Present Developments in Control Theory

IFAC 50th Anniversary Celebration

Heidelberg

Brian DO Anderson

The Australian National University

and

National ICT Australia Limited

THANKS

to IFAC for inviting me.

It is an honour to be here today.

Aim of Presentation

- To suggest directions for the future development of control theory
- To provide reasons for the suggestions drawing on:
  - Past history
  - Current drivers

Outline

- **Drivers of Control Theory Development**
- **History**
- **Near term drivers**
- **Life Sciences**
- **Managing Complexity**
- **Conclusions**

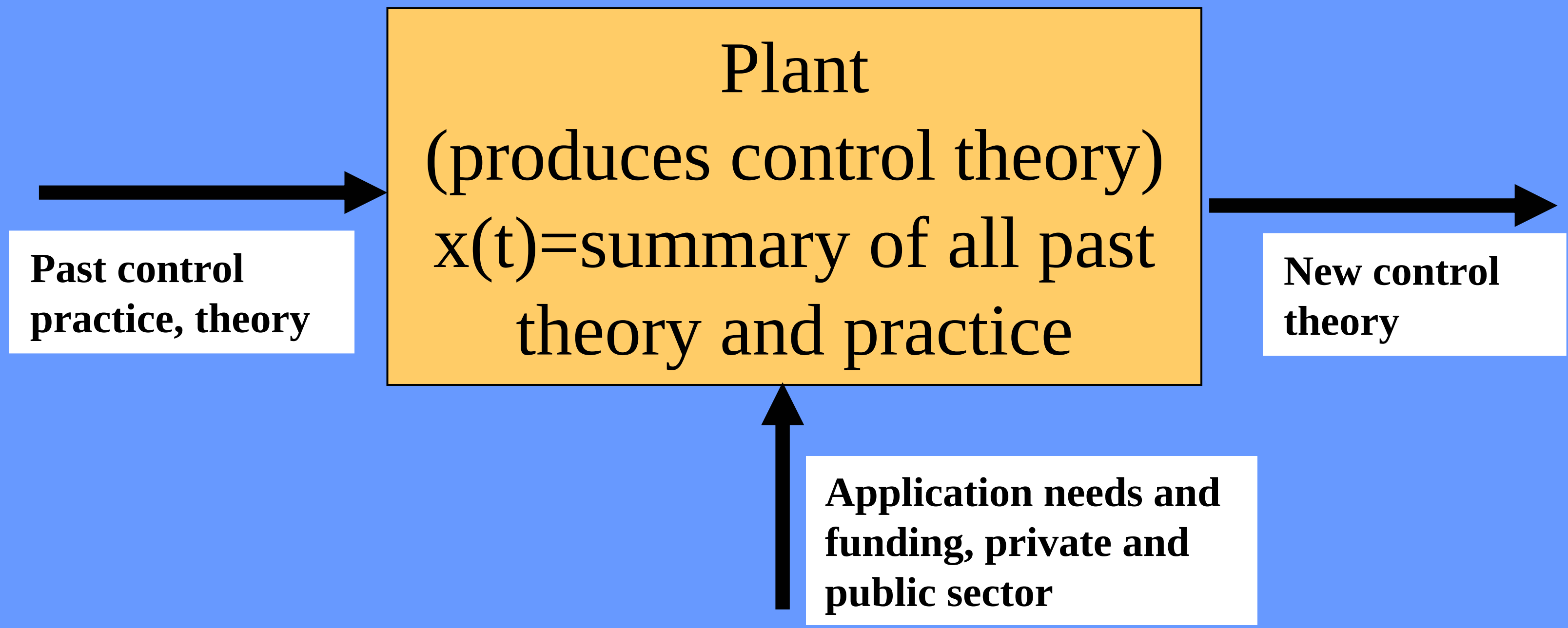
Drivers

Past control practice, theory

Plant
(produces control theory)
x(t)=summary of all past theory and practice

New control theory

Drivers


Plant
(produces control theory)
x(t)=summary of all past theory and practice
Past control practice, theory
New control theory
Application needs and funding, private and public sector

Drivers

Control theorist activity and intellectual drivers

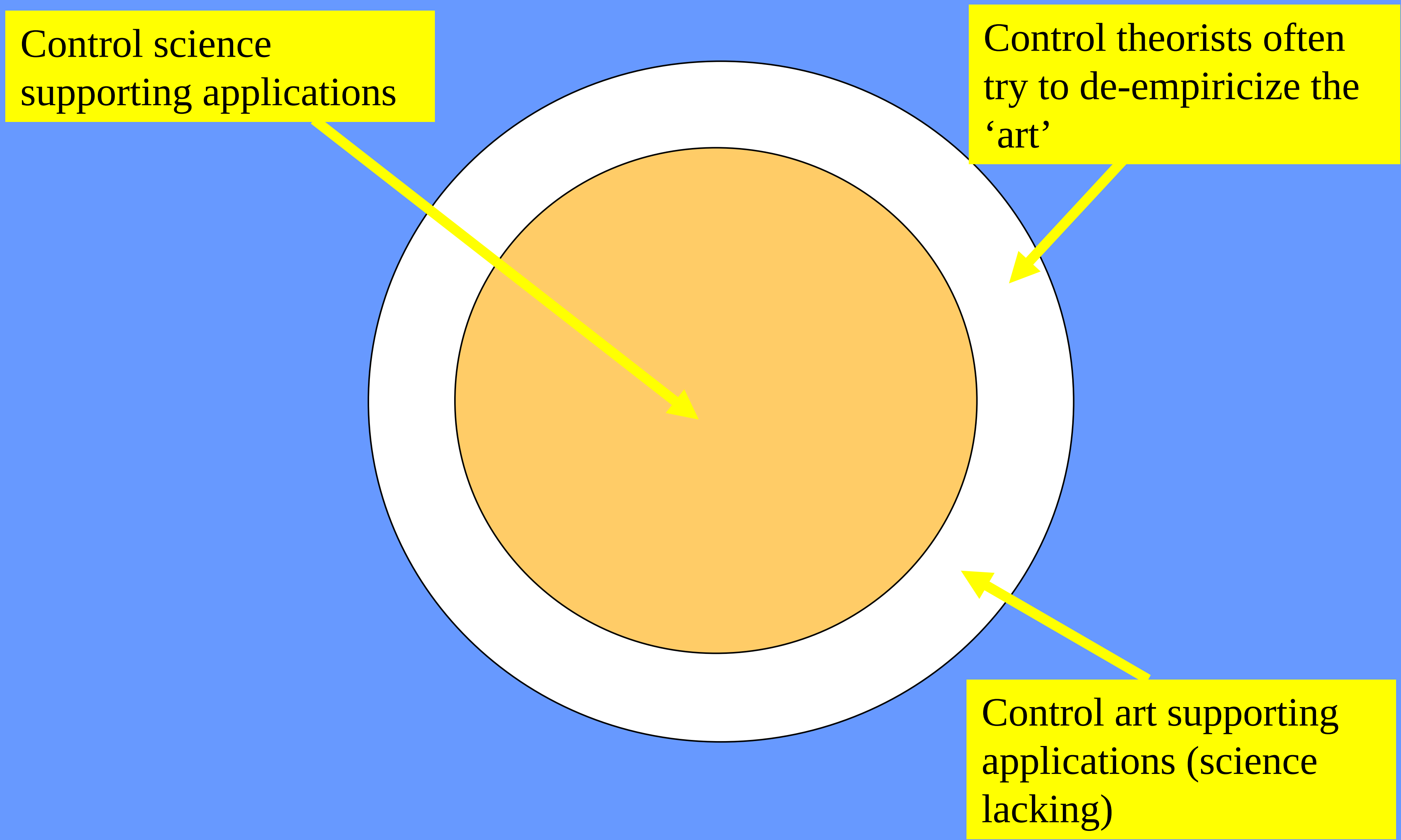
Past control practice, theory

Plant
(produces control theory)
x(t)=summary of all past theory and practice

New control theory

Application needs and funding, private and public sector

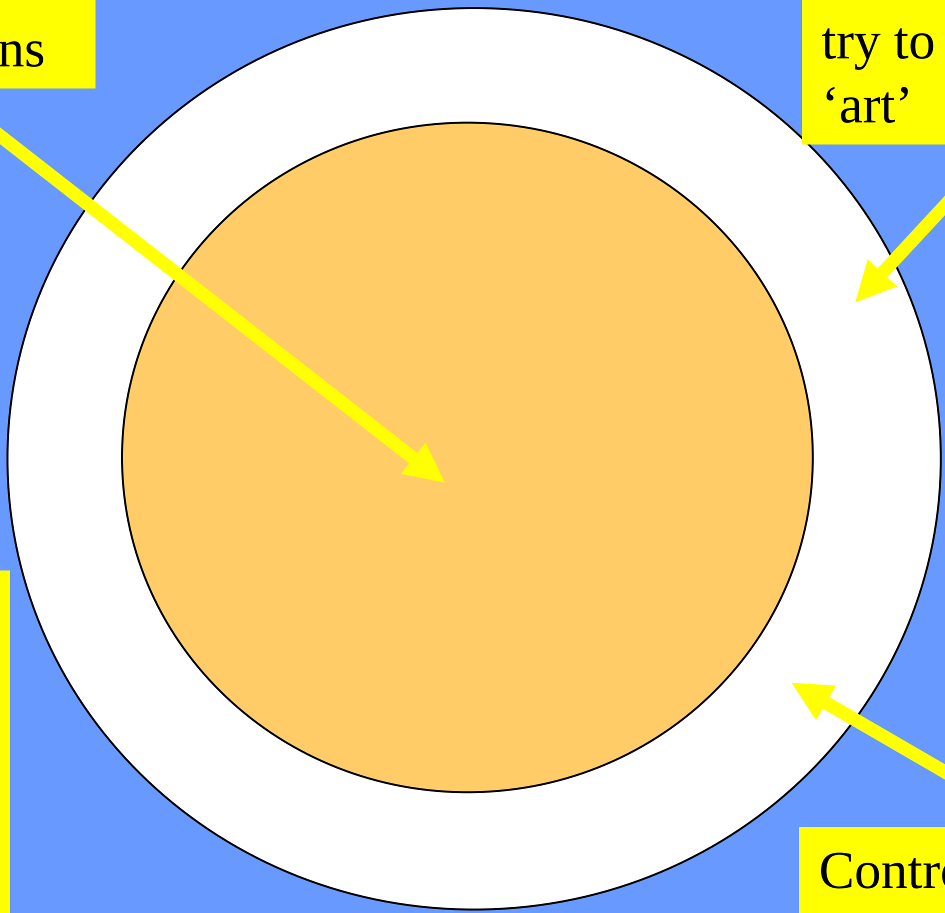
Drivers


Control science supporting applications
Control theorists often try to de-empiricize the 'art'
Control art supporting applications (science lacking)

Drivers

Control science supporting applications

Control theorists often try to de-empiricize the ‘art’



Past examples of science replacing art:

linear to describing functions to nonlinear theories.

SISO to graphical MIMO to LQG

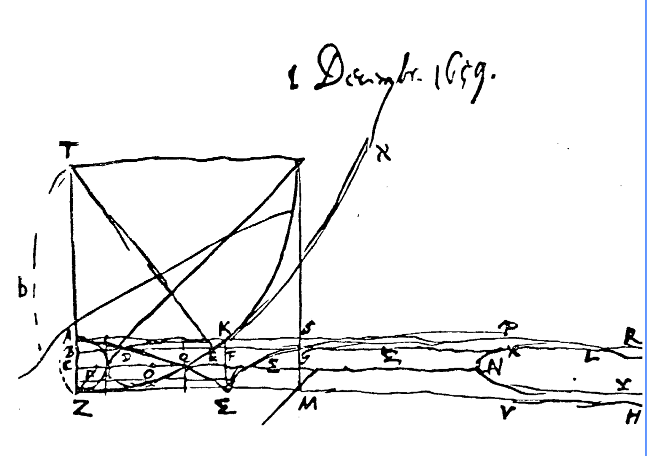
Control art supporting applications (science lacking)

Outline

- Drivers of Control Theory Development
- History
  - Ancient History
  - Classical Control
  - Modern Control
- Near term drivers
- Life Sciences
- Managing complexity
- Conclusions

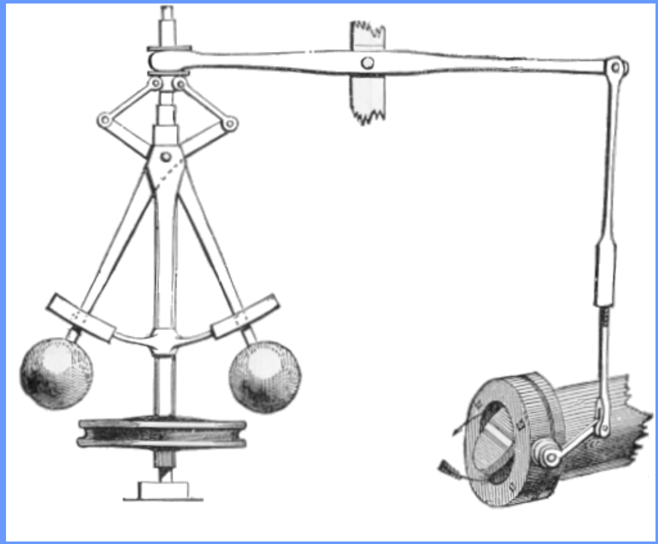
Ancient History--I

- Some of the earliest control included:
  - Time keeping with water clocks
  - Clocks with a conical pendulum
  - Windmills:
    - facing sails into the wind,
    - controlling the sail speed with a governor,
    - adjusting the crushing parameters (gap and supply rate).
  - No theory backing. Control was empirical.



Ancient History--II

- The industrial revolution brought steam and the problem of speed control
- Main tool: centrifugal governor
- Practical problems :
  - Control the speed to a set point
  - Avoiding overshoot (or worse, instability)
  - Stability problems given integral action



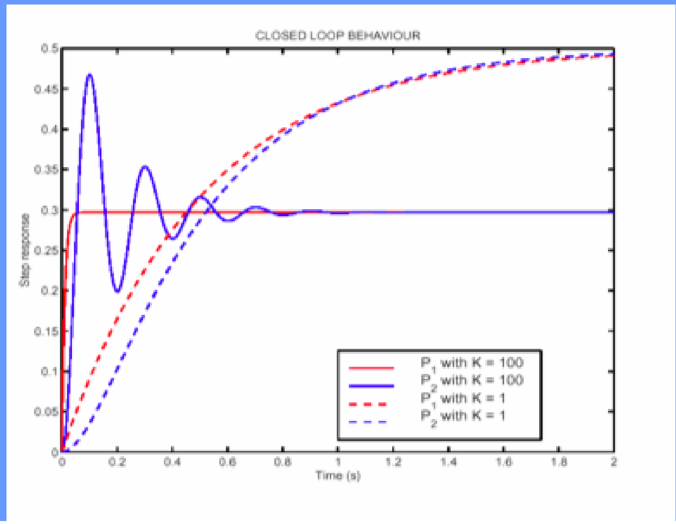
The notion of design trade-offs in control design had started to present itself. There was no theory.

Ancient History--III

- Application (centrifugal governor) motivated:
  - Differential equation modelling
  - Formulation of a stability problem (roots of a polynomial had to lie in the left half plane)
- Solution was achieved for low order polynomials.
- Regulation accuracy versus overshoot trade-off became understood
- Many modest inventions tweaked the ideas.

$$\frac{d^3x}{dt^3} + 3\frac{d^2x}{dt^2} + 2\frac{dx}{dt} + 3x = r$$

Maxwell recognized, but could not solve, the general stability problem.



Ancient History--IV

Maxwell recognized, but could not solve, the general stability problem.

while

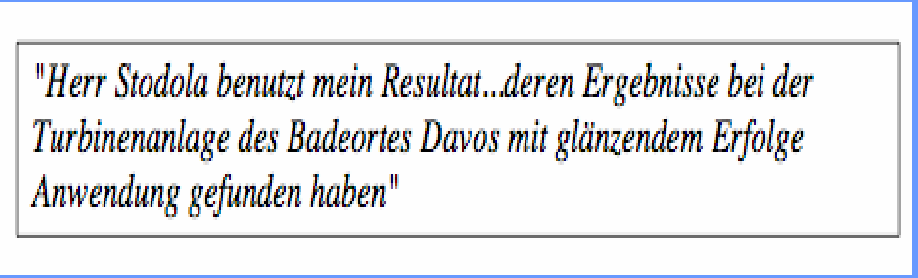
In France, Hermite formulated and solved the general stability problem, without recognising the application significance.

and

Vyshnegradskii analysed a third order system (centrifugal governor), neglecting friction, and linearizing. He used a ***graphical*** presentation.

Ancient History V

- Astronomer Royal Airy, used control to cause a telescope to rotate uniformly; he described
  - instability,
  - analysis via a linearized differential equation
  - adjustment of dynamics for stability (1840)
- Routh solved the general stability problem (UK)
- Round 1895, Stodola at ETH had to control some water turbines at Davos.
  - He enlisted the help of Hurwitz, a professor of mathematics to give him a stability criterion
- In 1892, Lyapunov's thesis on stability appeared,


"Herr Stodola benutzt mein Resultat...deren Ergebnisse bei der Turbinenanlage des Badeortes Davos mit glänzendem Erfolge Anwendung gefunden haben"

System state in 1900

ODE Stability and Lyapunov stability

Water turbines, governors, telescopes

Tradeoffs & graphical presentation

Control theorist activity and intellectual drivers

Plant
(produces control theory)
x(t)=summary of all past theory and practice

Past control practice, theory

New control theory

Application needs and funding, private and public sector

Classical Control

- ‘Classical Control’ covers approximately 1900-1955
- Applications drivers included
  - Electronics and telecommunications networks
  - Defence
  - General increasing industrialisation
- Most problems involved **linear, single-input, single-output, time-invariant, finite-dimensional** systems

Major Milestones

- Formal recognition of feedback concept
- Incorporation of transfer functions and Fourier transforms
- Establishing stability by a totally different method than manipulating coefficients in a linear differential equation: the Nyquist criterion:
  - It used measurements and not a model.
  - This was a huge piece of lateral thinking

Regeneration Theory

By H. NYQUIST

Regeneration or feed-back is of considerable importance in many applications of vacuum tubes. The most obvious example is that of vacuum tube oscillators, where the feed-back is carried beyond the singing point. Another application is the 21-circuit test of balance, in which the current due to the unbalance between two impedances is fed back, the gain being increased until singing occurs. Still other applications are cases where portions of the output current of amplifiers are fed back to the input either unintentionally or by design. For the purpose of investigating the stability of such devices they may be looked on as amplifiers whose output is connected to the input through a transducer. This paper deals with the theory of stability of such systems.

Major Milestones 2

- Design ideas like position feedback, rate feedback, PID control, elimination of offset by integral control became embedded.
- Graphical design tools with low computational complexity ruled

Feedback SWOT Analysis

Strengths	**Weaknesses**
Ameliorates plant parameter variations Ameliorates output disturbances Promotes reference input tracking	High gain may: produce instability amplify sensor noise saturate input
Opportunities	**Threats**
Integral feedback may eliminate steady state error Trade-off of rise-time, overshoot and steady state error	Unstable poles Nonminimum phase zeros Unmodelled high frequency dynamics Closed-loop > open-loop bandwidth

Modern Control

- Modern control began about the time that IFAC began!
- The biggest application driver was probably defence (including space race), especially in the US: manpower superiority was no longer the doctrine, but technological superiority was.
- Other western countries had national application drivers, such as cars, paper, steel, ships, minerals, etc.
- Control researchers still ***focussed on individual subsystems*** however.

Modern Control II

- The real subsystems were often one or more of:
  - Multivariable
  - High dimension
  - Nonlinear
  - Time-Varying
  - Poorly modelled
- Thus they were often ***outside the bounds of existing classical theory, and/or existing computational tools***

Modern Control III

- The digital computer arrived--first as a design tool, and later as a control system component
  - Progressively removed many limitations on design methods
  - Reduced restriction on graphical schemes, low order designs, small numbers of parameters, etc
  - Motivated sampled-data control and lately, hybrid systems

Modern Control IV

- State-variable descriptions of systems
- Linear systems and deempiricizing classical control
- Linear Quadratic Gaussian Design
- Optimisation and Optimal Control
- Dealing systematically with noise
- Sampled-Data control

- Identification
- Distributed systems
- H_∞ and robust control
- Theories of nonlinear systems, e.g.
  - Linearizations
  - Lie algebras etc
  - Backstepping
  - Lyapunov-based design

$$
\begin{aligned}
f_{h,\varepsilon}(x,y) &= \varepsilon \mathbf{E}_{x,y} \int_0^{t_\varepsilon} L_{x,y_\varepsilon(\varepsilon u)} \varphi(x)\, du \\
&= h \int L_{x,z} \varphi(x) \rho_x(dz) \\
&\quad + h \left[\frac{1}{t_\varepsilon} \left(\mathbf{E}_y \int_0^{t_\varepsilon} L_{x,y^x(s)} \varphi(x)\, ds - t_\varepsilon \int L_{x,z} \varphi(x) \rho_x(dz) \right) \right. \\
&\qquad \left. + \frac{1}{t_\varepsilon} \left(\mathbf{E}_y \int_0^{t_\varepsilon} L_{x,y^x(s)} \varphi(x)\, ds - \mathbf{E}_{x,y} \int_0^{t_\varepsilon} L_{x,y_\varepsilon(\varepsilon s)} \varphi(x)\, ds \right) \right] \\
&= h \widehat{L}_x \varphi(x) + h \theta_\varepsilon(x,y)
\end{aligned}
$$

Modern Control IV

- State-variable descriptions of systems
- Linear systems and deempiricizing classical control
- Linear Quadra… Gaussian…
- Optim…
- Sampled-…ata control

- Identifica…
- Dist… …s
- … …ntrol
- … of … …inear systems
  - Linearizations
  - Lie algebras etc
  - Backstepping
  - Lyapunov-based design

Forbiddingly mathematical on occasions

Modern Control IV

- State-variable descriptions of systems
- Linear systems and deempiricizing classical control
- Linear Quadra
  Gaussian
- Optim
- Sampled-
  ol

- Identifica
- Dist
  s
- ol
- ystems
  - arizations
  - Lie algebras etc
  - Backstepping
  - Lyapunov-based design

Far more ideas than in classical control, but far more R and D people too!

Modern Control IV

- State-variable descriptions of systems
- Linear systems and deempiricizing cl... control
- Linear... Gau...
- Optima...
- Sampled-...

- Id...
- ...s
- ...ol
- ...as etc
- ...kstepping
- Lyapunov-based design

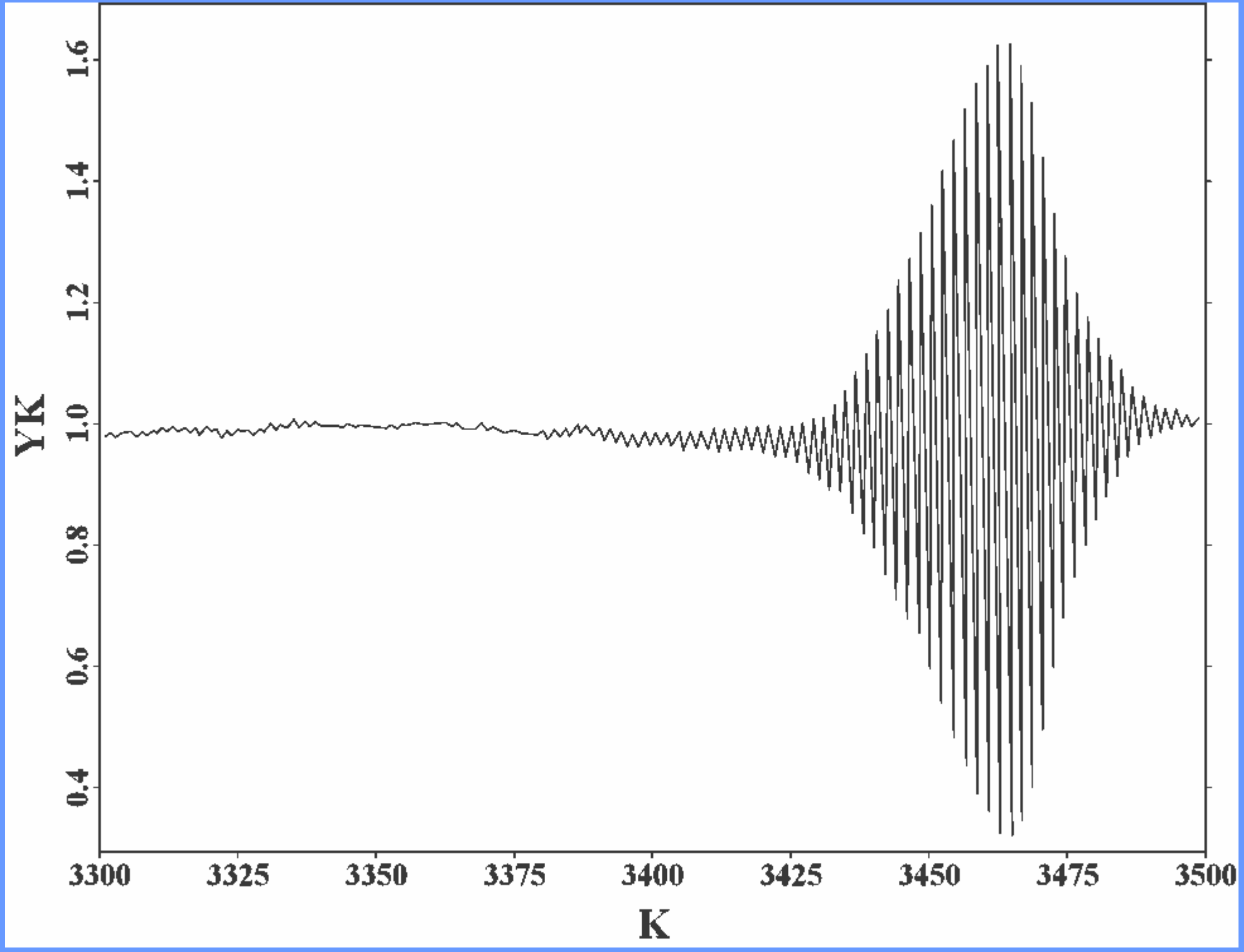
But **CONTROL AND INFORMATION ARCHITECTURES** stayed the same, like those of 19th Century!

Modern Control V

- Frustration at the ‘theory-practice’ gap. **Had applications ceased to drive theory?**
  - In part inevitable in any engineering discipline grounded in science
  - In part consequence of signals sent by funding entities, and public sector institution reward practices, with US a pattern-setter
  - In part reinforced by cultural differences
  - In part reinforced by uncautious claims of control theory people.

Bursting Phenomenon

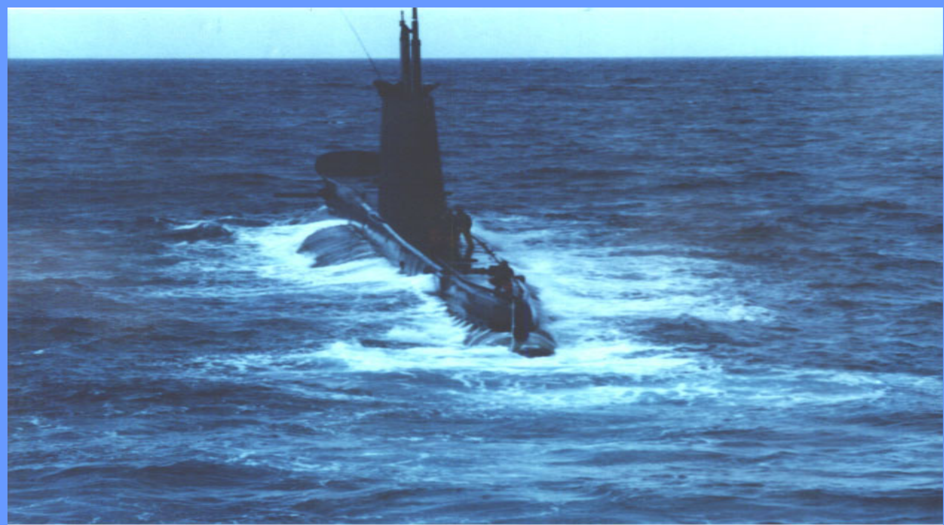
Theorem: Under conditions X, Y and Z the system is stable and errors go to zero as time goes to infinity.



1. Plant output should follow unit step input.
2. Plant output y_k well behaved till time 3400
3. Recovery occurs by time 3500

Application Driver Examples

- A cable is towed behind a ship. The ship is not travelling in a straight line. The cable is modelled by a nonlinear partial differential equation.
- How do you determine the shape of the cable with the aid of a **limited number** of compasses and depth sensors on it? How many and where?



Application Driver Examples

- The pitch control system on a commercial aircraft has two inputs, two outputs, stochastic disturbances, is open loop unstable and nonminimum phase. The state dimension is about 50
- How do you design a LOW ORDER controller

Outline

- Drivers of Control Theory Development
- History
- Near term drivers: public sector, private sector and science
- Life Sciences
- Managing Complexity
- Conclusions

Near Term Drivers

- Government Level Drivers
- Company Level Drivers
- Scientific Drivers
- Researchers

Near Term Drivers

- Government Level Drivers
  - Health and Ageing
  - Environment
  - Security, including (Asymmetric) Warfare
- Company Level Drivers
- Scientific Drivers
- Researchers

Near Term Drivers

- Government Level Drivers
- Company Level Drivers
  - Integration of systems
  - Finding single solutions using multiple technologies (engineering, IT, biology, etc)
  - Using the freedom of wireless, lower power devices, embedded systems,….in most domains
- Scientific Drivers
- Researchers

Near Term Drivers

- Government Level Drivers
- Company Level Drivers
- Scientific Drivers
  - Links with **Life sciences**
  - **Managing complexity**
  - Nanotechnology (but I am ignorant)
- Researchers

Near Term Drivers

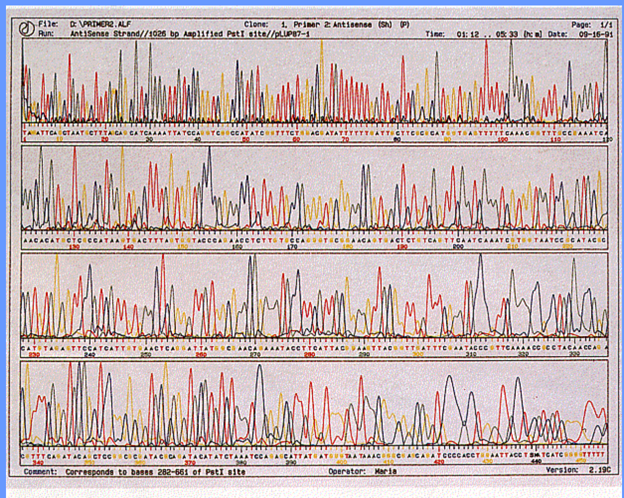
- Government Level Drivers
- Company Level Drivers
- Scientific Drivers
- Researchers
  - Intellectual interest
  - Some seek to couple applications to theory as a life-style

Outline

- **Drivers of Control Theory Development**
- **History**
- **Near term drivers**
- **Life Sciences**
  - **The link to control**
  - **Systems biology**
  - **Mega challenges for control engineers**
- **Managing Complexity**
- **Conclusions**

Links with Life Sciences

- The Government problem: increased life expectancy, and payment for health care
- The biotechnology **revolution**, which is forcing many biologists to:
  - Become mathematically more literate
  - To understand issues of feedback, modelling and ***system level*** behavior



Links with Life Sciences

- **Control, communications and computer devices in medicine:**
  - The technologies can be the basis of medical and veterinary interventions.
  - Technologies used include safety critical systems, adaptive systems, sensors, low power, optimal control.

Cardiac Pacemaker:

Many pacemakers are adaptive.

Some contain a defibrillator.

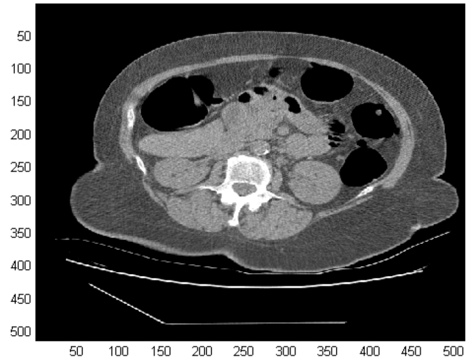
Links with Life Sciences

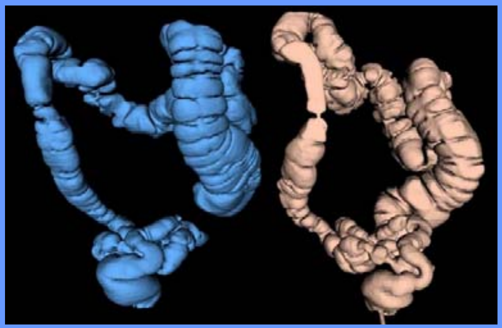
- Control, communications and computer devices in medicine
- **Biological structures and capabilities may inspire mimicry:**
  - The body's control systems exhibit hierarchy, learning and adaptivity, nonlinearity, multi-loop interaction.
  - Biological sensors and signal processing are different to what we are used to, and may be nonlinear--think how an insect lands on a flower.
  - What can we learn from nature's way of doing things?

.

Links with Life Sciences

- Control, communications and computer devices in medicine
- Biological structures and capabilities may inspire mimicry
- **Medical interventions may first require identification of very complex systems:**
  - The systems may not be linear
  - The signals may be pulses or chemicals, and not sine waves. They may be hard to define, isolate and measure
  - The systems are generally adaptive, and thus often not time-invariant





Computed Tomography Colonography: automatic and robust statistical method that can accurately differentiate between polyps and normal tissue.

The bigger picture: Systems biology

- **Systems biology** studies how an organism functions, viewed as an ***interacting network*** of genes, proteins and biochemical reactions, together with external environment.
- It aims at a system-level understanding, including:
  - the **internal structure** (genetic, biochemical and physical)
  - **Dynamical behaviour** (qualitative and quantitative), with predictive models and theoretical **explanation** of behaviour
  - How to **control** the system (biochemical, pulse signals etc)
  - **Design** aspects of the system
- Ultimate goal: **improve human health and disease management**

Specific Problem

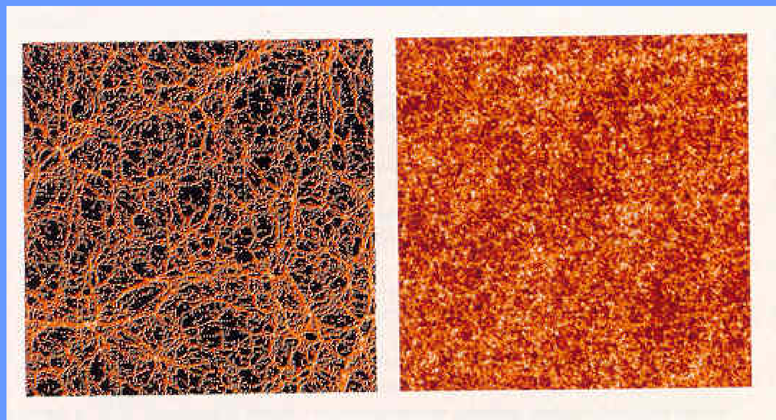
- A car accident occurs…..

- The victim arrives. What measurements should one take? What control systems should be connected up to the interacting respiration, cardiovascular and nervous systems to stabilise and then promote recovery of the patient?

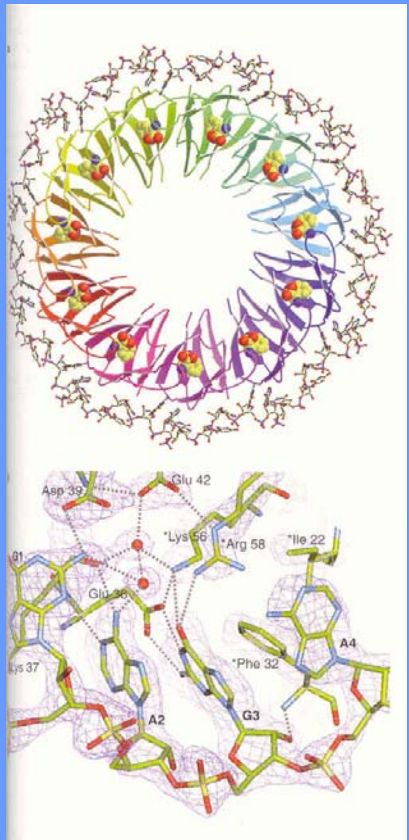
- Answers today are very empirical

Mega-Challenges for control engineers

- Types of models to identify are unclear; **internal** structures may have to be identified
- Inputs may be pulse sequences or chemicals, and hard to pin down
- Signalling pathways may have large delay
- Centralized and decentralized control actions may occur simultaneously
- Responses to inputs may be very hard to forecast



Mega-Challenges for control engineers



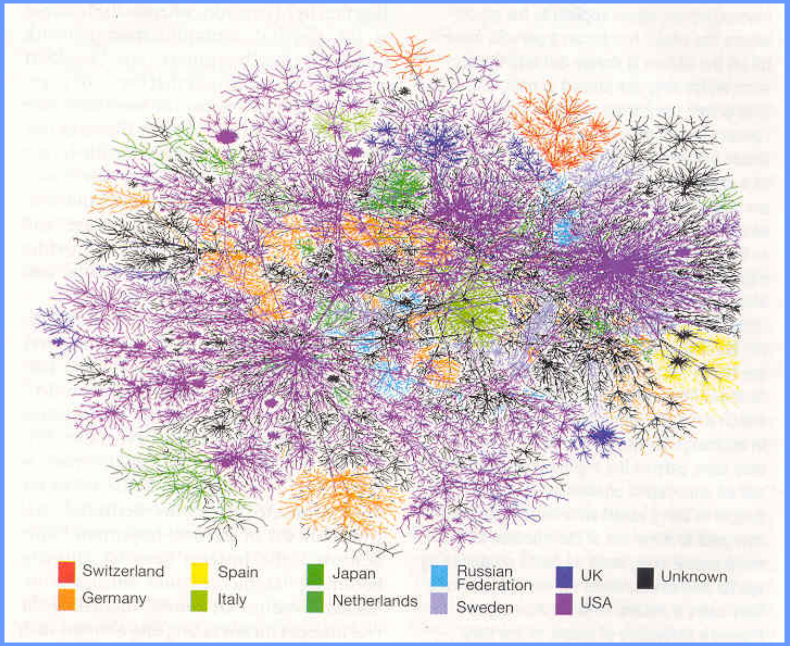
- Measurements are taken over very variable time scales: X-rays, pathology tests through to emergency room cardiac monitoring
- Many systems in body include an adaptive component --which must be allowed for in identification and control
- System inputs may include persistently exciting signals generated from another part of the whole organism
- **Nature has NOT done analytic design; it has produced brilliant iterative design. How do we shift our thinking to do the same?**

Outline

- **Drivers of Control Theory Development**
- **History**
- **Near term drivers**
- **Life Sciences**
- **Managing Complexity**
  - **Isolating the issues**
  - **Specific examples: communications systems and power systems**
  - **The architecture problem, and examples**
- **Conclusions**

Complexity Management

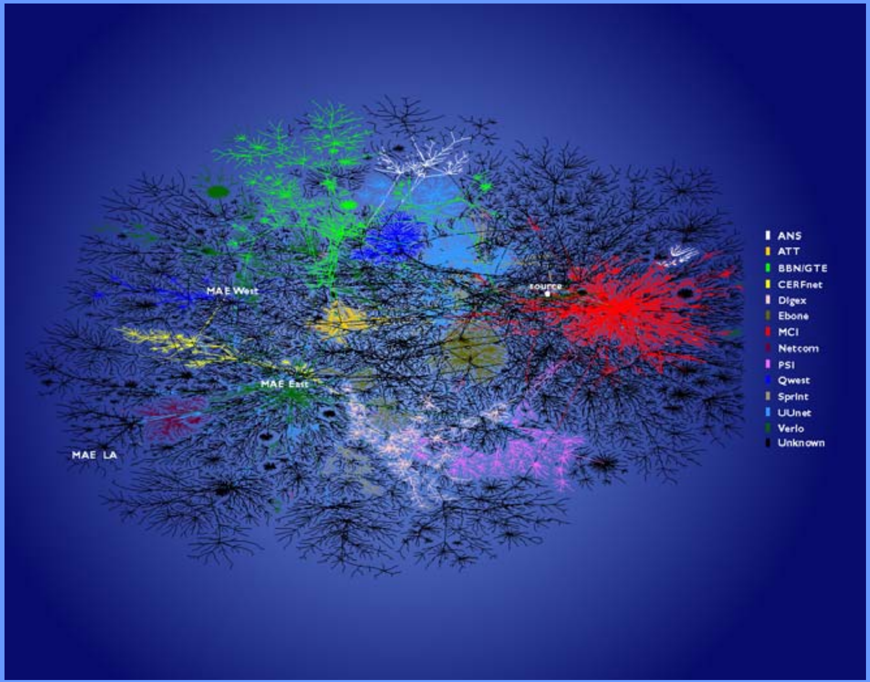
- Domain of discourse:
  - No one person can grasp it all
  - Information from many sensors, sources, possibly heterogeneous, and/or masses of data
  - Large size
  - Systems of systems
  - Sometimes large legacy component



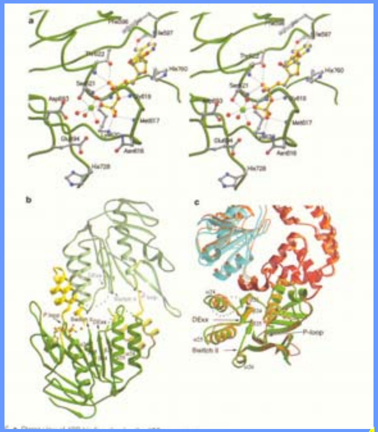
Internet

Complexity Management

- At the highest level, the complexity is ***overwhelming*** designers and managers
- Examples: telecom network, power system, a national economy, the human body, natural language processing, automatic real-time language translation, chips with 10^7 components, etc



www and a biological system



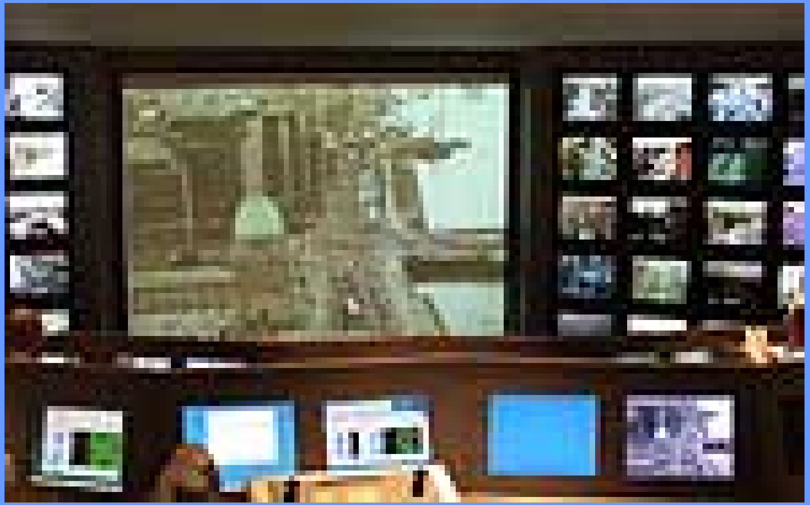
Complexity Management

- Complexity management in this sense ***is not just***
  - Developing algorithms that will handle bigger and bigger matrices, even if new numerical analysis tools are used
  - Creating design tools that can easily portray four, five,… dimensional surfaces
  - Replacing deterministic algorithms of very high computational complexity by probabilistic algorithms that work well most of the time and have low computational complexity
  - Discretizing partial differential equations
- These are **linear extrapolations of existing activity**.

Complexity Management

New issues can appear in managing complexity, including:

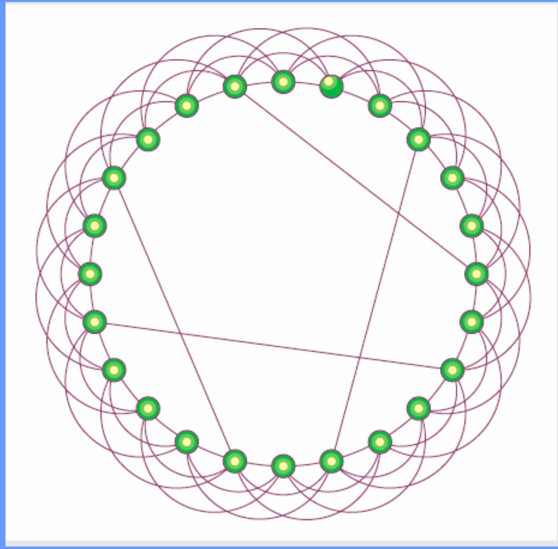
- Securing **scalability**
  - Can an optimized adaptive traffic control system be expanded indefinitely as roads and cars as added?
- **Architectures**
  - How are information flow and control actions to be handled in an emergency response system
- **Self-organization and repair**
  - Can we build systems that do what the human body does?

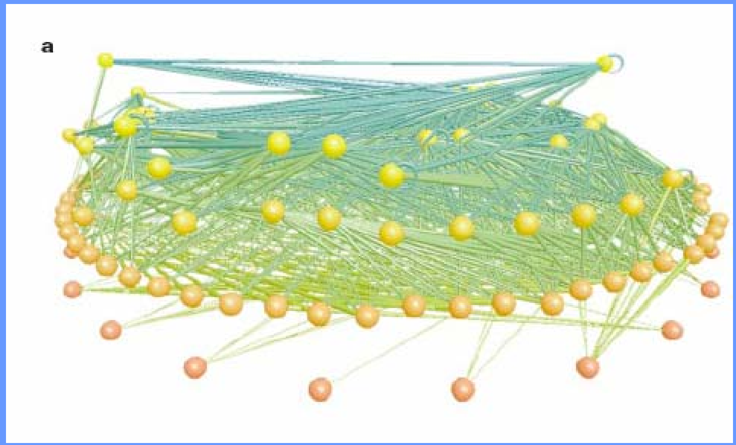


Complexity Management

New issues can appear in managing complexity, including:

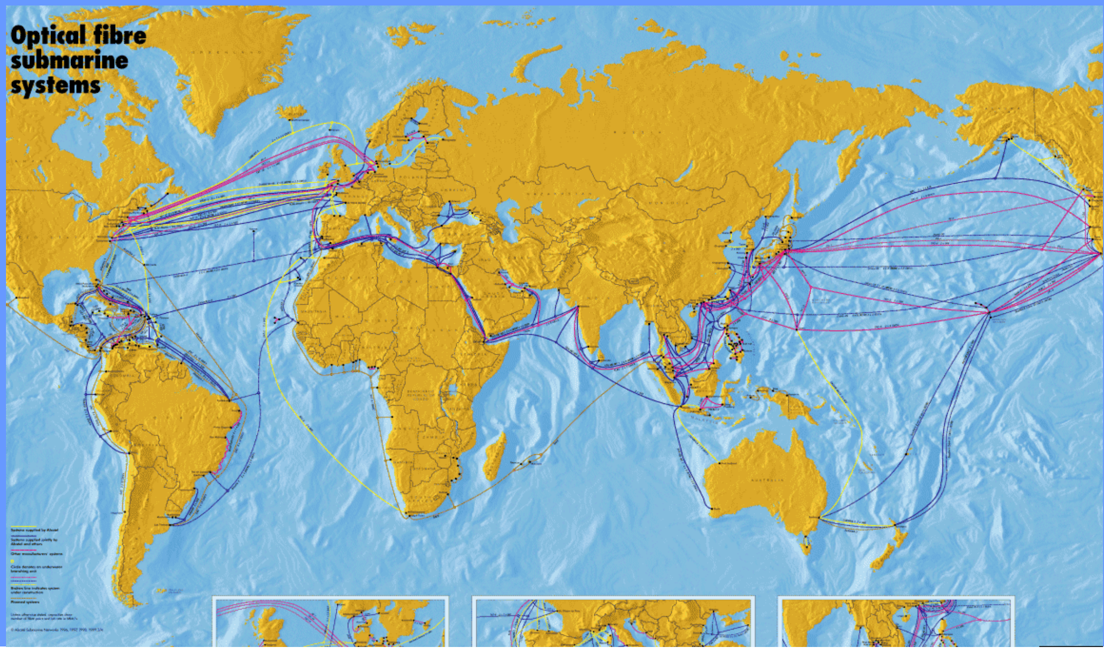
- **New phenomena** (emergent properties, small-world, notion of scale-free)
- The **applications themselves** (mobile telephony, mobile communications, biological terrorism defence in cities, etc)--because they are so big.
- Are **standards** good or not good?
  - Nature thrives on diversity, the military probably abhors it.





Communication System Complexity

- **Scalability** World wide interconnection required, with many legacy systems
- **Adaptivity:** Desire self-configuring, **self-**healing**, self**-protecting**, self-**optimizing, **self**-optimizing
- **Decentralized Architecture** There is a need for ***Distributed*** computing, ***Distributed*** control, ***Distributed*** optimization
- **Application Specific Design** There is a need for new paradigms like:
  - ***Opportunistic and collaborative*** communications, giving resources to the best channel (noise, bandwidth, power, etc)
  - New OSI-type layer modelling, to handle architectures

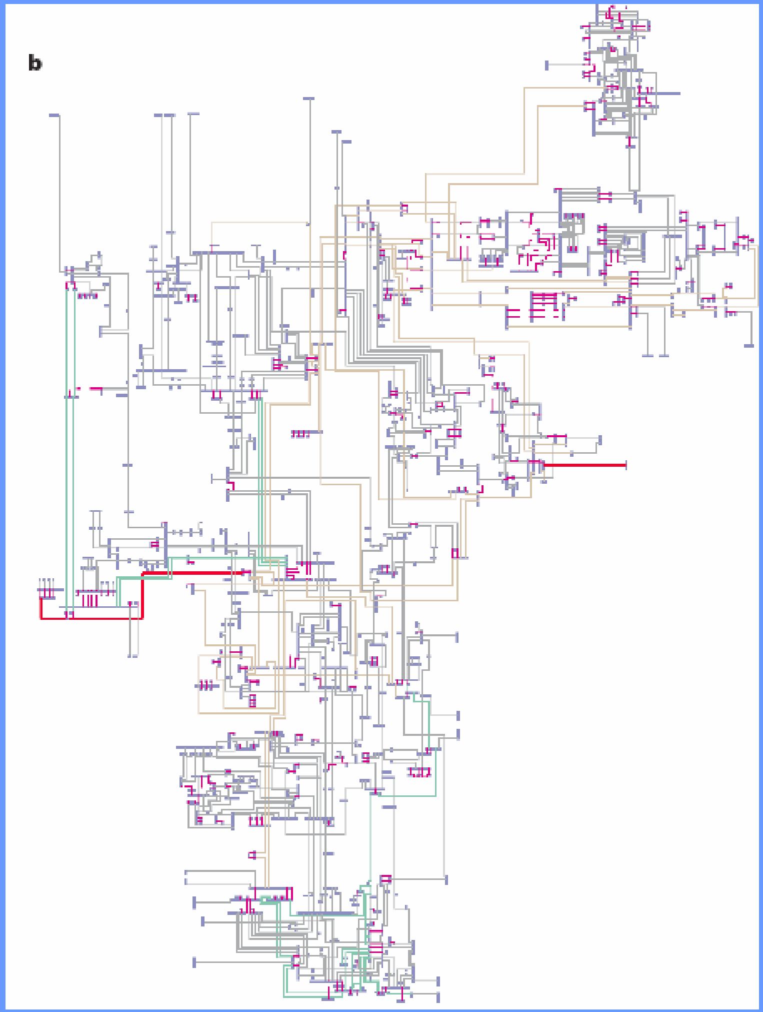


Communication System Complexity

- **Information Theory:** Do we know enough distributed system theory, or enough Shannon theory for multi-users?
- **Robustness**: What are the principles of designing systems that allow A to make local modifications while not knowing what B is doing, and what C did many years ago, in relation to performance, stability, software engineering, security, economic return to owners, reliability, etc

Power System Complexity

- Very long range interconnections required, with many legacy systems, and different operators
- Stability problem exists! It is made worse by:
  - Frequent lack of central coordinating entity
  - Unpredictability of fault type and timing
  - Economic incentives on operators to minimise stability margins
- Dynamic modelling would require nonlinear equations with hundreds or thousands of variables
- Big dollars!



New York State Grid

Power System Complexity

- Very long range interconnections required, with many legacy systems, and different operators
- Stability problem exists! It is made worse by:
  - Frequent lack of central coordinating entity
  - Unpredictability of fault type and timing
  - Economic incentives on operators to minimise stability margins
- Dynamic modelling would require nonlinear equations with hundreds or thousands of variables
- Big dollars!

Swarm Problems

- Rendezvous
- Consensus and flocking
- Station keeping
- Maintaining shape of a moving formation
- Splitting and merging formations
- Giving autonomy to a collection of agents to execute different classes of missions
- Self-repair

Architectures and Complexity

- Understanding these swarms requires answers to a fundamental problem:

What are the ARCHITECTURES for each of:
SENSING,
COMMUNICATIONS,
CONTROL?

This question underpins MANY COMPLEX SYSTEMS. We are not used to asking it.

Architectures and Complexity

- Large scale systems have been discussed for several decades
- Discussions usually focus on
  - Hierarchical control, or
  - Decentralized control
- This is ***nothing more*** than imposing certain control, sensing and communications architectures….and look how difficult the problems have been!

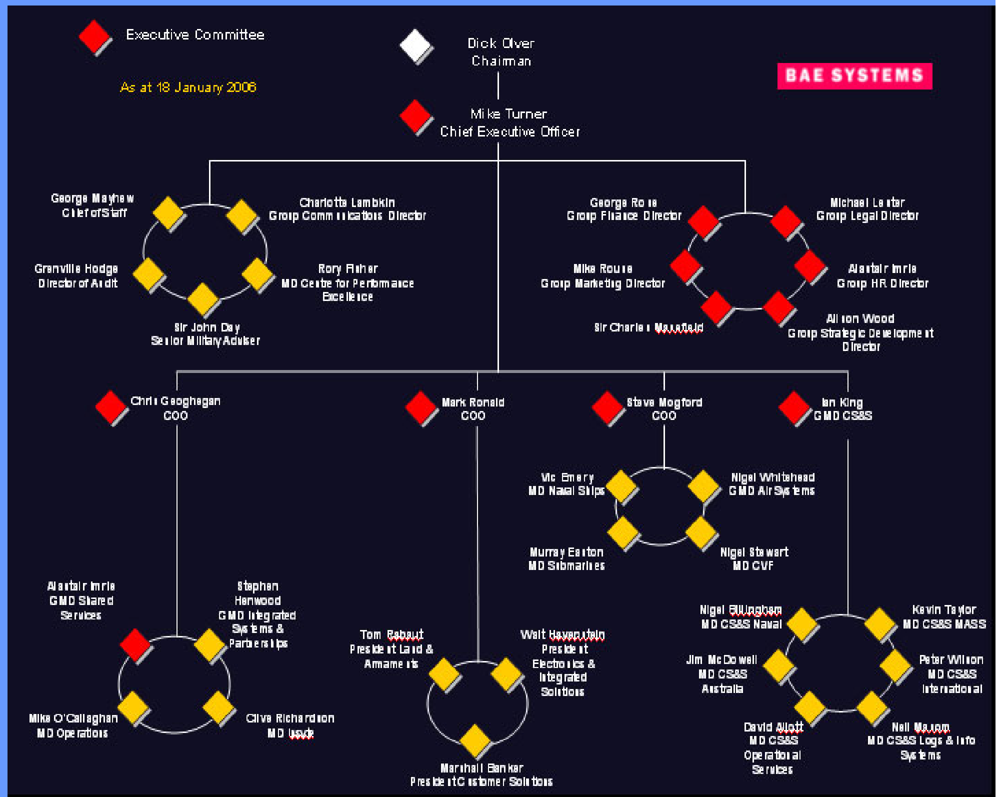
An applications problem needing theory

- How should a corporation, or the Australian Army be organised?
  - How many levels should there be?
  - How big can each level be?

- This is obviously a problem involving data collection (sensing), communications and control with decentralization, adaptivity, robustness requirements

- Our existing theory is not suited.

- How do we know we have it right at the moment? We have no way of knowing, apart from empirical observation!

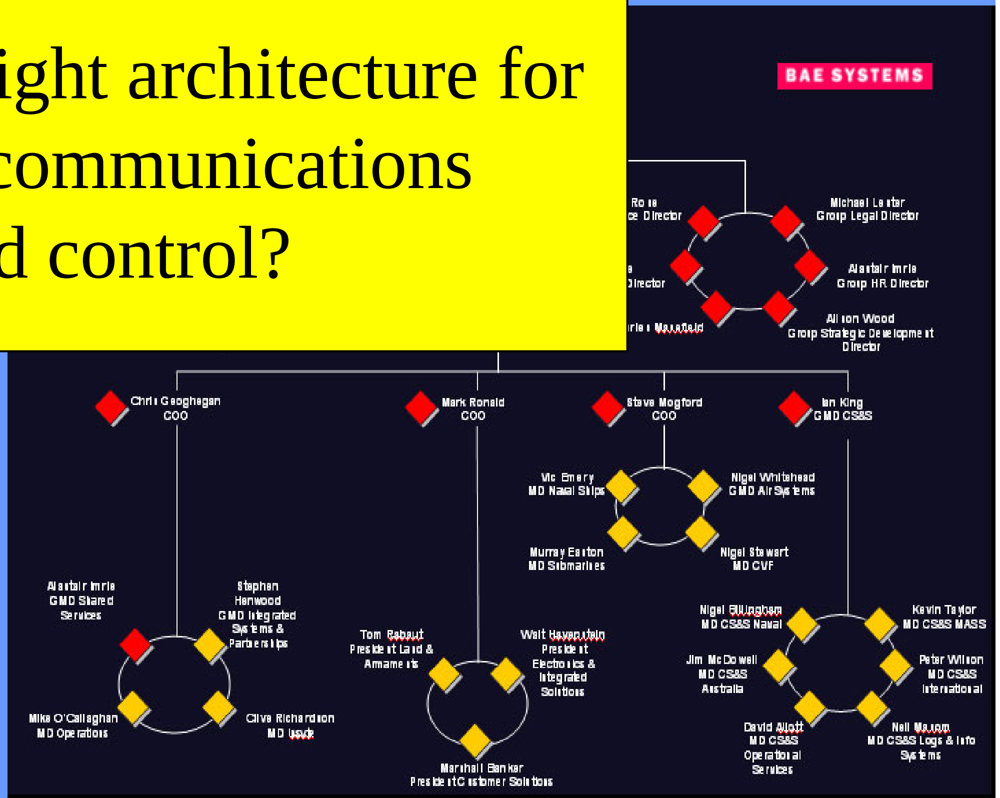


An applications problem needing theory

- How should a corporation, or the Australian Army be organised?
  - How many levels should there be?
  - How big can each level be?

- This is obviously
problem involving
collection (sensin
communications ar
decentralization,
robustness requirements

What is the right architecture for sensing, communications and control?



- Our existing theory is not suited.

- How do we know we have it right at the moment? We have no way of knowing, apart from empirical observation!

The National Economy

- A national economy is part of the world economy, which has many agents
- Central banks probably have little idea as to how much data needs to be collected to ‘control’ a national economy
- Humans are in the economic loop, complicating control
- Elements of game theory are relevant; information is viewed as crucial by individual players
- Billions of dollars/euros are at stake. Livelihoods of families are at stake.

The National Economy

- A national economy is part of the world economy, which has many agents
- Central banks probably hav… to how much data need… …ed to ‘control’ a nati…
- Huma… …onomic loop, …ontrol
- …nts of game theory are relevant; …nformation is viewed as crucial by individual players
- Billions of dollars/euros are at stake. Livelihoods of families are at stake.

Could central banks and governments do a better job of controlling national economies?

The National Economy

- A national economy is part of the world economy, which has many agents
- Central banks probably ha… how much data need… 'control' a nati…
- Huma…
- …ory are relevant; …ewed as crucial by individual p…
- Billions of dollars/euros are at stake. Livelihoods of families are at stake.

How can we know what the gold standard for control of an economy is? So how do we know whether central banks and governments are or are not performing well?

The National Economy

- Could central banks and governments do a better job of controlling national economies?
- How can we know what the gold standard for control of an economy is? So how do we know whether central banks and governments are or are not performing well?
- Where is the theory that says the more you plan and the more you measure, the more you might trip up--like the Soviet Union?

Outline

- **Drivers of Control Theory Development**
- **History**
- **Near term drivers**
- **Life Sciences**
- **Managing Complexity**
- **Conclusions**

Conclusions: system state evolution

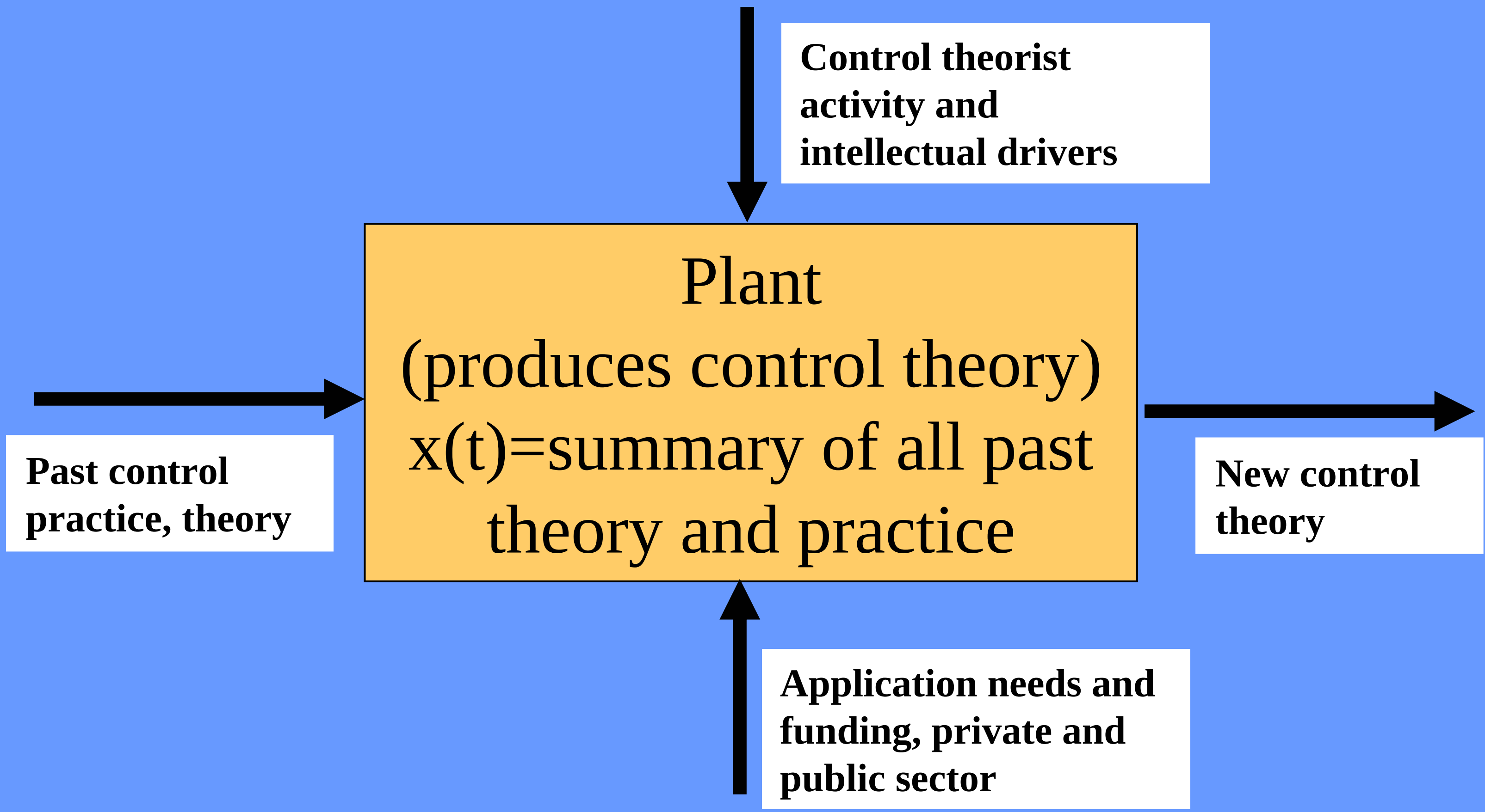
Empirical
Till end 19th C

Classical
LTI, SISO
Graphical

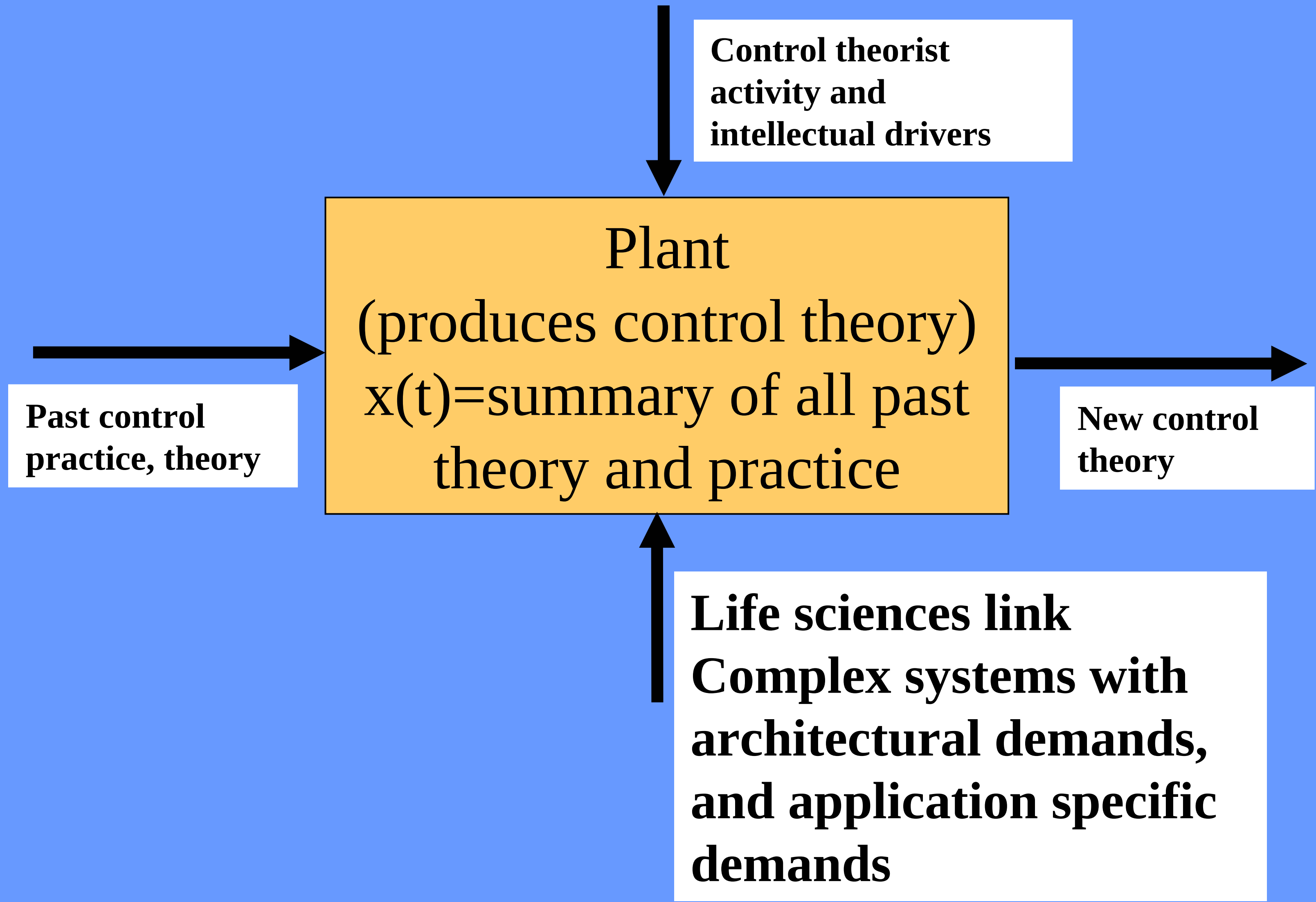
Modern
Not classical
EXCEPT
Architectures remain classical

?

Drivers


Control theorist activity and intellectual drivers
Plant
(produces control theory)
x(t)=summary of all past theory and practice
Past control practice, theory
New control theory
Application needs and funding, private and public sector

Conclusions



Conclusions

Control theorist activity and intellectual drivers

Past control practice, theory

Plant
(produces control theory)
x(t)=summary of all past theory and practice

Life sciences link
Complex systems with architectural demands, and application specific demands

New control theory:

including marriage of control, information and communications theory and probably theoretical computer science, much directed at solving the architecture problem

AND

Identification and modelling where little is known about structures, signals, and in presence of self-adaptive processes