Foundations of Cyberphysical Systems

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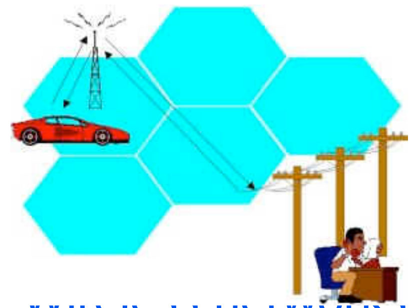
Several paths to cyberphysical systems

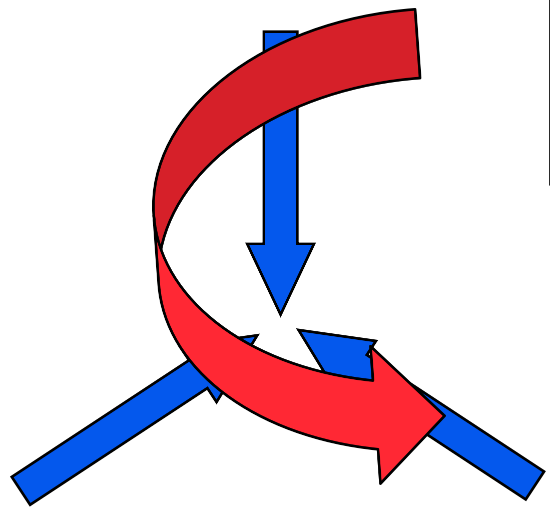
One path: From computation to real-time and hybrid systems

- Computers for computation (1949)
- Real-time computation (1973)
- Hybrid systems (1990s)
- Cyberphysical systems
  (Phrase coined around 2006)
  - “Instigators”: Gill, Kumar, Lee, Midkiff, Mok, Rajkumar, Sastry, Sha, Shin, Stankovic, Sztipanovits, …

Another path: From communication to sensing to acting

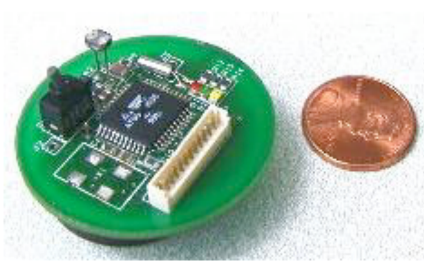


Cellular systems



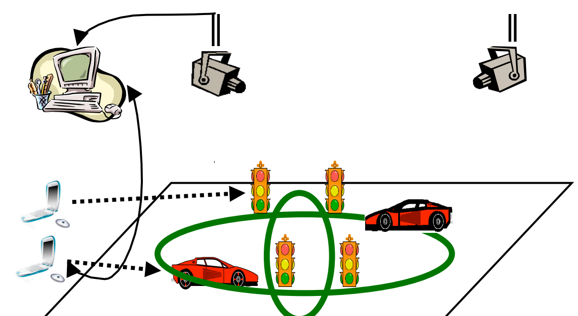
Convergence of communication, computation and control

Cyberphysical Systems



Sensor Networks

Networked Embedded Control



Yet another path

- First generation: Analog Control
  - Technology: Feedback amplifiers
  - Theory: Frequency domain analysis
    Bode, Evans, Nyquist
- Second generation: Digital Control
  - Around 1960
  - Technology: Digital computers
  - Theory: State-space design
  - Real-Time Scheduling

- Foundation of system theory
  - Linear systems
  - Nonlinear systems
  - Estimation
  - Optimal control
  - System identification
  - Adaptive control
  - Robust control
  - Discrete event systems
  - Hybrid systems
- Bouquet of books

The third generation of control

- Third generation: Networked Control
  - Embedded computers
  - Wireless and wired networks
  - Software

- Made possible by the convergence of computing, communication and control

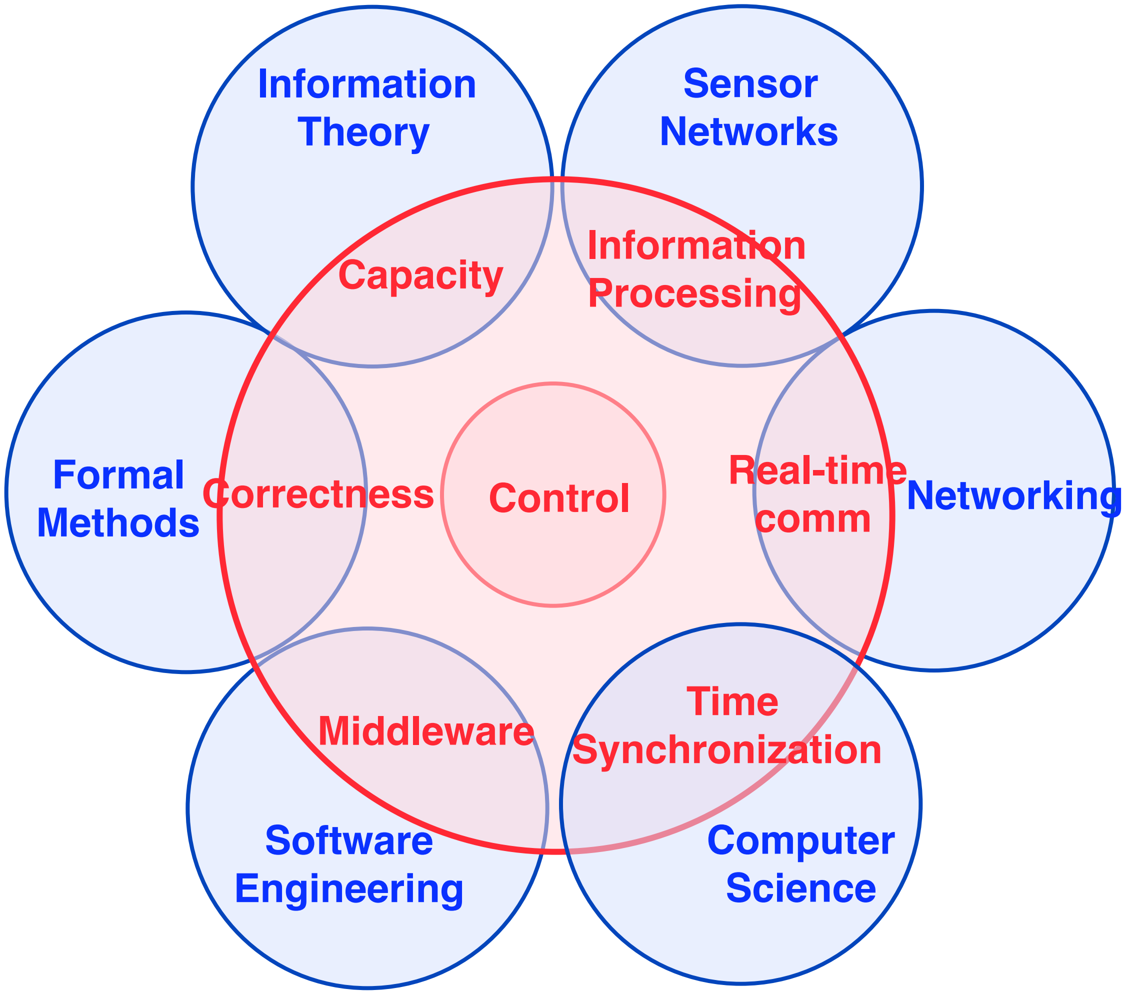
- Platform revolution

- Just in time for resource-aware system building era of 21st century
  - Zero-accident highways, smart grid, tele-operation rooms

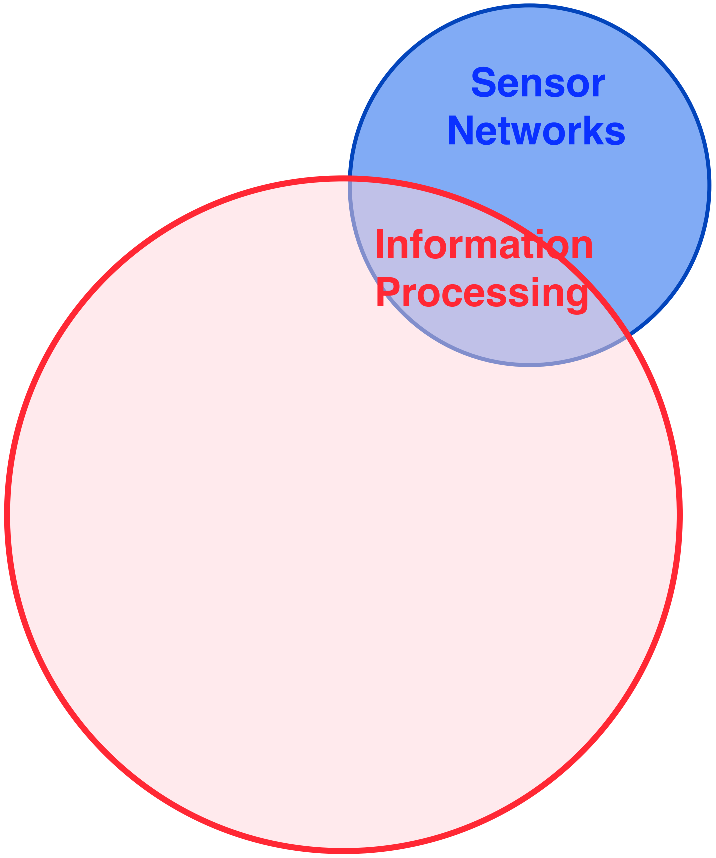
"What's in a name? That which we call a rose
By any other name would smell as sweet"

– Shakespeare

Foundational issues in cyberphysical systems

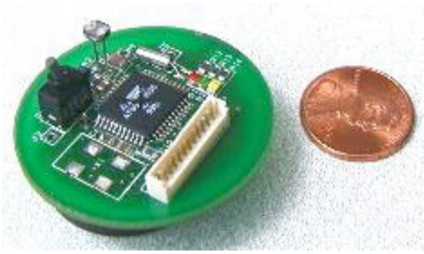


From data to information

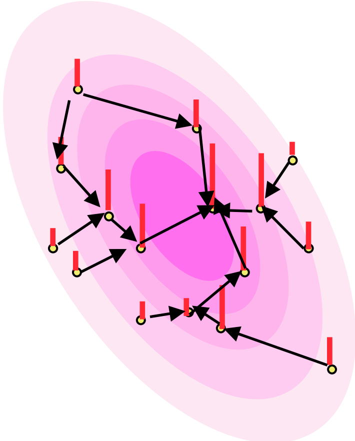


Information processing in networks

- Environmental monitoring
  - n nodes take temperature measurements $x_1, x_2, . . , x_n$
  - Determine the Mean temperature: $(x_1 + x_2 + \ldots + x_n)/n$



- Alarm networks
  - Determine the Max temperature: Max x_i

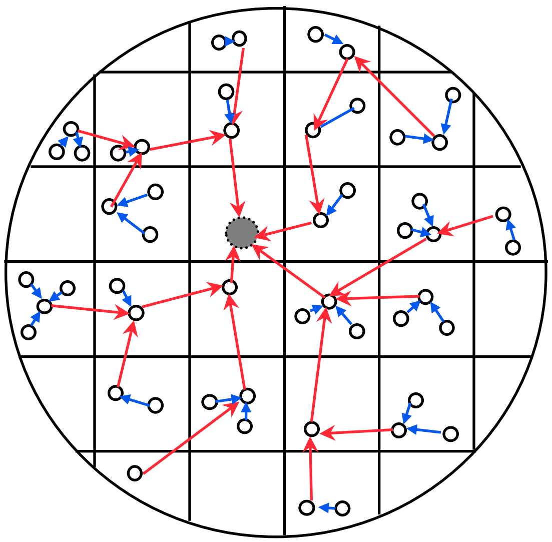


- Sensor networks are not data networks
  - Nodes can change/create/discard packets

- How should we process information in-network?

Mean versus *Max*

- **Theorem**: The Mean can be computed at rate $\Theta\left(\frac{1}{\log n}\right)$



- **Theorem**: The Max can be computed at rate $\Theta\left(\frac{1}{\log \log n}\right)$
  - Block Coding
    - First node announces times of max values: (1 1 1)
    - Second node announces times of additional max values: (1 1)
    - Third node announces of yet more max values: (1)

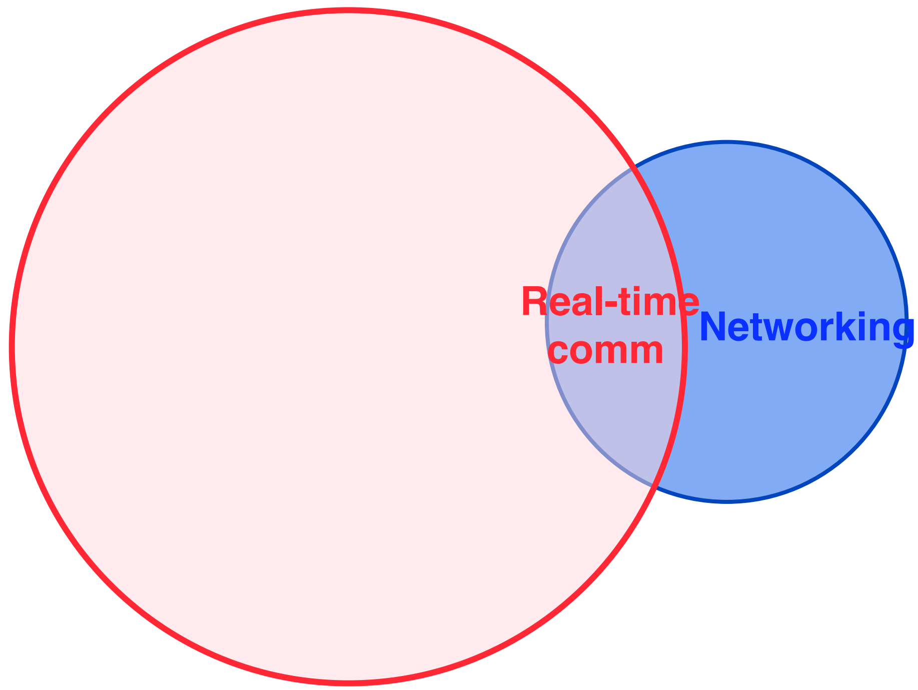
(Giridhar & K '03)

Complexity hierarchy

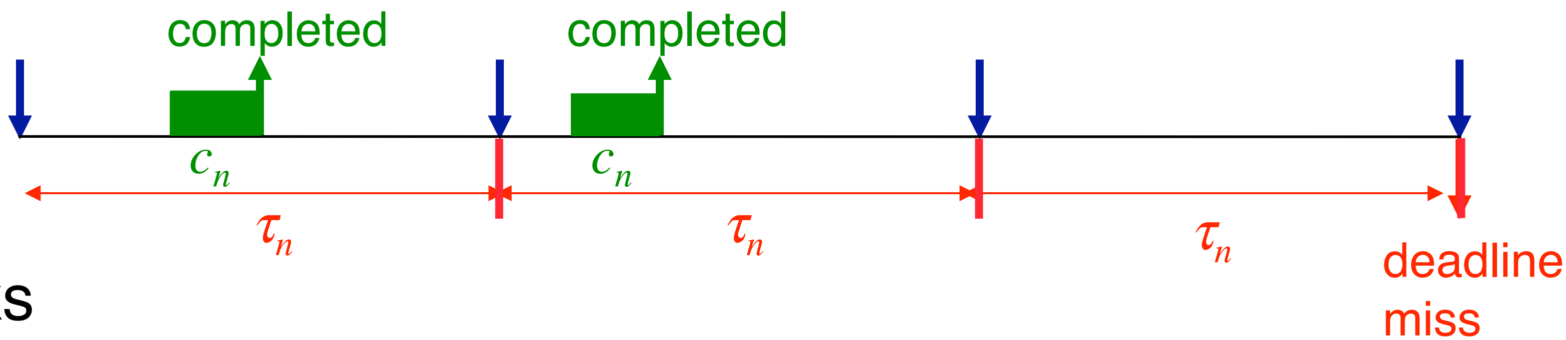
$\Theta\left(\frac{1}{n}\right)$	Downloading all data from all nodes	Collocated network: Mean, Mode, Type
$\Theta\left(\frac{1}{\log(n)}\right)$	Multi-hop random network: Mean, Mode, Type	Collocated network: Max
$\Theta\left(\frac{1}{\log\log(n)}\right)$	Multi-hop random network: Max	

(Giridhar & K '03)

Delivering packets on time



Real-time scheduling: (Liu and Layland `73)



- N tasks
  - Jobs of Task n arrive with period τ_n
  - Deadline is end of period
  - Worst case execution time c_n

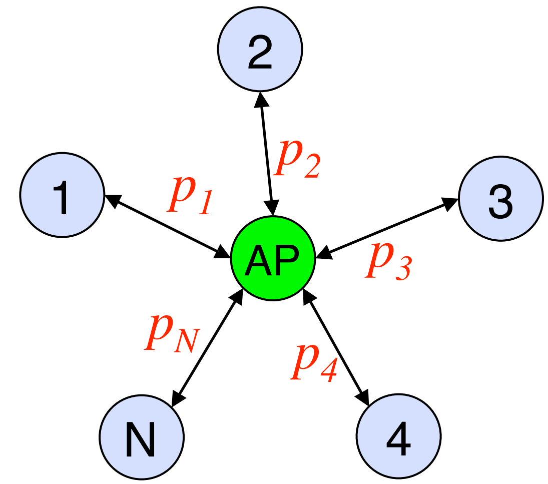
- Rate monotone scheduling: Priority to smallest period task

- All deadlines met if $\sum_{n=1}^{N} \frac{c_n}{\tau_n} \leq N(2^{1/N} - 1)$ $(\rightarrow \ln 2 = 0.69$ as $N \rightarrow \infty)$

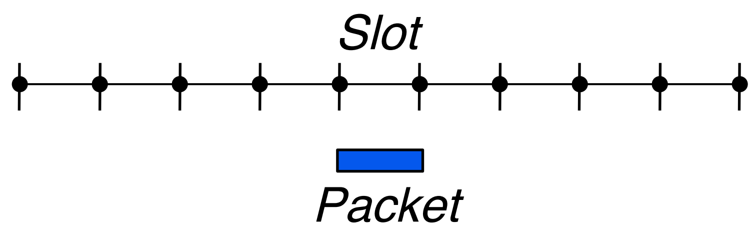
- If any priority policy can meet all deadlines, then this policy can

Formulation of real-time communication

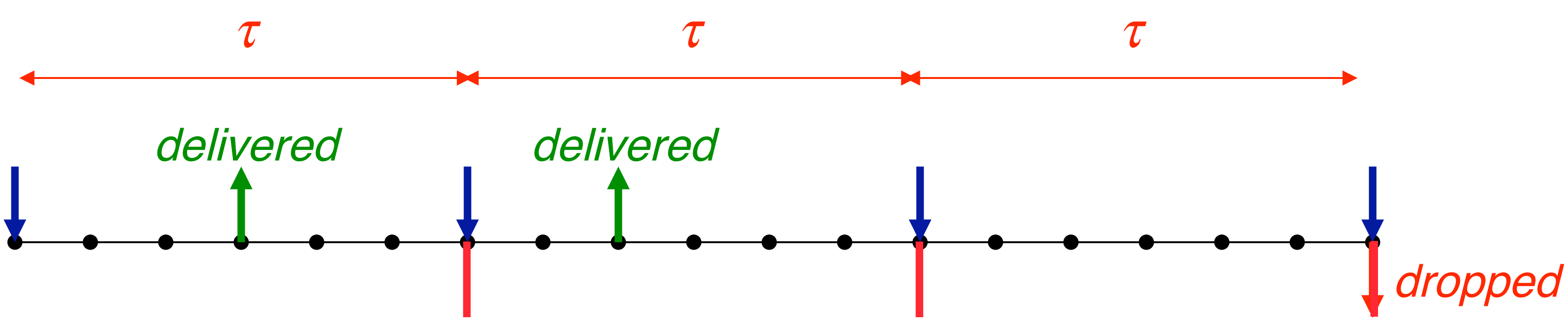
- Access Point serving N clients



- Slotted



- Unreliable channels

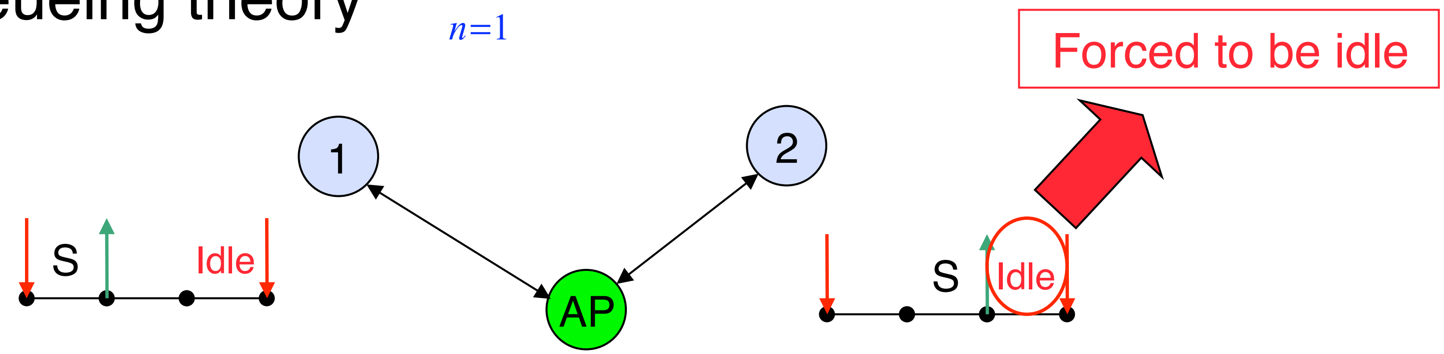


- Require *timely throughput* of q_n packets per period

- Are the requirements $\{(q_n, p_n, \tau), 1 \leq n \leq N\}$ feasible?

Characterization of feasibility

- Load due to Client n is $w_n = \dfrac{q_n}{p_n \tau}$
- Necessary condition from classical queueing theory $\sum_{n=1}^{N} w_n \leq 1$
- Unavoidable idle time



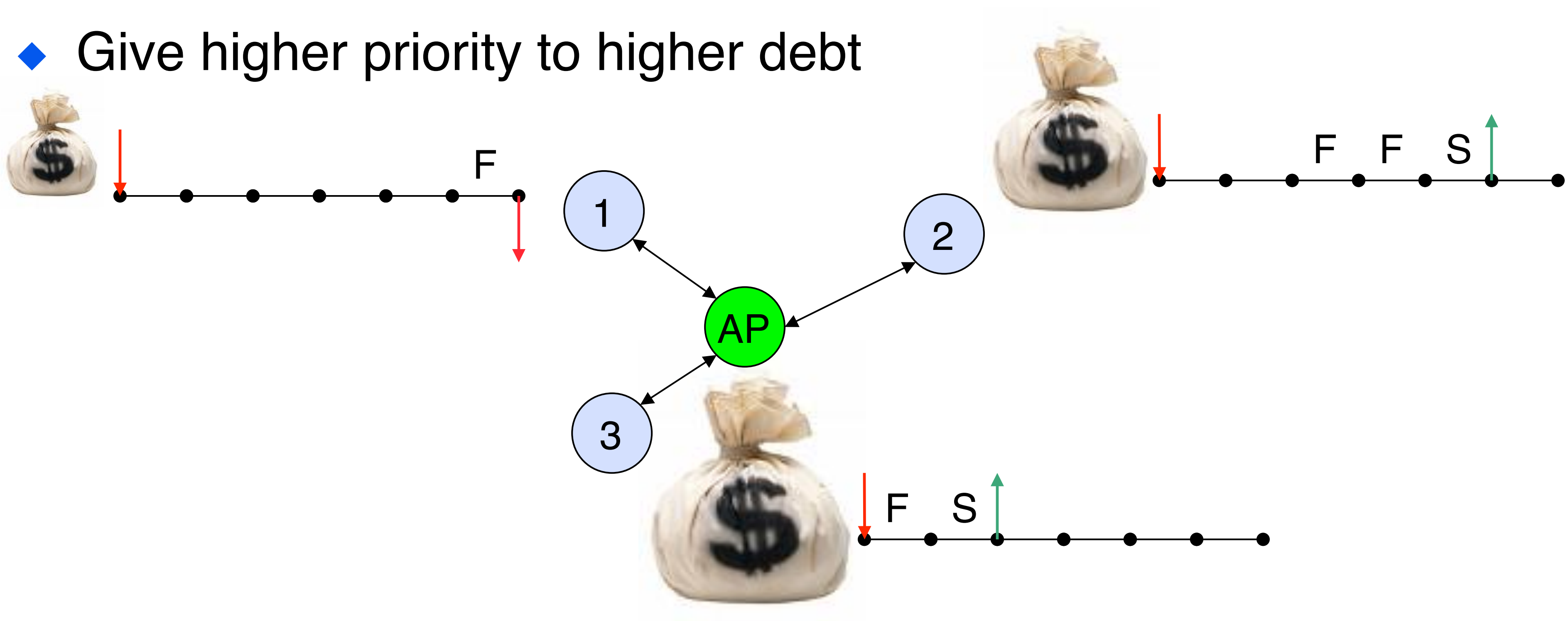
- But *every subset* of clients should also be feasible $\sum_{n=1}^{N} w_n + I(1,2,\ldots,N) \leq 1$
- **Theorem**: Feasible iff $\sum_{n \in S} w_n + I(S) \leq 1, \ \forall S \subseteq \{1,2,\ldots,N\}$

(Hou, Borkar & K 09)

Scheduling policies

- **Delivery debt** of Client n $= \dfrac{q_n - \text{Actual timely throughput to Client } n}{p_n}$

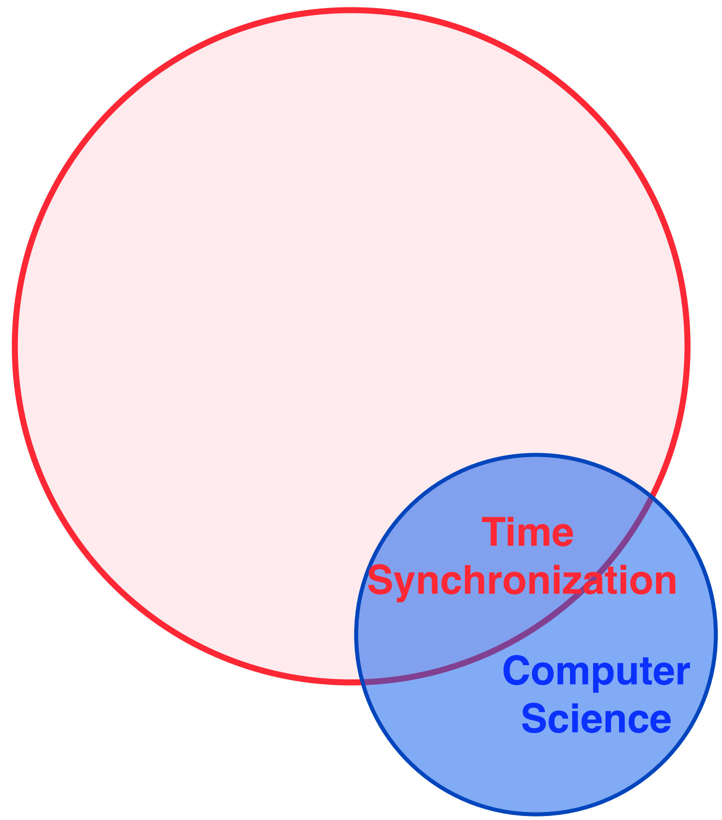
- Give higher priority to higher debt



- **Theorem:** This policy is feasibility optimal

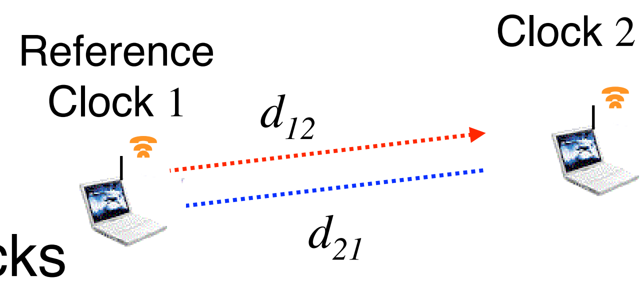
(Hou, Borkar & K 09)

Synchronizing clocks in a network



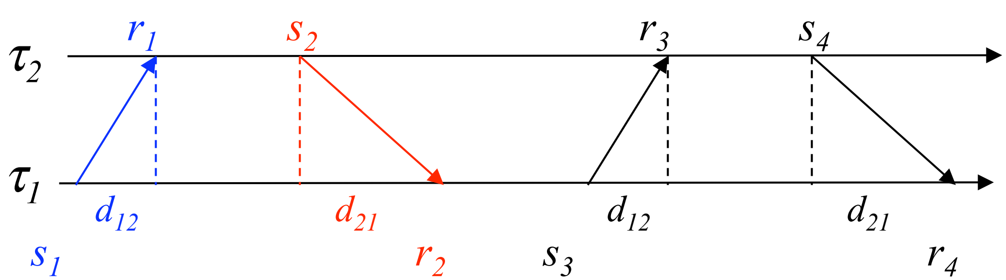
Clock synchronization

- Knowledge of time is important

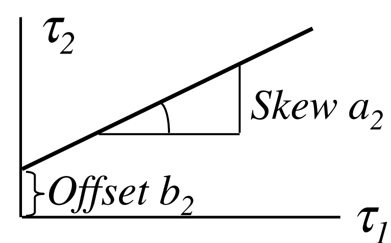


- **Theorem:** It is impossible to synchronize clocks

$$r_1 = a_2(s_1 + d_{12}) + b_2$$



$$s_2 = a_2(r_2 - d_{21}) + b_2$$



$$\begin{bmatrix} r_1 \\ s_2 \\ r_3 \\ s_4 \\ \cdots \end{bmatrix} = \begin{bmatrix} s_1 & 1 & 0 & 1 \\ r_2 & 0 & -1 & 1 \\ s_3 & 1 & 0 & 1 \\ r_4 & 0 & -1 & 1 \\ \cdots & \cdots & \cdots & \cdots \end{bmatrix} \begin{bmatrix} a_2 \\ a_2 d_{12} \\ a_2 d_{21} \\ b_2 \end{bmatrix}$$

Rank 3:
Cannot estimate
4 parameters

So assume symmetric delays

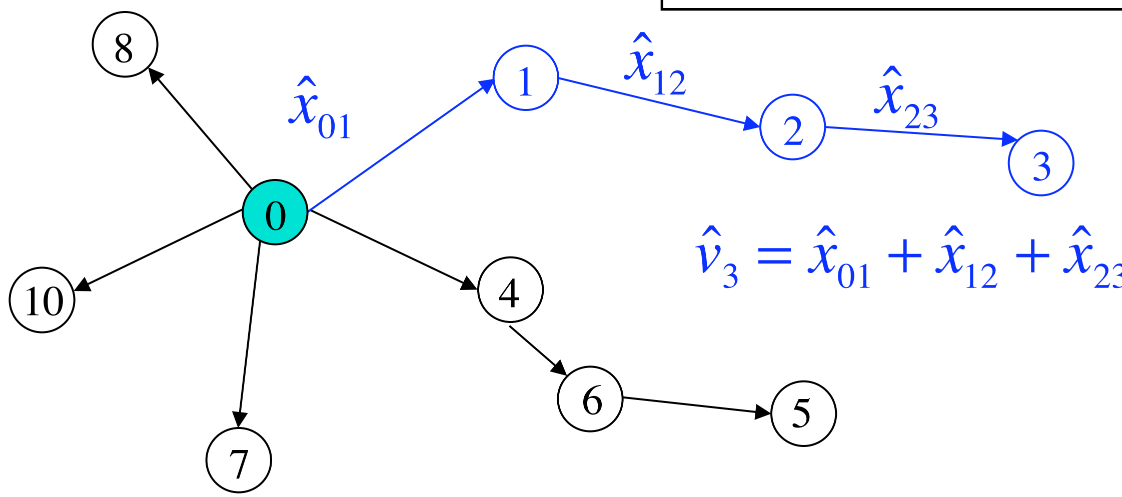
Noisy observations?
Network?

(Graham & K '04)

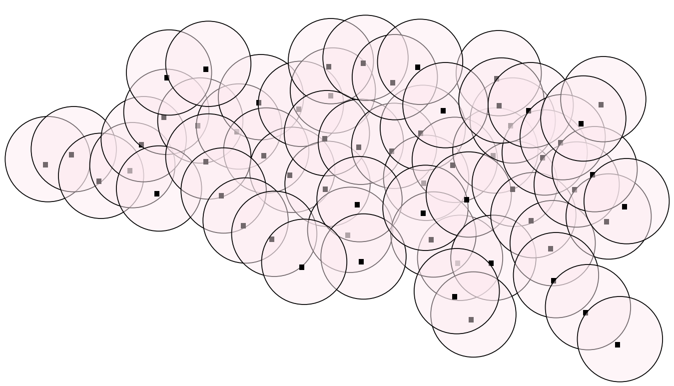
Traditional approach

- Std. Dev of Error $= \Theta\left(\sqrt{Diameter}\right)$

Assume all skews = 1



- Random multi-hop network with n nodes

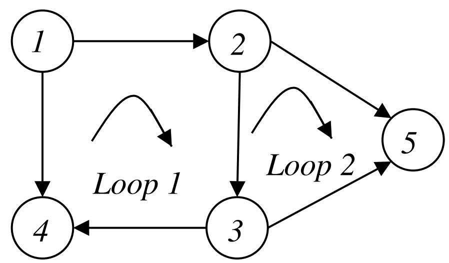


- Critical radius for connectivity $= \Omega\left(\sqrt{\frac{\log n}{n}}\right)$ (Gupta & K '98)
- Std. Dev of Error $= O\left(\left(\frac{n}{\log n}\right)^{1/4}\right)$
- Error grows polynomially
- Can we do better?

Improving synchronization

- Sum of offsets along any loop is zero

$$\sum_{e \in Directed\ Cycle} x_e = 0$$



$$x = A^T v$$

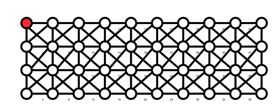
- Minimization problem: $\underset{\hat{v}}{\text{Min}} \left\| \hat{x} - A^T \hat{v} \right\|^2$
- Coordinate descent: Spatial smoothing

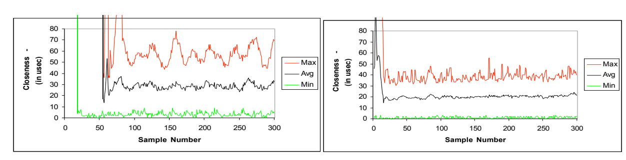
$$\hat{v}_{j,\text{new}} = \frac{1}{|N_j|} \sum_{\text{edges } (i,j)} \left(\hat{v}_{i,\text{old}} + \hat{x}_{ij} \right)$$

- Similarly for skew: $\sum_{e \in Directed\ Cycle} \log \hat{\alpha}_e = 0$

(Solis, Borkar and K '05)

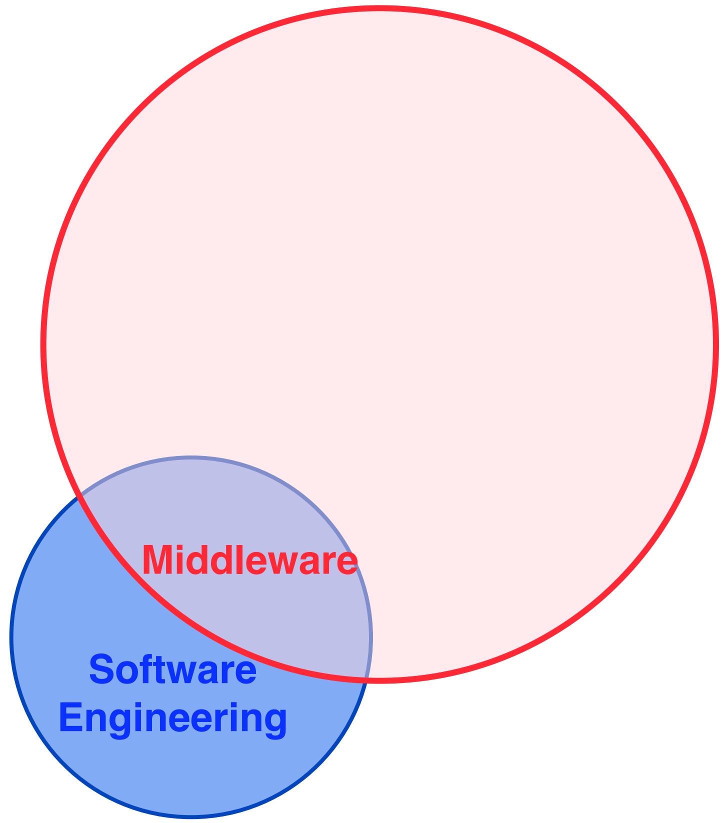
- **Theorem (Karp et al `03)**
  - Asymptotic error variance is *Resistance Distance* of network
- **Theorem**
  - Error is bounded for large random networks
  - Error = $O(1)$
- Lends support for feasibility of time-based computing



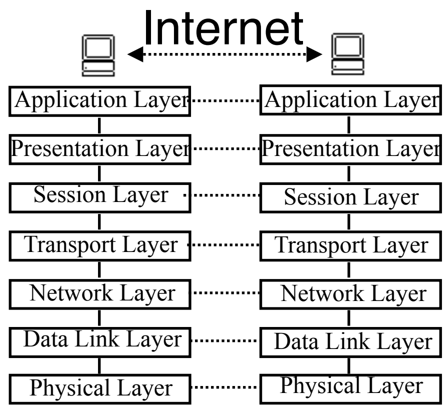


(Giridhar & K '06)

Abstractions and architecture



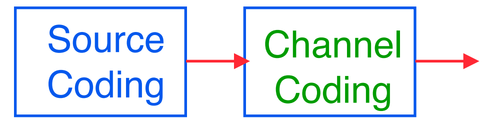
Challenge of abstractions

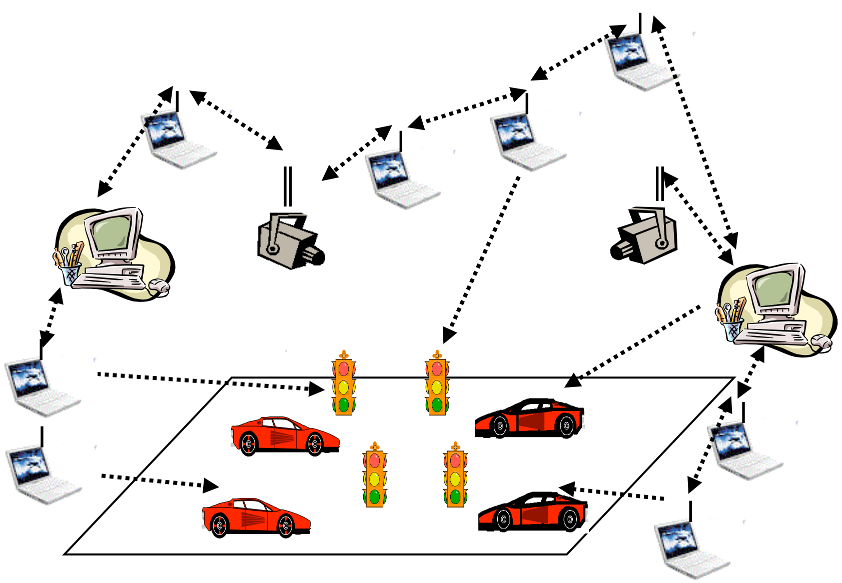


Serial computation

von Neumann Bridge (Valiant `90)

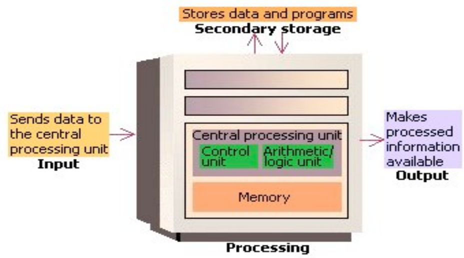
Digital Communication

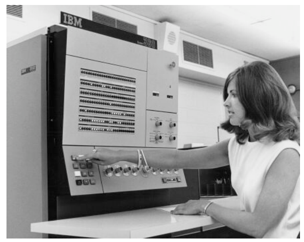




- What are the abstractions for convergence of control with communication and computing?
- Goal is to enable rapid design and deployment
  - Critical Resource: Control Designer’s Time
- Standardized abstractions
  - Minimal reconfiguration and reprogramming
- Hopefully leading to proliferation

Challenge of architecture

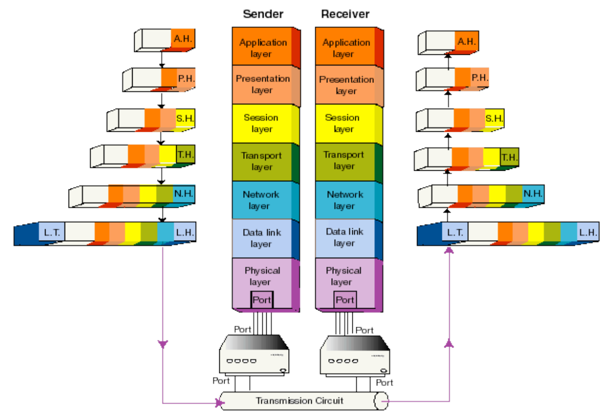




IBM 360

- First commercially successful model
- 360 – All round capability

- Program as data
- Interfaces
- Ease of customization
- Modular design of software
- Portability – High level languages
- Reusability – Component libraries



Standard software architecture

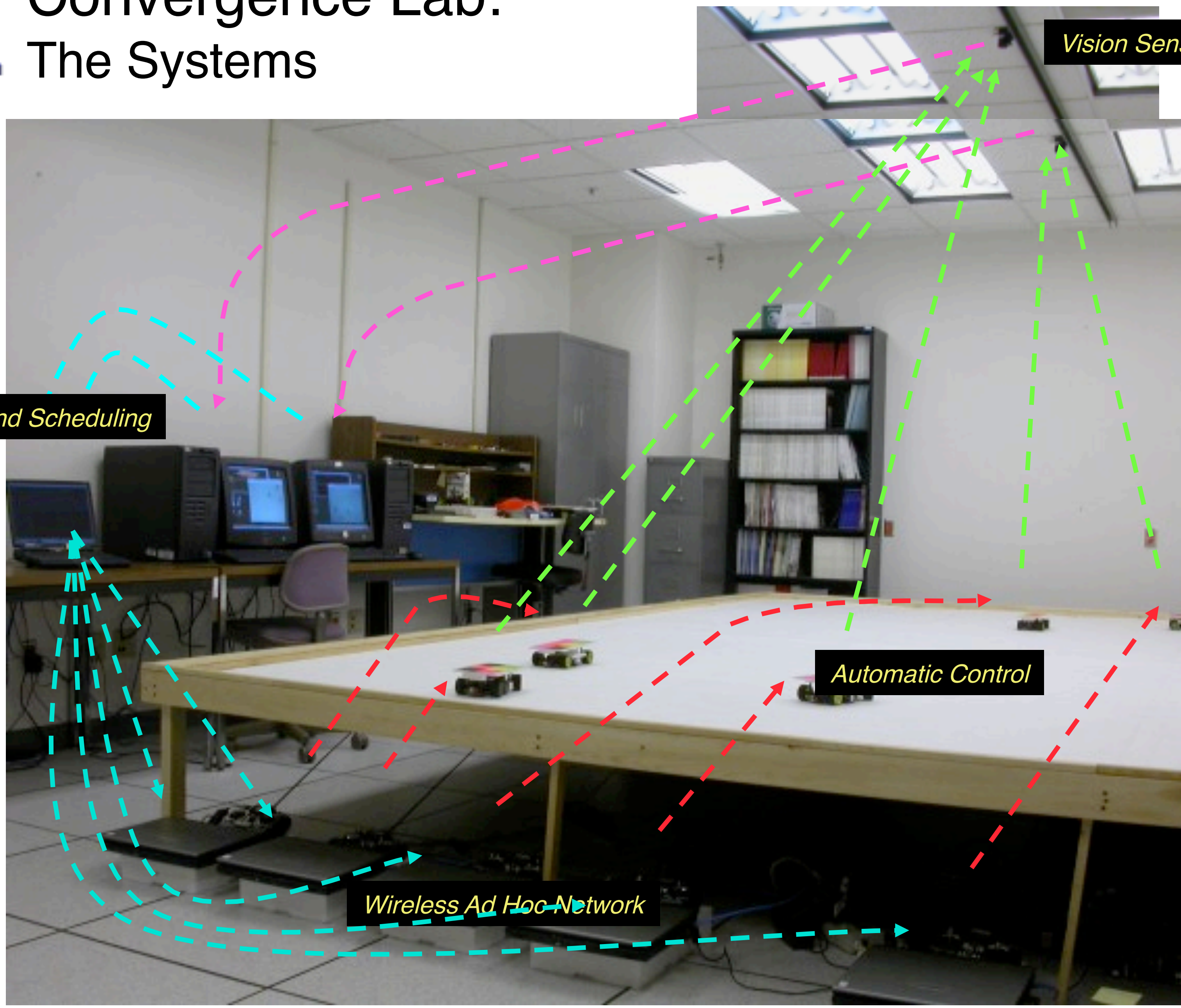
- TCP/IP is de facto standard

Layers of protocols

- Breakdown networking into sub-problems
- Solve sub-problems in different layers
- Compose solutions into a working stack

Mechanism: Encapsulation of packets

Convergence Lab:
The Systems

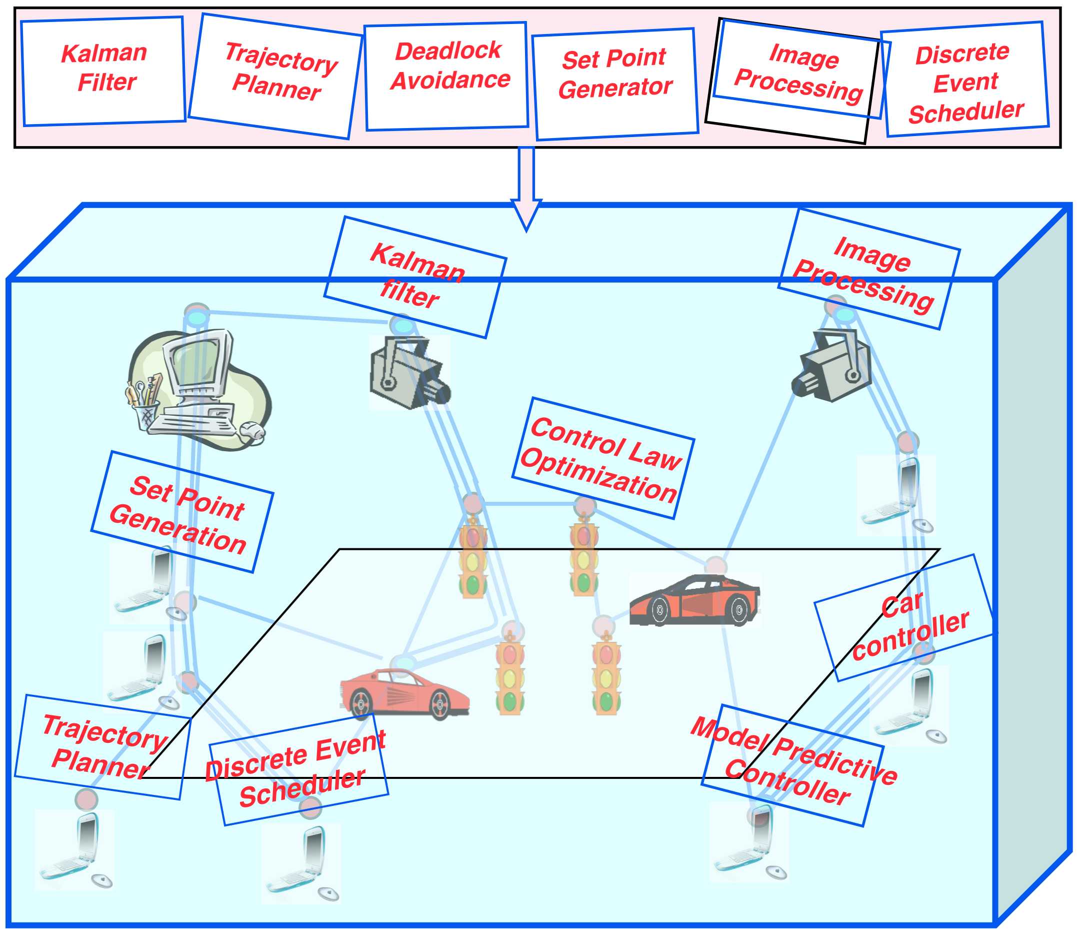


(Baliga, Graham, Huang & K '02)

Abstraction layers

- Middleware manages the *Components*

Application Layer	Components
Clock / Service 2 / Service 3 — System Layer	Middleware
Transport Layer	TCP
Network Layer	DBF
PHY/MAC Layer	Modulation



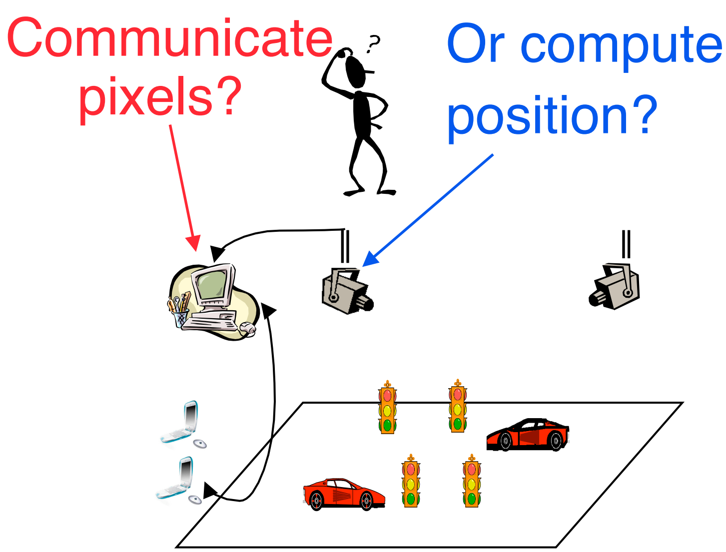
(Baliga, Graham & K '04) (Graham, Baliga & K '09) (Kim & K '08)

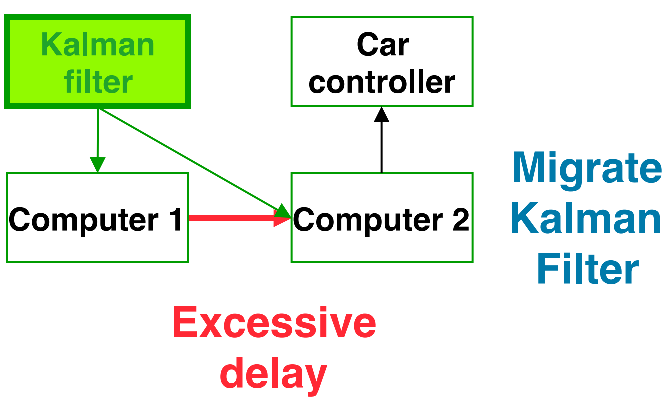
Collision avoidance

(Schuetz, Robinson & K ’05)

http://decision.csl.uiuc.edu/~testbed/videos/CollisionAvoidance.mpg

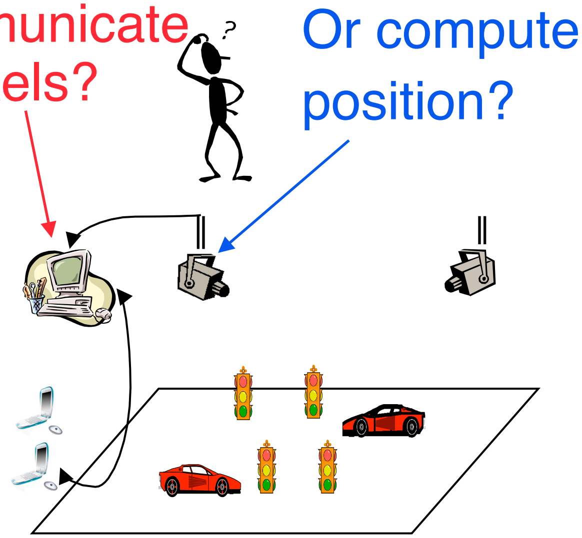
Example of capabilities: Component migration

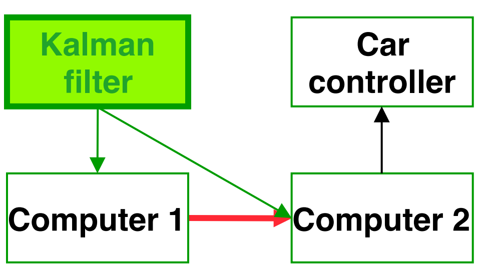




(Baliga, Graham & K '04)

Example of capabilities: Component migration





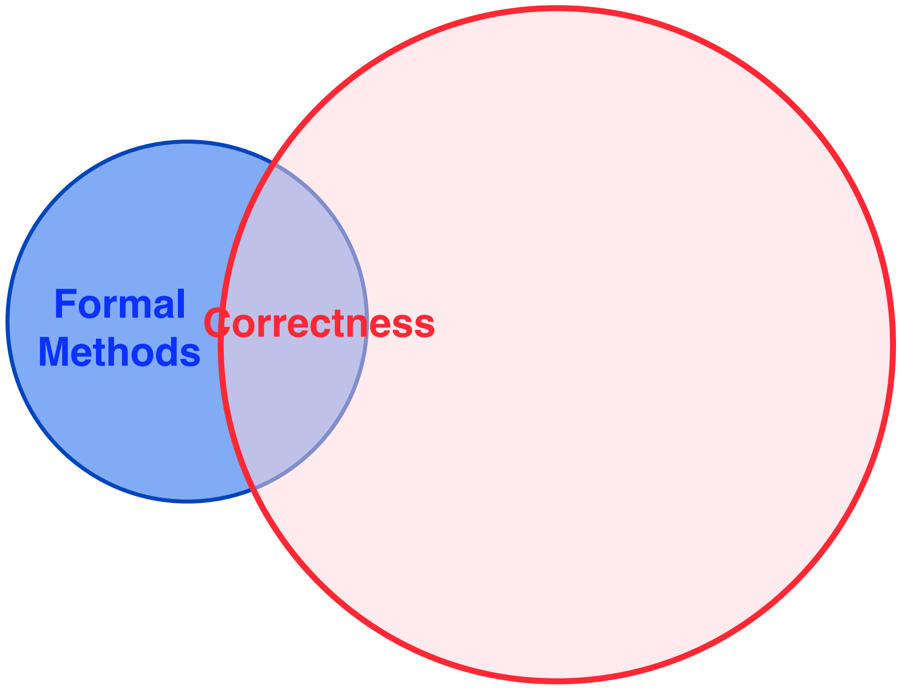
Excessive delay

Migrate Kalman Filter

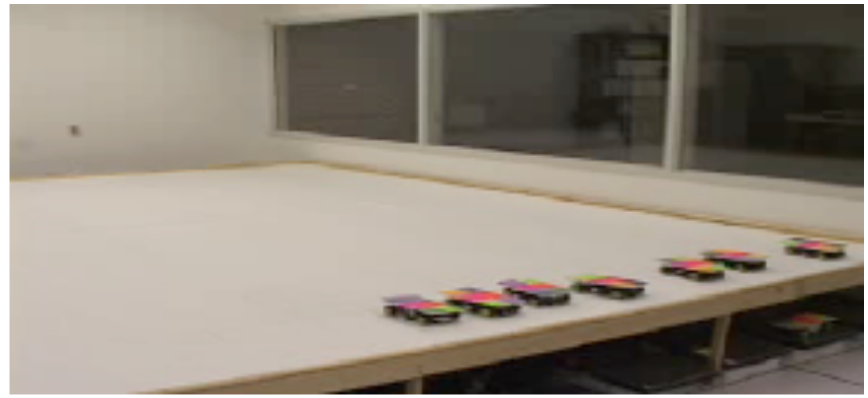
Real-time middleware

(Kim & K ’09)

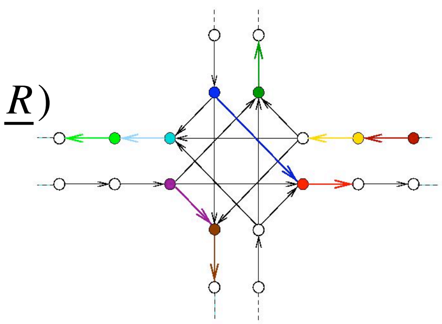
Proofs of correctness

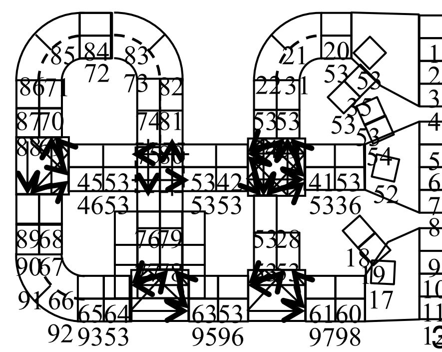


Provably correct behavior



- **Theorem**
  - Directed graph model of road network
    - Each bin has in-degree 1 or out-degree 1
    - System has no occupied cycles initially
  - Road width: $W = R(1 - \cos\beta(2\cos\alpha - 1))$
    - Initial condition: $(d, \theta) : d + R(1 - \cos\theta) < W$
    - Intersection angles $\leq \gamma$, and road lengths: $L = (2\gamma R\underline{R}) / (R - \underline{R})$
    - Multiple cars with appropriate spacing
  - Car control model: Kinematic model with turn radii $\underline{R}$ and R
  - Real time renewal tasks: HST scheduling with $\sum C_i / D_i \leq 1$
  - Then cars can be operated
    - Without collisions (Safety) or
    - Gridlocks (Liveness)

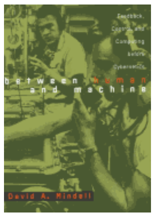




(Baliga & K '05)

http://decision.csl.uiuc.edu/~testbed/videos/city_7cars.mpg

Re-convergence: The pedagogical challenge



"*…the era of cyberspace and the Internet, with its emphasis on the computer as a communications device and as a vehicle for human interaction connects to a longer history of control systems that generated computers as networked communications devices*."

– D. Mindell in "Feedback, Control and Computing before Cybernetics," 2002

- 1950 — 2000 and continuing
  - Computation: ENIAC (1946), von Neumann (1944), Turing,..
  - Sensing and inference: Fisher, Wiener (1949),…
  - Actuation/Control: Bode, Kalman (1960),…
  - Communication: Shannon (1948), Nyquist,…
  - Signal Processing: FFT, Cooley-Tukey (1965),…

- 2000 — onwards: Age of system building
  - Nodes that can communicate, control, compute
  - Larger grand re-unification of control, communication and computation
  - Pedagogical challenges: Knowledge of all these fields may be important
  - Undergraduate education?
  - Postgraduate education?

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Thank you