Cyberinfrastructure and the Role of Computer Networking

CSE 3300/5299: Computer Networking

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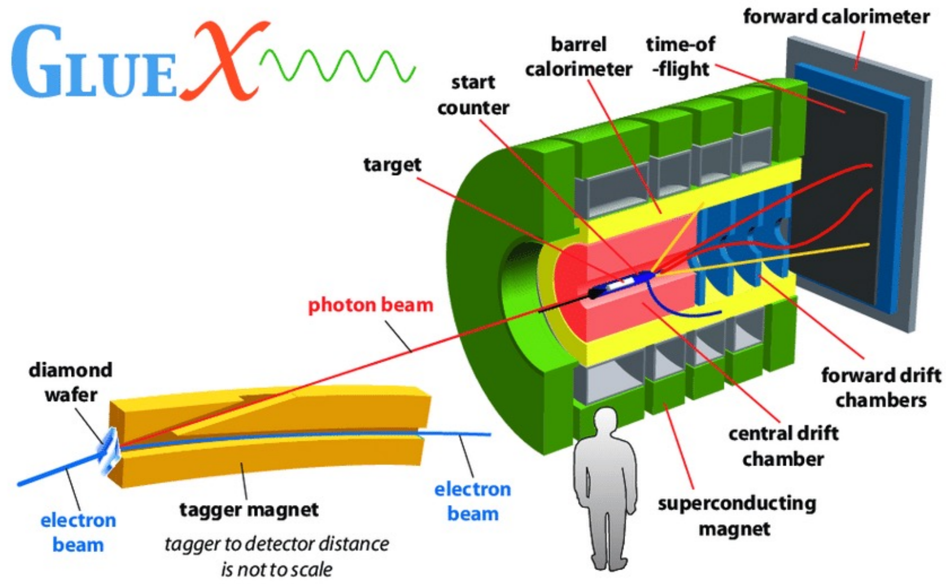
Some materials contributed by Prof. Suining He.

What is Cyberinfrastructure (CI)?

- computing systems, data, sensors, software, visualization environments, and people
- all linked by computer networks to make innovation and discoveries not otherwise possible.
- In general, information technology systems that provide powerful and advanced capabilities.

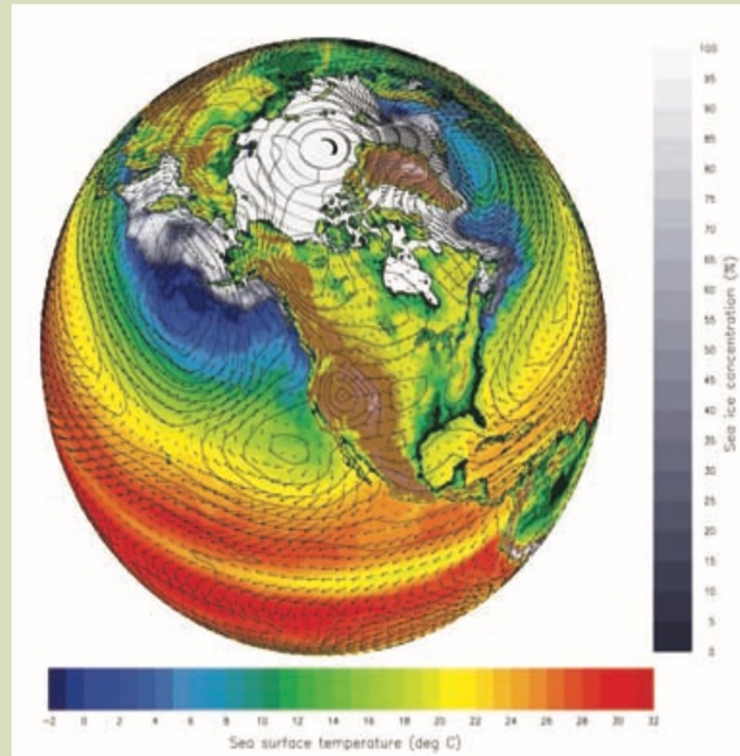
CI Enables Scientific Discoveries & Innovations

- GlueX: multi-country particle physics project
  - search for and study hybrid mesons
  - Physics apparatus, simulation
  - Large data transfer and collaborative simulation
    - massive instances of simulation code distributed over large number of computers in the Internet



CI Enables Scientific Discoveries & Innovations: All Scientific Areas

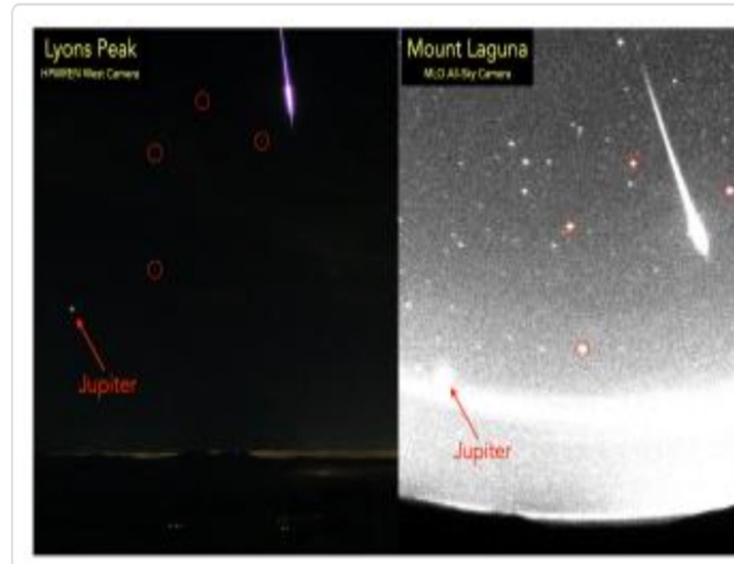
Images produced by Montage on SDSC TeraGrid from the 2MASS all-sky survey, provide astronomers with new insights into the large-scale structure of the Milky Way.



Results from the Parallel Climate Model, prepared from data in the Earth System Grid, depict wind vectors, surface pressure, seas surface temperature and sea ice concentration.

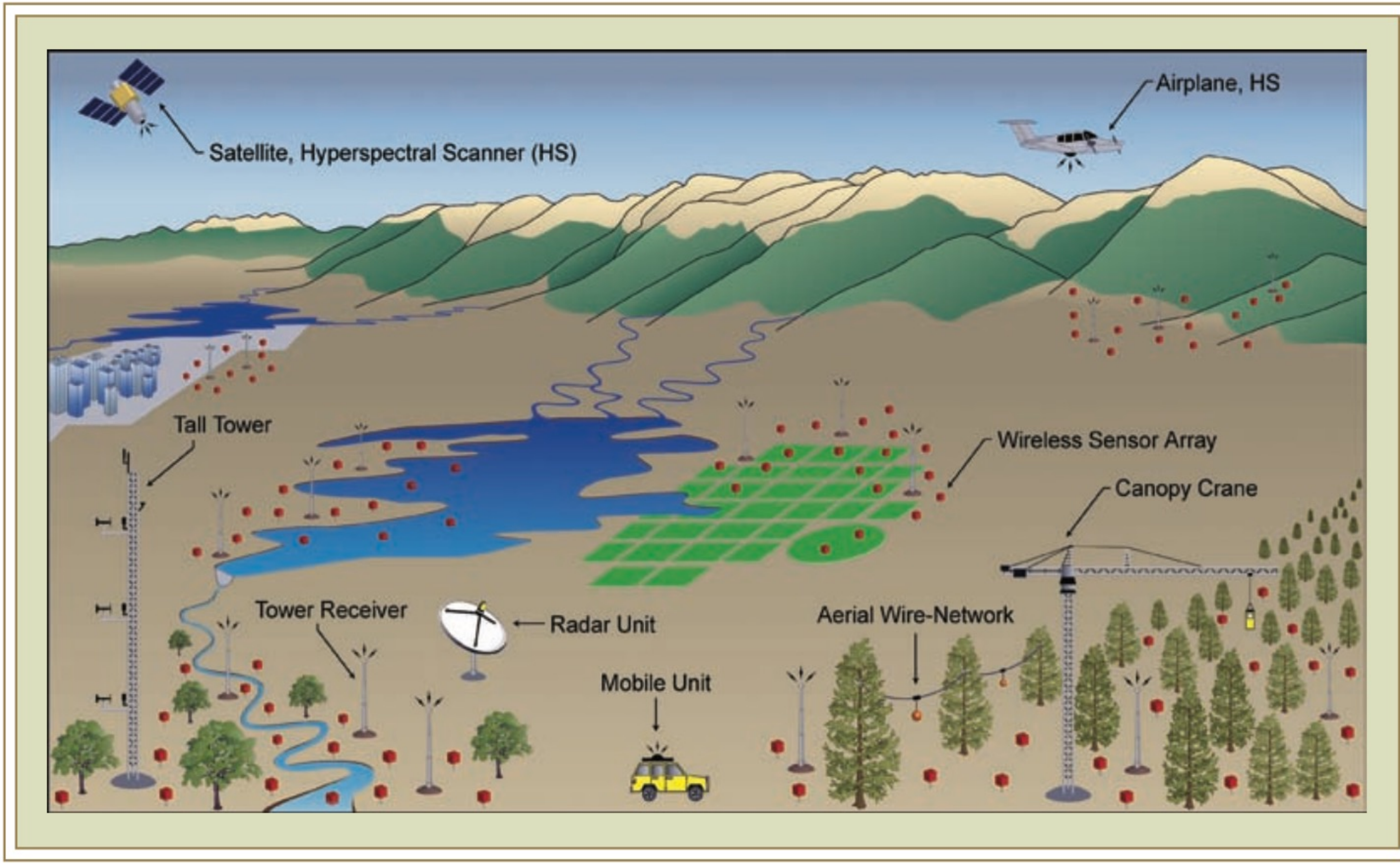
CI Enables Scientific Discoveries & Innovations: All Scientific Areas (cont'd)

HPWREN, a high performance wireless research network, expands he reach of cyberinfrastructure into remote environments in and sur- ounding San Diego County to support a range of science, engineering ducation, and emergency response initiatives.

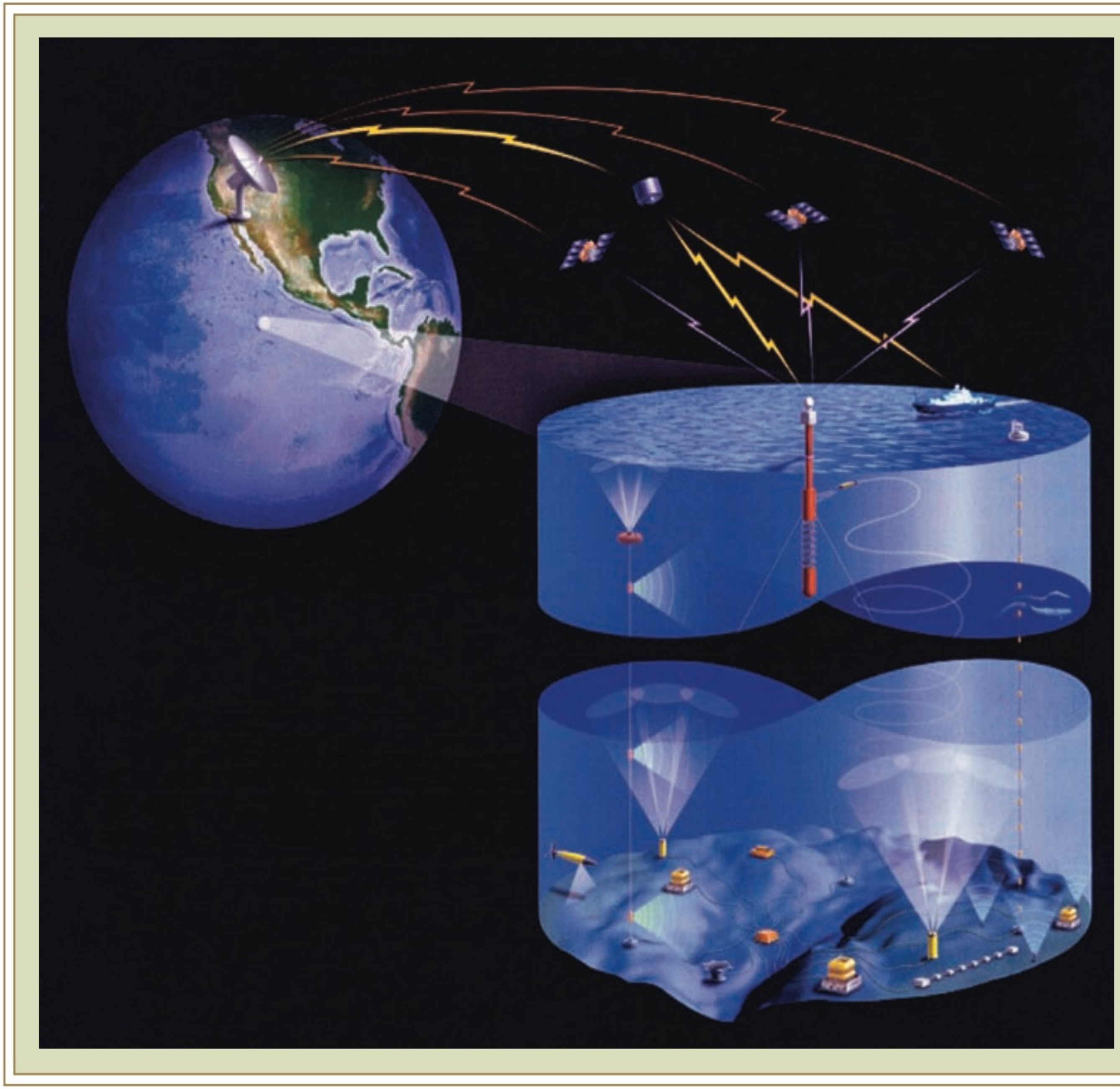


Meteor images

Example CI System: National Ecological Observatory Network (NEON)



Example CI System: Ocean Observatory

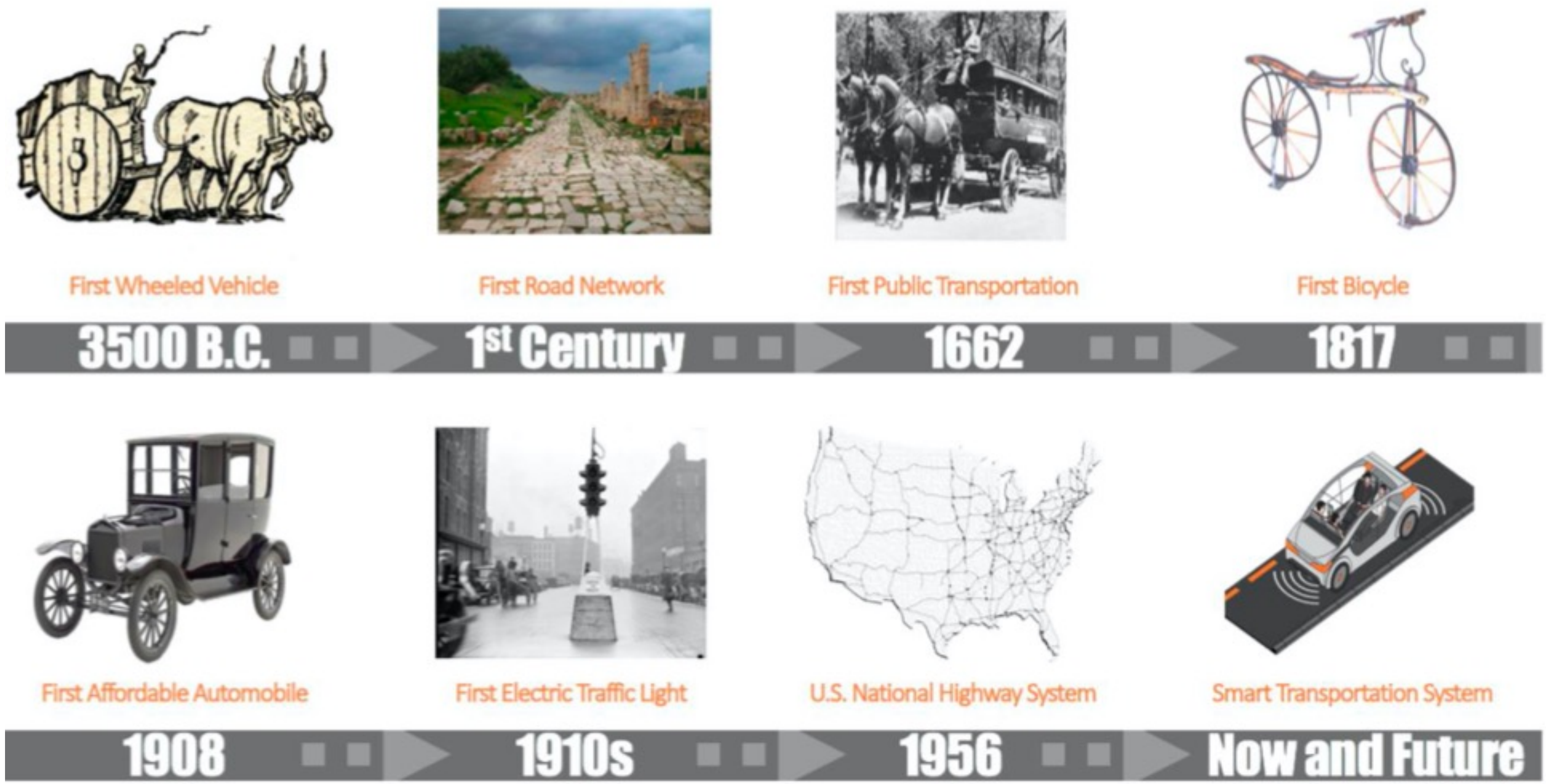


The Ocean Observatories Initiative promises to provide the ocean sciences research community sustained, long-term and adaptive measurements in the oceans via a fully operational research observatory system.

What will we cover?

- CI system case study: smart transportation
- Main components in CI system
- Role of computer networking
- Interaction of computer networking with other components

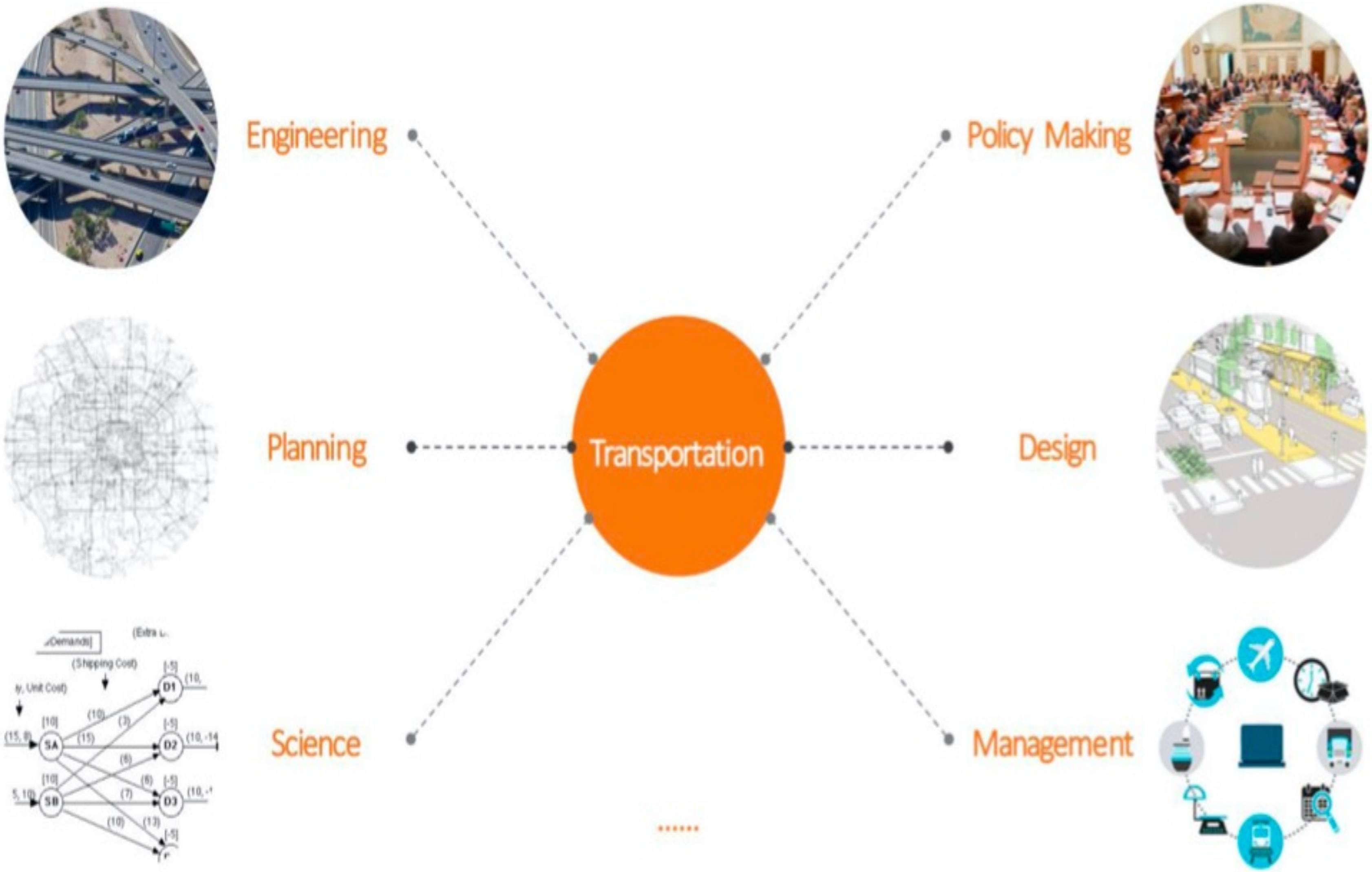
History of Urban Transportation



Transportation Nowadays

- Traffic congestion…
- Traffic accidents…

Smart Transportation



Emerging areas: ride sharing, bike sharing…

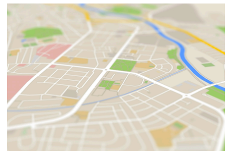
Smart Transportation: Applications

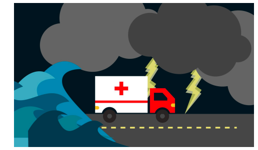
- Route navigation
  - e.g., waze, live traffic conditions
- Traffic predictive modeling
  - Predict speed (how fast cars are driving)
  - Predict traffic flow (traffic goes from one road to another)
  - Traffic accident risk prediction
- Road planning
- Disaster route navigation
- Arrival time estimation
- …

These applications are supported by components of CI

CI Case Study: Smart Transportation

Visualization



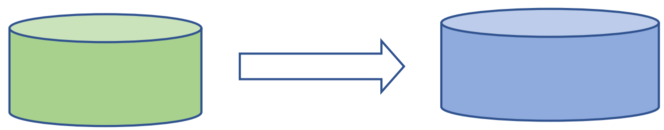


Data analytics & discovery

- Traffic modeling
- Traffic speed prediction
- Traffic flow prediction
- Route navigation
- Road planning
- Disaster route navigation

Data storage & synthesis

Realtime data



Historic data

Data acquisition & transfer

Main Components of CI

- Data acquisition and transfer
- Data storage and synthesis
- Data analytics and discovery
- Visualization
  - Maps, routes, graphs, …

Computer networking is the glue:

- Transfer data
- Transfer analytics results
- Transfer visualization results
- Complex interactions with other components

Data Acquisition

- Road infrastructure sensors
  - Loop detectors, traffic cameras, radars
  - Electronic Toll Collection (ETC)
  - Automatic fare collection (subways/buses/taxis)
- Ubiquitous sensing
  - Mobile devices with GPS enabled (in cars, buses)
- Other (non-traditional) sources
  - Accident reports
  - Social networking
  - Weather conditions
  - Satellite images
  - …

Challenges of Data Acquisition

- Heterogeneous sensors
  - Customized approaches for data acquisition
  - Different data characteristics (videos, images, counting)
- Sensor reliability
  - Calibration
  - limited battery
  - missing data, frequency of data collection
- Unreliable data transfer
  - Some form of data need to be transmitted out of sensors
  - Limited network bandwidth
    - Local processing, e.g., taking the mean of several sensor readings instead of sending individual data
- Privacy and security issues
  - e.g., Location data sensitive
    - Aggregate or perturbed data affect usability

What to do after data are collected?

- Data are at distributed locations
  - Single type of data: can be sparse, local view, not very useful for data analysis
- Traditional approach
  - Transfer data to a single location (e.g., cloud)
  - Drawbacks?
- Better approaches
  - Mobile edge computing
    - Transfer data to local edge servers (e.g., located at base stations)
    - processing at edge servers + cloud when needed
  - Devices + (edge servers) + cloud
    - Federated learning

First-hop Data Transfer

- Road infrastructure sensors
  - Loop detectors, traffic cameras, radars
  - Electronic Toll Collection (ETC)
  - Automatic fare collection (subways/buses/taxis)

Wired or wireless network

- Ubiquitous sensing
  - Mobile devices with GPS enabled (in cars, buses)

Wireless network

- Other sources
  - Accident reports
  - Social networking
  - Crowdsourcing system
  - Weather conditions
  - Satellite images…

Wired or wireless network

Data Transfer Requirement

- Application-driven delay requirement
  - Some need to be transferred before a deadline, otherwise not useful
    - e.g., real-time traffic prediction, disaster route navigation
  - Some are not delay sensitive
    - e.g., route planning (long-term effort)
- Reliability requirement
  - Some tolerate missing data, as long as sufficient amount (only need statistical results) are transferred
    - e.g., traffic flow prediction
  - Some require higher data transfer reliability
    - e.g., traffic accident risk analysis
  - In general, corrupted/faulty data need to be detected

Requirements dictated by applications!

Satisfying Data Transfer Requirements

- Transport protocols
  - Out-of-the-box TCP or UDP (e.g., in smartphone apps)
  - Directly on top of IP
    - no notion of transport protocol, e.g., on embedded devices
  - Specialized error detection/correction techniques
    - Based on characteristics of the communication channel
- Routing
  - One-hop transfer (e.g., over cellular network, 5G supports massive machine-type communication)
  - Multi-hop network (e.g., multi-hop zigbee network)
- MAC
  - Standard or specialized MAC
- Power control
  - Control the transmission power of wireless devices
  - Tradeoffs in throughput, energy consumption, interference, and topology (in multi-hop network)

Secure and Privacy-preserving Data Transfer

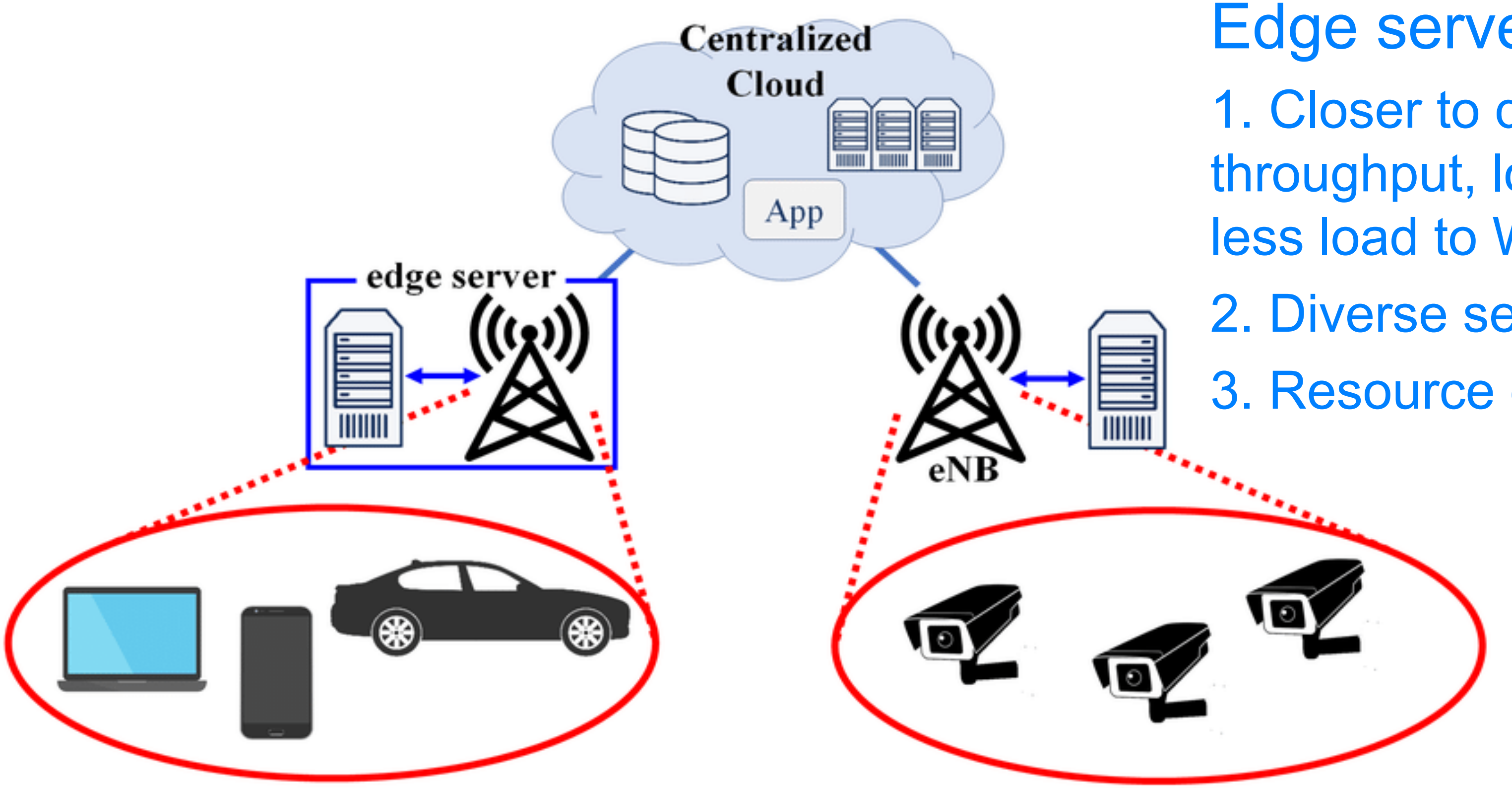
- Security (confidentiality, integrity)
  - Standard techniques
    - Authentication, TLS, IPSec, message authentication code, those developed for wireless networks
  - Customized encryption/decryption techniques
    - e.g., for embedded devices with low memory, computation capabilities
- Privacy preserving
  - Human data (e.g., location) is sensitive
  - Location cloaking: a large region is returned instead of precise location
  - K-anonymity: make a user’s location indistinguishable from k-1 other users
  - Aggregation
    - only record the number and (average) velocity of cars at intersections, highway tunnels, or ramps
  - …

Other Architectures

- Mobile edge computing
  - Transfer data to local edge servers (e.g., located at base stations)
  - processing at edge servers + cloud when needed
  - Low latency, reduce congestion in wide-area network
- Federated Learning: Devices + (edge servers) + cloud
  - Data stay at devices
    - Only transfer meta-data, summary data or machine learning model parameters
    - Much less data need to be transferred
  - Privacy preserving
    - Particularly suitable for sensitive applications (e.g., health)

Mobile Edge Computing (MEC)

Also called multi-access edge computing



Edge servers:

1. Closer to devices (higher throughput, lower latency, less load to WAN)
2. Diverse servers
3. Resource constrained

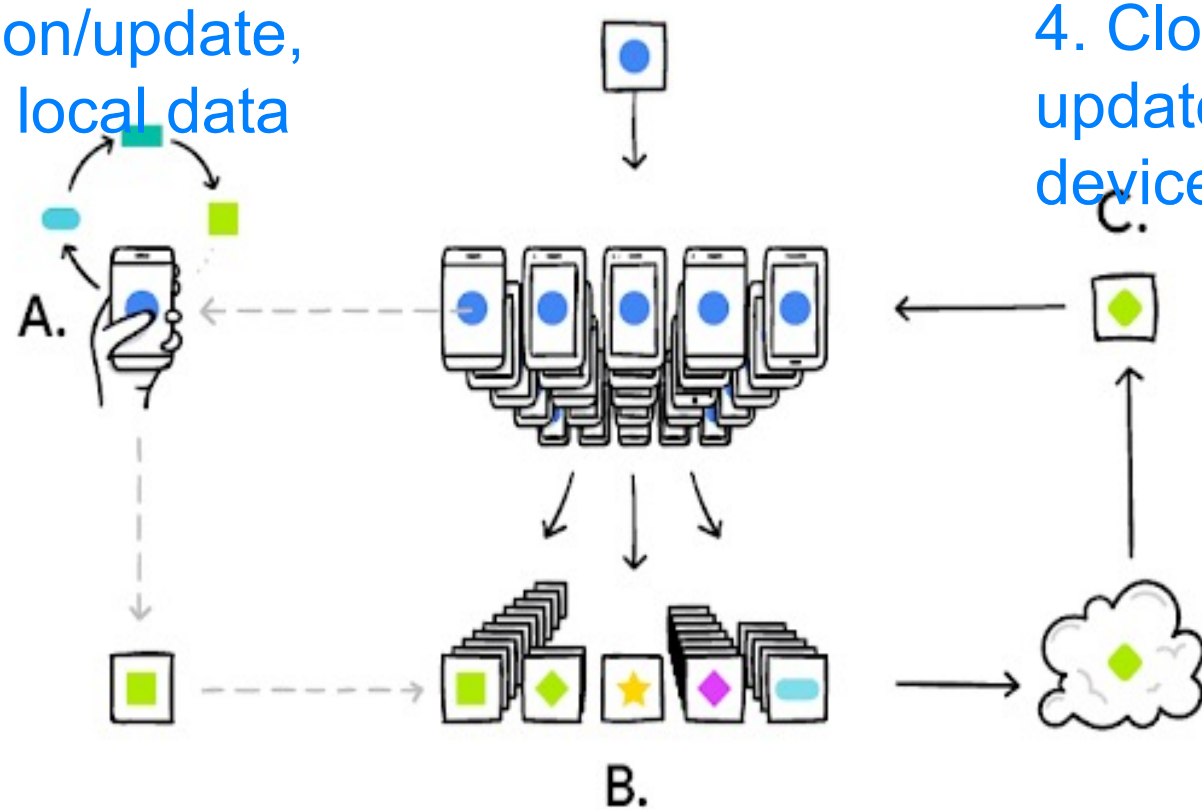
- Research problems
  - Offloading: what to offload to edge server and to cloud
  - Resource allocation: heterogeneous devices and requirements, fairness, optimize overall latency/energy consumption, communication and computation tradeoffs

Federated Learning: Main Idea

5. Devices update local models

1. devices: local iteration/update, using local data

4. Cloud transmits updated model to devices



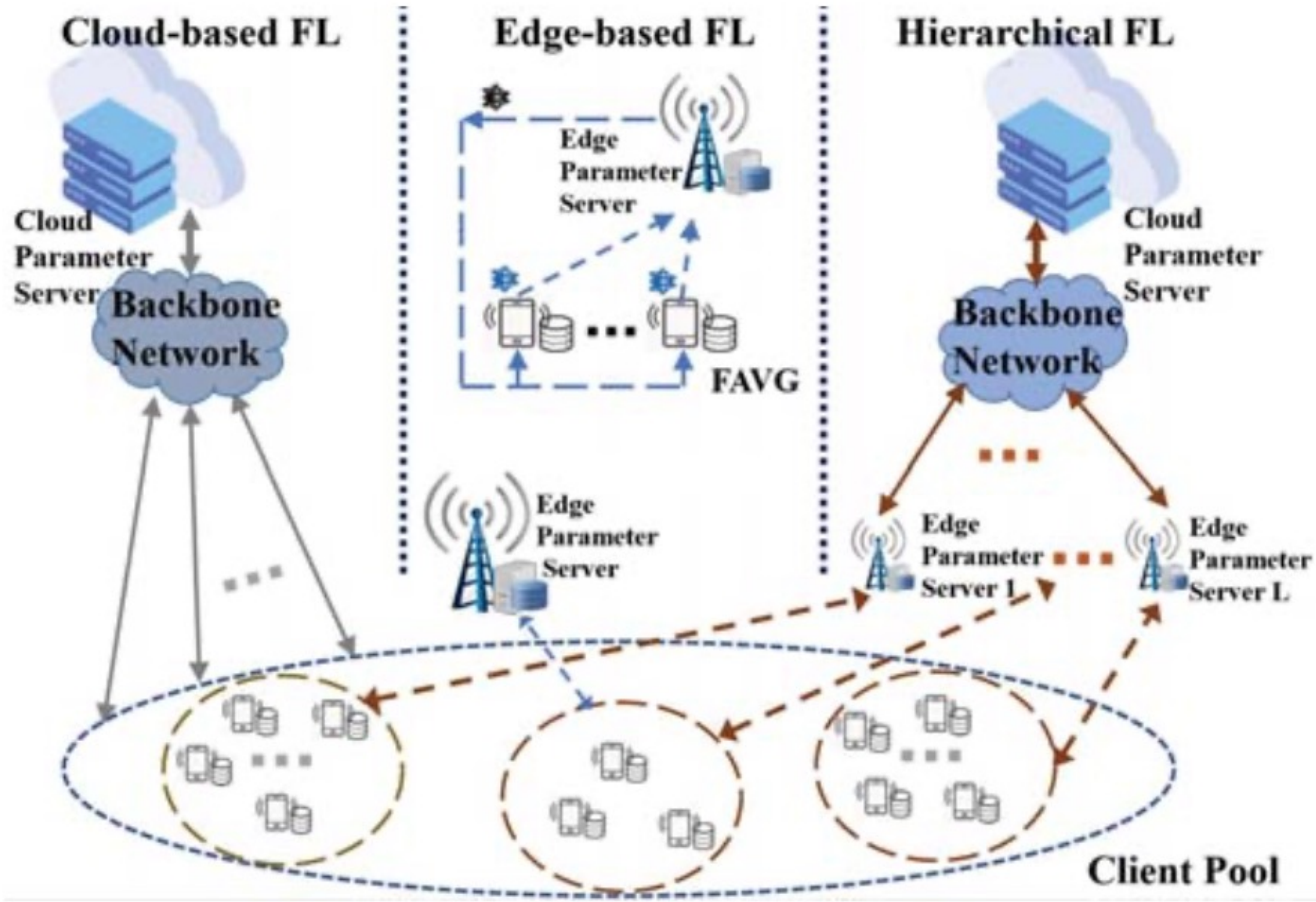
2. Devices transmit model parameters to cloud

3. Cloud: global aggregation

Federated Learning: Advantages and Challenges

- Decentralized learning: in iterations
  - Devices never send raw data to cloud
    - Low communication overhead
    - Preserving privacy
    - but local device data is limited and potentially skewed
  - Cloud server aggregates models from devices
    - Sort of using all the data from devices
  - New model is better than individual local models
  - Devices update to new model
- Research problems
  - Local device data not independent and identically distributed (i.i.d.)
  - Constraints of communication networks
    - Update frequency, user selection, straggler problem
  - …

Federated Learning Architectures



- 2-layer devices+edge or devices+cloud
- 3-layer architecture: devices+edge+cloud
- Consider constraints in communication and computation

Summary

- What is CI?
- Importance of CI
- Case study: smart transportation
- Data acquisition and transfer in CI
- Data collection and analysis architectures

Many open problems, exciting and fast evolving area!

What can you do?

- Use CI in scientific and engineering domains
- Develop, deploy, expand, maintain CI

References

1. CyberinfrastruCture Vision for 21st Century Discovery, National Science Foundation, Cyberinfrastructure Council March 2007
2. Privacy-preserving techniques for location-based services. Article in SIGSPATIAL Special · January 2008
3. https://en.wikipedia.org/wiki/Multi-access_edge_computing
4. https://ai.googleblog.com/2017/04/federated-learning-collaborative.html
5. Client-Edge-Cloud Hierarchical Federated Learning, Lumin Liu, Jun Zhang, S.H. Song, and Khaled B. Letaief, IEEE ICC 2020.

Suining’s comments:

- Slide 18: Ubiquitous Sensing is not limited to mobile devices or GPS, but also with on-board sensors/sensing/communication techniques such as LIDAR and DSRC.
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- Slide 24: Intro of FL might need some context layout of application scenarios. For instance, FL might help learn personal/local features of the human health data. Model parameters, such as gradients (explicit intro of this context would also help), instead of explicit data sharing, will help preserve the privacy.