Challenges of Cyberphysical systems

P. R. Kumar

with Girish Baliga, Vivek Borkar, Derek Caveney, Scott Graham, Arvind Giridhar, I-Hong Hou, Kun Huang, Kyoung-Dae Kim, Craig Robinson, Hans Schuetz

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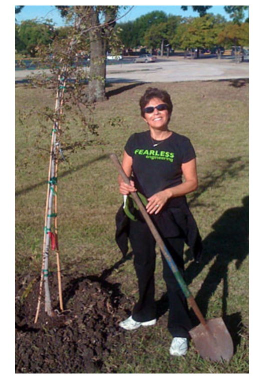
Happy 60th Birthday, Mark!



Happy Birthday from Jaya, Ashwin and Shilpa and ME (not I)!

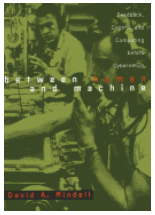
Happy 60th Birthday, Mark!

Happy Birthday from Jaya, Ashwin and Shilpa and ME (not I)!

It has been a pleasure to know you and Lila for several decades!

What are cyberphysical systems?

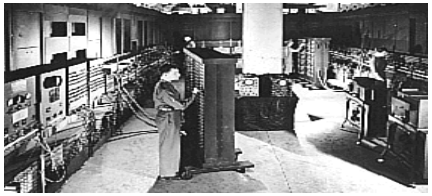
Re-convergence of control, communications and computing



"...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?

From real-time and hybrid systems

Computers were developed for computation (1949)

Real-time computation (1973)

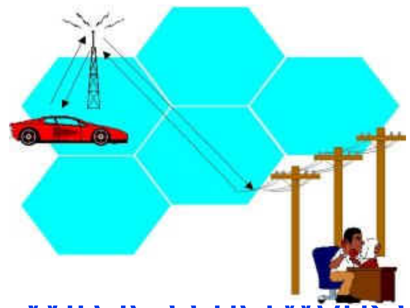
Hybrid systems (1990s)

Around 2006

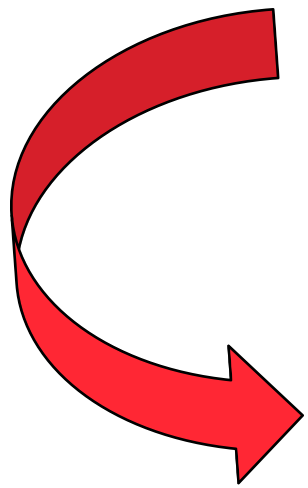
“Instigators”: Gill, Krogh, K, Lee, Midkiff, Mok, Rajkumar, Sastry, Sha, Shin, Stankovic, Sztipanovits, …

Cyberphysical systems

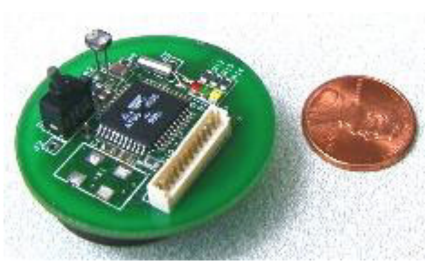
From communicating to sensing to acting



Cellular systems

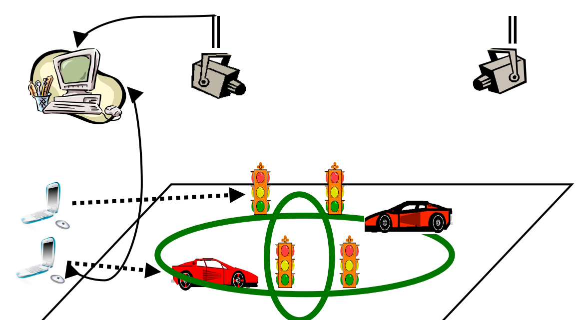


Convergence of communication, computation and control



Sensor Networks

Networked Embedded Control



The third generation of control systems

- First generation: Analog Control
  - Technology: Feedback amplifiers
  - Theory: Frequency domain analysis
    Bode, Evans, Nyquist
- Second generation: Digital Control
  - Technology: Digital computers
  - Theory: State-space design
  - Real-Time Scheduling
- Third generation: Networked Control
  - Embedded computers
  - Wireless and wireline networks
  - Software
- Platform revolution: Mechanisms and Polic
- Just in time for the resource-aware system building era of the 21st century

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

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Centennial special issue

A special 13 May centennial issue will be published as the thirteenth issue of 2012, which will review 19 key technologies from three perspectives: the past, the present, and prospects for developments in the future. Technical topics include:

1. cyber-physical systems;
2. electric power and energy engineering;
3. engineering education;
4. entertainment technologies;
5. hjardware/software co-design;
6. mass storage and data retrieval;
7. materials for electronics, photonics & energy storage;
8. medical devices and electronics;
9. neurotechnological systems: the brain-computer interfac
10. optics and photonics;
11. personal and home electronics;
12. privacy and cybersecurity;
13. radio spectrum access;
14. the search for life: SETI;
15. science and engineering beyond Moore's Law;
16. social implications of technology;
17. space exploration and science;
18. transportation and navigation technology;
19. wireless communications technology.

Centennial Celebration

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Proceedings of the IEEE is celebrating its centennial year of publication during 2012. Many exciting features and events are being planned to mark this wonderful occasion!

On this Page:
- Historical perspectives
- Centennial special issue
- Engineering Innovation Forum
- Future technology predictions

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This is an important celebratory moment not only for the journal but also for all IEEE members since 2012 commemorates the centennial of the founding of the Institute of Radio Engineers, which helped to create the current international perspective of today's IEEE.

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INVITED PAPER

Cyber–Physical Systems: A Perspective at the Centennial

This paper surveys cyber–physical systems and the potential benefits of the convergence of computing, communications, and control technologies for developing next-generation engineered systems.

By Kyoung-Dae Kim and P. R. Kumar, Fellow IEEE

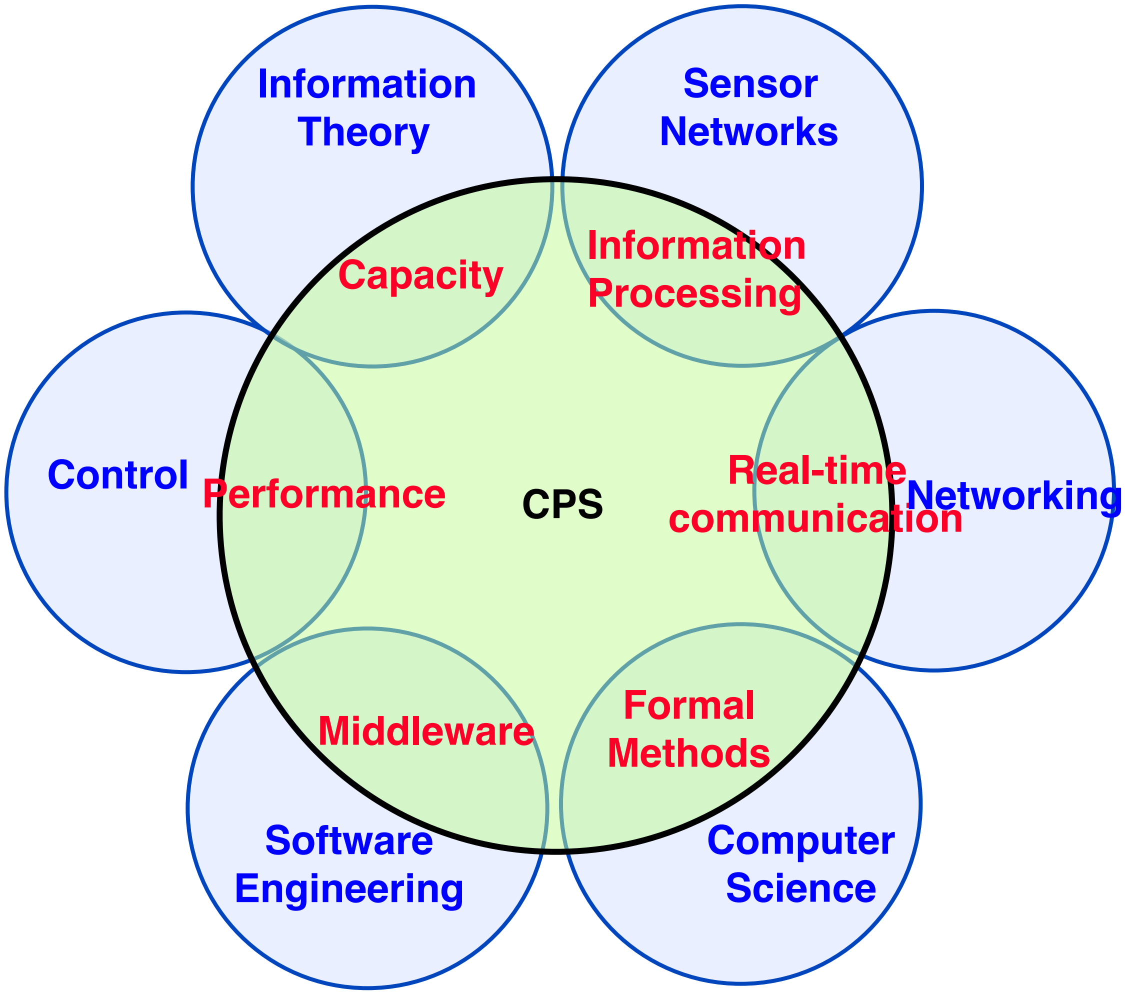
Mechanisms and policies

- Platform revolution
- Mechanisms
  - *How to implement*?
- Policies
  - *What to implement*?

- Policies
  - Control law issues due to sensing and actuating over a network
  - Holistic cross-domain theory

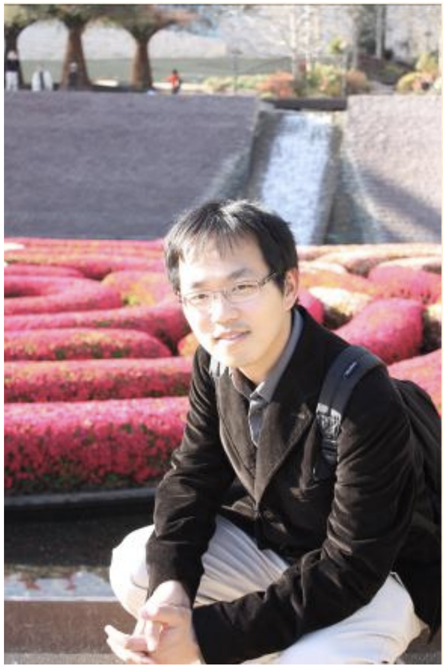
- Mechanisms
  - Architecture and Abstractions
  - Theories to support mechanisms

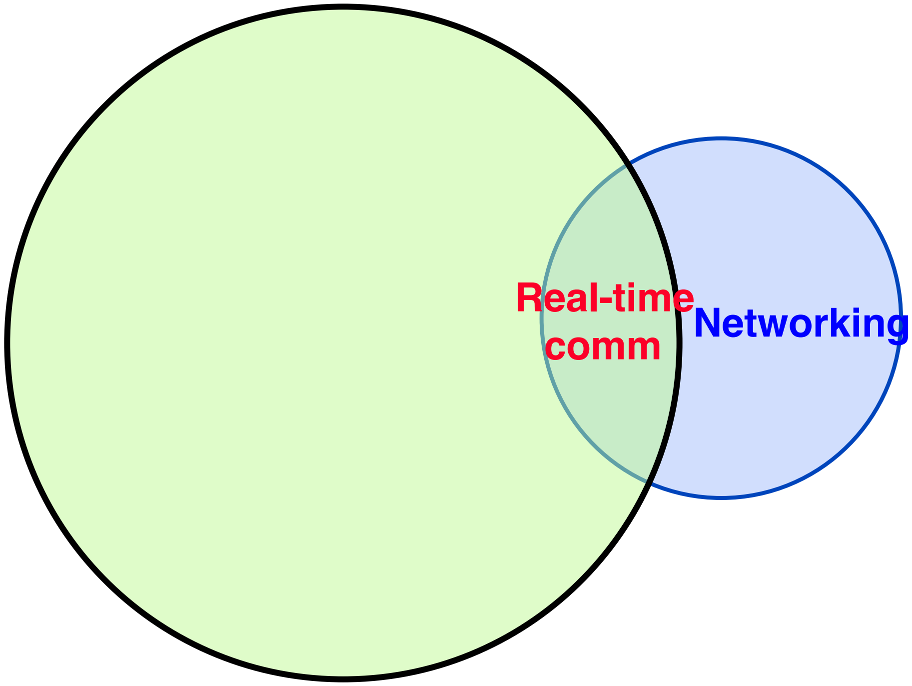
Several issues in cyberphysical systems



How can we deliver packets on time in a shared wireless network?

With I-Hong Hou





and Vivek Borkar

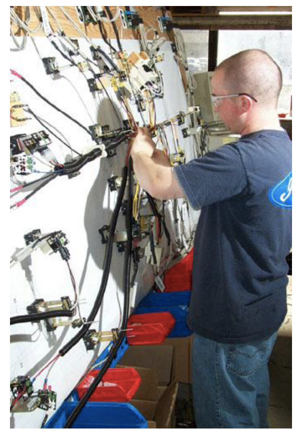
Importance of providing latency guarantees: Wireless Tomorrow

- Current Internet
  - No guarantees – “Best effort”
  - At best – Throughput

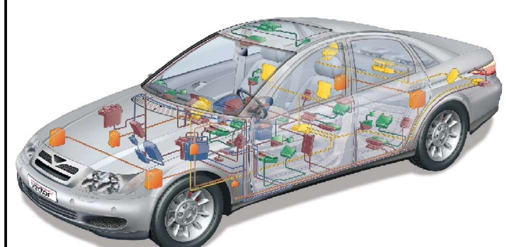
- Increasing traffic with delay constraints
  - VoIP
  - Interactive Video
  - Cyberphysical systems

- How to support delay guarantees over an unreliable medium like wireless?

In-Vehicle Networks



Wire harnesses are:
Costly (>$1000.00)
Complex (>4,000 parts)
Heavy (>40kg)
Warranty issues (>65 IPTV)



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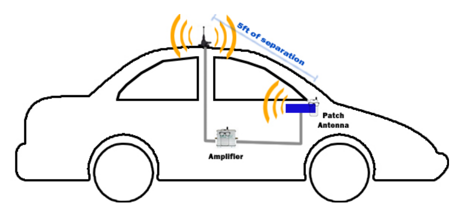
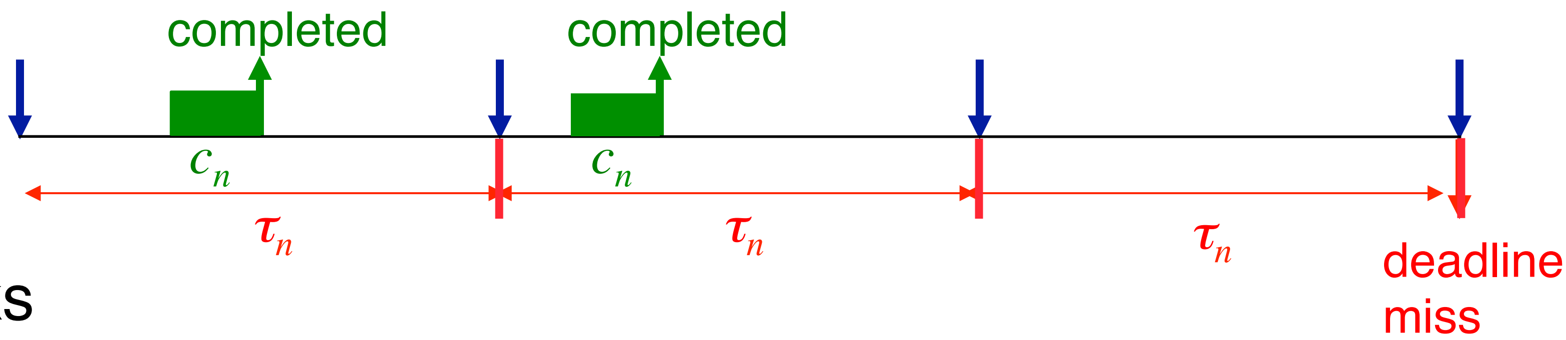


Replace wires by an access point

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

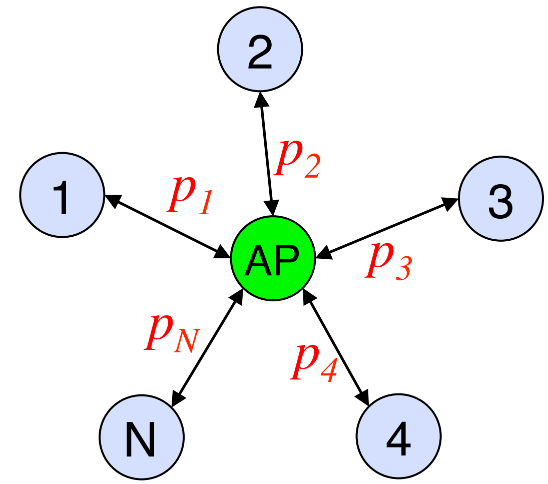
- Rate monotone scheduling: Priority to smallest period task

- 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 $N \rightarrow \infty)$

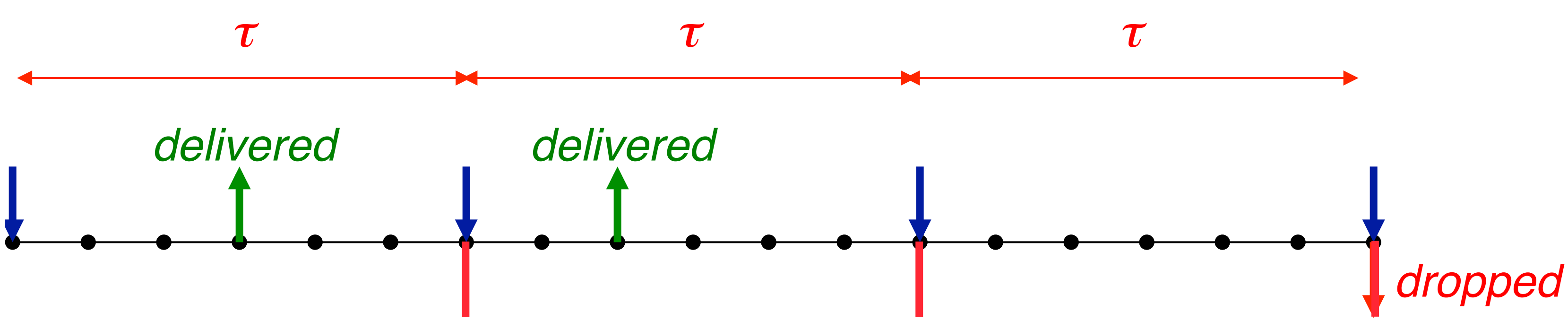
- If any priority policy can meet all deadlines, then this policy can

Formulation of real-time communication

- Access Point serving N clients



- Unreliable channels
- Slotted



- Require timely throughput of q_n packets per period
- Are the requirements $\{(q_n, p_n, \tau), 1 \leq n \leq N\}$ feasible?

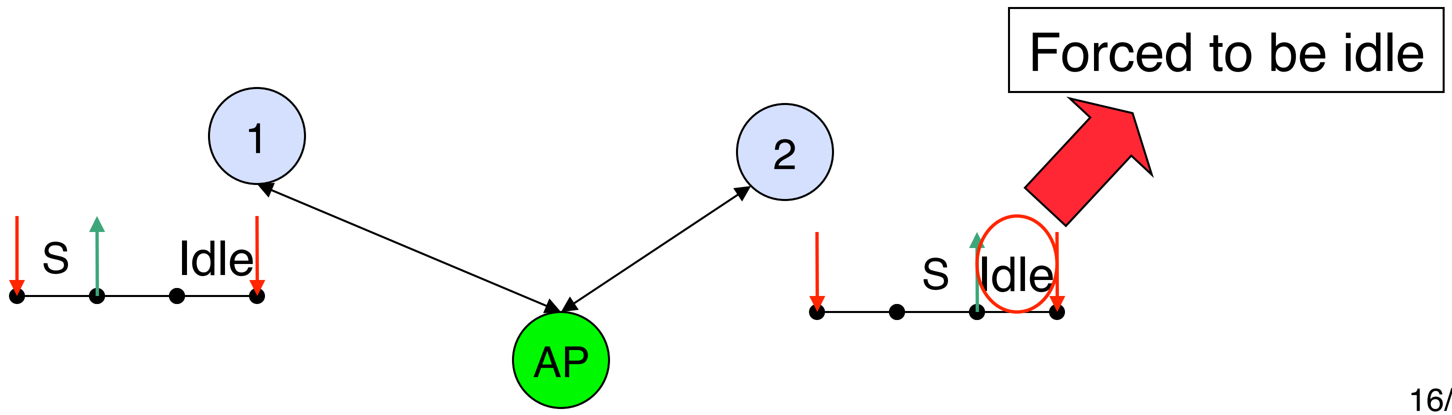
Necessary condition for feasibility of QoS requirements

- Necessary condition from classical queueing theory

$$\sum_{n=1}^{N} w_n \leq 1 \quad \text{where} \quad w_n = \frac{q_n}{p_n \tau}$$

- But not sufficient

- Reason: Unavoidable idle time
  - No queueing: At most one packet



Stronger necessary condition

- Stronger necessary condition

$$\sum_{n=1}^{N} w_n + I(1,2,\ldots,N) \le 1$$

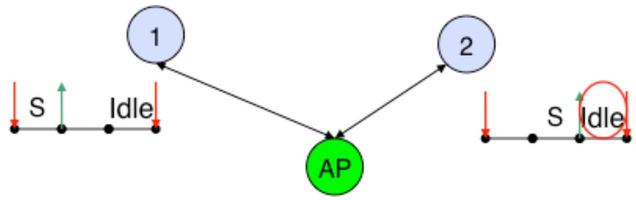
- where $I(1,2,\ldots,N)$ = Unavoidable idle time after serving $\{1,2,,N\}$

$$I(1,2,\ldots,N) = \frac{1}{\tau} E\left[\left(\tau - \sum_{n=1}^{N} \gamma_n\right)^+\right] \quad \text{where } \gamma_n \sim \text{Geom}(p_n)$$

- Sufficient?

- Still not sufficient!

Counterexample



- Period $\tau = 3$

- Client 1
  - $p_1 = 0.5$
  - $q_1 = 0.876$
  - $w_1 + I_1 = 3.002/3 > 1$ ×

$$w_1 = \frac{q_1}{p_1 \tau} = \frac{1.752}{3}$$

$$I_1 = \frac{\left(2p_1 + (1-p_1)p_1\right)}{3} = \frac{1.25}{3}$$

Even stronger necessary condition

- Every *subset* of clients $S \subseteq \{1, 2, \ldots, N\}$ should also be feasible

- Stronger necessary condition: $\sum_{n \in S} w_n + I(S) \quad \leq 1, \ \ \forall S \subseteq \{1, 2, \ldots, N\}$

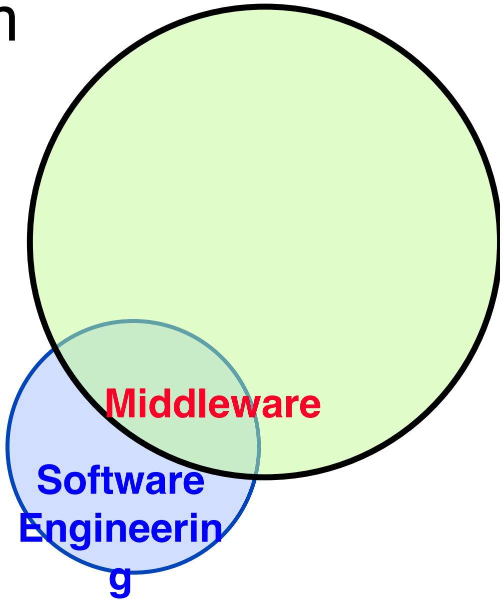
  $\underbrace{\sum_{n \in S} w_n}_{\nearrow \text{ with } S}$ $\underbrace{I(S)}_{\searrow \text{ with } S}$

- Not enough to just evaluate for the whole set $\{1, 2, \ldots, N\}$

- **Theorem (Hou, Borkar & K '09): Admission Control**
  Condition is necessary and sufficient for a set of clients to be feasible

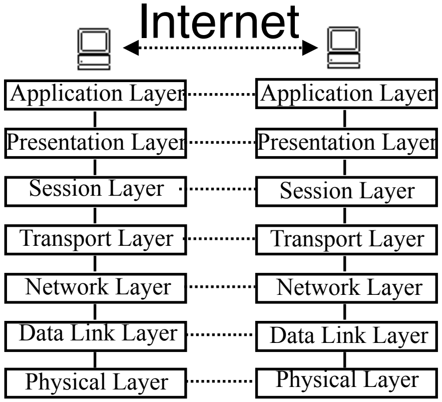
What are the appropriate abstractions and architecture for CPS?

Girish Baliga, Scott Graham and Kyoung-Dae Kim



Challenge of abstractions

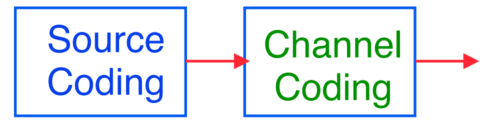
Internet

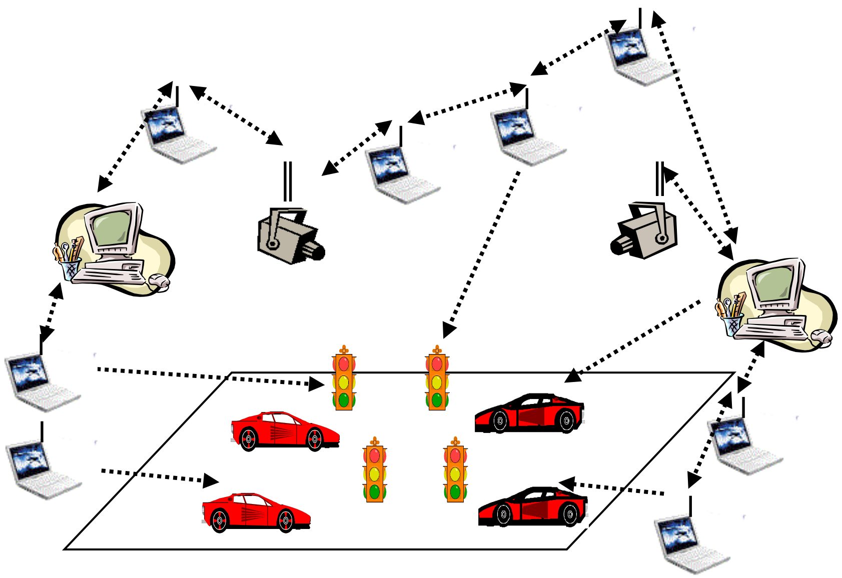


Serial computation

von Neumann Bridge (Valiant `90)

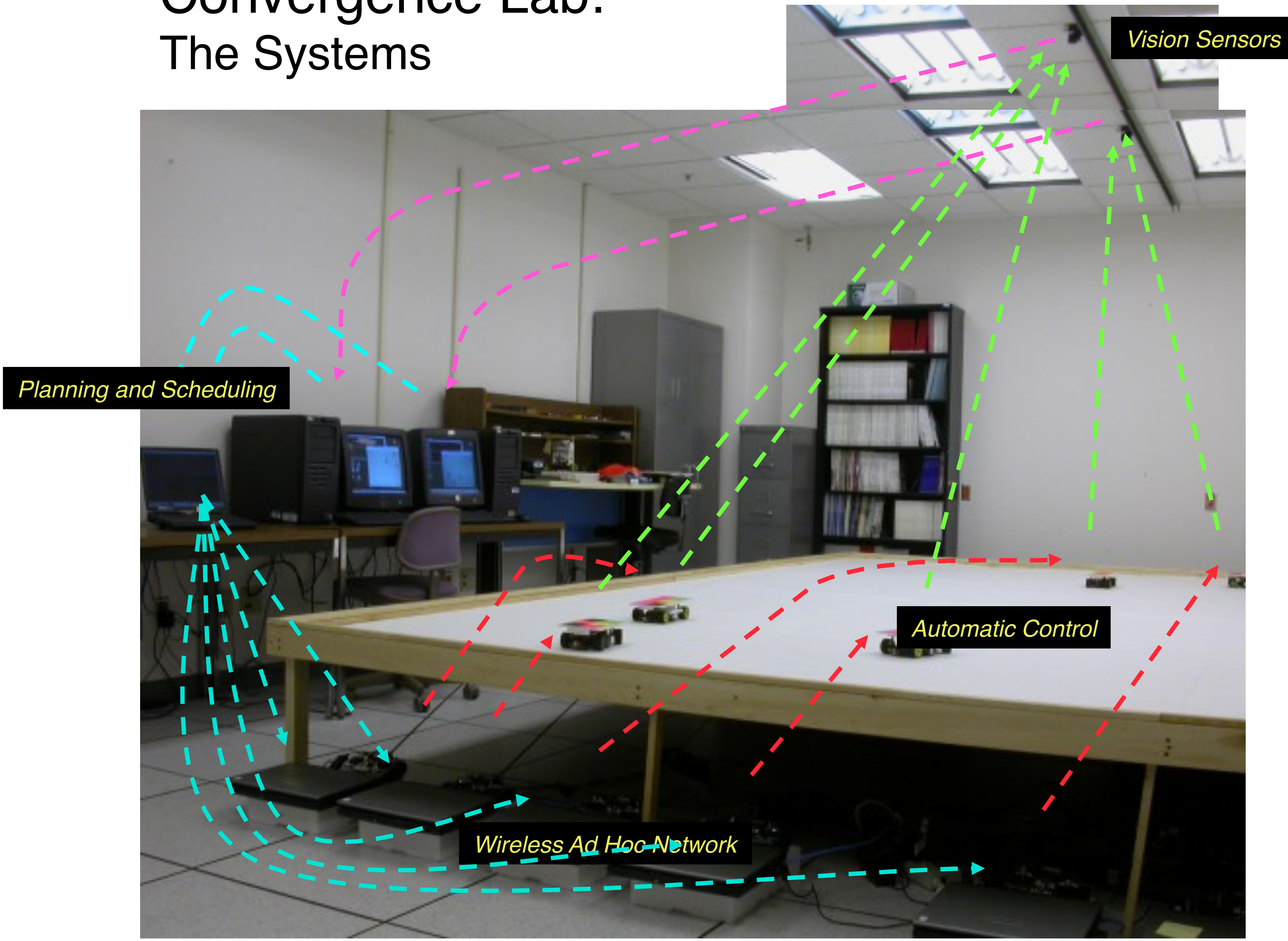
Digital Communication





- 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

Convergence Lab:
The Systems

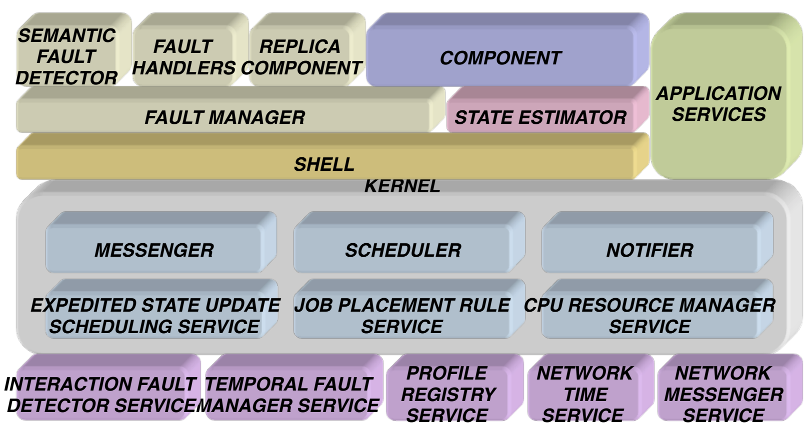


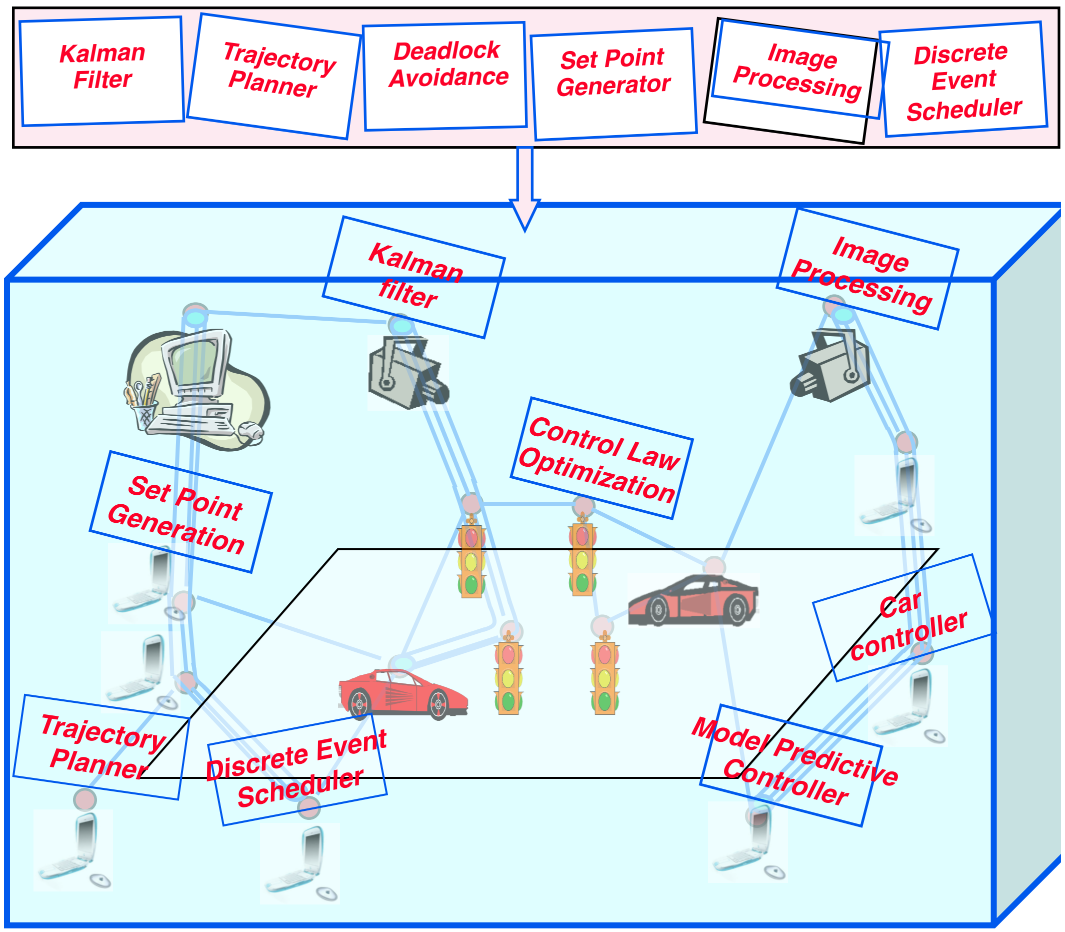
(Baliga, Graham, Huang & K '02)

Abstraction layers

- Middleware manages the *Components*

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



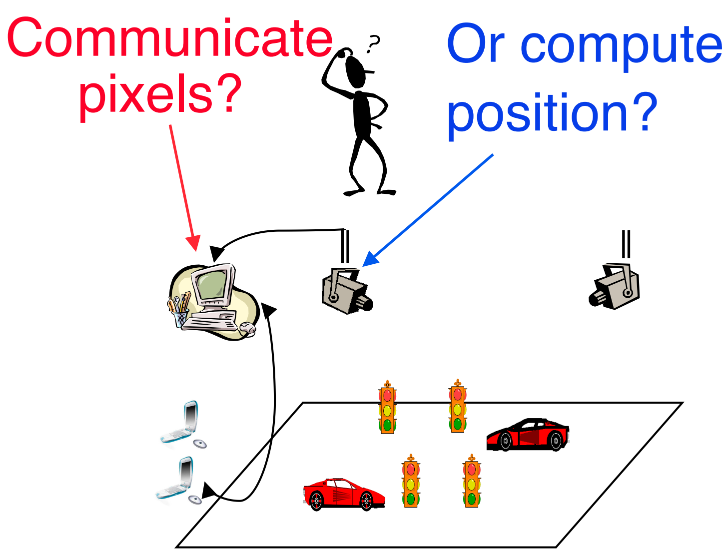


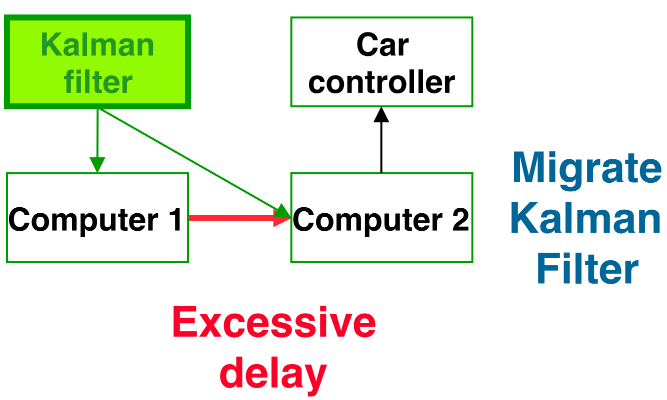
(Baliga, Graham & K '04) (Graham, Baliga & K '09) (Kim & K '08)

Collision avoidance

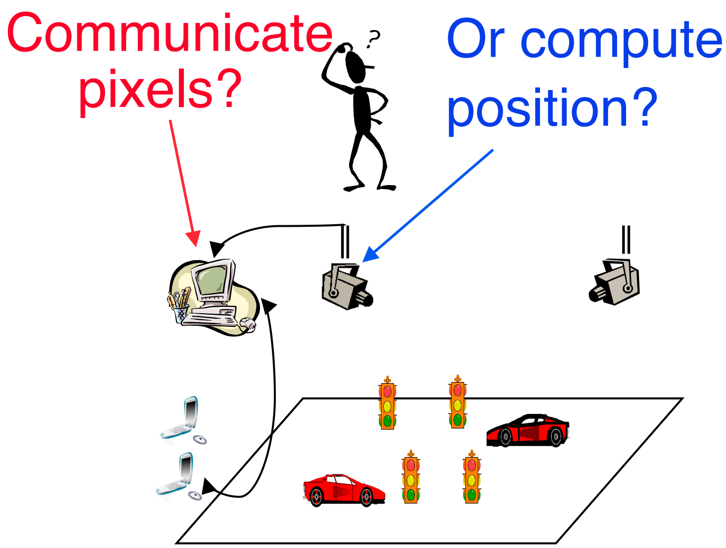
(Schuetz, Robinson & K ' 05)

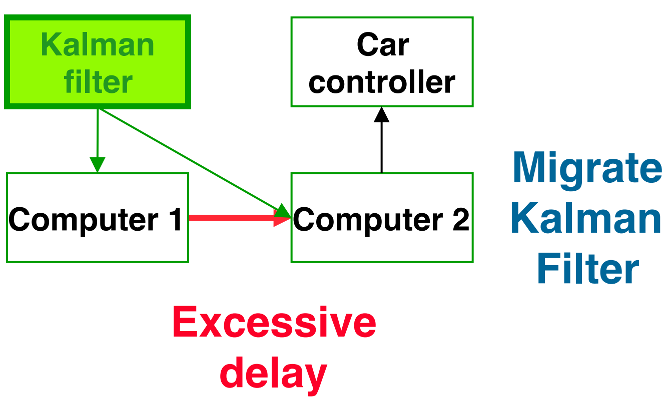
Example of capabilities: Component migration





Example of capabilities: Component migration

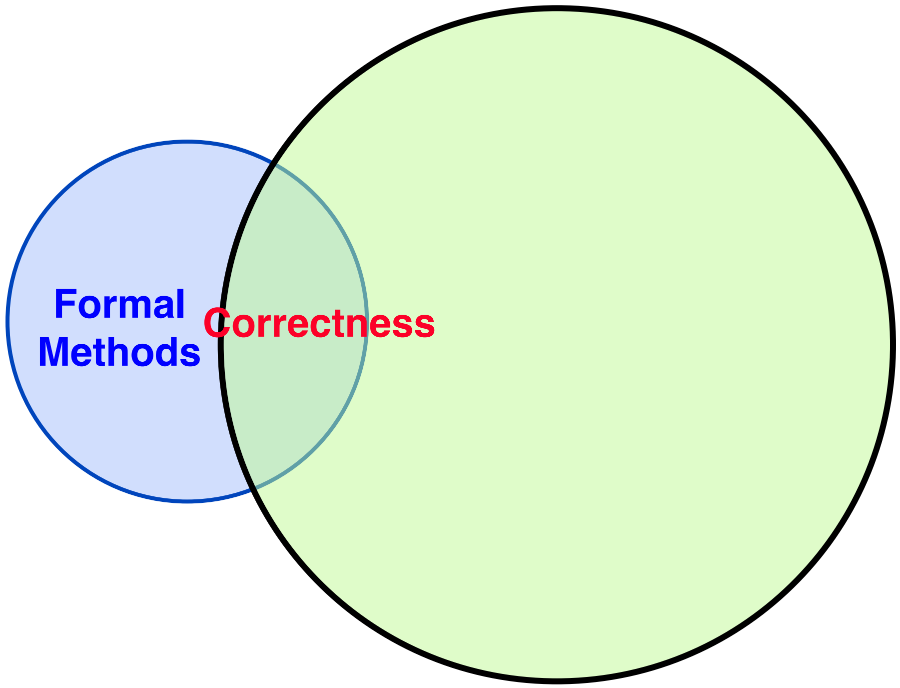


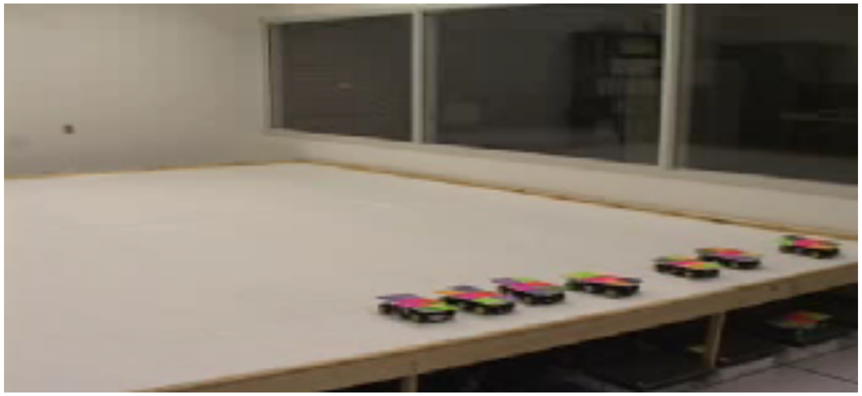


Real-time middleware

(Kim & K’09)

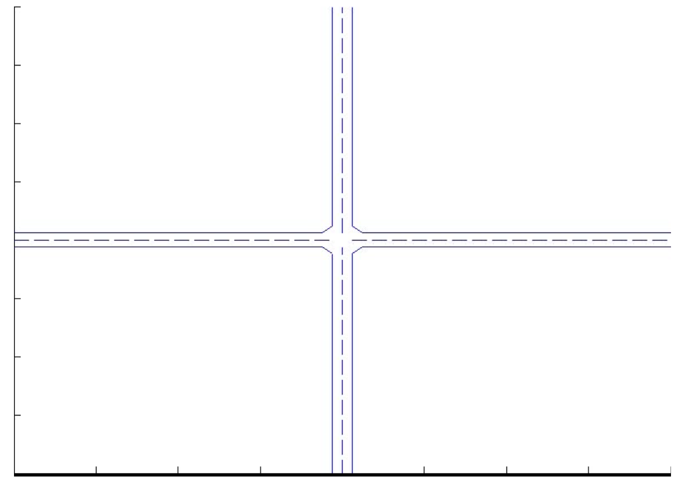
How can we prove that systems behave correctly and are safe?





A larger problem

- Intelligent intersections

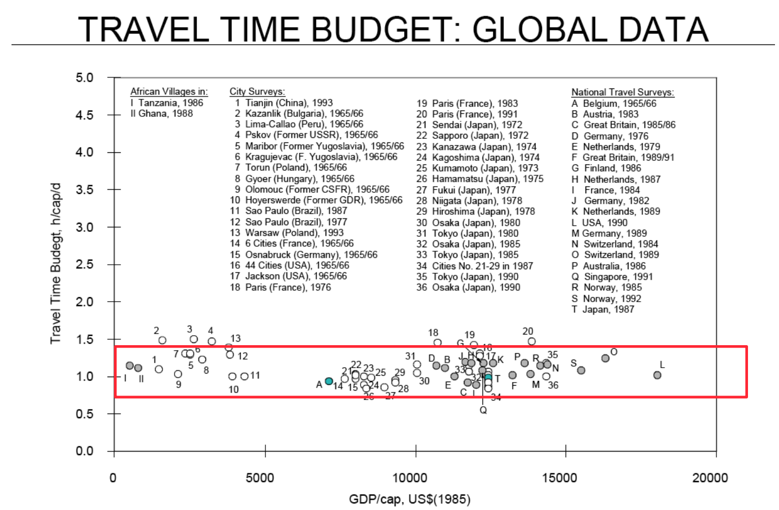


- Cars negotiate via packet exchanges
  - Lower fuel consumption
  - Lower traffic delays
  - Greater safety

- Human beings seem to have decided to dedicate one hour per day for travel

- So should we we actually make it easier for people to travel greater distances in the same time?

- So what is the right problem to solve?



Reference: Schafer and Victor (2000) The future mobility of the world population, Transportation Research A34(3), 171-205.

From Frank Kelly's talk at StochNet 2006

Happy Birthday, Mark!