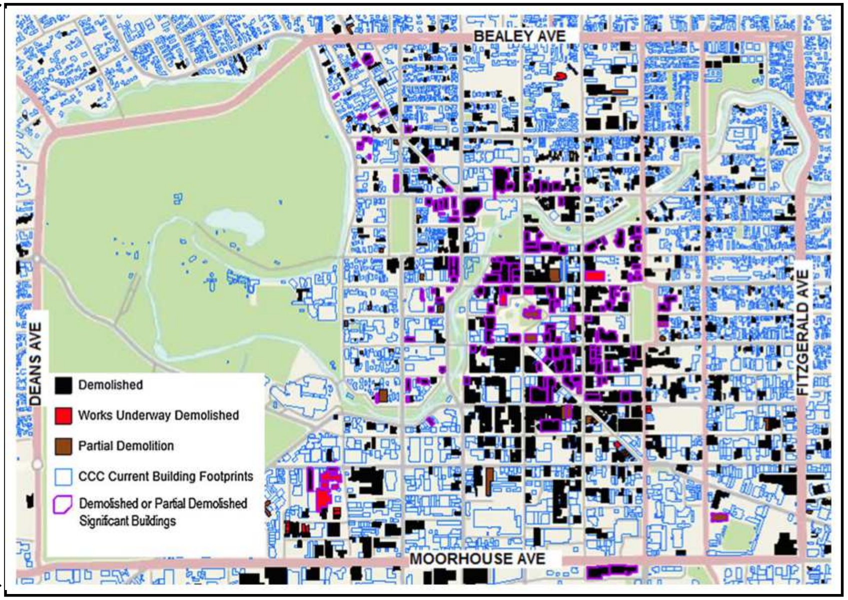
> **... improve resiliency and sustainablilty while preserving performance.**

Issue 4. Disaster Resilience and Recovery

Example. Cascading failure of networks caused by earthquakes.

Christchurch, New Zealand, 4.30 am, September 4, 2010. A magnitude 7.2 earthquake rolls into town ....





Issue 4. Cascading Network Failures

Spatial Distributions of Damage

20% of homes are uninhabitable. Many transportation links are damaged. Street flooding in low-lying areas → Widespread power outages → Disruption of many services.

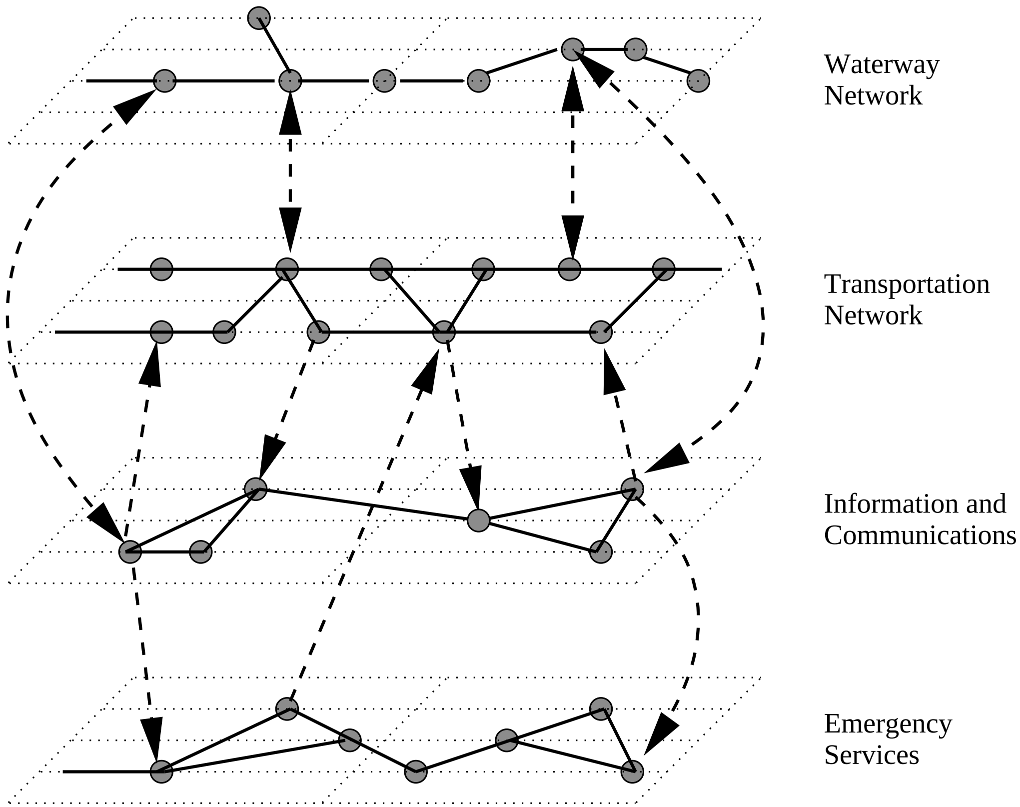
Issue 4. Cascading Network Failures

Planning for Disaster Relief

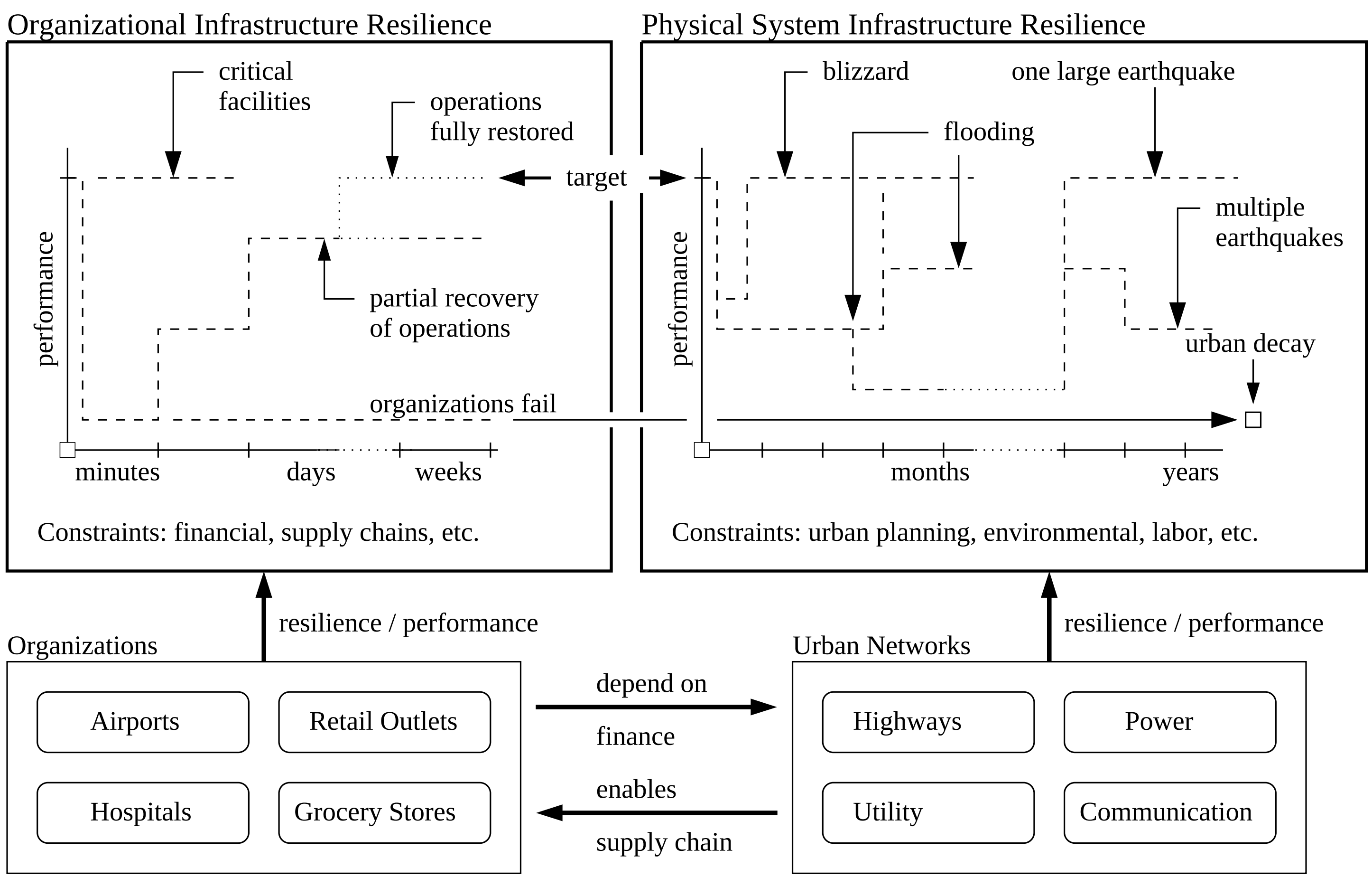
Needs to look at the connections between network models.

Basic questions:

- What kinds of dependencies exist between the networks?
- How will a failure in one network impact other networks?
- What parts of a system are most vulnerable?
- Does it make sense to stockpile supplies of water and food?
- How much should we spend to prepare for an inevitable attack?



Coupled Model for Organizational/Physical System Resilience



Issue 5. Automated Systems Safety

Washington D.C. Metro Train Crash (June 2009)

Issue 5. Automated Systems Safety

Key points:

- Investigations invariably focus our attention on discrete aspects of machine or human error, whereas ...

  ... the real problem often lies in the relationship between humans and their automated systems.

- You really need to trace the cause of an accident back to the underlying fault.
- Safer automated systems leads to a paradox at the heart of all human-machine interactions:

  “...The better you make the automation, the more difficult it is to guard against these catastrophic failures in the future, because the automation becomes more and more powerful, and you rely on it more and more.”

- In another incident the National Transportation Safety Board found that:

  ....the driver of the train had reported overshooting problems at earlier stops but was told not to interfere with the automated controls.

Part 4. Information-Age Systems

Information-Age Capability

IBM Smarter Planet Initiative.

We now have the ability to measure, sense, and see the exact condition of almost everything (IBM, 2009):

More Instrumented

- By the end of 2010 there will be 1 billion trasistors per human and 30 billion RFID (radio frequency id) tags;

More Interconnected

Due to transformational advances in (wireless) communications technology, people, systems and objects can communicate and interact with each other in entirely new ways.

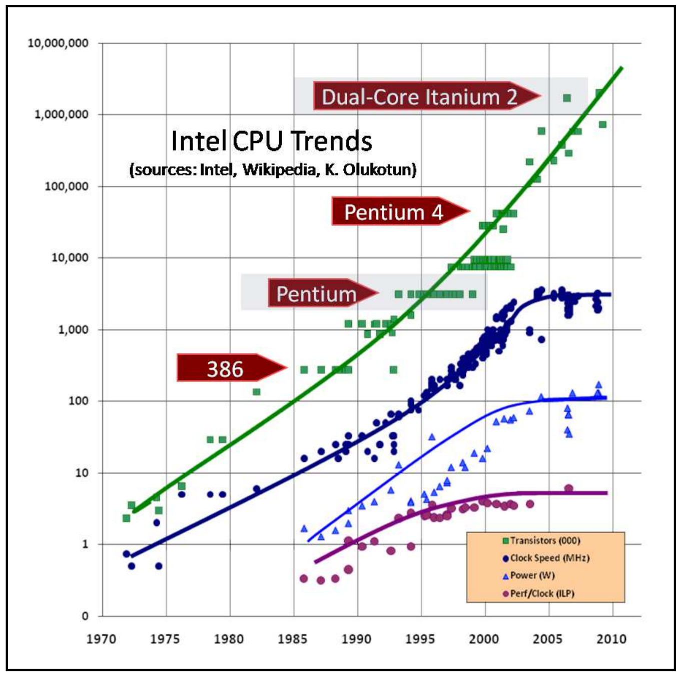
- We are heading toward one trillion connected objects (Internet of Things).

More Intelligent

- More intelligent behavior means an ability to respond to changes quickly, accurately and securely, predicting and optimizing for future events.

Information-Age Capability

IBM Smarter Planet Initiative: Vision 2025

Enablers	Speed of a Single Microprocessor
• Integrated components will approach **molecular level** and may cover complete walls. • Every object will be smart. The ensemble is the function • Function determined by ... **...availability of sensing, actuation, connectivity, computation, storage and energy.** • Challenge. Elements need to collaborate to present unifying experiences.	

Pathway to Information-Age Systems

Limitations of Industrial-Age Systems

Many present-day systems rely on human involvement as a means for sensing and controlling behavior, e.g.,

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

Key disadvantages:

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

Pathway to Information-Age Systems

Information-Age Systems

Developed under the premise that advances in

- Computing,
- Sensing, and
- Communications

technologies will allow for

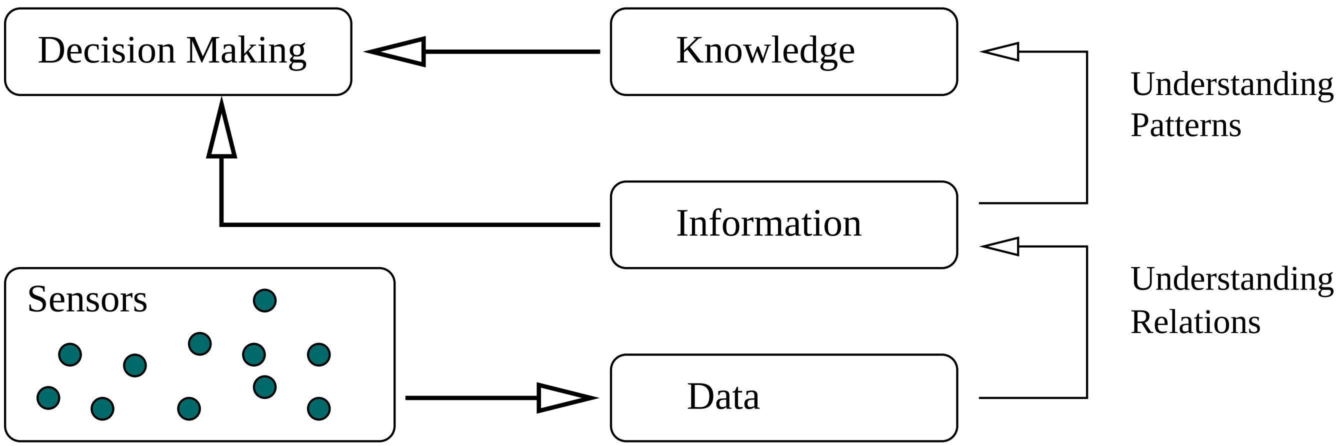
... new types of systems where human involvement is replaced by automation.

and where critical constraint values in the design space are relaxed, e.g.,

- Autofocus camera,
- Electronic systems in automobiles and planes $\longrightarrow$ self-driving cars.
- Baggage handling systems at airports.

Pathway to Information-Age Systems

Pathway from data to information and knowledge



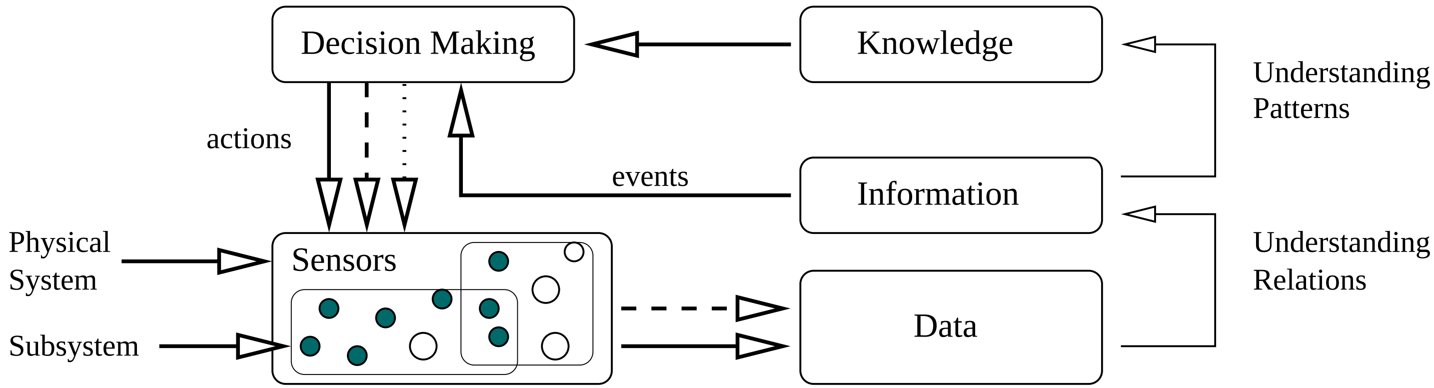
The generated information enables better (i.e., most timely, more accurate) decision making, which in turn, allows for extended functionality and improved performance.

Key Point

Algorithms for understanding relations and patterns will be implemented in software.

Preliminary Assessment

Abstract Sensor Model is Too Simple!



Real-World Complications

- Multiplicity of sensor types distributed across subsystems.
- Concurrent real-time behaviors in subsystems.
- Intended and unindented interactions among subsystems.
- Cooordination of subsystem behaviors to meet stringent performance requirements.

Pathway to Information-Age Systems

New Computing Infrastructure → New 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.

Table 2: Decade-long stages in the evolution of computing focus and capability.

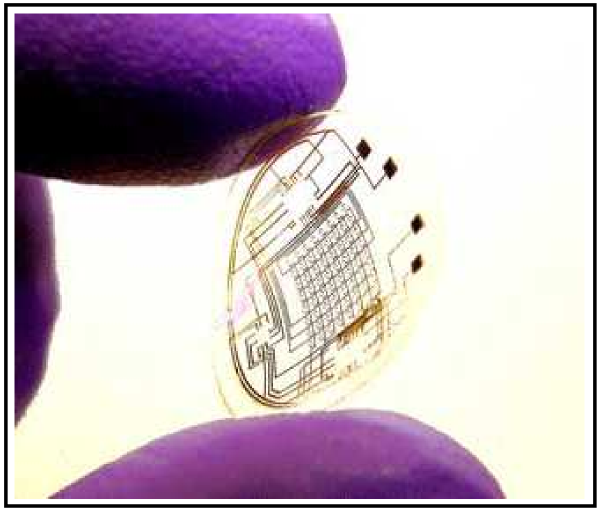
CyberPhysical Systems

General Idea of CyberPhysical Systems

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

Two Examples

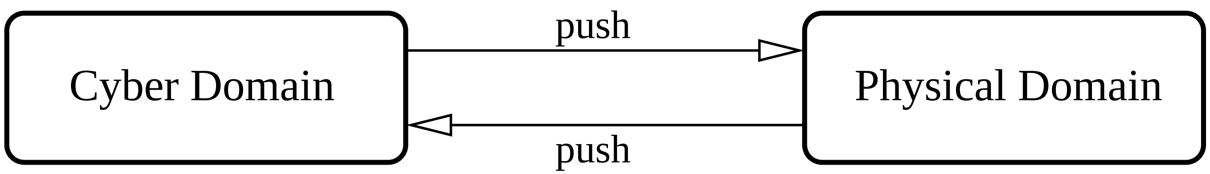
Programmable Contact Lens



Programmable Windows

CyberPhysical Systems

CyberPhysical 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.

CyberPhysical Systems

Many modern engineering systems are a combination of physical and computational/software systems.

Physical System Concerns

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

Software System Concerns

1. Design success corresponds to notions of correctness of functionality and timeliness of computation.
2. Computational systems are **discrete and inherently logical.** Notions of energy conservation ...etc... and differential equations do not apply.
3. Does not make sense to apply a safety factor. If a computational strategy is logically incorrect, then "saying it louder" will not fix anything.
4. The main benefit of software is that ...

   ... functionality can be programmed and then re-programmed at a later date.

5. A small logical error can result in a system-wide failure.

CyberPhysical Systems

CPS Research Challenges

- Today, CS is boolean – a system either works or it doesn't. CS needs to ...

  ... move from exact to approximate so that it can quantitatively evaluate systems having high levels of reliability.

- CPS systems are dynamic, and maybe nonlinear. Optimization and control procedures that do not recognize this are probably sub-optimal.
- Modern vehicles have 100 million of lines of code, so manual methods of validation don't work. We need ...

  ... formal methods for designing reliable software.

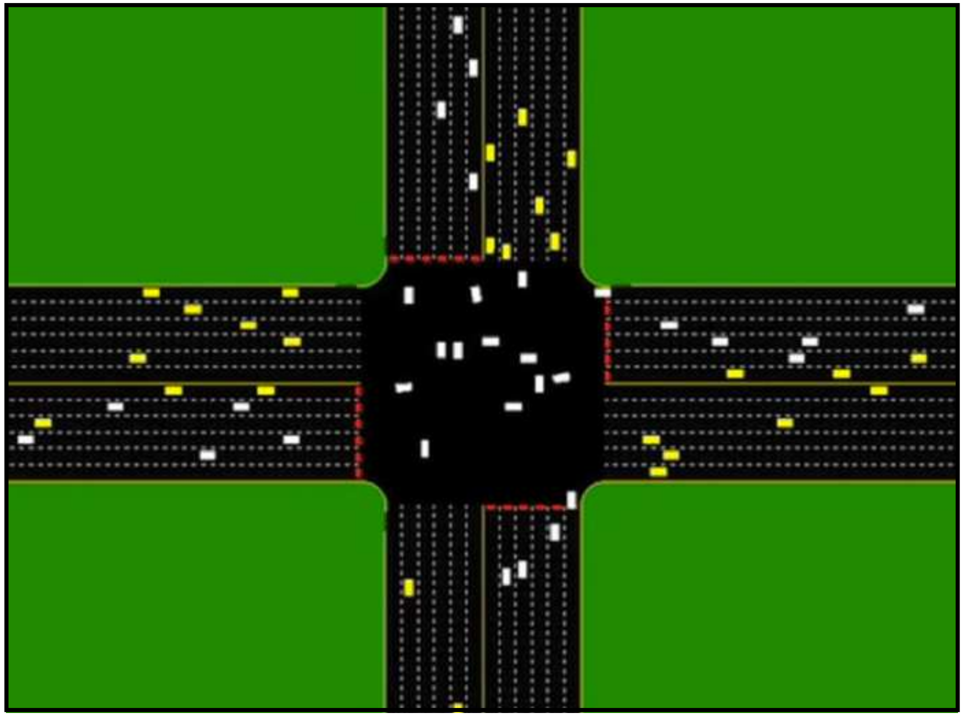
- System integration is HARD. Integration reveals ...

  ... interactions that were not considered and/or are incomplete or have inconsistent requirements.

  Platform-based design methdologies and model-based design offer approaches that reduce development time, cost and increase quality.

CyberPhysical Systems

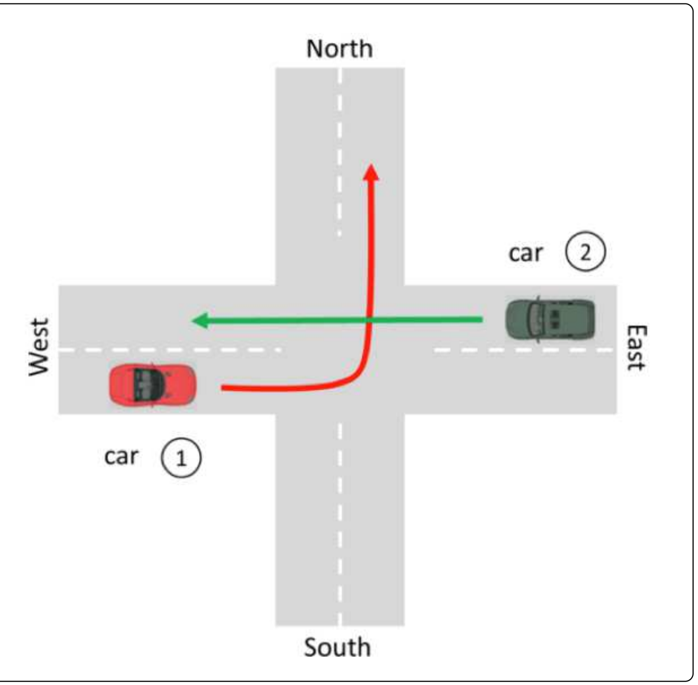
Case Study: Behavior of Self-Driving Cars at a Busy Traffic Intersection (2017 – 2025).

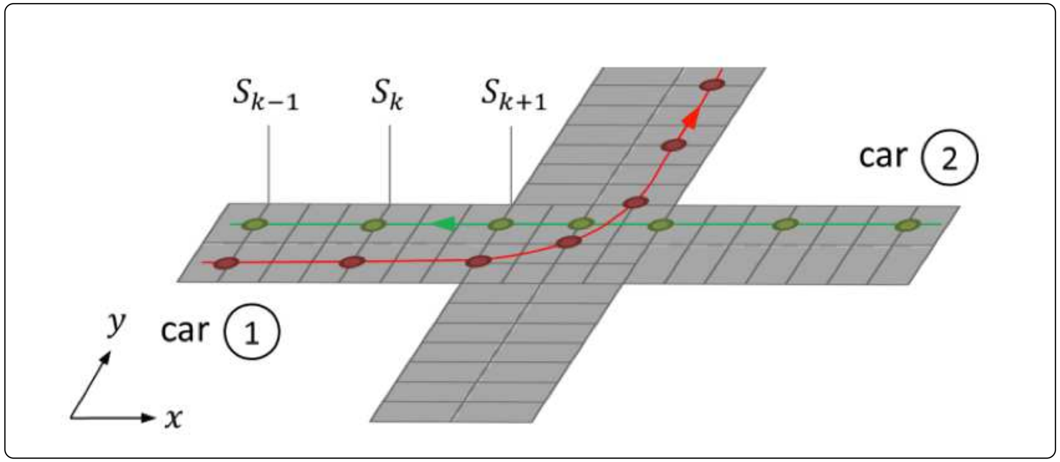


Stop signs and traffic lights are replaced by mechanisms for vehicle-to-vehicle communication (Adapted from http:citylab.com).

Case Study B: Self-Driving Cars at a Busy Traffic Intersection

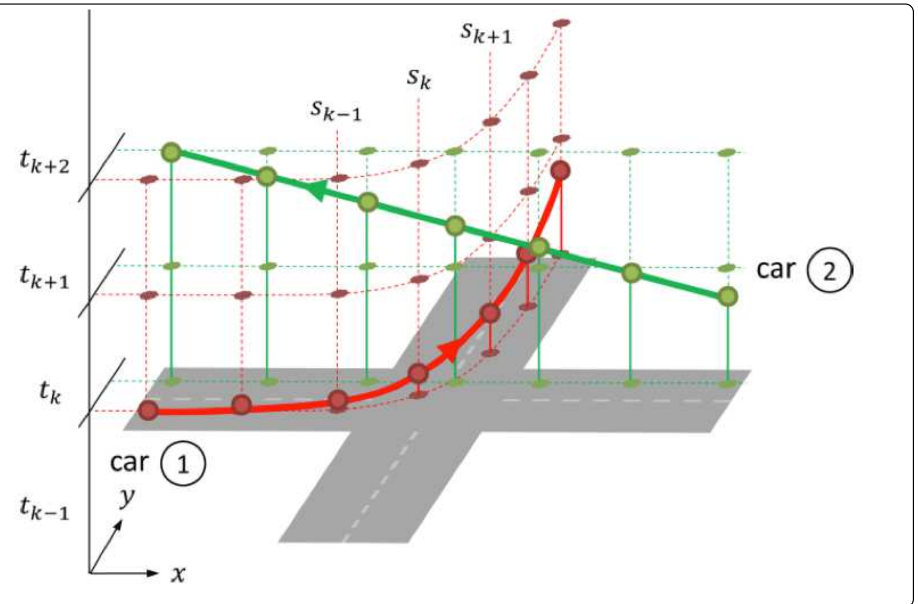
Simplified Approach to Safety: Reservation Model ....

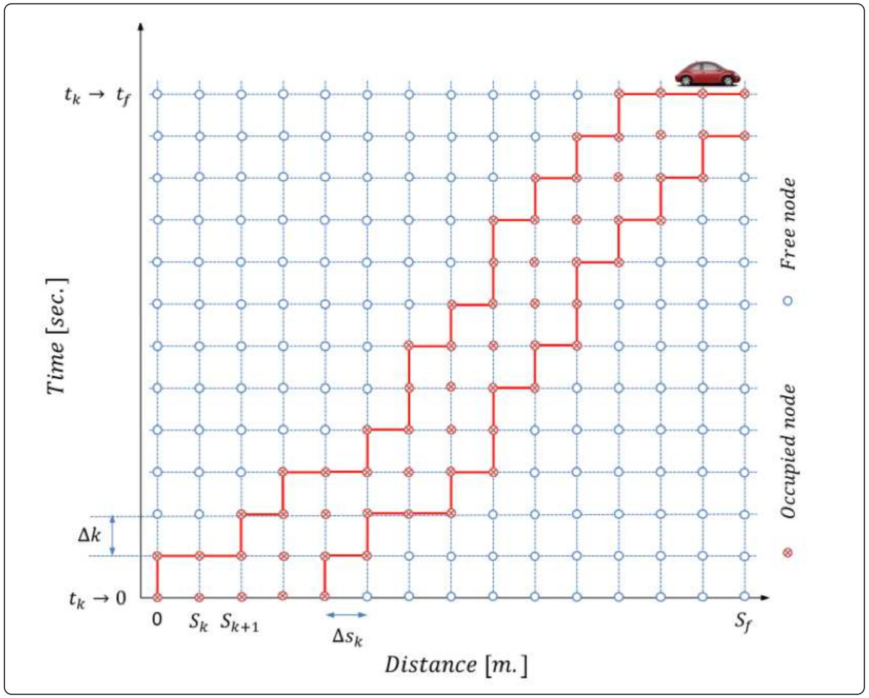




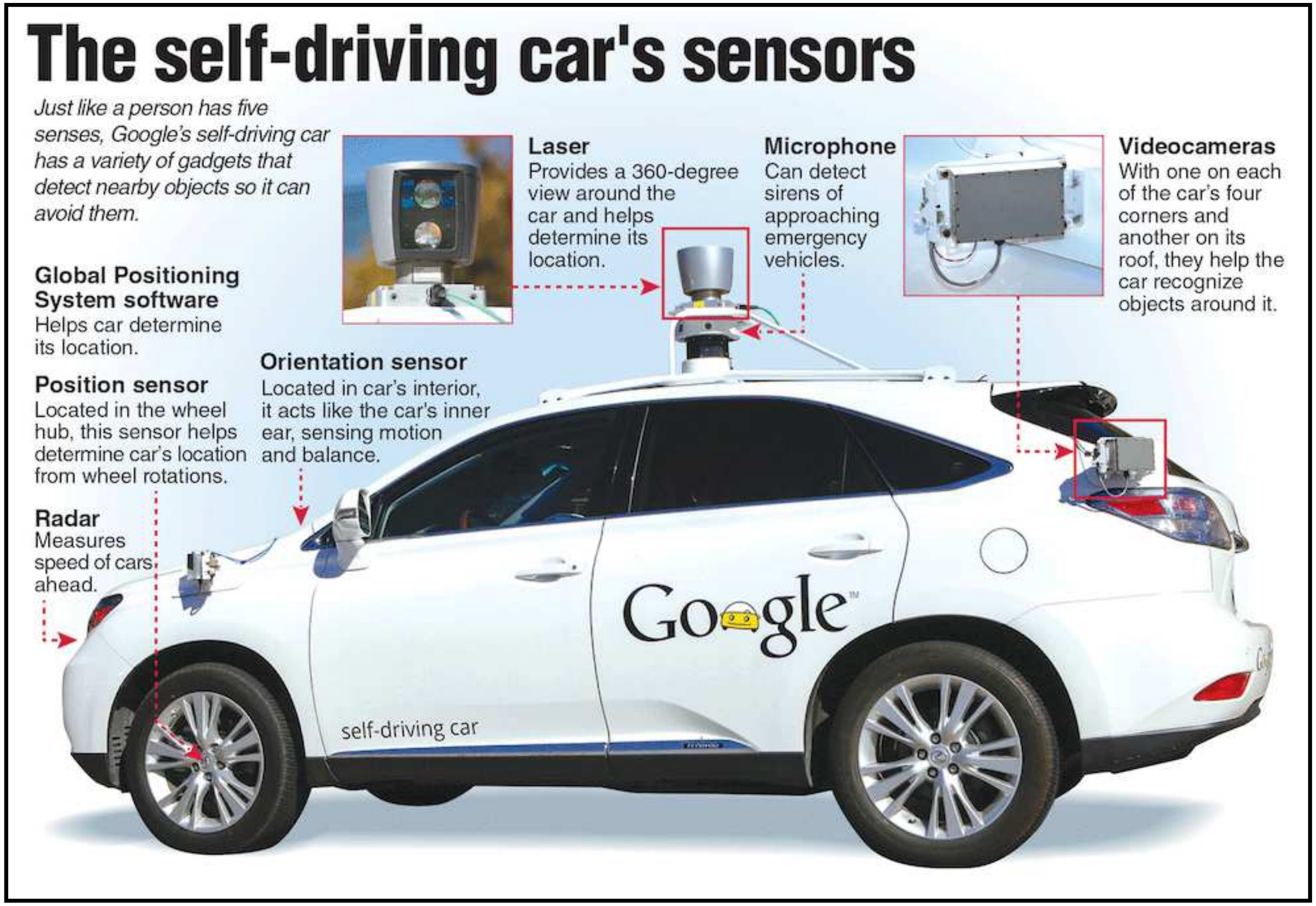
Case Study B: Self-Driving Cars at a Busy Traffic Intersection

Simplified Approach to Safety: Reservation Model ....



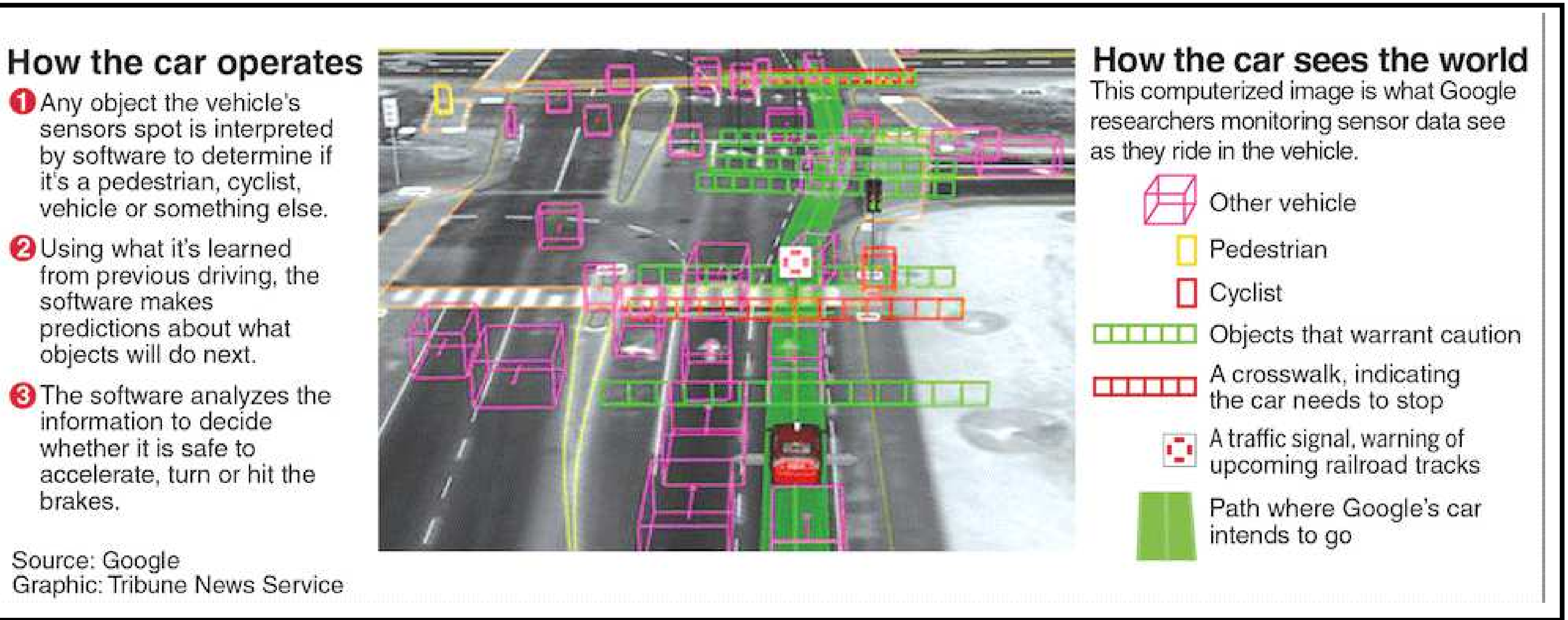


Case Study B: Self-Driving Cars at a Busy Traffic Intersection



CyberPhysical Systems

Case Study B: Self-Driving Cars at a Busy Traffic Intersection



Today: Modern automobiles → 100 million lines of software.

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

Part 5. Recurring Themes

Recurring Themes

- Many Civil Engineering Systems can be ...

  ... modeled as either networks or networks-of-networks.

- We need to design and manage the interactions among networked systems.
- Information-age systems offer enhanced functionality and beter 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!

References

Background and Motivation

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