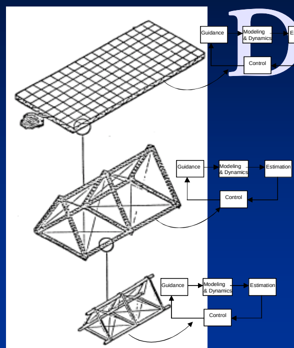
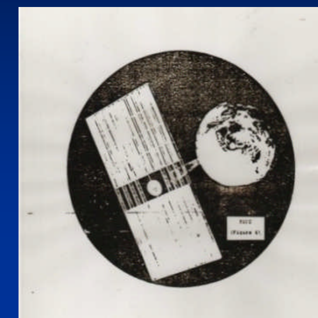
Emerging New Directions in Infinite-Dimensional Adaptive Control





Mark J. Balas
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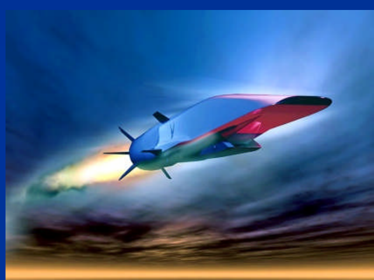
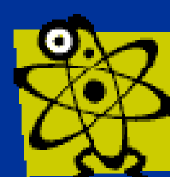


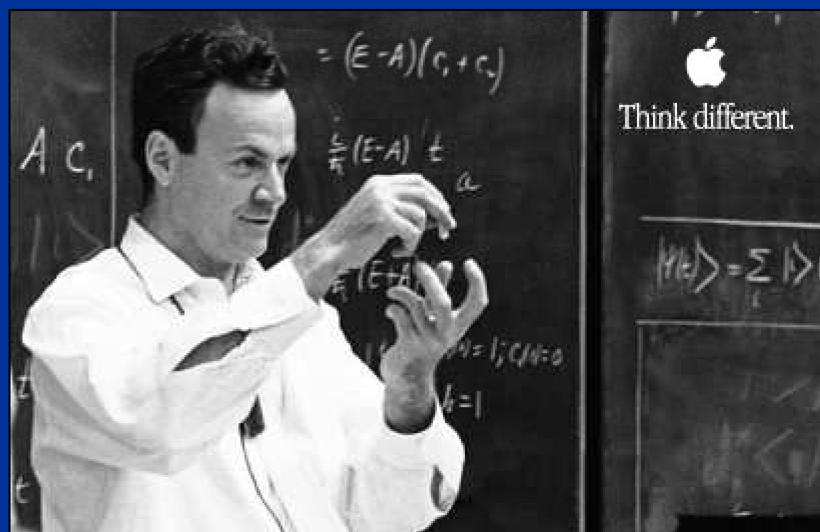


Thank you Petre

ADAPTIVE 2015, The Seventh International Conference
on Adaptive and Self-Adaptive Systems and Applications
March 22 - 27, 2015 - Nice, France

Infinite-Dimensional Adaptive Control Theory

"~~Physics~~ is like sex: sure, it may give some practical results, but that's not why we do it."
— Richard P. Feynman



In a tile motif on the back of the Ross Dress For Less building on Lake Ave, Pasadena, CA

F-16 Flexible Structure Model: Fluid-Structure Interaction

Flutter

USAF-Edwards AFB
Flight Test Center

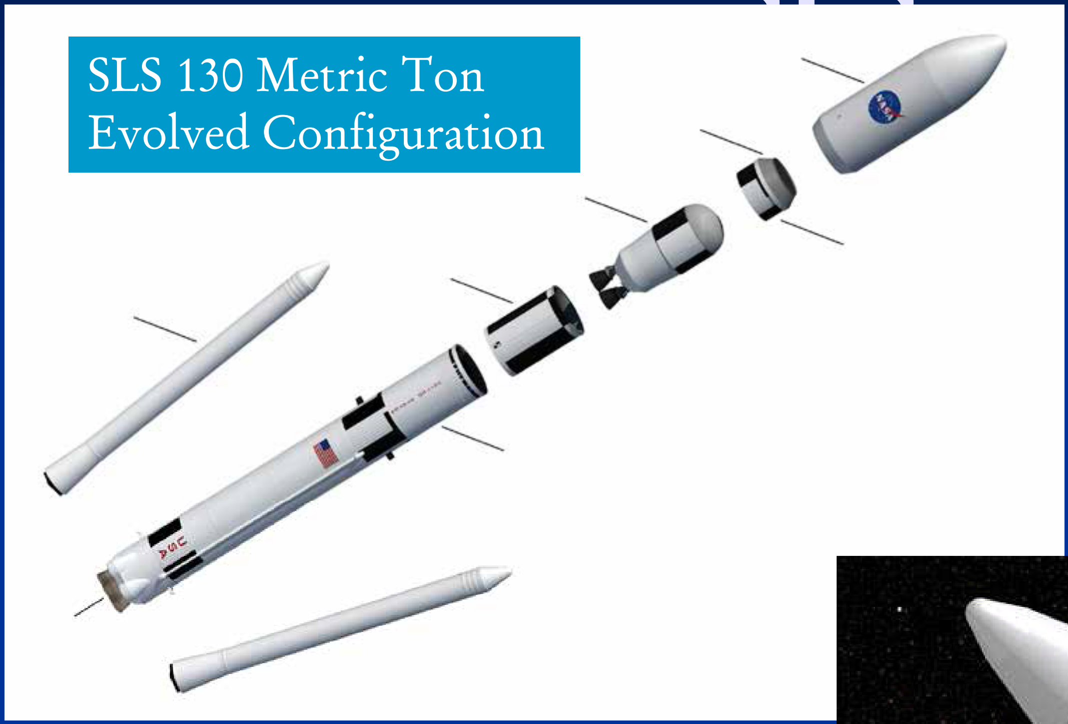
Many Emerging Solutions

Hypersonic Aircraft X51A Wave Rider

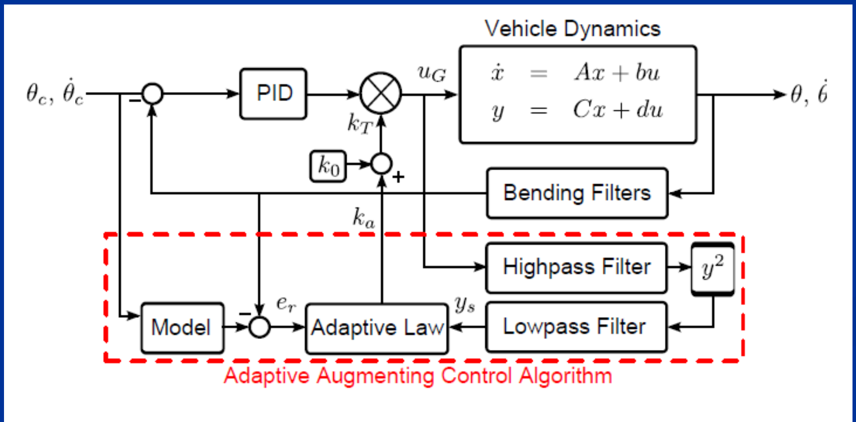
6 Minutes at Mach 5.1

The X-51A WaveRider is an unmanned, autonomous supersonic combustion, ramjet-powered hypersonic flight-test demonstrator for the U.S. Air Force. The X-51A demonstrates a scalable, robust endothermic hydrocarbon-fueled scramjet propulsion system in flight, as well as high temperature materials, airframe/engine integration and other key technologies within the hypersonic range of Mach 4.5 to 6.5.

NASA Space Launch System SLS



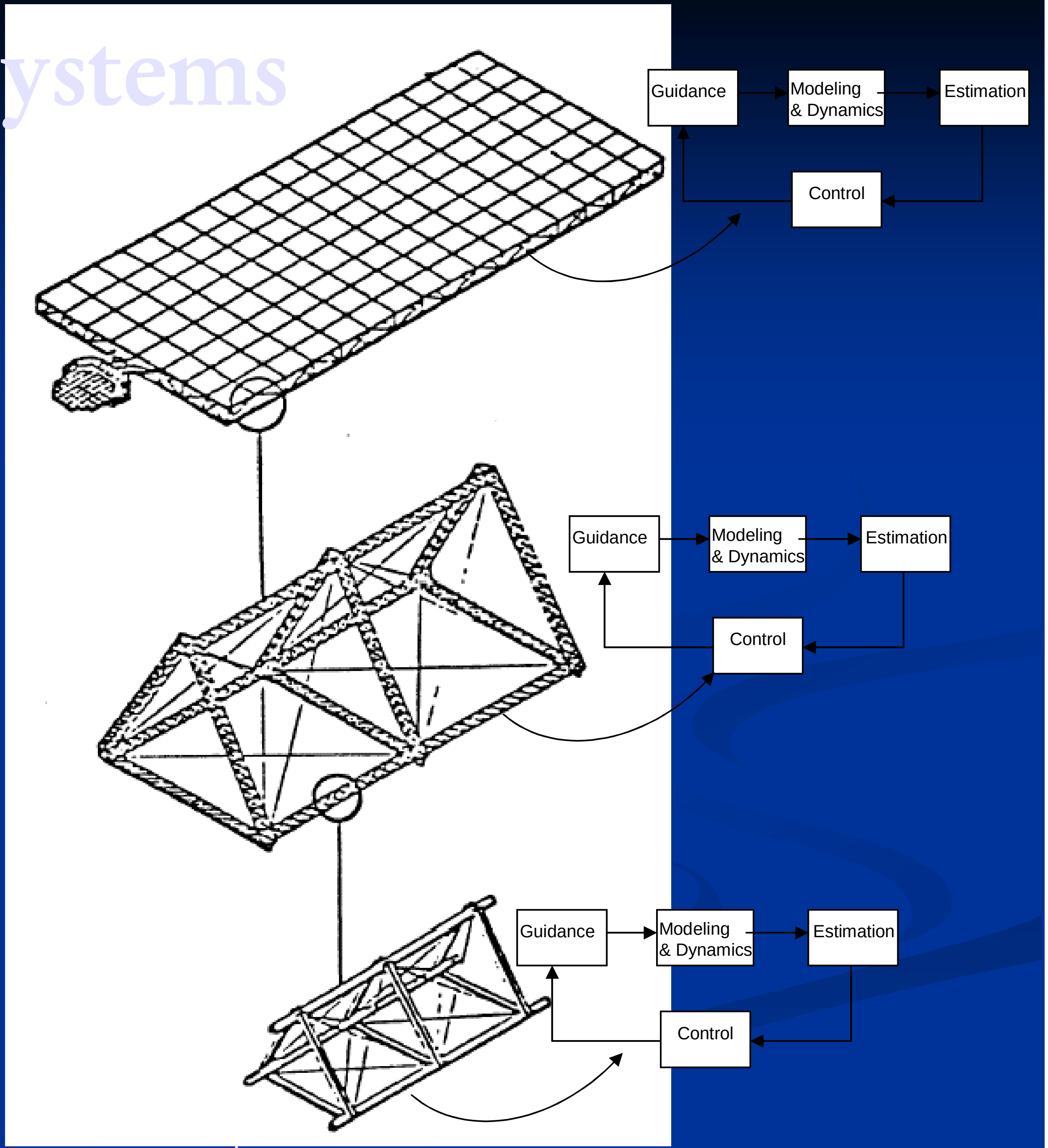
NASA MSFC



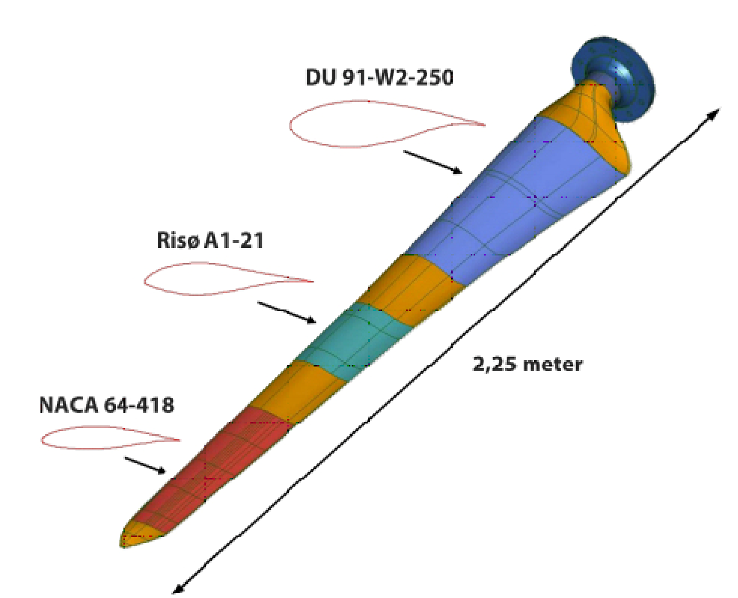
Evolving Systems

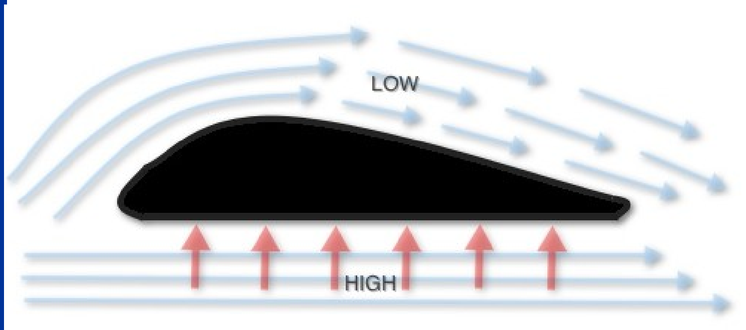
Evolving Systems=
Autonomously
Assembled
Active Structures

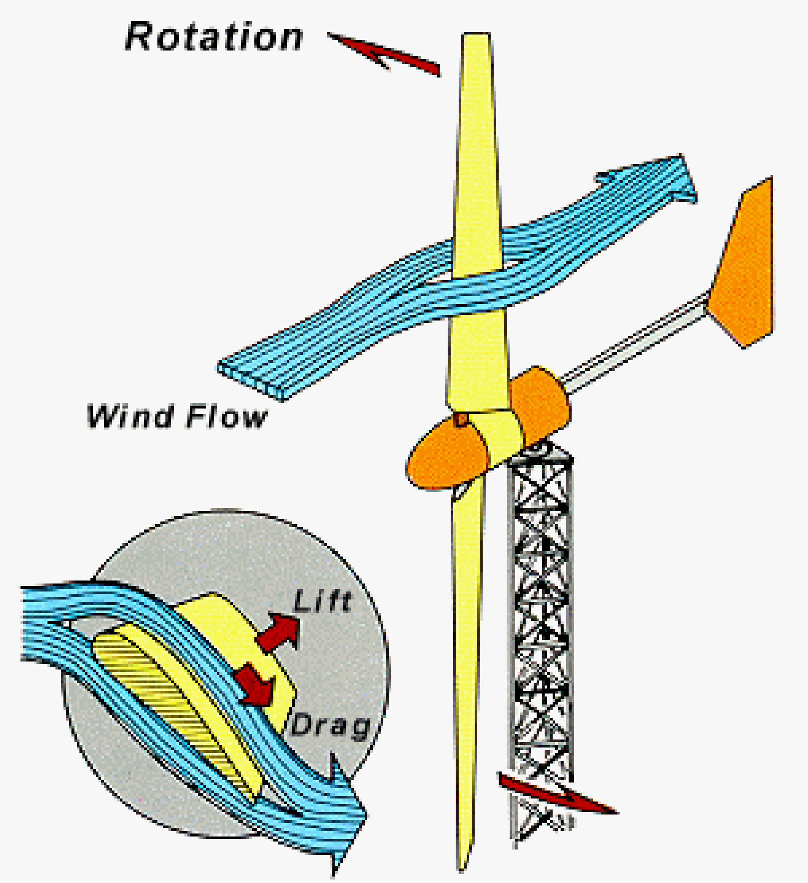
Or Self-Assembling
Structures,
which Aspire to a
Higher Purpose;
Cannot be attained
by Components Alone



Flow Control of Wind Turbine Aerodynamics



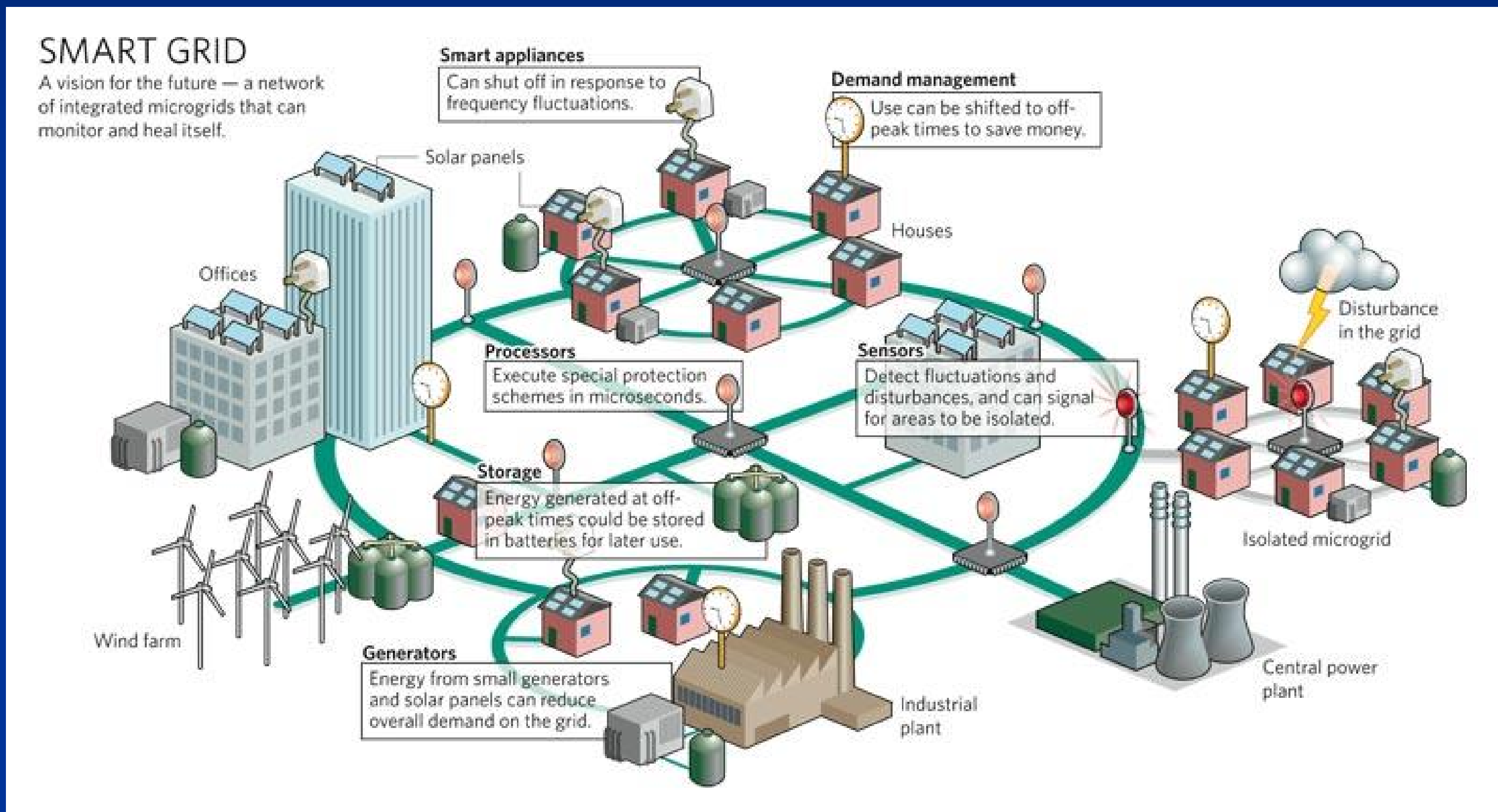




Principles of Wind Turbine Aerodynamic Lift

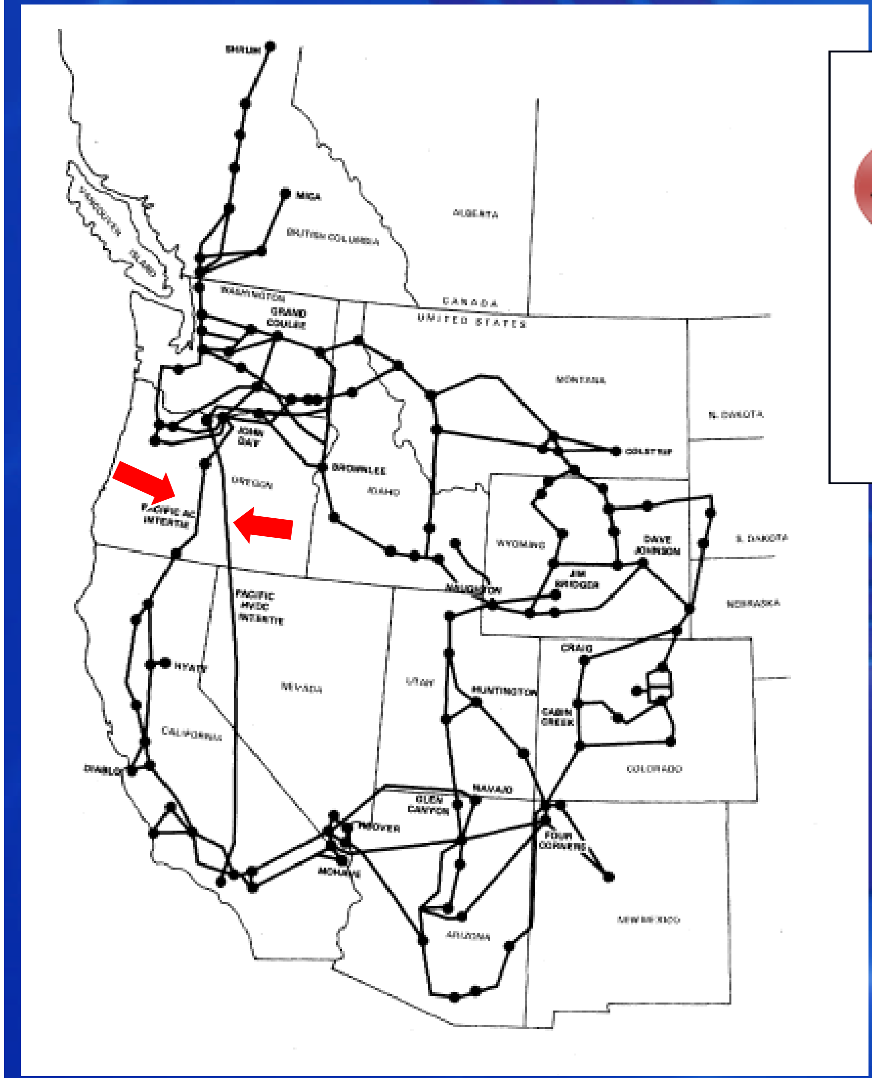
UNIVERSITY OF WYOMING

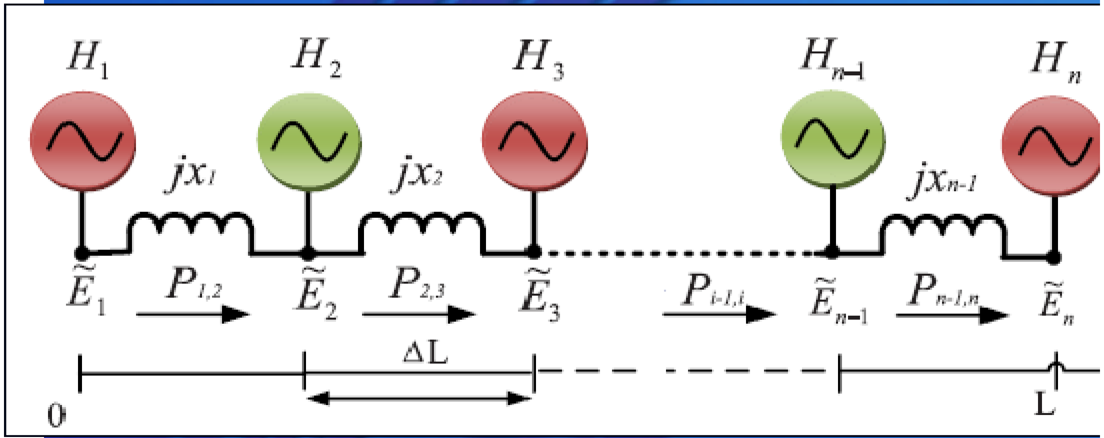
Smart Grids:
Virtual Interconnecting Forces



"It is surprising how quickly we replace a human operator with an algorithm and call it SMART"

Power System as Distributed Parameter System

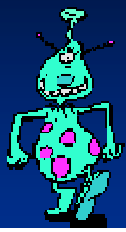




Subarea Oscillations

$$\frac{\partial^2 \delta(u,t)}{\partial t^2} + \eta \frac{\partial \delta(u,t)}{\partial t} = \nu^2 \frac{\partial^2 \delta(u,t)}{\partial u^2}$$

"Simplicity" via Infinite Dimensional Spaces



$$\begin{cases} \frac{\partial x}{\partial t} = Ax + Bu = Ax + \sum_{i=1}^{m} b_i u_i \\ x(0) = x_0 \in D(A) \subset X \\ y = Cx = \left[(c_1, x) \quad (c_2, x) \quad \dots \quad (c_m, x) \right]^T \end{cases} \Rightarrow x(t, w_0) = \underbrace{U(t)}_{\text{Evolution in } X} x_0 ; \forall t \geq 0$$

"Boil Away" all the special properties of $\Re^N$

C_0 – Semigroup of Bounded Operators $U(t)$:

$$\begin{cases} U(t+s) = U(t)U(s) \text{ (semigroup property)} \\ \frac{d}{dt}U(t) = AU(t) = U(t)A \text{ (} A \text{ generates } U(t)\text{)} \\ U(t)x_0 \xrightarrow[t \to 0]{} x_0 \text{ (continuous at t = 0)} \end{cases}$$

J. Wen & M.Balas, "Robust Adaptive Control in Hilbert Space ", J. Mathematical. Analysis and Applications, Vol 143, pp 1-26,1989.

J. Wen & M.Balas ,"Direct Model Reference Adaptive Control in Infinite-Dimensional Hilbert Space," Chapter in Applications of Adaptive Control Theory, Vol.11, K. S. Narendra, Ed., Academic Press, 1987

The Devil Lurks in the Details

Semigroups

Closed Linear Operator

Solve $\begin{cases} \dfrac{\partial x}{\partial t} = Ax \\ x(0) = x_0 \in D(A) \end{cases} \Rightarrow x(t) = U(t)x_0$

$\dim X = N < \infty$

$\Rightarrow U(t) = e^{At} = \sum_{k=0}^{\infty} A^k \dfrac{t^k}{k!}$

C_0 – Semigroup

$U(t): X \to X$ bounded operators $t \geq 0$

Generator: $Ax = \lim_{t \to 0+} \dfrac{U(t)x - x}{t}$ with $D(A) \equiv \{x / \lim_{t\to 0+} \text{ exists } \}$ dense in X

LaPlace Transform $\begin{cases} L(U(t)) = (\lambda I - A)^{-1} \equiv R(\lambda, A) \text{ Resolvent Operator} \\ L^{-1}(R(\lambda, A)) = U(t) \end{cases}$

Spectrum of A

Resolvent Set $\rho(A) \equiv \{\lambda / R(\lambda, A) : X \to X \text{ bounded linear op on } X\}$

Spectrum $\sigma(A) \equiv \rho(A)^{C} = \sigma_{\text{point}}(A) \cup \sigma_{cont}(A) \cup \sigma_{residual}(A)$

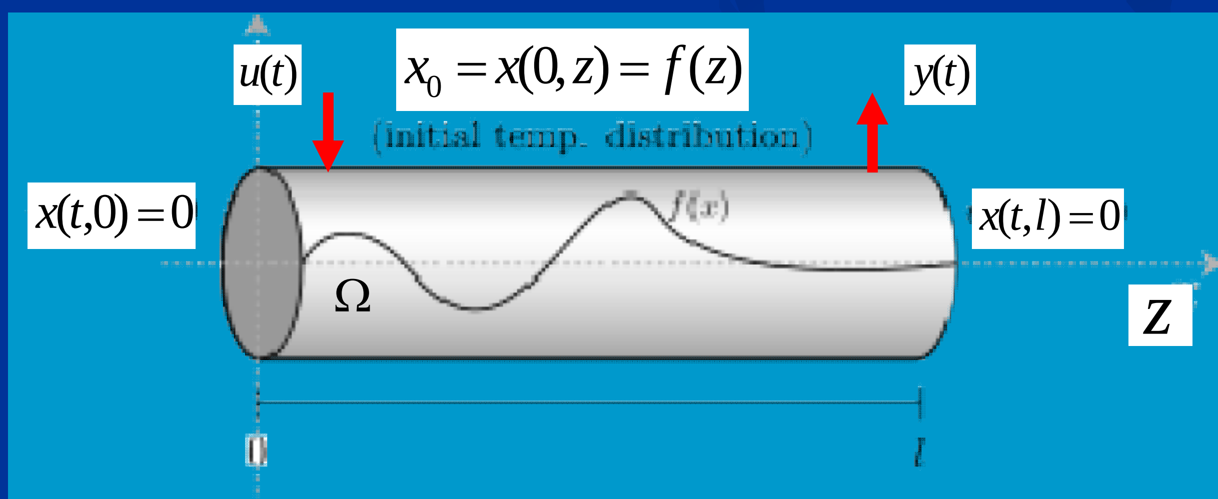
$$\sigma_{point}(A) \equiv \{\lambda / R(\lambda, A) \text{ is NOT 1-1}\} = \{\lambda / \exists \phi \neq 0 \ni \lambda\phi = A\phi\}$$

$$\sigma_{cont}(A) \equiv \{\lambda / R(\lambda, A) \text{ is 1-1, but its range is only dense in } X\}$$

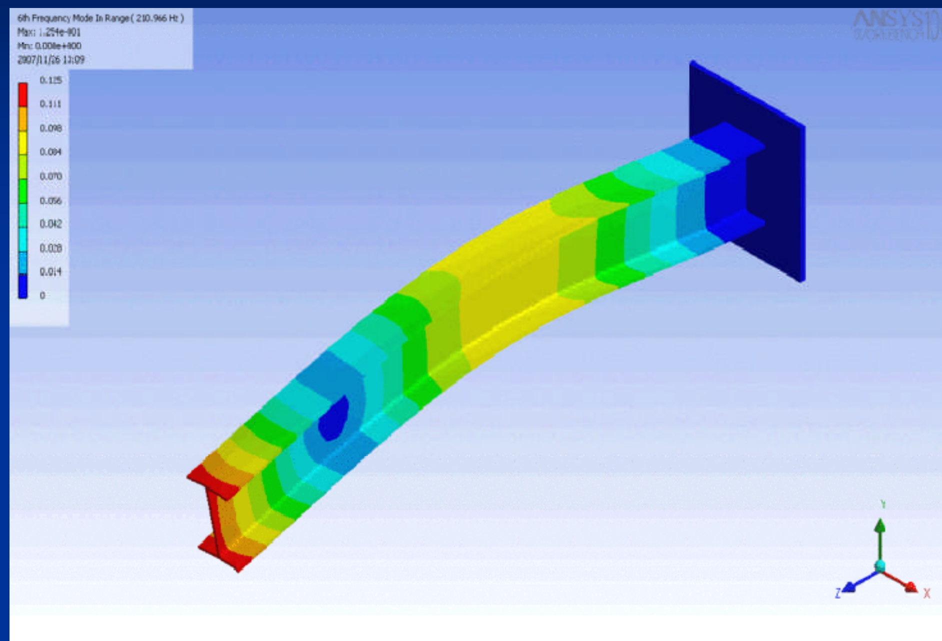
$$\sigma_{residual}(A) \equiv \{\lambda / R(\lambda, A) \text{ is 1-1, but range is a proper subspace of } X\}$$

Example: Heat Diffusion

$$
\begin{cases}
\dfrac{\partial x}{\partial t} = \underbrace{\dfrac{\partial^2 x}{\partial z^2}}_{Ax} + bu; \\
b(z) \in D(A) \equiv \left\{ x \,/\, \text{smooth and BC:} x(t,0) = x(t,l) = 0 \right\} \\
\qquad\qquad\qquad \subset X \equiv L^2(\Omega) \\
\text{with } (x,y) \equiv \int_\Omega x(t)y(t)dt \\
x(0) = x_0 \in D(A) \\
y = (c,x); \quad c(z) \in D(A)
\end{cases}
$$



Euler-Bernoulli Beam



$$\frac{\partial}{\partial t}\begin{bmatrix} w \\ w_t \end{bmatrix} = \underbrace{\begin{bmatrix} 0 & I \\ -\frac{EI}{\rho}\frac{\partial^4}{\partial z^4} & 0 \end{bmatrix}}_{A} \begin{bmatrix} w \\ w_t \end{bmatrix} + \underbrace{\begin{bmatrix} 0 \\ b(z) \end{bmatrix}} u(t)$$

Symmetric Hyperbolic Systems

$$\frac{\partial \underline{\varphi}}{\partial t} = \underbrace{\sum_{i=1}^{n} \underbrace{A_i}_{\substack{lxl \text{ constant} \\ \text{symmetric}}} \frac{\partial \underline{\varphi}}{\partial z_i} + \underbrace{A_0}_{lxl \text{ constant}} \underline{\varphi}}_{A\varphi}; \underline{x} \in D(A) \subset X \equiv L^2(\Omega; \Re^l)$$

Boundary

$$\textit{Conditions}: \Lambda(z)\varphi(z,t) = 0 \forall z \in \partial\Omega; t \geq 0$$

Theorem :

1) Symbol : $A(\xi) \equiv \sum_{i=1}^{n} \xi_i A_i$ is nonsingular $\forall \xi \neq 0 \in \Re^n$

2) $A_0 + A_0^* < 0$

3) $\dim N(A) < \infty$

4) Boundary Conditions are <u>Coercive</u> $(\therefore \overbrace{\|\underline{\varphi}\|}^{\text{Sobolev Norm}}{}_1 \leq \|\underline{\varphi}\| + \|A\underline{\varphi}\|)$

$\Rightarrow$ A has compact resolvent and A generates an <u>exponentially stable</u> C_0 semigroup.

Examples

Wave Equation

$$\text{2-dim wave equation } \frac{\partial^2 x}{\partial^2 t} = \underbrace{\left(\frac{\partial^2 x}{\partial^2 z_1} + \frac{\partial^2 x}{\partial^2 z_2}\right)}_{\Delta x} + \gamma x$$

$$\Leftrightarrow \frac{\partial \underline{x}}{\partial t} = \underbrace{\begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}}_{A_1} \frac{\partial \underline{x}}{\partial z_1} + \underbrace{\begin{bmatrix} 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \\ -1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}}_{A_2} \frac{\partial \underline{x}}{\partial z_2} + \underbrace{\begin{bmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ -1 & -1 & 0 & 1 \\ 0 & 0 & \gamma & 0 \end{bmatrix}}_{A_0} \underline{x} \text{ where } \underline{x} \equiv \begin{bmatrix} x_{z_1} \\ x_{z_2} \\ x \\ x_t \end{bmatrix}$$

Smart Grid : Interarea Oscillations

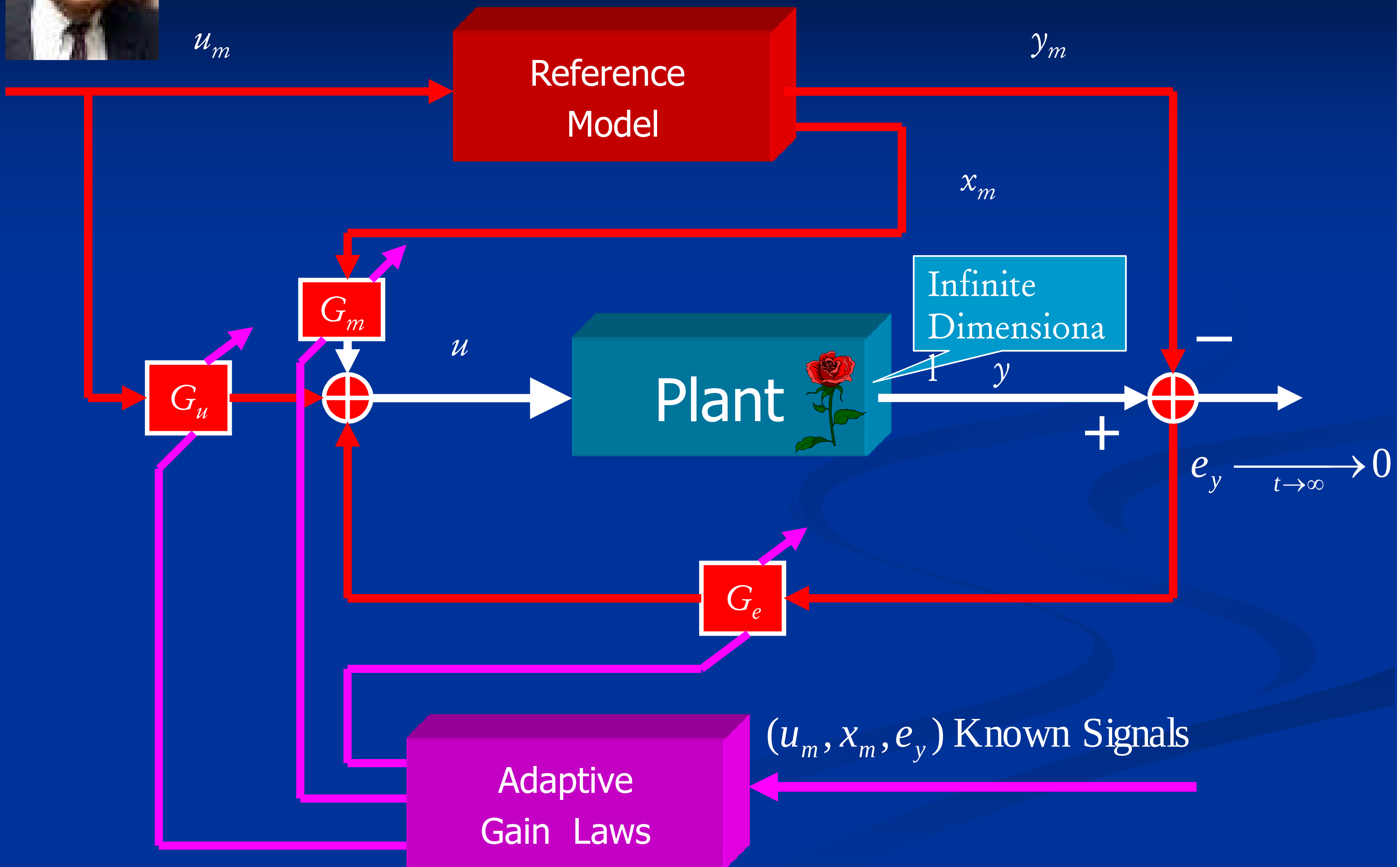
$$: \ x_{tt} = v^2 x_{zz} - \eta x_t$$

$$\Leftrightarrow \underline{x} \equiv \begin{bmatrix} x_z \\ x_t \end{bmatrix} \Rightarrow \underline{x}_t = \underbrace{\begin{bmatrix} 0 & v \\ v & 0 \end{bmatrix}}_{A_1} \underline{x}_z + \underbrace{\begin{bmatrix} 0 & 0 \\ 0 & -\eta \end{bmatrix}}_{A_0} \underline{x} \equiv A\underline{x}$$

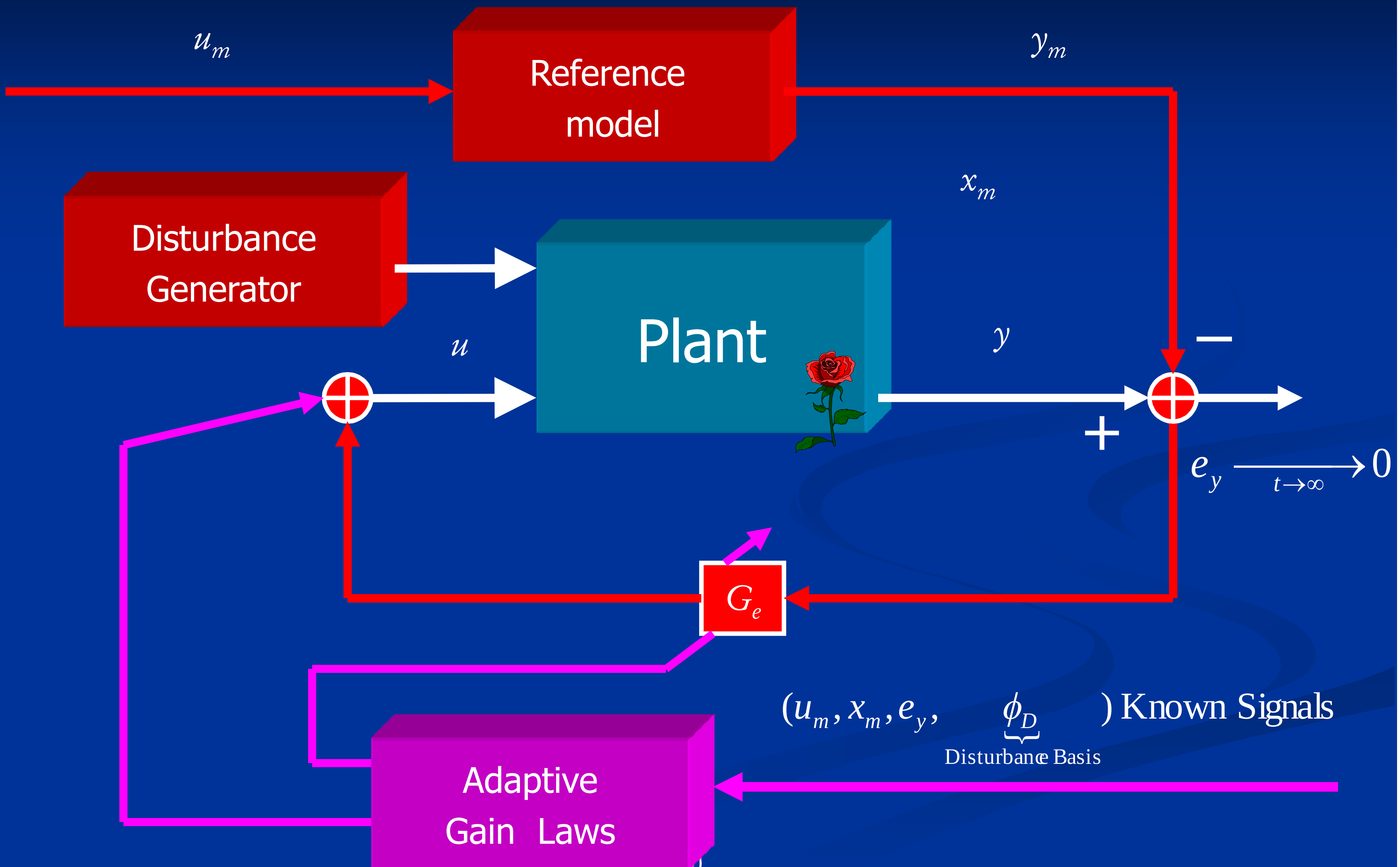
Relativistic Fields (Mandl & Shaw 2010)

$$\text{Dirac Equation: } \frac{\partial \phi}{\partial t} = -c\left(\sum_{i=1}^{3} \underbrace{A_i}_{\substack{\text{Pauli} \\ \text{Spin} \\ \text{Matrices}}} \frac{\partial \phi}{\partial x_i}\right) + \left(i\frac{mc^2}{\hbar} I_4\right)\phi$$

Direct Adaptive Model Following Control (Wen-Balas 1989)



Direct Adaptive Persistent Disturbance Rejection (Fuentes-Balas 2000)



Persistent Disturbance Example

$$\begin{bmatrix}\dot{\theta}\\ \ddot{\theta}\end{bmatrix} = \underbrace{\begin{bmatrix}0 & 1\\ 0 & 0\end{bmatrix}}_{A}\begin{bmatrix}\theta\\ \dot{\theta}\end{bmatrix} + \underbrace{\begin{bmatrix}0\\ 1\end{bmatrix}}_{B}u(t) + \underbrace{\begin{bmatrix}0\\ 1\end{bmatrix}}_{\Gamma}u_D$$

$$\text{Disturbances}\begin{cases} u_D \equiv A_D \sin(\omega_D t + \varphi_D) = \underbrace{\begin{bmatrix} l_1 & l_2 \end{bmatrix}}_{L\theta}\underbrace{\begin{bmatrix}\sin \omega_D t\\ \cos \omega_D t\end{bmatrix}}_{\phi_D} \\ u_D \equiv a_0 + a_1 t + a_2 t^2 = \underbrace{\begin{bmatrix} a_0 & a_1 & a_2 \end{bmatrix}}_{L\theta}\underbrace{\begin{bmatrix}1\\ t\\ t^2\end{bmatrix}}_{\phi_D} \end{cases}$$

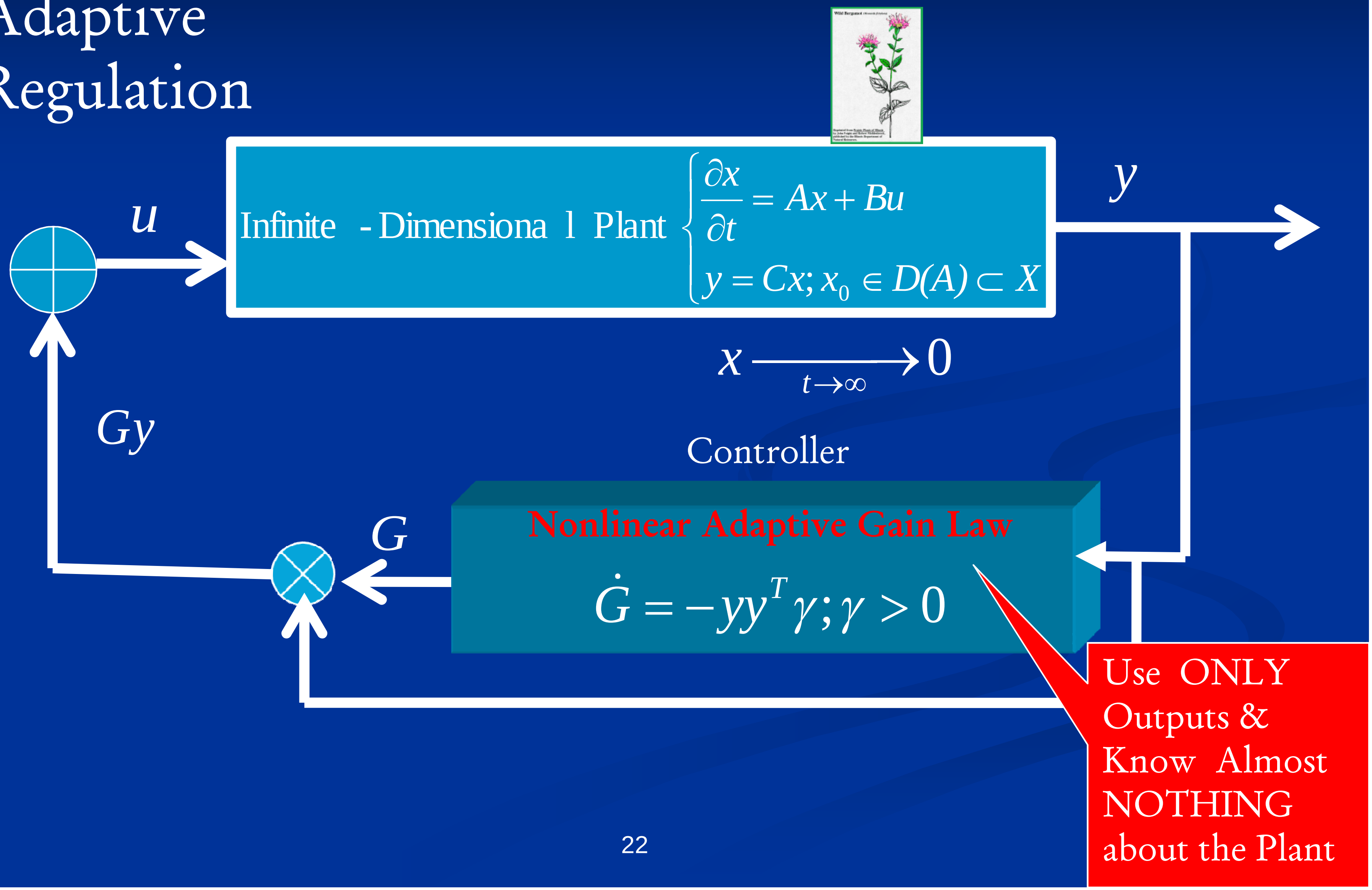
Unknown

Known Basis

Known Basis

Adaptive Control Is Not Complicated !

Adaptive Regulation



Stability via Lyapunov-Barbalat

$$\text{Nonlinear Dynamics}\begin{cases}\dot{x} = f(x) \\ x(0) = x_0 \in \Re^N\end{cases}$$

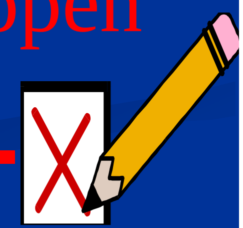
$$\text{Find Energy-like Function}: V(x)$$

$$V(x) > 0 \text{ when } x \neq 0$$

$$V(0) = 0$$

~~$\dot{V} = gradV * f(x) < 0 \Rightarrow x(t) \to 0 \text{ as } t \to \infty \text{ for all } x_0$~~

Often does <u>Not</u> happen

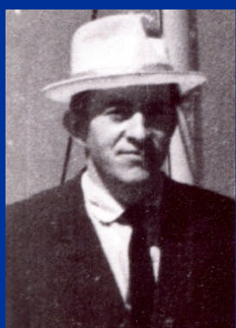


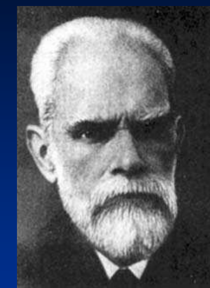
$$\dot{V} \leq 0 \Rightarrow \text{All trajectories } x(t) \text{ are bounded}$$

From Barbalat's lemma:

$$\dot{V}(t) \leq 0 \text{ and uniformly continuous} \Rightarrow \dot{V}(t) \to 0 \text{ as } t \to \infty$$

Infinite-Dimensional Lyapunov-Barbalat Theory: PDE & Delay Systems





X Hilbert or Banach Space

$$\text{Let } \begin{cases} V(t,x,\Delta G) \equiv V(t,x) + \frac{1}{2} tr(\Delta G \gamma^{-1} \Delta G^{T}) \\ \text{with } x(t) = U(t) x_0 \in X; t \geq 0 \end{cases}$$

Linear or Nonlinear Evolution

$$\text{Theorem: If } \begin{cases} \alpha(\|(x,\Delta G)\|) \leq V(t,x,\Delta G) \leq \beta(\|(x,\Delta G)\|) \\ \dot{V}(t,x,\Delta G) \leq -W(x) \leq 0 \end{cases}$$

and $\frac{dW(x(t))}{dt} = \Big(\underbrace{\frac{\partial W}{\partial x}}_{\substack{Frechet \\ Deri\,var\,ive}} \Big) \frac{\partial x(t)}{\partial t}$ is bounded, then $W(x(t)) \xrightarrow[t \to \infty]{} 0$ and ΔG bounded.

If *W(x)* is <u>coercive</u> in the partial state x ,or $W(x) \geq \gamma(\|x\|)$, then $x(t) \xrightarrow[t \to \infty]{} 0.$

Linear System Strict Dissipativity (Balas-Frost)

$$\underline{\text{Energy Storage Function}} : \begin{cases} V(x) \equiv (x, Px) > 0; \forall x \neq 0 \\ V(0) = 0 \end{cases}$$

A <u>Linear</u> Dynamic Infinite-Dimensional System is STRICTLY DISSIPATIVE when

$$\exists P : X \xrightarrow[\text{Positive}]{\substack{LinearOp \\ Self-Adjoint}} X$$

$$p_{\min}\|x\|^2 \le V(x) \equiv (Px, x) \le p_{\max}\|x\|^2 \ni$$

$$\begin{cases} \operatorname{Re}(PAx, x) \equiv \frac{1}{2}[(PAx, x) + (x, PAx)] \le \underbrace{-\alpha\|x\|^2}_{W(x)}; \forall x \in D(A) \\ PB = C^* \end{cases}$$

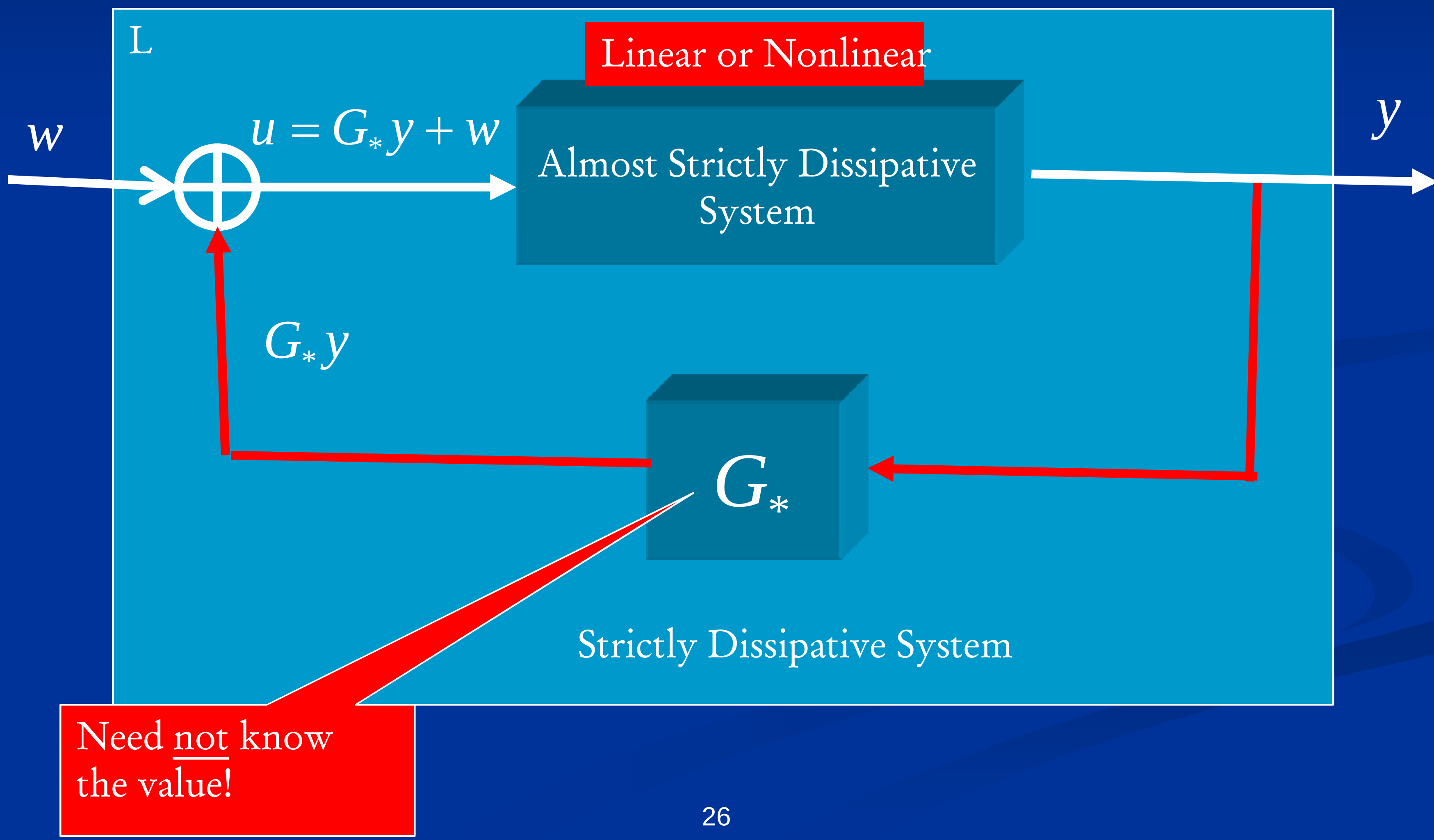
DISSIPATIVE when $\alpha = 0$

$$\Rightarrow \underbrace{\frac{dV}{dt}}_{\substack{Energy \\ Storage \\ Rate}} \le \underbrace{(y, u)}_{\substack{External \\ Power}} - \underbrace{\alpha\|x\|^2}_{\substack{Internally \\ Dissipated \\ Power}}$$

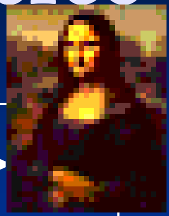
Almost Strictly Dissipative (ASD) Systems

$(A(x), B(x), C(x))$ ASD means

$\exists G_* \ni (A_C(x) \equiv A(x) + B(x)G_*C(x), B(x), C(x))$ Strictly Dissipative



Finite- Dimensional LINEAR ASD: Two Simple Open-Loop Properties



High Frequency Gain is Sign-Definite (CB >

Open-Loop Transfer Function is Minimum Phase (all transmission zeros stable)

⟺ **Almost Strictly Dissipative**

⟹ Adaptive Regulation $\begin{cases} u = Gy \\ \dot{G} = -yy^T\gamma; \gamma > 0 \end{cases}$

produces $x(t) \xrightarrow[t\to\infty]{} 0$

with bounded adaptive gains $G(t)$

An Infinite-Dimensional Version

$$\begin{cases} \dfrac{\partial x}{\partial t} = Ax + Bu = Ax + \sum_{i=1}^{m} b_i u_i ; A \text{ generates a } C_0 \text{ semigroup} \\ x(0) = x_0 \in D(A) \subset X \\ y = Cx = \left[(c_1, x) \quad (c_2, x) \quad \dots \quad (c_m, x) \right]^T ; b_i, c_j \in D(A) \end{cases}$$

(My) $\underline{Theorem}$: Def : $\lambda_* \in C$ is a t$\underline{\text{ransmission zero}}$ of (A, B, C) when $N(H(\lambda_*)) \neq \{0\}$

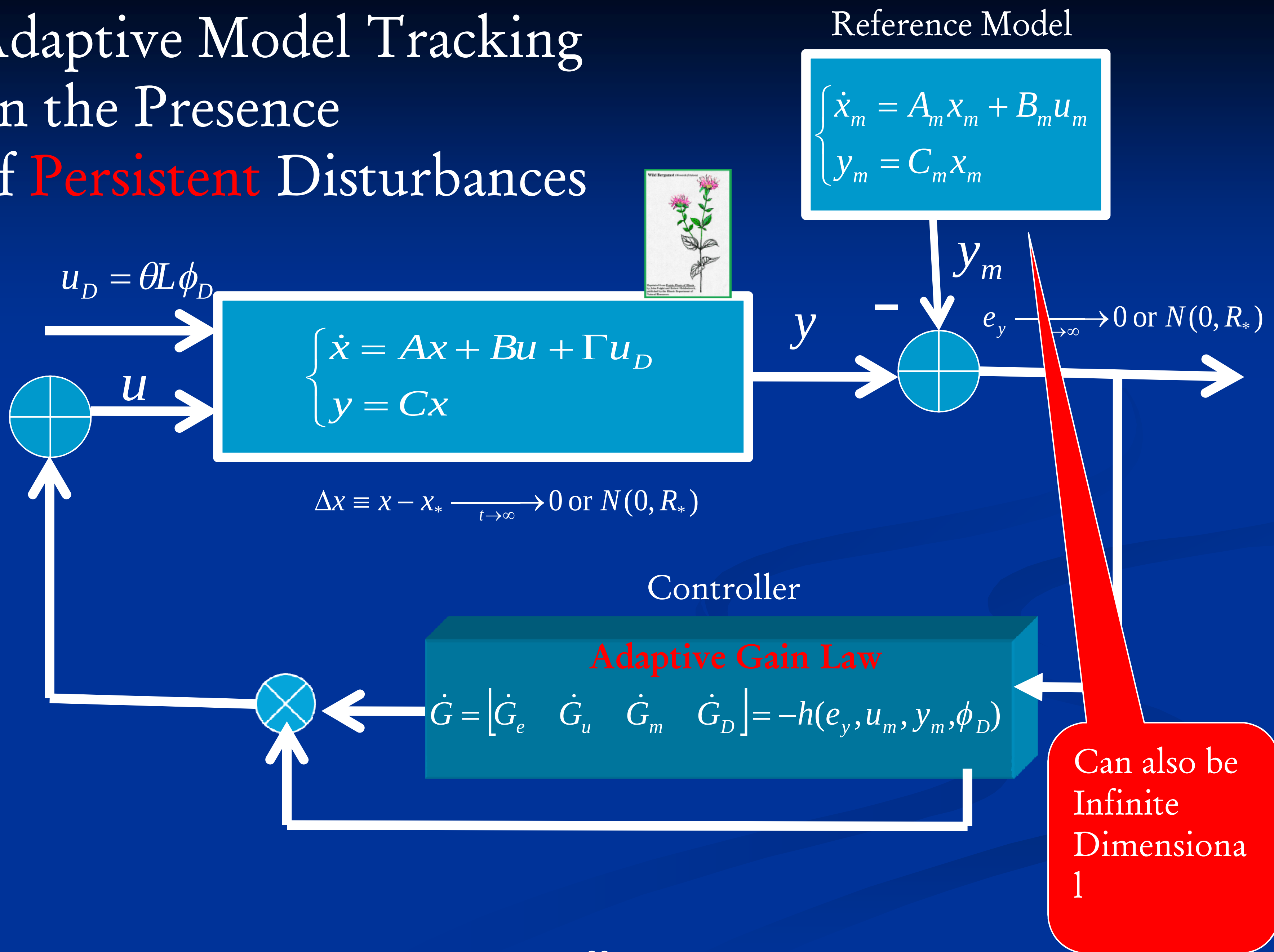
where $H(\lambda) \equiv \begin{bmatrix} A - \lambda I & B \\ C & 0 \end{bmatrix} : D(A) x \Re^M \to X x \Re^M$ closed linear operator

(A, B, C) is Almost Strictly Dissipative

$\Leftrightarrow CB = \left[(c_j, b_i) \right]_{\text{mxm}}$ nonsingular and Zeros$(A,B,C) \equiv \left\{ \lambda / N(H(\lambda)) \neq \{0\} \right\} = \sigma_p(\overline{A}_{22})$ "$stable$"

(i.e. $\overline{A}_{22}$ satisfies spectrum determined growth condition)

Adaptive Model Tracking in the Presence of Persistent Disturbances



Adaptive Control Law

$$u = \underbrace{G_u u_m + G_m w_m}_{\text{Model Tracking}} + \underbrace{G_D \phi_D}_{\text{Disturbance Rejection}} + \underbrace{G_e e_y}_{\text{Stabilization}}$$

where

$$\begin{cases} \dot{G}_u = -e_y \cdot u_m^* \cdot \sigma_u ; \sigma_u > 0 \\ \dot{G}_m = -e_y \cdot x_m^* \cdot \sigma_m ; \sigma_m > 0 \\ \dot{G}_D = -e_y \cdot \phi_D^* \cdot \sigma_D ; \sigma_D > 0 \\ \dot{G}_e = -e_y \cdot e_y^* \cdot \sigma_e ; \sigma_e > 0 \end{cases}$$

Gain Adaptation Laws

$S_{11}^* : D(A_m) \to D(A), S_{ij}^*$ and H_1, H_2

Ideal Trajectories

$$\begin{cases} \dfrac{\partial x_*}{\partial t} = Ax_* + Bu_* + \Gamma u_D \\ y_* = Cx_* = y_m \end{cases}$$

$$\begin{cases} x_* = S_{11}^* x_m + S_{12}^* u_m + S_{13}^* z_D = S_1 z \\ u_* = S_{21}^* x_m + S_{22}^* u_m + S_{23}^* z_D = S_2 z \end{cases}$$

Matching Conditions $\begin{cases} AS_1 + BS_2 = S_1 \bar{A}_m + H_1 \\ CS_1 = H_2 \end{cases}$

$$S_1 \equiv \begin{bmatrix} S_{11}^* & S_{12}^* & S_{13}^* \end{bmatrix} : D(\bar{A}_m) \to D(A) \subset X$$

$$S_2 \equiv \begin{bmatrix} S_{21}^* & S_{22}^* & S_{23}^* \end{bmatrix} : D(\bar{A}_m) \to \Re^m,$$

$$\bar{A}_m \equiv \begin{bmatrix} A_m & B_m & 0 \\ 0 & F_m & 0 \\ 0 & 0 & F \end{bmatrix}$$

with $D(\bar{A}_m) \equiv D(A_m) x \Re^m x \Re^{N_D}$

and $D(\bar{A}_m)$ dense in $\bar{X}_m \equiv X_m x \Re^m x \Re^{N_D}$,

and $\begin{cases} H_1 \equiv \begin{bmatrix} 0 & 0 & -\Gamma\theta \end{bmatrix} \\ H_2 \equiv \begin{bmatrix} C_m & 0 & 0 \end{bmatrix} \end{cases}$

An Infinite Dimensional Internal Model Princip

Theorem : Assume CB is nonsingular and the open loop zeros $(\sigma(\overline{A}_{22}))$ are (exponentially) stable.

Then <u>the zeros of the open loop plant must not overlap with the poles of the tracked reference model</u>:

$$\sigma(\overline{A}_m) = \sigma_p(A_m) \cup \sigma_p(F_m) \cup \sigma_p(F)$$

$$\subset \rho(\overline{A}_{22}) \equiv \{\lambda \in C / (\lambda I - \overline{A}_{22})^{-1} : l_2 \to l_2 \text{ is a bounded linear operator}\}$$

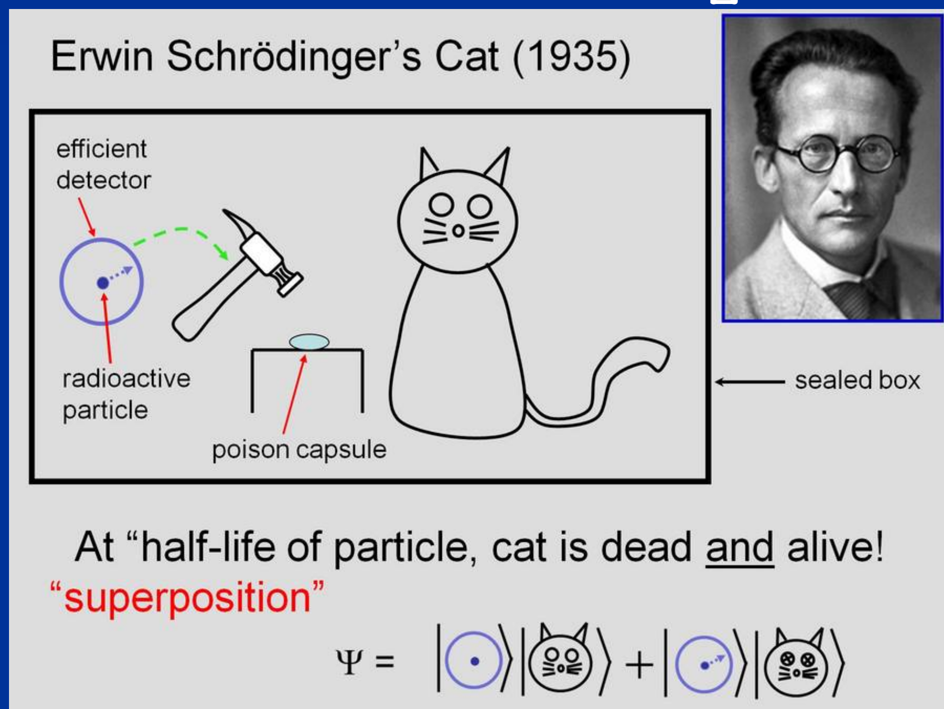
$$(\text{or } \sigma(\overline{A}_m) \cap \sigma(\overline{A}_{22}) = \phi \text{ where } \sigma(\overline{A}_{22}) \equiv [\rho(\overline{A}_{22})]^c) \Leftrightarrow$$

There exist unique *bounded* linear operator soluti (S_1, S_2)

satisfying the Matching Conditions

Adaptive Control in Quantum Information Systems

This might be the most fundamental application of direct adaptive control



Ontology (what is) vs Epistemology (What is measured)

Quantum Computing

A Quantum computer will operate differently from a Classical on
It will be involved w physical systems on an atomic scale,
eg atoms, photons, trapped ions, or nuclear magnetic moments

Unitary → Reversible

Entanglement produces Decoherence

Quantum Basics (Dirac & Von Neumann)

Orthonormal Eigen –Basis for X

$$\text{Observable } A : X \xrightarrow[\text{self-adjoint}]{\text{bounded}} X$$

$$\text{Compact Resolvent} \Rightarrow Ax = \sum_{k=1}^{\infty} \lambda_k \underbrace{(x,\varphi_k)\varphi_k}_{P_k x}$$

$\underline{\text{Pure States}} : \varphi_k$ eigenfunctions of A

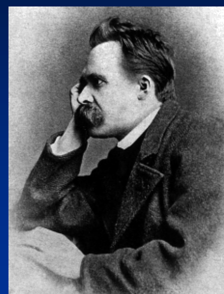
$\underline{\text{Mixed}}$ $\underline{\text{State}}$ $\varphi \in X$ complex Hilbert Space:

$$(\varphi,\varphi) = 1 \text{ or } \|\varphi\| = 1 \Rightarrow \varphi = \sum_{k=1}^{\infty} c_k \varphi_k \;\&\; 1 = \|\varphi\|^2 = \sum_{k=1}^{\infty} |c_k|^2$$

where $|c_k|^2 = \underline{\text{probability of being in the pure state}}\ \varphi_k$

Quantum Measurement

"...for when you gaze long into the abyss. The abyss gazes also into you."

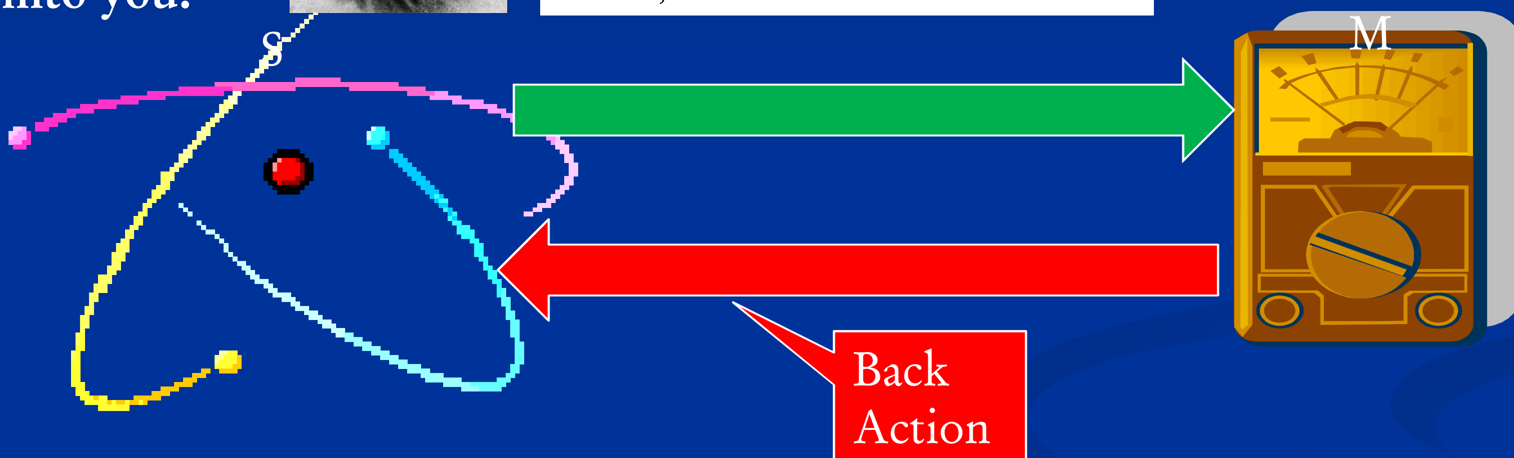


Entanglement

$$X = X_S \otimes X_M$$

$$\varphi = \sum_{k,l} \alpha_{kl} (\varphi_k^S \otimes \varphi_l^M) \neq h \otimes w$$

Nietzche!!! Never around when you need him



Observable $A : X \xrightarrow[\text{self-adjoint}]{\text{bounded}} X$ Hilbert

Heisenberg Uncertainty Princip

$$\begin{cases} \text{Mean } \langle A \rangle \equiv Tr(\rho A) \\ \text{Dispersion } \Delta A \equiv \sqrt{Tr(\rho (A - \langle A \rangle)^2)} \end{cases}$$

where ρ is a state or density operator $(\rho > 0 \,\&\, Tr(\rho) = 1)$

Heisenberg Uncertainty Principle : Simultaneous Measurement of $A \,\&\, B$

$$(\Delta A)^2 (\Delta B)^2 \geq \frac{\hbar}{2} |Tr(\rho [A, B])|;$$ commutator $[A, B] \equiv AB - BA$

Schrodinger Wave Equation

$\varphi \in X$ complex Hilbert Space

$$i\hbar \frac{\partial \varphi}{\partial t} = \underbrace{H_0}_{\text{Self – Adjoint}} \varphi + \underbrace{H_C(u)\varphi}_{\text{Disturbance Hamiltonian}}$$

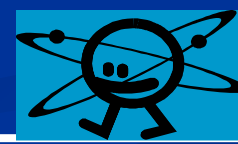
Self – Adjoint
Compact
Resolvent

Disturbanc e
Hamiltonia n

Diffusion with
Imaginary Time :

$$t_{NEW} \equiv \frac{it_{OLD}}{\hbar}$$

$\therefore$ Discrete Real Spectrum $\sigma(H_0) = \{\lambda_k\}_{k=1}^{\infty}$



$-\infty$

Marginall yStable

$\Rightarrow U_0(t) : X \to X$ Unitary Group (reversible)

and $U_0(t)\varphi = \sum_{k=1}^{\infty} e^{i\lambda_k t} \langle \varphi, \phi_k \rangle \phi_k$ with $\langle \phi_k, \phi_l \rangle = \delta_{kl}$

Small Quantum Systems

- We can begin to experiment with just one electron, atom or small molecule
- Need:

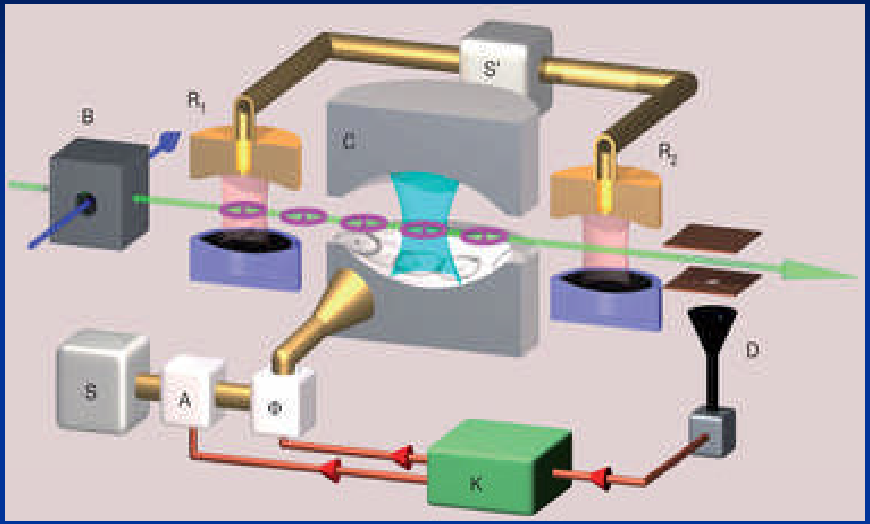
Precise control

Isolation from the environment

Simple small systems : single particles or small groups of particles

...... David Wineland NIST

Control of Individual Quantum Systems: Quantum Feedback Loop

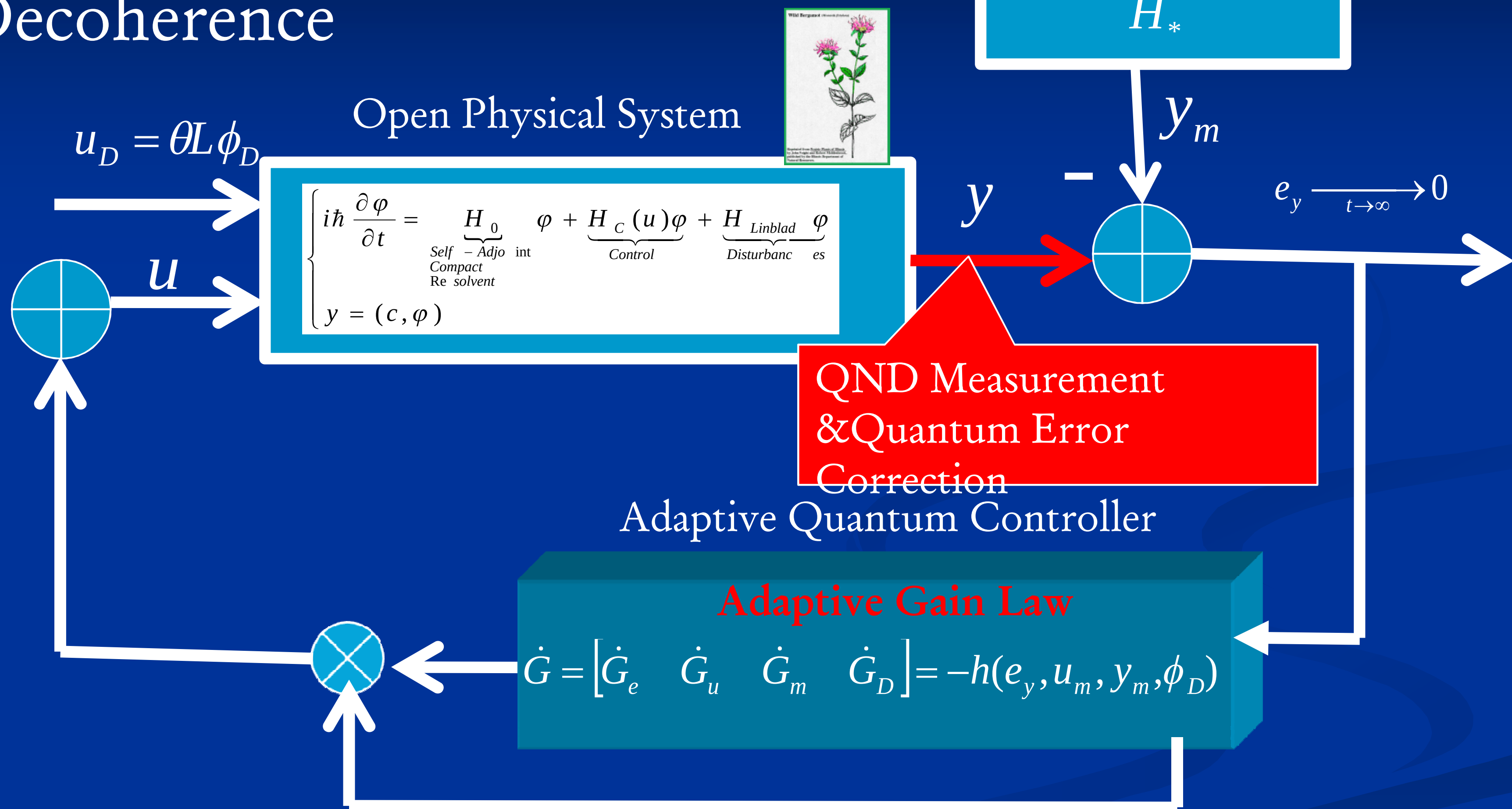


Physics Nobel Prize 2012
S. Haroche & D. Winelan

Purpose:
Use information from weak QND measurements to prepare photon number (Fock) states of a cavity field and
protect them against decoherence.

Method:
Quantum feedback realized by atoms as QND probes and small coherent field injections into the cavity mode as an actuator.

Adaptive Quantum Model Tracking to Reduce Decoherence



Famous
Lisbon Poet

"No intelligent idea can gain general acceptance unless some stupidity is mixed in with it" .....

Fernando Pessoa, The Book of Disquiet