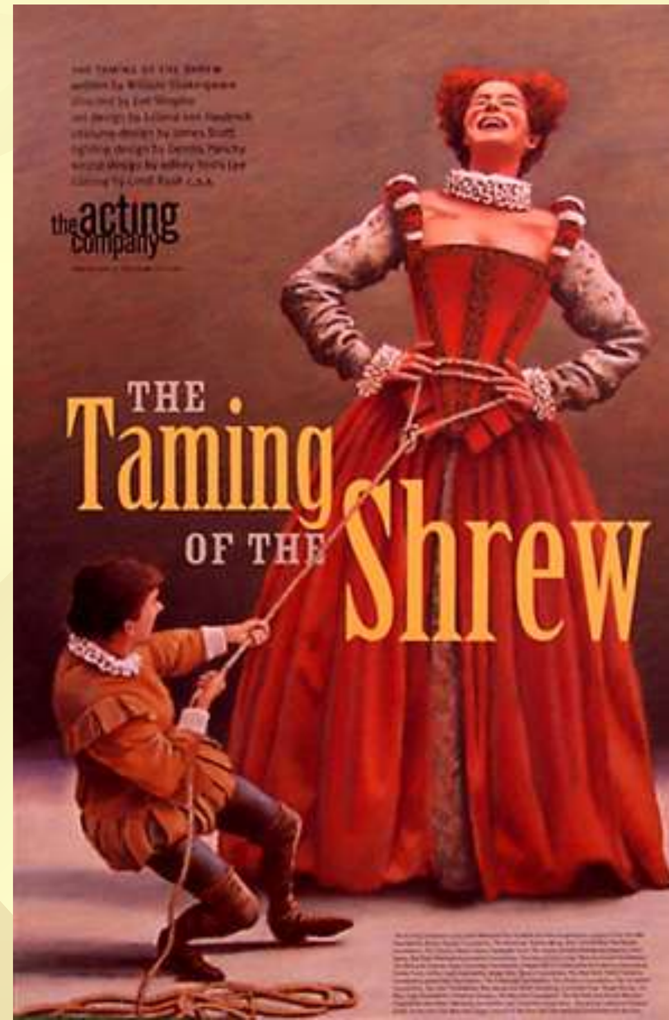
Turbulence Control and Applications



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Emphasis

- Control of TBL to achieve a variety of beneficial changes
  - Unifying principles
  - Coherent structures
  - Targeted/selective control

    (issues involved & feasibility)
  - Outlook for the future

But before we proceed…

- Control of turbulence is much more difficult than controlling laminar flow
- While always possible, the challenge is to do it with the least penalty
- Suppression, or taming, of turbulence is as arduous as *The Taming of the Shrew*

Why is it so difficult to understand turbulence?

- Instantaneous, nonlinear equations have no known analytical (stochastic) solution

- Equation for the mean velocity, say, contains new unknowns that must be *heuristically* related to other mean quantities

- Nonlinear dynamical system with infinite degrees of freedom

- Computers are not big enough to integrate those equations either

Why is it so difficult to tame turbulence?

- Multiscale problem that goes down in scale to the micron and ms level
- Unlike separating and transitioning flows, most turbulent flows are not critical flow regimes
- Penalty typically exceeds the benefit
- As one attempts to achieve one type of control, another is made worse (e.g., reducing skin friction at the expense of more pressure drag, and vice versa)

Five eras of flow control

- Empirical Era (prior to 1900)
  - Streamlined spears; boomerangs; arrows
- Scientific Era (1900–1940)
  - Prandtl's (1904) boundary layer theory; flow separation physics and control;…
- World War II Era (1940–1970)
  - Fastest submarine; most agile aircraft;…
- Energy Crisis Era (1970–1990)
  - Drag reduction for civil transport…
- The 1990s and beyond
  - MEMS; neural nets; dynamical systems theory
    - Reactive control

Outline

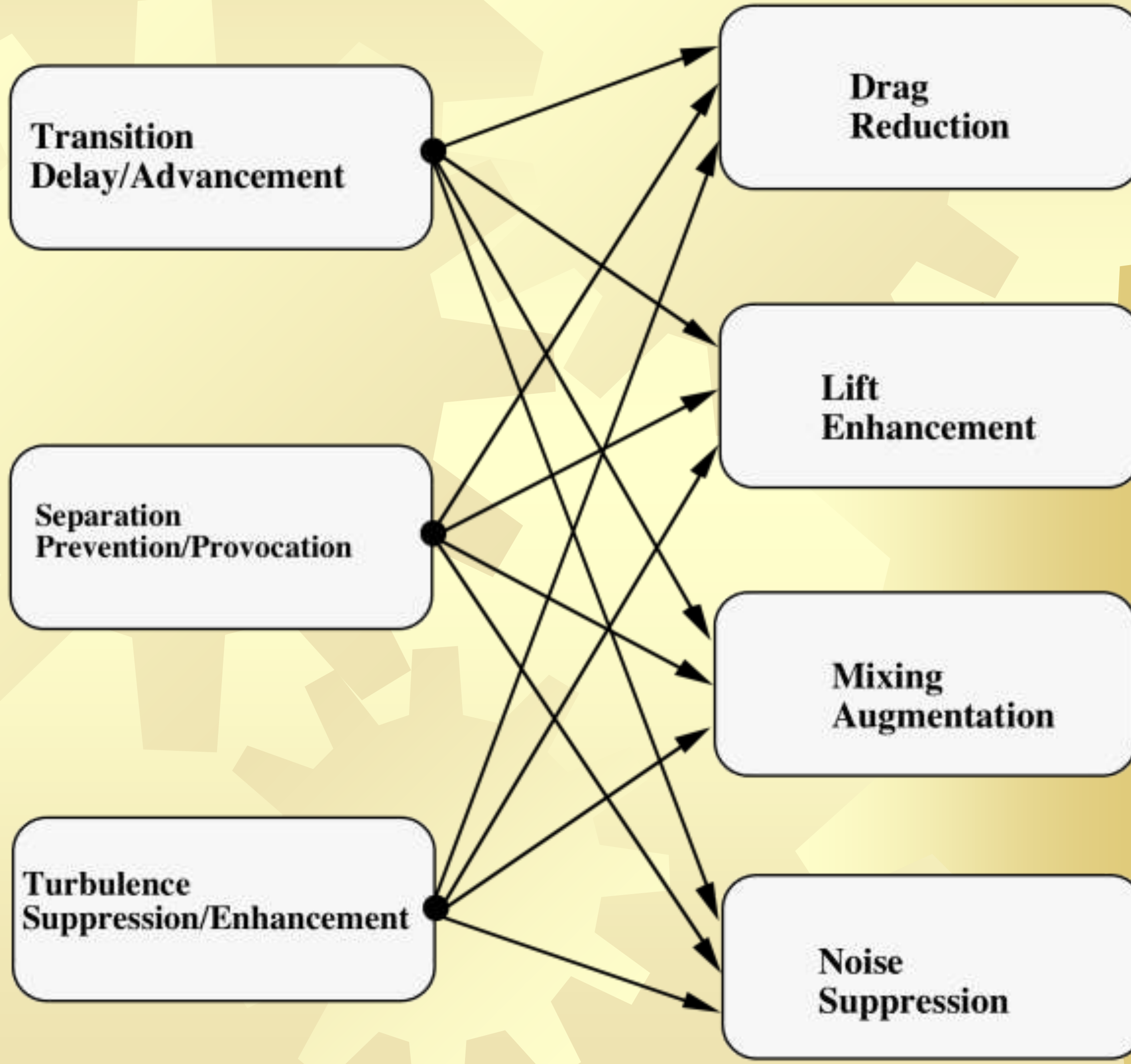
- The common thread
- Reactive flow control
- What changed?
  - Emerging fields
    - Chaos control
    - MEMS
    - Neural networks
    - Other soft computing tools

Flow control goals

- Transition delay/advancement.
- Turbulence enhancement/suppression/ relaminarization
- Separation prevention/provocation

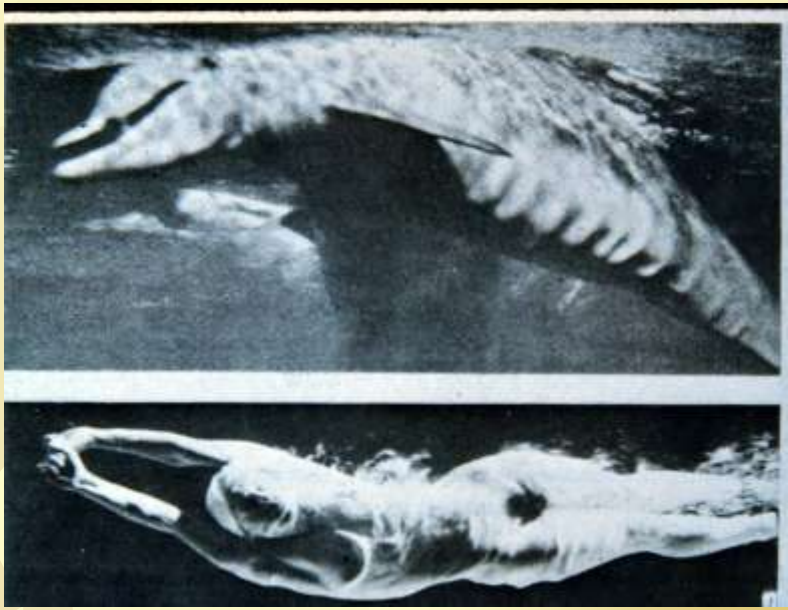
- Skin-friction/pressure drag reduction
- Lift enhancement
- Heat transfer/mixing/chemical reaction augmentation
- Noise suppression

Flow control goals



Tools for controlling

- **<u>Surface</u>:**
  - Roughness; Riblets; Fences
  - Curvature
  - Shape
  - Compliant
  - Mass Transfer (primary fluid or otherwise)
  - Acoustics
  - Heat Transfer



Tools for controlling (cont.)

- **<u>Freestream</u>:**
  - LEBU
  - Acoustics
  - Turbulence levels; Gust

- **<u>Additives</u>:**
  - Polymers; surfactants
  - Micro-bubbles
  - Particles; dust; fibers

Silent Aircraft Initiative (SAX-40)

- Goal: develop a conceptual design for an aircraft whose noise would be imperceptible outside the perimeter of a daytime urban airport.
- MIT/Cambridge University; 6 November 2006.

Incompressible flows

- **Continuity:**

$$\frac{\partial u_k}{\partial x_k} = 0$$

- **Momentum:**

$$\rho\left[\frac{\partial u_i}{\partial t} + u_k \frac{\partial u_i}{\partial x_k}\right] = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_k}\left[\mu\left(\frac{\partial u_i}{\partial x_k} + \frac{\partial u_k}{\partial x_i}\right)\right] + \rho\, g_i$$

- **Energy:**

$$\rho\left[\frac{\partial h}{\partial t} + u_k \frac{\partial h}{\partial x_k}\right] = \frac{\partial}{\partial x_k}\left(k \frac{\partial T}{\partial x_k}\right) + \phi^*$$

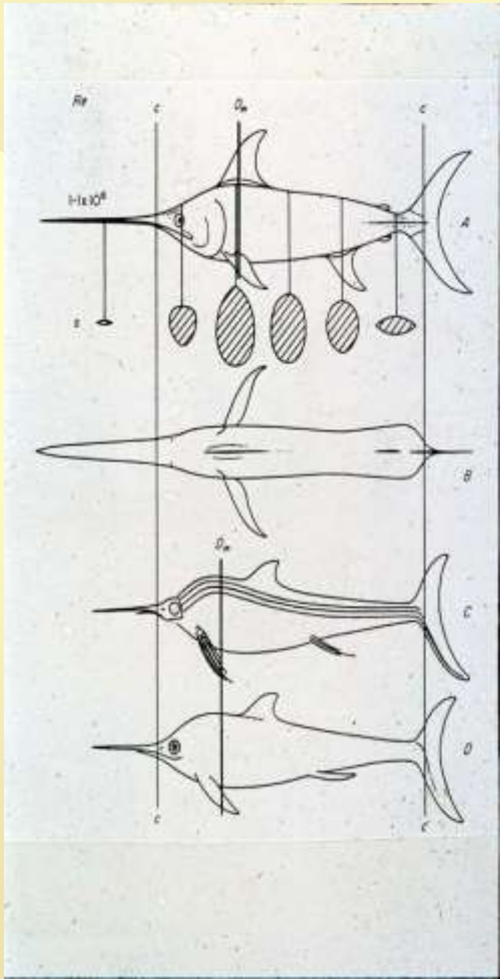
Navier–Stokes equations at wall

- For an incompressible fluid, over a non-moving wall:

$$\rho v_{\mathrm{w}} \left.\frac{\partial u}{\partial y}\right|_{y=0} + \left.\frac{\partial p}{\partial x}\right|_{y=0} - \left.\frac{\partial \mu}{\partial y}\right|_{y=0} \left.\frac{\partial u}{\partial y}\right|_{y=0} = \mu \left.\frac{\partial^2 u}{\partial y^2}\right|_{y=0}$$

$$\rho \frac{\partial v_{\mathrm{w}}}{\partial t} + 0 + \left.\frac{\partial p}{\partial y}\right|_{y=0} - 0 = \mu \left.\frac{\partial^2 v}{\partial y^2}\right|_{y=0}$$

$$\rho v_{\mathrm{w}} \left.\frac{\partial w}{\partial y}\right|_{y=0} + \left.\frac{\partial p}{\partial z}\right|_{y=0} - \left.\frac{\partial \mu}{\partial y}\right|_{y=0} \left.\frac{\partial w}{\partial y}\right|_{y=0} = \mu \left.\frac{\partial^2 w}{\partial y^2}\right|_{y=0}$$



Navier–Stokes equations at wall

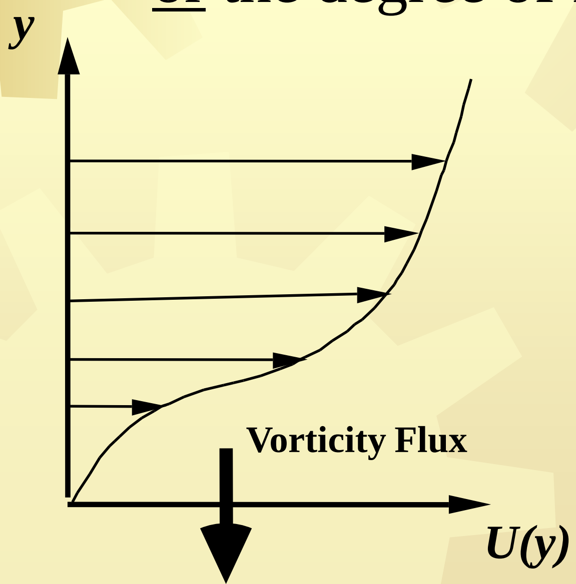
- <u>Streamwise momentum equation at the wall</u>:

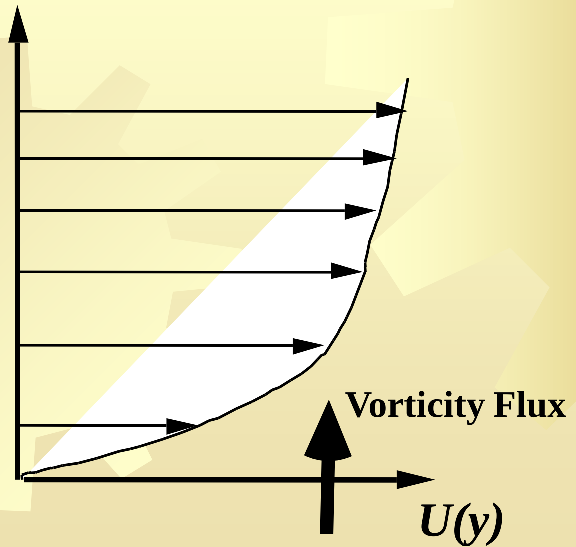
$$\rho v_w \left.\frac{\partial u}{\partial y}\right|_{y=0} + \left.\frac{\partial p}{\partial x}\right|_{y=0} - \left.\frac{\partial \mu}{\partial y}\right|_{y=0} \left.\frac{\partial u}{\partial y}\right|_{y=0} = \mu \left.\frac{\partial^2 u}{\partial y^2}\right|_{y=0}$$

- <u>RHS is the wall flux of spanwise vorticity</u>

<u>or</u> curvature of the streamwise velocity profile at the wall

<u>or</u> the degree of fullness of the velocity profile

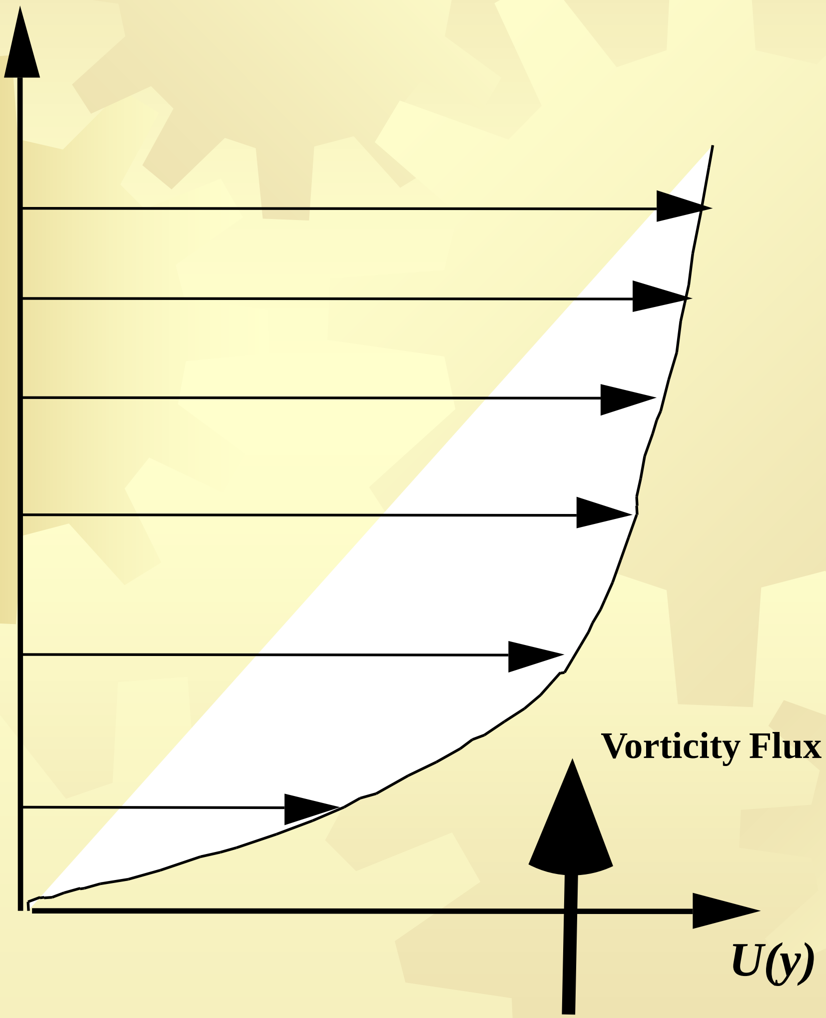




Wall flux of spanwise vorticity

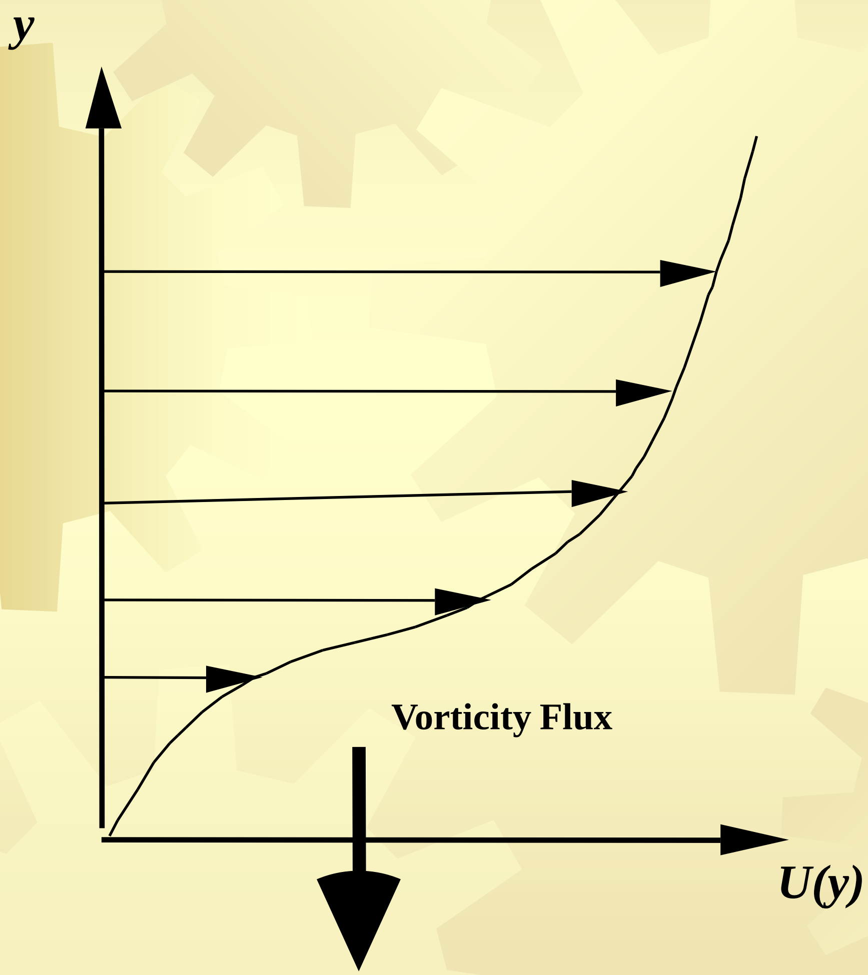
- Is affected by:
  - Suction/injection
  - (Streamwise) pressure gradient
  - (Normal) viscosity gradient
- Can also be affected by:
  - Wall motion (rigid or compliant)
  - Body forces (e.g. stratification; electromagnetic forces; …)

Full profile



- Suction
- Favorable P-grad.
- Heating (water)

Inflectional profile



- Injection
- Adverse P-grad
- Cooling

Coherent structures

- Large outer-structures
- Intermediate Falco’s eddies
- Near-wall events
  - Low-speed streaks
  - Ejection
  - Sweep

Bursting

Important question

- Is skin-fiction reduction associated with turbulence suppression?
  - Yes:
    - Polymers; particles; LEBUs; riblets
    - Act *selectively* on a particular structure
  - No:
    - Suction; wall cooling/heating; favorable pressure gradient
    - Act *globally* on all eddies

Successful techniques

- Polymers, *etc.*, act indirectly through local interaction with discrete turbulent structures
  - Particularly, small-scale eddies

Less efficient methods

- Suction, *etc.*, act directly on mean flow
  - Mean-velocity modifiers

Suction

- Flat Plate:

$$C_f = 2\,(d\delta_\theta / dx) + 2\,C_q$$

- No suction:

0.003 = 2 x 0.0015 + 0.0

- Suction (asymptotic velocity profile):

0.006 = 0.0 + 2 x 0.003

Control of a TBL

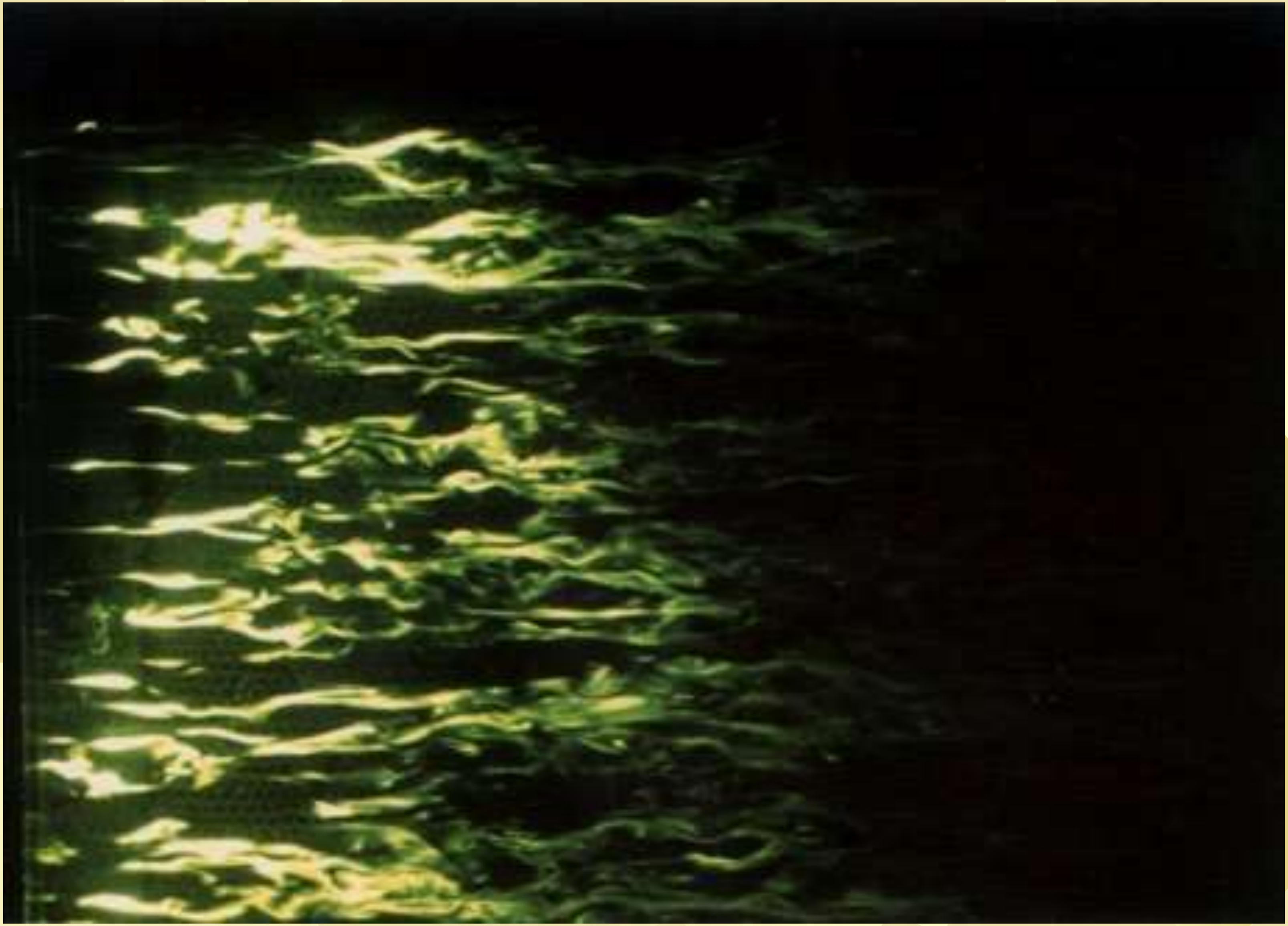
- Global
- <u>Selective</u>:
  - By the flow
  - By design
- <u>Near-wall events</u>:
  - Very intermittent and random in space and time
- Temporal phasing and spatial selectivity are needed for *targeted control*

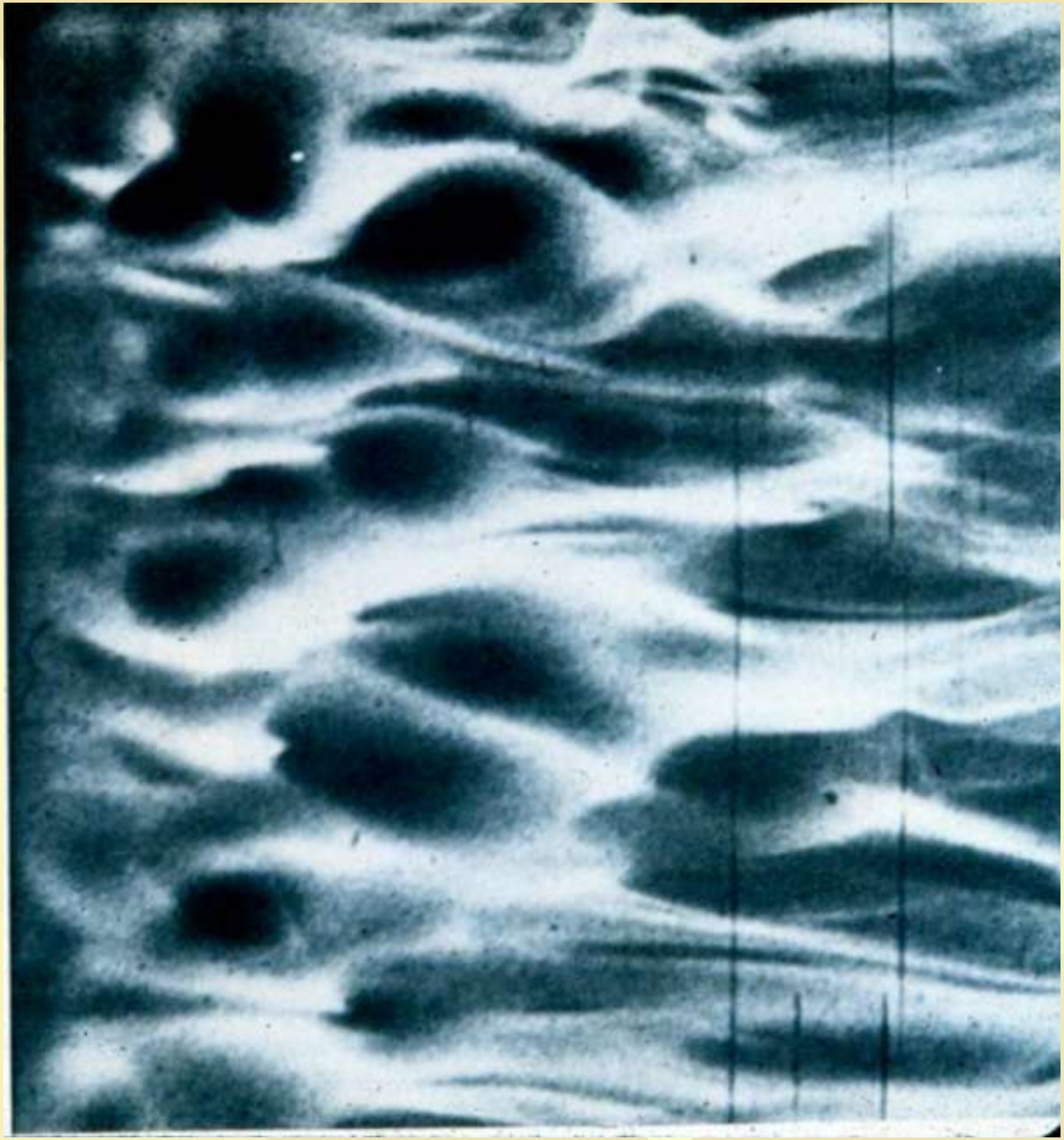
What to target?

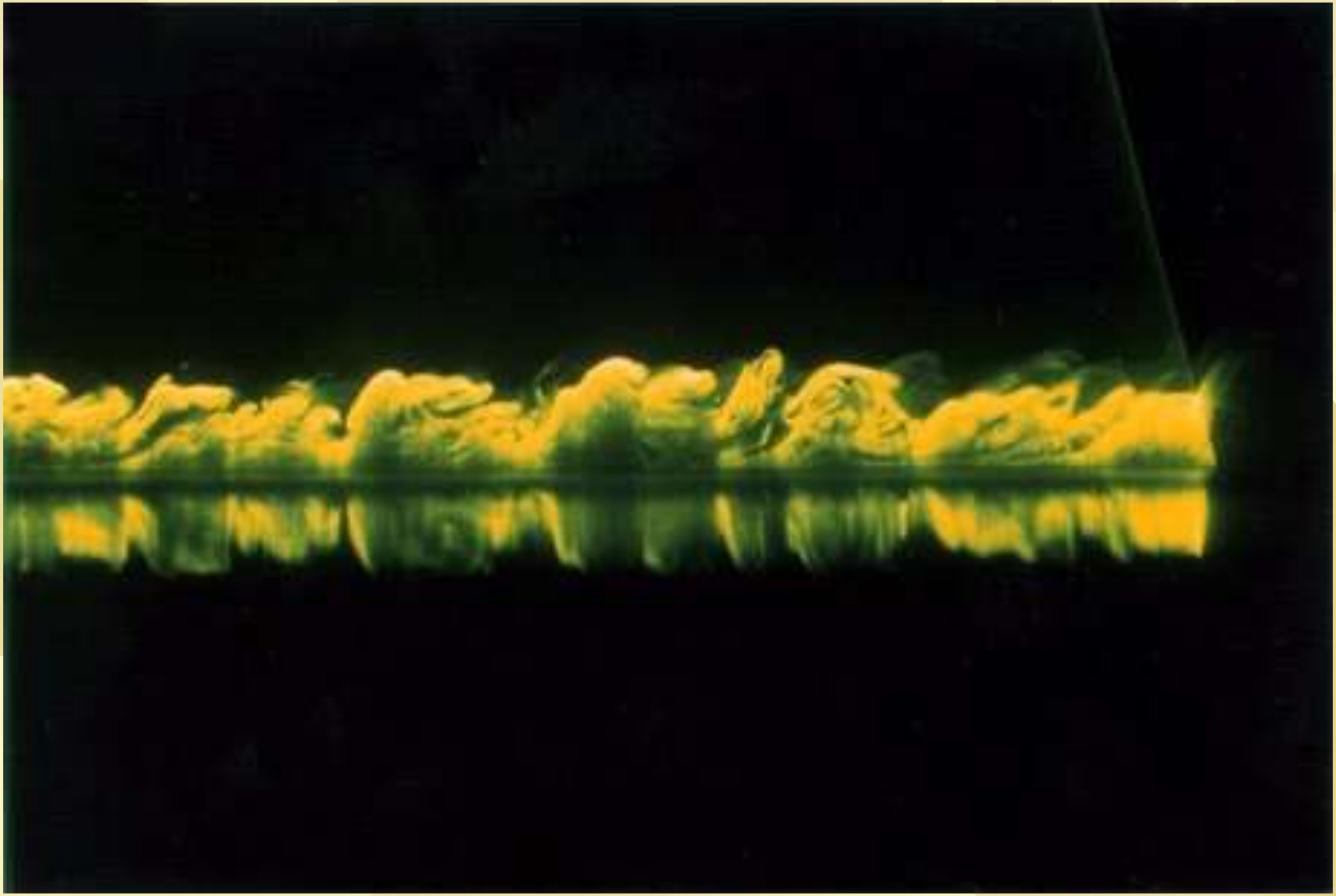
- Low-speed streaks are the most

  - visible
  - reliable
  - detectable

  indicators of the pre-burst turbulence production process







Vision for a control system

- Checkerboard of wall sensors and actuators
  - Sensors:
    - Pressure; velocity; wall shear; etc.
  - Actuators:
    - Heating/cooling; suction/injection; wall movement; etc.
      - For example:
        - Piezoelectric devices under flexible skin
        - Terfenol-d materials

Liepmann (1979)

Gad-el-Hak and Blackwelder (1986;1987;1989)

Lumley (1991)

Choi, Moin and Kim (1992)

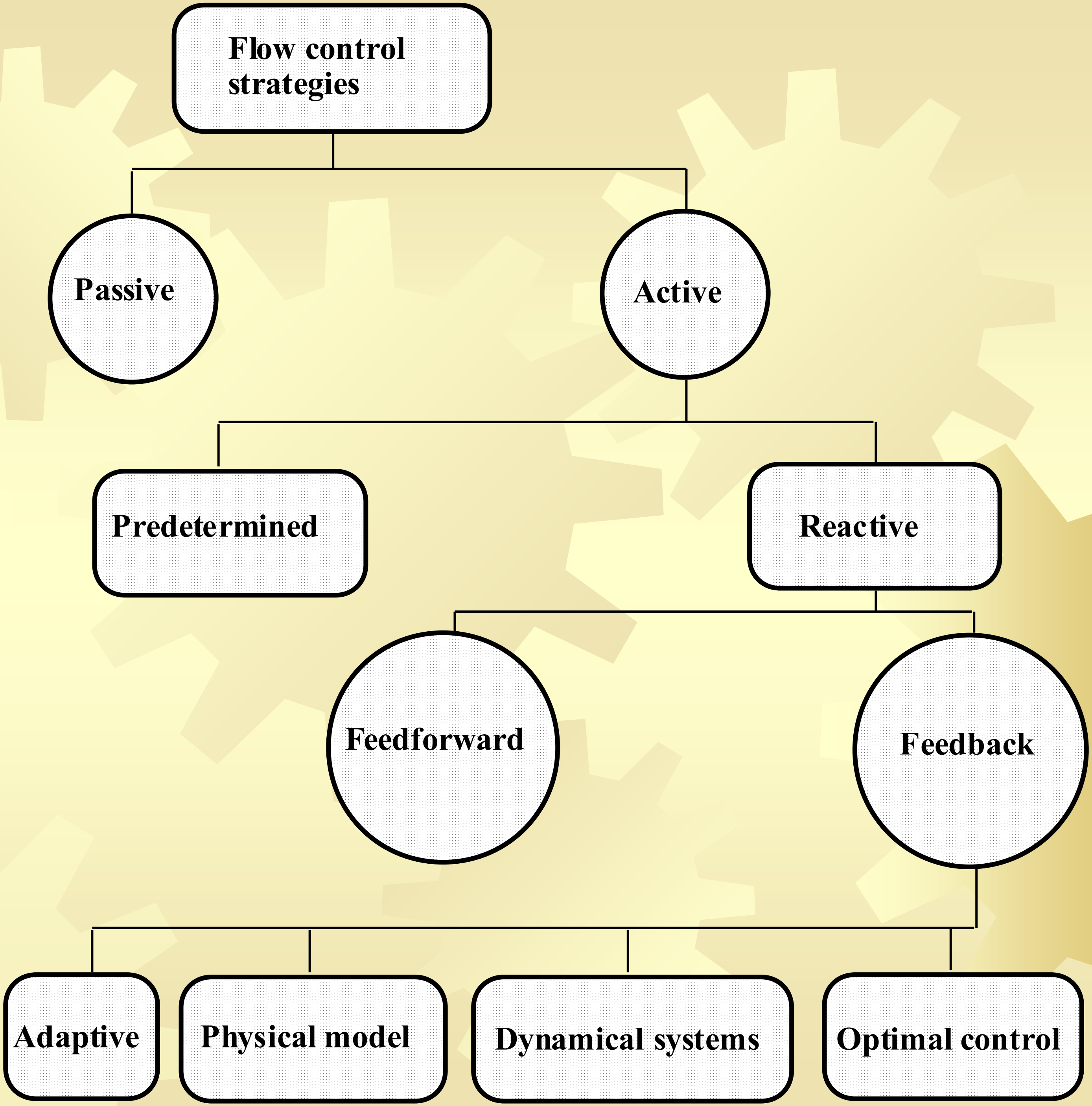
Jacobson and Reynolds (1993)

Flow control classification schemes

- Wall control *versus* in-stream control
  - Riblets *vs*. LEBU
- Velocity-profile modifiers *versus* small-eddy targeting
  - Pressure gradient *vs*. polymer
- Passive *versus* active control
  - Shaping *vs*. suction
  - <u>Active</u>: predetermined or reactive

Classification of flow control strategies

(Based on energy expenditure and control loop)

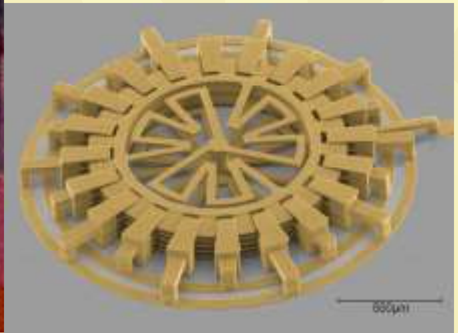


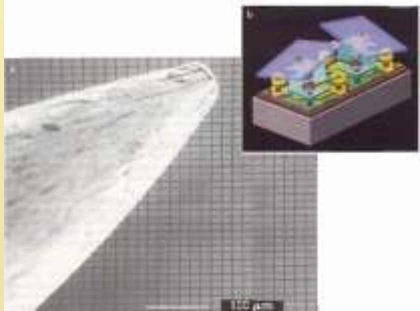
The Taming of the Shrew
& the Monday morning quarterbacks

- Petruchio was able to tame his Katharina in the course of one Shakespearean boisterous farce
  - How come fluid mechanists are <u>not</u> able to *tame* turbulence after centuries of trying?
- (1986) Control strategy specifically targeted towards near-wall events
  - Do you know what kind of field scales you’re dealing with?
  - No available technology can do that!

The Monday morning quarterbacks (cont.)

- (1990) Explosive growth of microfabrication technology
- (1993) Calculated the relevant time and length scales for typical aircraft/submarine, and the number of sensors/actuators to do the job
  - But energy consumption by all those sensors/actuators would overwhelm any potential benefit!



What does it take?

- <u>Submarine</u>

  ρ = 1000

  ϖ = 10^{-6}

  U_o = 10

  Re = 10^7/m

- <u>Aircraft</u> (10 km)

  0.4 kg/m^3

  30 x 10^{-6} m^2/s

  300 m/s

  10^7/m

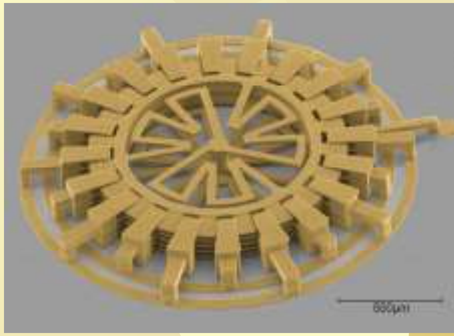
$$C_f \equiv 2\left(\frac{u_\tau}{U_o}\right)^2 = 0.003$$

ν/u_τ = 2.6 ⌠

2.6 ⌠

SENSORS/ACTUATORS

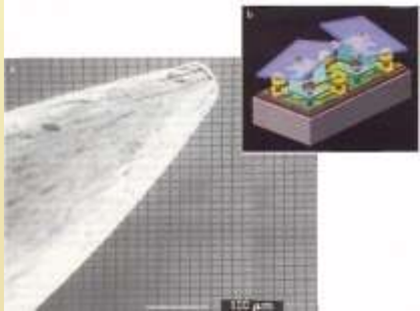
- Spanwise separation
  = 100 wall unit (260 ∫m)



- Streamwise separation
  = 1000 wall units (2.6 mm)

- Number of elements
  = $1.5 \times 10^6/m^2$

- Frequency = 600 Hz
  (submarine)
  = 18 kHz
  (aircraft)



Actuator’s response

- Wall displacement = 10 wall units = 26 ∫μ

- $C_q = 0.0006$

  $C_f = 0 + 2 \times 0.0006 = 0.0012$

- ΔT = 2°C (heating in water)

  = 40°C (cooling in air)

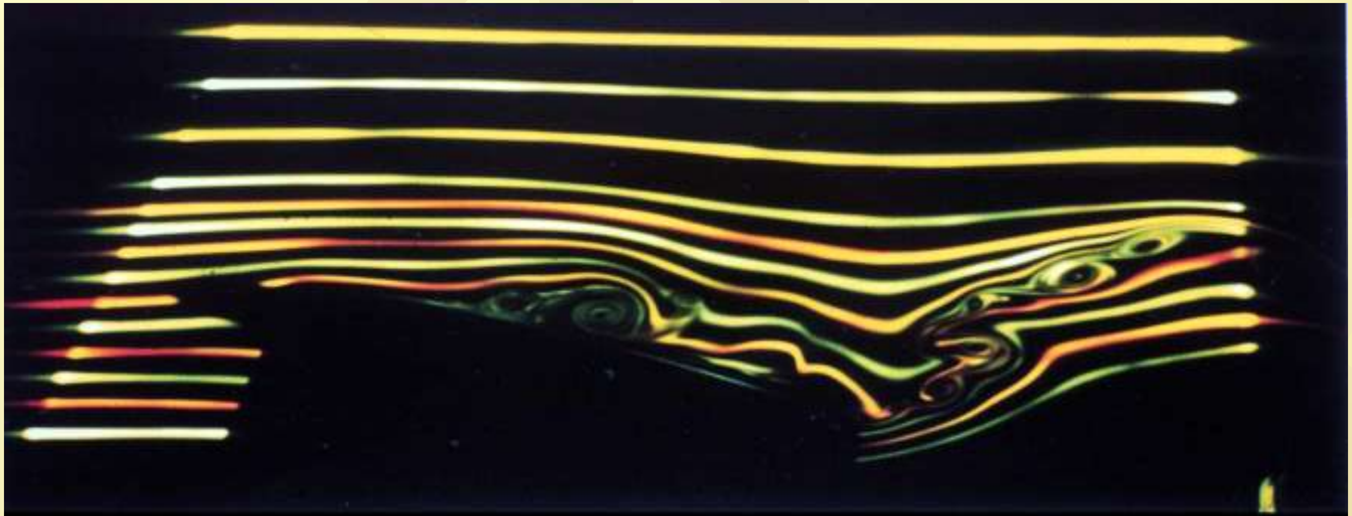
Energy considerations

	Submarine	Aircraft
➢ Drag =	150 (C_f = 0.003)	54 N/m^2
➢ Power =	1.5	16 kW/m^2
	(cruising power for a jumbo jet = 50,000 kW)	
➢ Power =	10^3	10^4 ⌠W/sensor

Energy considerations

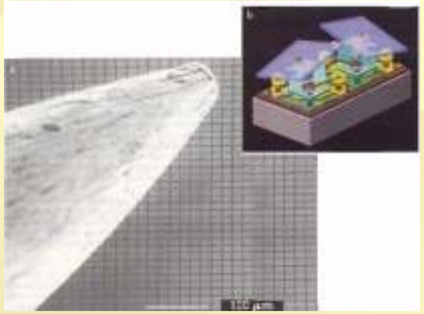
If reactive control is applied ($C_f = 0.0012$)

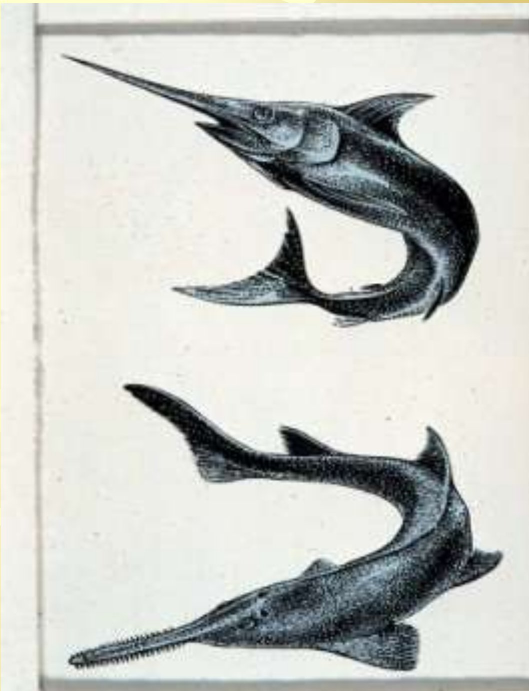
	Submarine	Aircraft
▪ Drag =	60	22 N/m^2
▪ Power =	0.6	6.5 kW/m^2
▪ Power =	400	4320 ⌠W/sensor



Energy considerations

- What does it take to operate 1.5×10^6 sensors & actuators?
- Energy penalty relative to saving?





Sensors

- Voltage = 0.1–1 V

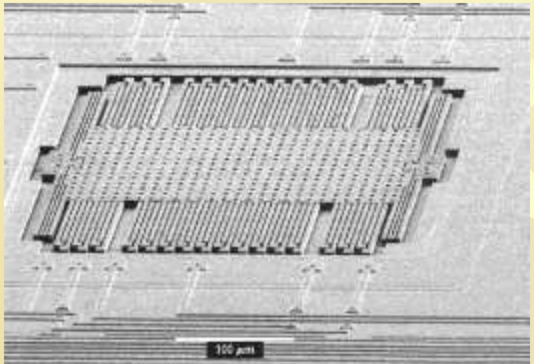
  Resistance = 100 kΩ–MΩ

  Power consumption = 0.1–10 ∫W/Sensor

  (0.00015–0.015 kW/m^2)

- Compare to anticipated power reductions:

	Submarine	Aircraft
From	Power = 1.5	16 kW/m^2
To	Power = 0.6	6.5 kW/m^2



Actuators

- Consider a 26-micron oscillating motion of a diaphragm having a spring constant k = 100 N/m:

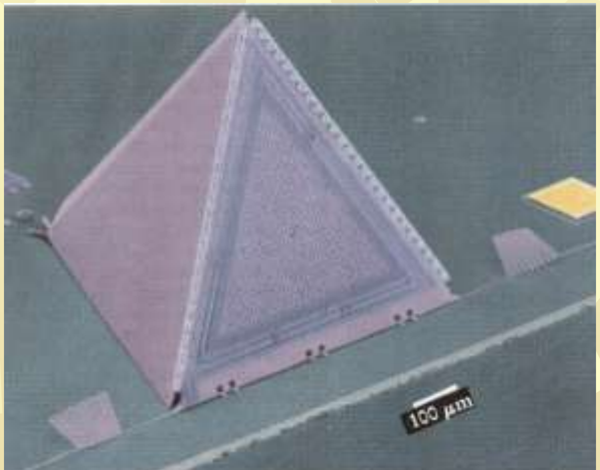
$$\text{Work} = \tfrac{1}{2}\, k\, x^2 \quad \text{(J)}$$
$$\text{Power} = W \times f \quad \text{(W)}$$

	<u>Submarine</u>	<u>Aircraft</u>
➢ Frequency	= 0.6	18 kHz
➢ Power	= 20	600 ⌠W/actuator
<u>or</u>	= 0.03	0.9 kW/m^2

Oscillating diaphragm

- Compare to anticipated power reduction:

	Submarine	Aircraft
From	Power = 1.5	16 kW/m^2
To	Power = 0.6	6.5 kW/m^2



Actuators

- Consider a suction coefficient of $C_q = 0.0006$, across a pressure difference of 0.1 atm

$$\Delta p = 10^4 \ \mathrm{N/m^2}$$

$$\dot{m} = \rho \times C_q U_o \times A$$

$$\text{Power} = \dot{m} \times \frac{1}{\rho} \times \Delta p$$

	Submarine	Aircraft
U_o	= 10	300 m/s
Power	= 40	1200 ⌠W/actuator
or	= 0.06	1.8 kW/m^2

Suction

- Compare to anticipated power reduction:

	Submarine	Aircraft
From	Power = 1.5	16 kW/m^2
To	Power = 0.6	6.5 kW/m^2

Can it be done?

- Breakthrough #1:

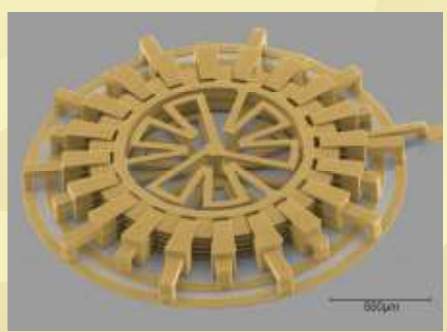
  Microfabrication

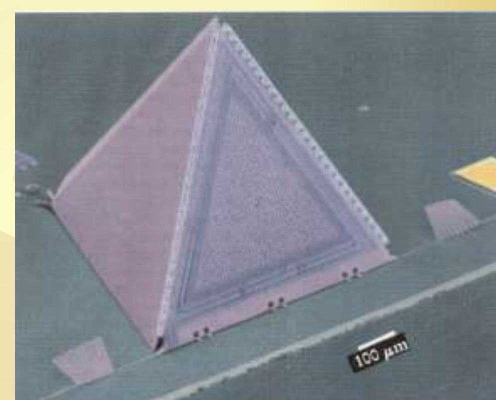
- Breakthrough #2:

  Control of Chaos

- Computer to do it all:

  Massively-parallel, self-learning neural networks





Active control

- Predetermined
- Reactive
  - Feedforward, open loop
  - Feedback, closed loop
    - Adaptive
    - Physical-model based
    - Dynamical-system based
    - Optimal control

Reactive control

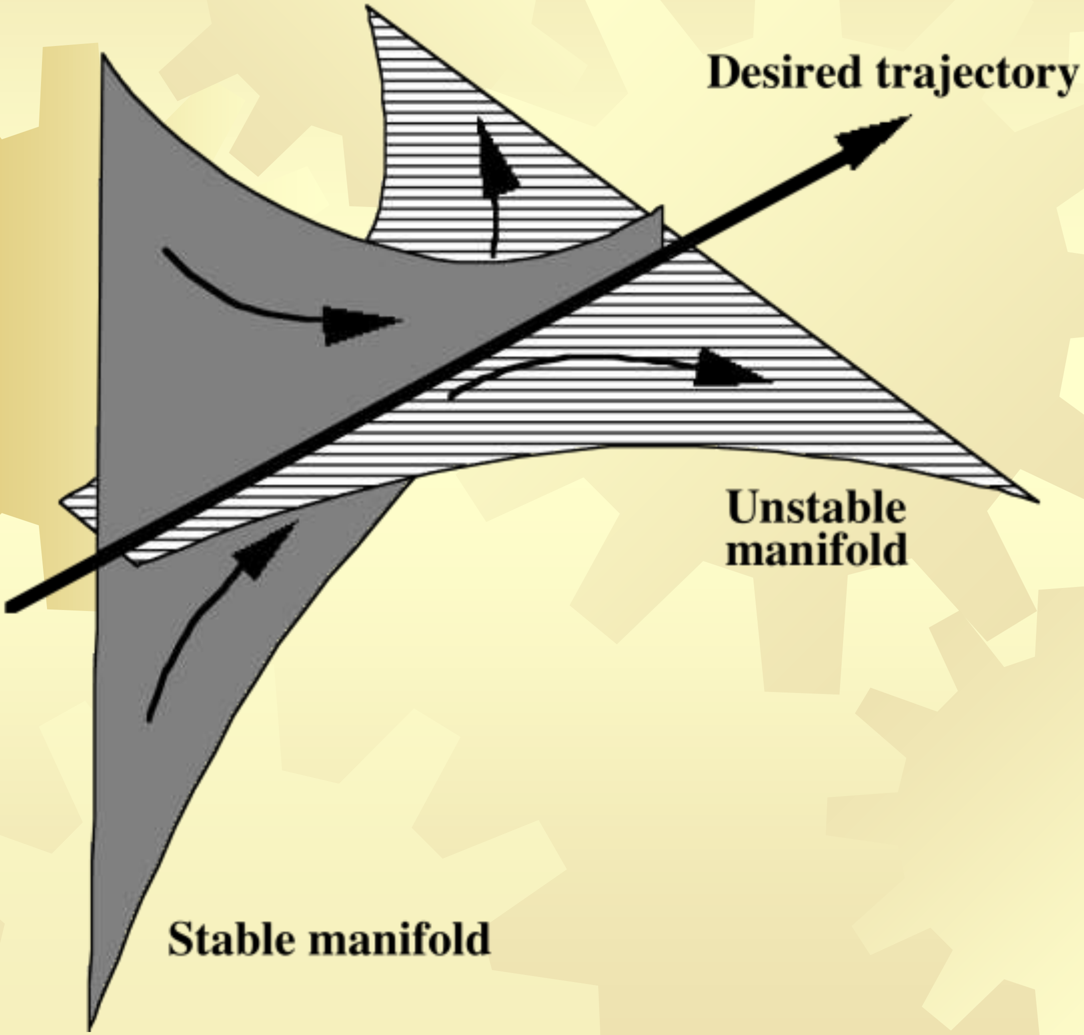
In order of the degree of reliance on governing equations:

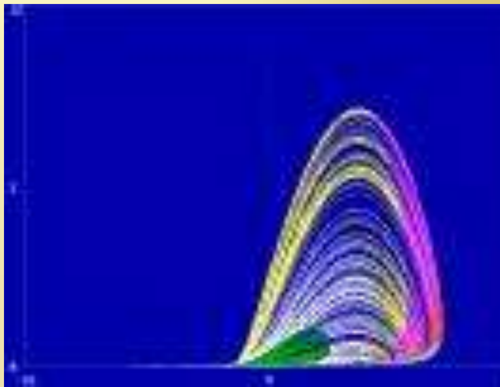
- Adaptive
  - Develop model/controller *via* learning algorithm
  - Self-learning neural network; back-propagation algorithm
- Physical-model based
  - Establish control law *via* heuristic physical arguments
  - Selective/targeted suction; compliance; heating

Reactive control (cont.)

- Dynamical-system based
  - Chaos control: OGY strategy, Hübbler method
  - Stabilization with minute expenditure energy
- Optimal control theory
  - Most efficient control effort to achieve a desired goal
  - OCT applied directly to Navier–Stokes equations

The OGY method for controlling chaos



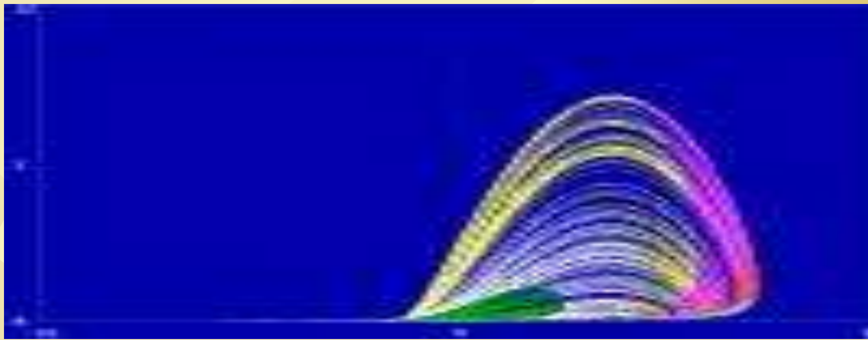


OGY method: possible pitfalls

- System with infinite number of degrees of freedom are not readily susceptible to an easy dynamical systems approximation

- Noise in the system tends to kick the orbit out of the circle of stability
  (surrounds the unstable fixed point)

  - Forces the operator to increase the control amplitude in order to keep the orbit close to the fixed point

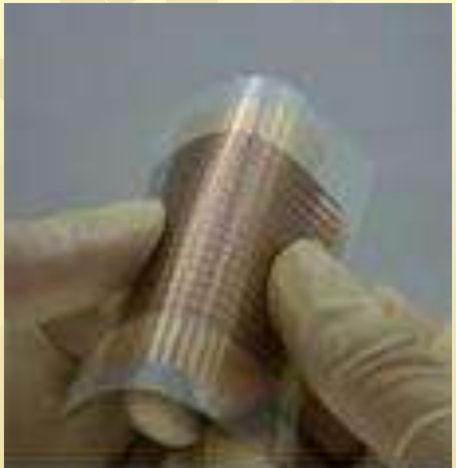


Possible pitfalls (cont.)

- Manifold along which the system leaves fixed point might not be one-dimensional
- A burst is assumed to leave a fixed point along the *average path.* Actuator pushes back along the same path
  - In reality, most bursts would leave one side or the other of the average path

Wall-only or global?

- Global array of sensors and actuators unrealistic
- Either global or wall must be finite number
- Checkerboard of wall sensors and actuators has its own pitfalls



Wall only: possible pitfalls

- Information sensed incomplete
  - Might be misinterpreted
- Checkerboard actuators might be less effective
- That is where dynamical systems theory and soft computing can help
  - Low-dimensional dynamical model used in Kalman filter can make the most of the partial information
  - Fuzzy logic, genetic algorithms, neurocomputing, and probabilistic reasoning can take into account system uncertainties

The future

- Classical methods:
  - Suction
  - Compliant coatings
- Emerging strategies:
  - Reactive control of turbulent flows
    - Inexpensive, durable microsensors/microactuators
    - Efficient control algorithms
    - Colossal computers
    - Neural nets

Microfabrication

+

Nonlinear Dynamics
Systems Theory

+

Massively-Parallel, Self-Learning Neural Networks

Reactive Control

And now that we have finished…

- The American journalist, critic and controversialist Henry Louis Mencken (1880–1956) once wrote:

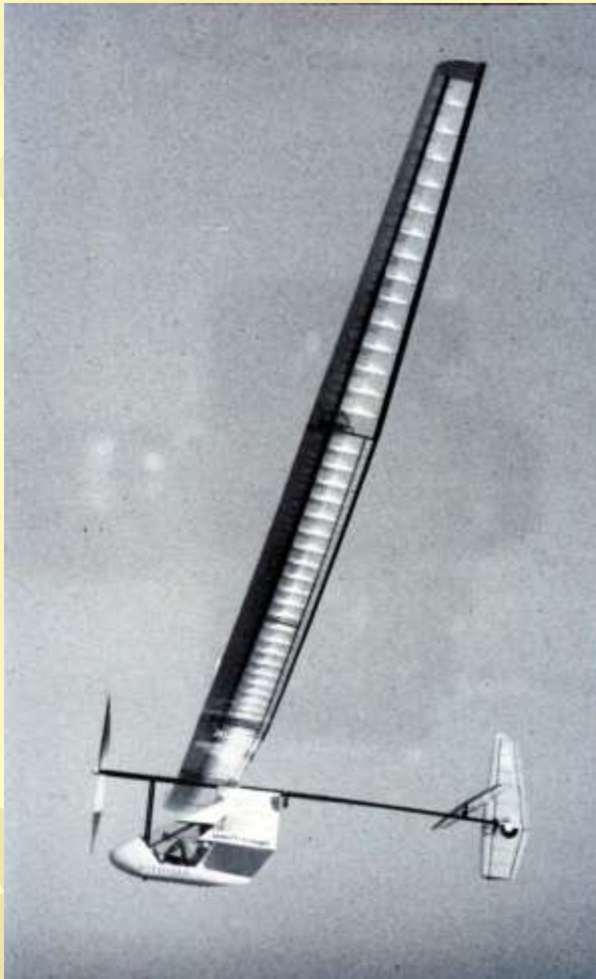
"There is always an easy solution to every human problem—neat, plausible and wrong."

Additional reading

- Gad-el-Hak, M. (1996) “Modern Developments in Flow Control,” *Applied Mechanics Reviews*, vol. 49, pp. 365–379.
- Gad-el-Hak, M., Pollard, A., and Bonnet, J.-P. (editors) (1998) *“Flow Control: Fundamentals and Practices,”* Springer-Verlag, Berlin..
- Gad-el-Hak, M. (2000) *“Flow Control: Passive, Active and Reactive Flow Management,”* Cambridge University Press, London, United Kingdom.
- Gad-el-Hak, M. (editor) (2006) *“The MEMS Handbook,”* second edition, CRC Press, Boca Raton, Florida.

Five eras of flow control

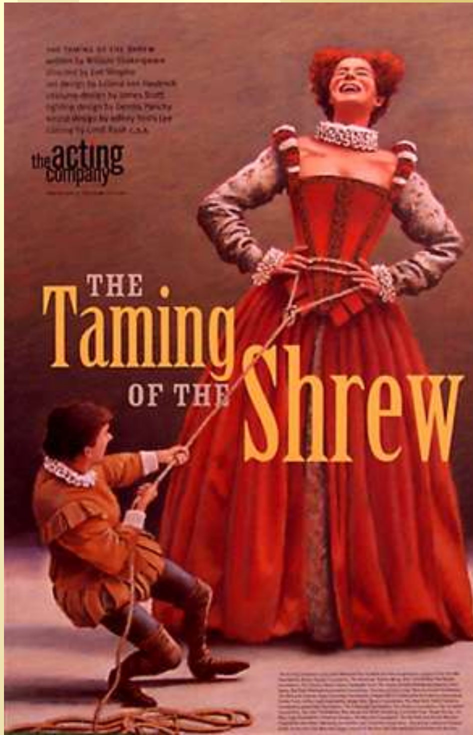
- Empirical Era (prior to 1900)
- Scientific Era (1900–1940)
- World War II Era (1940–1970)
- Energy Crisis Era (1970–1990)
- The 1990s and beyond



From William Shakespeare's *The Taming of the Shrew*

Curtis (Petruchio's servant, in charge of his country house): *Is she so hot a shrew as she's reported?*

Grumio(Petruchio's personal lackey): *She was, good Curtis, before this frost. But thou know'st winter tames man, woman, and beast; for it hath tamed my old master, and my new mistress, and my self, fellow Curtis.*



Prospects for taming turbulence

- Always possible, but never easy
- Future is bright, nevertheless
  - Efficient reactive control, where the control input is optimally adjusted based on feedforward/feedback measurements, is now in the realm of the possible for future practical devices

Taming of the shrew

- But turbulence can and will be tamed!

Curtis (Petruchio’s servant, in charge of his country house)**:** *Is she so hot a shrew as she’s reported?*

Grumio (Petruchio’s personal lackey)**:** *But thou know’st winter tames man, woman, and beast; for it hath tamed my old master, and my new mistress, and my self, fellow Curtis.*

Hortensio (a gentleman of Padua)**:** *Now go they ways, thou hast tam’d a curst shrew.*

Lucentio (a gentleman of Pisa)**:** *’Tis a wonder, by your leave, she will be tam’d so.*

Reynolds number

- *Re* determines whether the flow is laminar or turbulent
- Free-shear flows transition to turbulence at rather low *Re*, as compared to wall-bounded flows
- Flow control is most effective near critical flow regimes (e.g. near transition or separation points), where flow instabilities magnify quickly

Reynolds number (cont.)

- Skin friction in a wall-bounded flow:
  - $Re < 10^6$ ⟶ flow is laminar
    - Adverse p-gradient; higher wall-viscosity; and injection: lead to lower skin friction
  - $10^6 < Re < 4 \times 10^7$ ⟶ transitional flow
    - Methods to delay transition include favorable p-gradient; suction; lower wall-viscosity; compliant coatings;…
  - $Re > 4 \times 10^7$ ⟶ turbulent flow
    - Methods to lower skin friction include riblets; LEBUs; polymers;…
      - & Reactive control

Mach number

- Tollmien–Schlichting modes
  - Dominate for *Ma* < 4
  - Damped by *Ma* increase, wall cooling (for gases), favorable pressure-gradient, and suction
- Mack modes
  - Dominate for *Ma* > 4
  - Damped by *Ma* increase, favorable pressure-gradient, and suction
  - Destabilized by wall cooling
- Crossflow instabilities
- Görtler instabilities

Mach number (cont.)

- Tollmien–Schlichting modes
- Mack modes
- Crossflow instabilities
  - Caused by inflectional crossflow velocity
  - Unaffected my *Ma* and wall cooling
  - Enhanced by favorable pressure-gradient
  - Suppressed by suction
- Görtler instabilities
  - Caused by concaved streamline curvature
  - Unaffected by *Ma*, wall cooling and favorable pressure- gradient
  - Suppressed by suction

Governing equations

- For a Newtonian, Fourier, isotropic fluid:
  - Continuity:

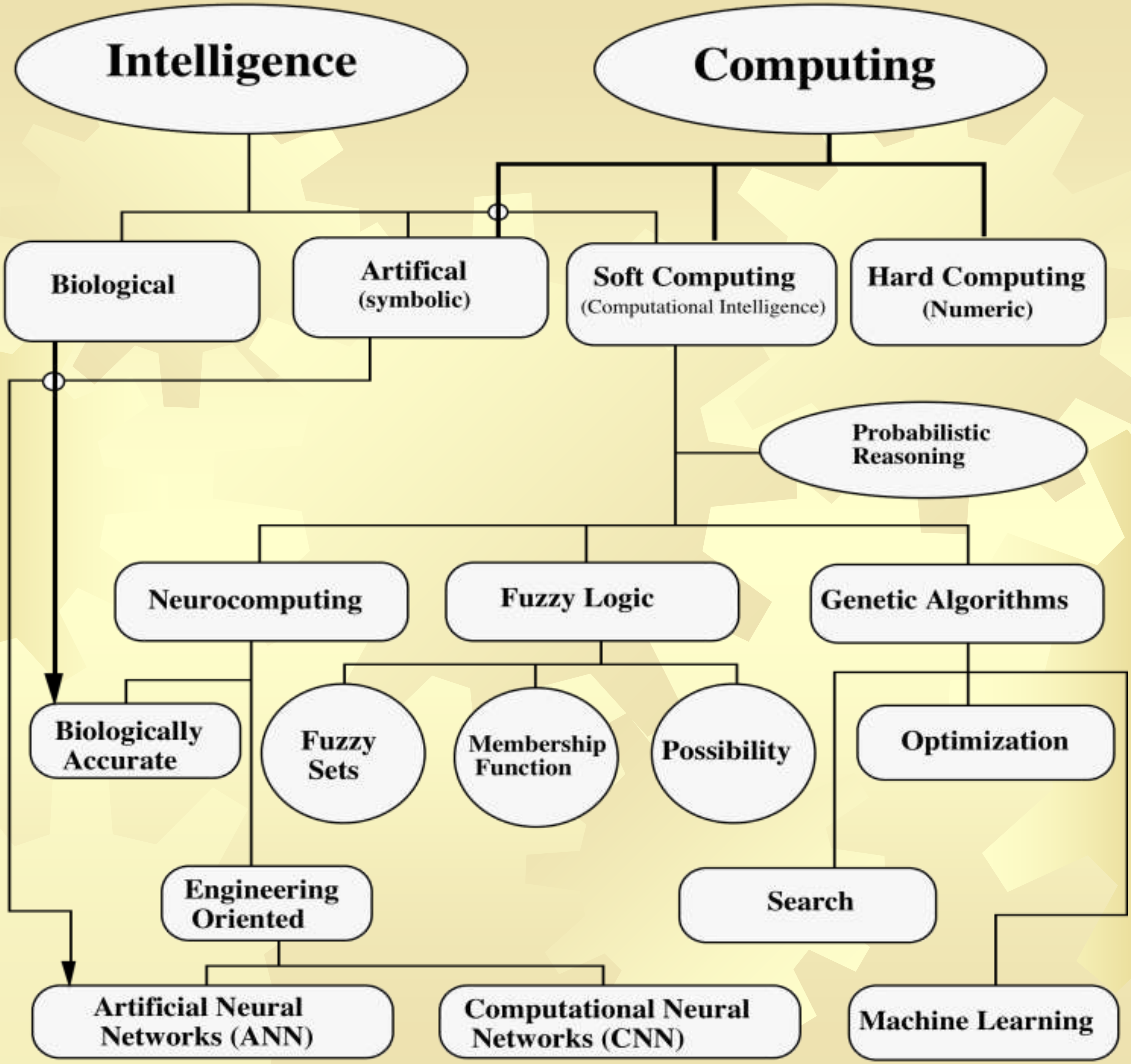
$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_k}(\rho u_k) = 0$$

  - Momentum:

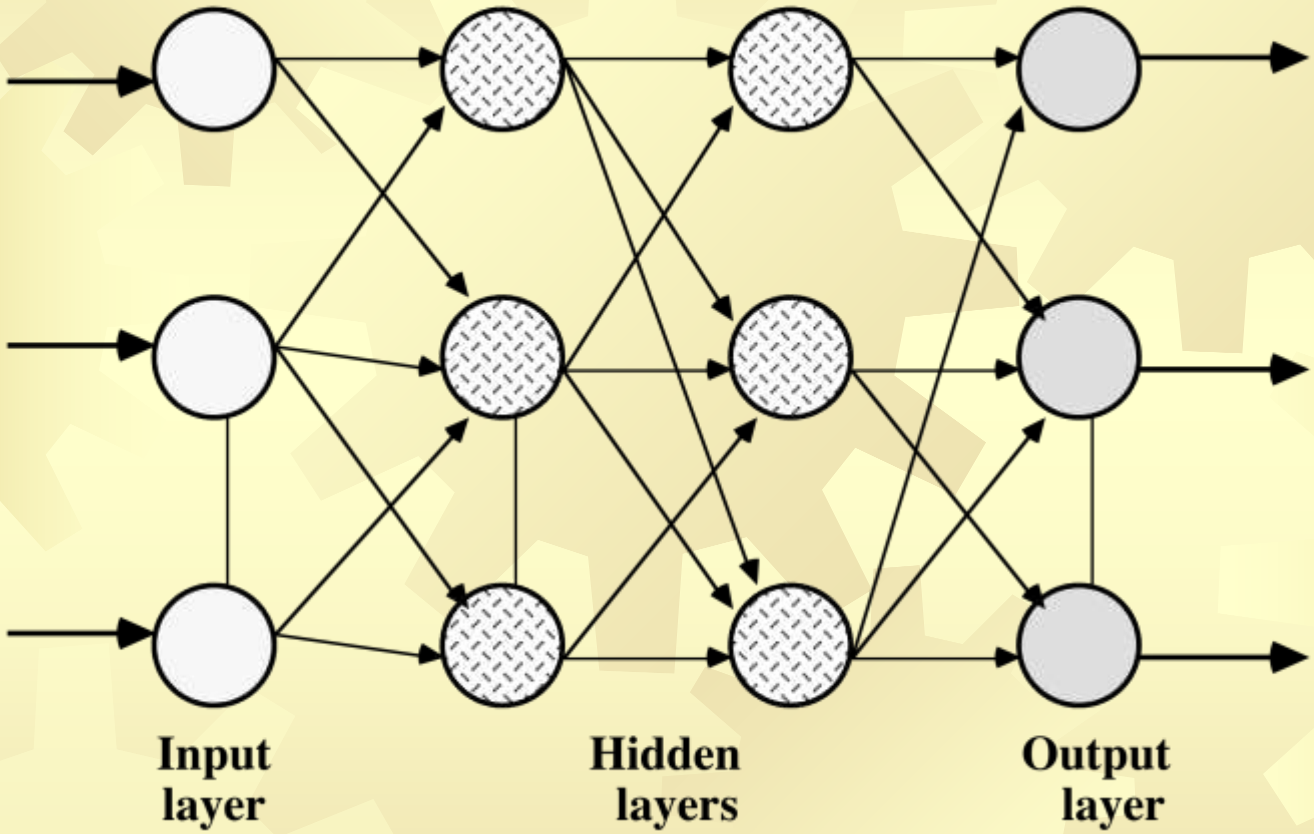
$$\rho\left[\frac{\partial u_i}{\partial t} + u_k \frac{\partial u_i}{\partial x_k}\right] = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_k}\left[\mu\left(\frac{\partial u_i}{\partial x_k} + \frac{\partial u_k}{\partial x_i}\right) + \delta_{ik}\,\lambda\,\frac{\partial u_j}{\partial x_j}\right] + \rho\, g_i$$

  - Energy:

$$\rho\left[\frac{\partial e}{\partial t} + u_k \frac{\partial e}{\partial x_k}\right] = \frac{\partial}{\partial x_k}\left(k\frac{\partial T}{\partial x_k}\right) - p\frac{\partial u_k}{\partial x_k} + \phi$$


Intelligence
Computing
Biological
Artifical
(symbolic)
Soft Computing
(Computational Intelligence)
Hard Computing
(Numeric)
Probabilistic
Reasoning
Neurocomputing
Fuzzy Logic
Genetic Algorithms
Biologically
Accurate
Fuzzy
Sets
Membership
Function
Possibility
Optimization
Engineering
Oriented
Search
Artificial Neural
Networks (ANN)
Computational Neural
Networks (CNN)
Machine Learning

Neural networks



Elements of a Neural Network

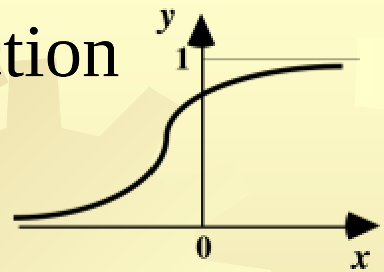
Neural networks

- Input layer; hidden layers; output layer
- Neuron (<u>or</u> node <u>or</u> processing element)

<u>Multi-tasks</u>:

- Weighted sum of all inputs

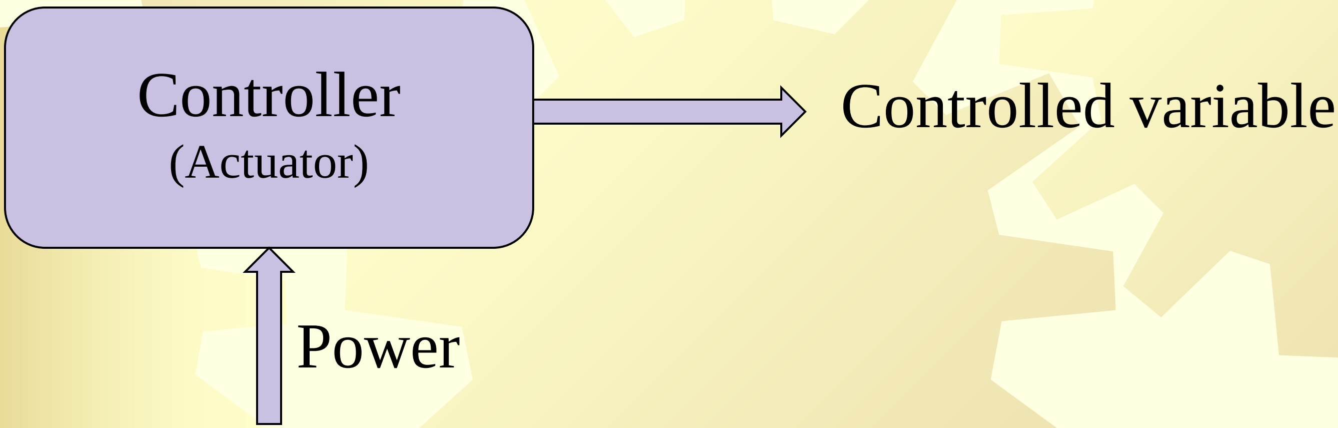
  (adaptive coefficients vary dynamically as the net learns)
- Threshold (transfer) function
  - Nonlinear sigmoid curve



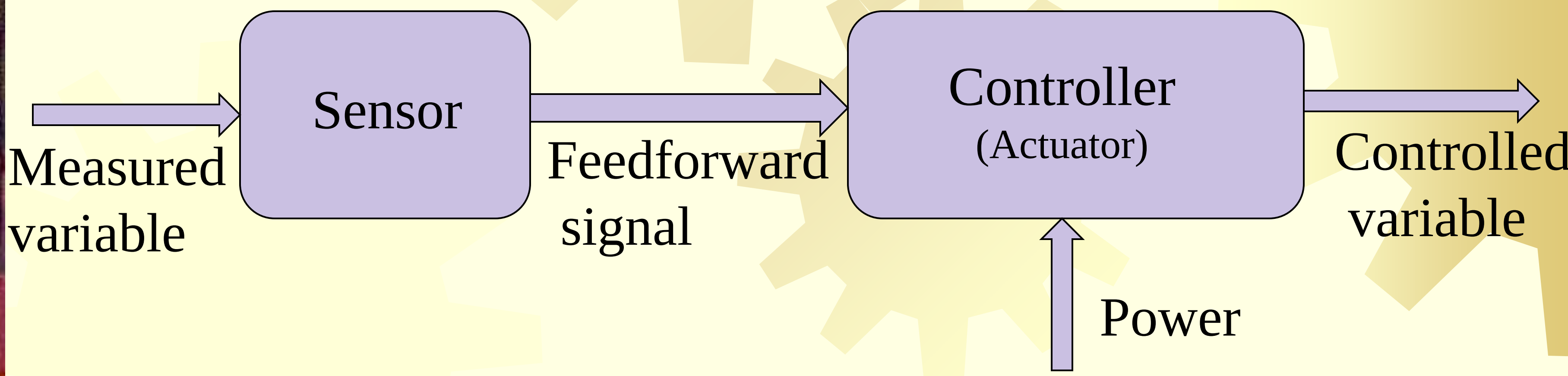
- Compare sum to threshold
  - *Fire* or not fire an output

Different control loops for active flow control

- Predetermined, open loop

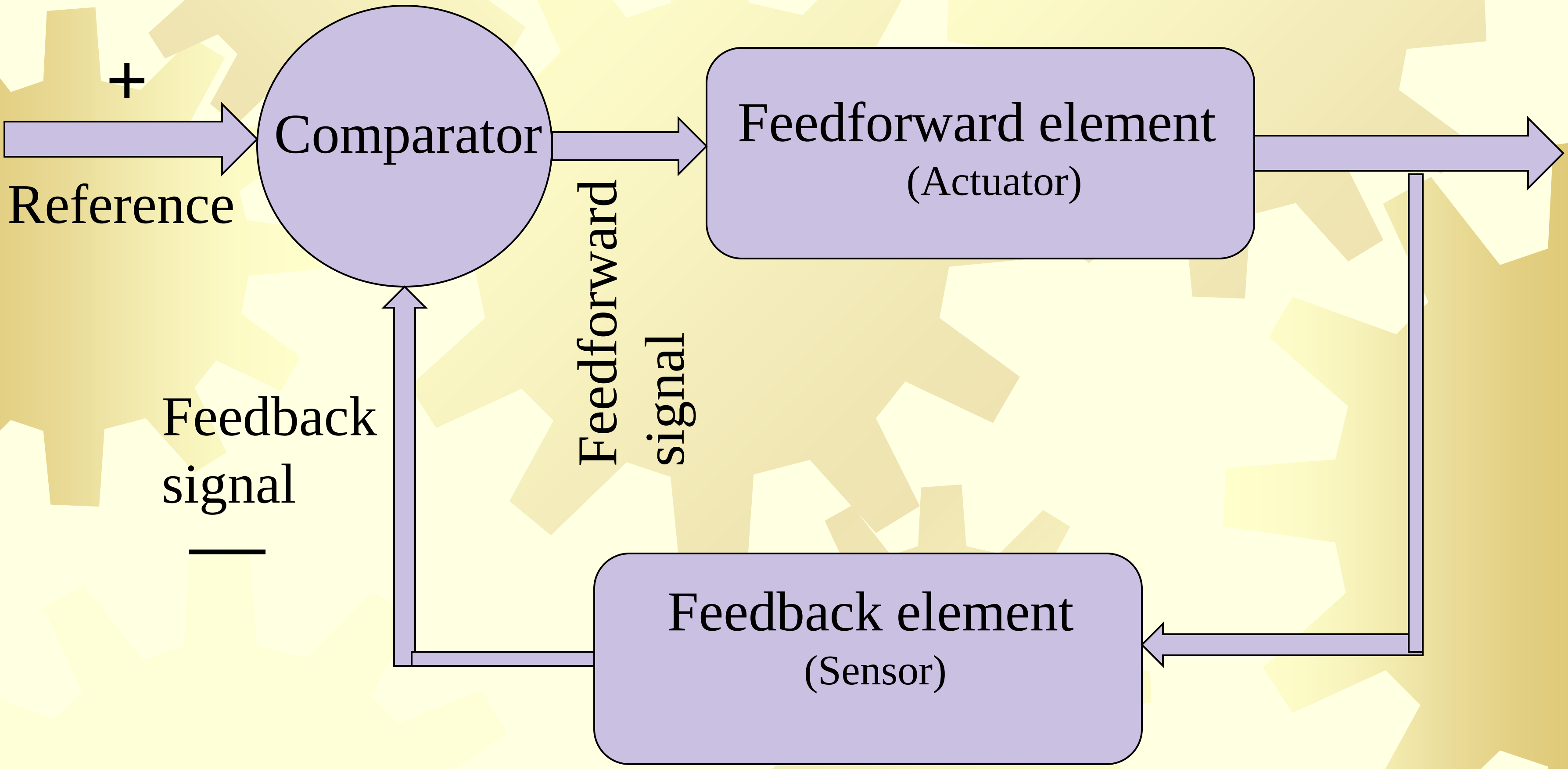


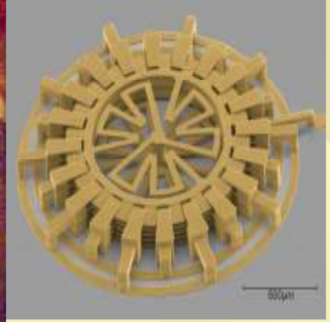
- Reactive, feedforward, open loop



Different control loops for active flow control

- Reactive, feedback, closed loop





Outlook

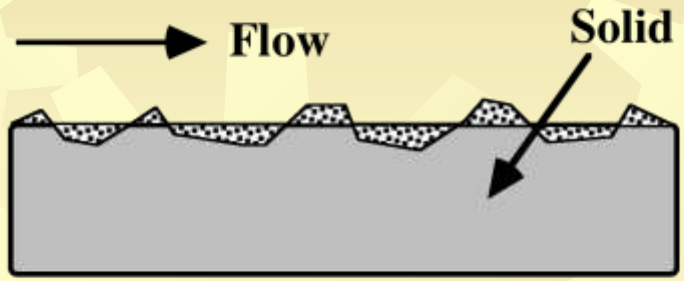
- Tremendous energy saving potential for vehicles which have notoriously high drag: automobiles; trucks; helicopters; …
- *Stand-by* techniques for *off-design* situations??
- Combination of approaches??
- Microfabrication + Nonlinear Dynamical Systems Theory + Massively-Parallel, Self-Learning Neural Networks

Reactive Control

Additional reading

- Gad-el-Hak, M. (1989) "Flow Control," *Applied Mechanics Reviews* 42, pp. 261–293.
- Gad-el-Hak, M. (1990) "Control of Low-Speed Airfoil Aerodynamics," *AIAA Journal* 28, pp. 1537–1552.
- Gad-el-Hak, M., and Bushnell, D.M. (1991) "Separation Control: Review," *Journal of Fluids Engineering* 113, pp. 5–30.
- Gad-el-Hak, M. (1994) "Interactive Control of Turbulent Boundary Layers: A Futuristic Overview," *AIAA Journal* 32, pp. 1753–1765.
- Gad-el-Hak, M. (1996) "Modern Developments in Flow Control," *Applied Mechanics Reviews* 49, pp. 365–379.

What is a compliant coating?

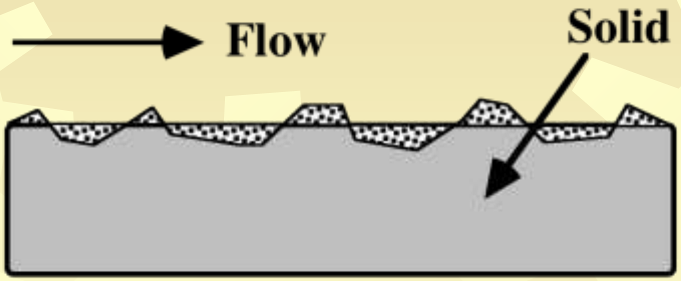


- The solid is compliant if the flow speed *begins to approach* the transverse free-wave speed in the solid

$$U = \mathcal{O}[C_t] = \mathcal{O}\left[\sqrt{G/\rho_s}\right]$$

  - *G* is the shear modulus of rigidity of the solid
  - Is the solid *soft* enough; or *U* high enough?

Advantages of compliant coatings



- <u>This flow control technique is</u>:
  - Simple
  - Passive
  - Easy to retrofit on an existing vehicle
  - Requires no slots, ducts, or internal equiptment of any kind
  - Not too expensive
- The subject is, however, the *Rodney Dangerfield* of fluid mechanics research
  - (Justly) gets <u>**no respect**</u> from a skeptical community
  - Justly again, it has often been called *Complaint* Coating

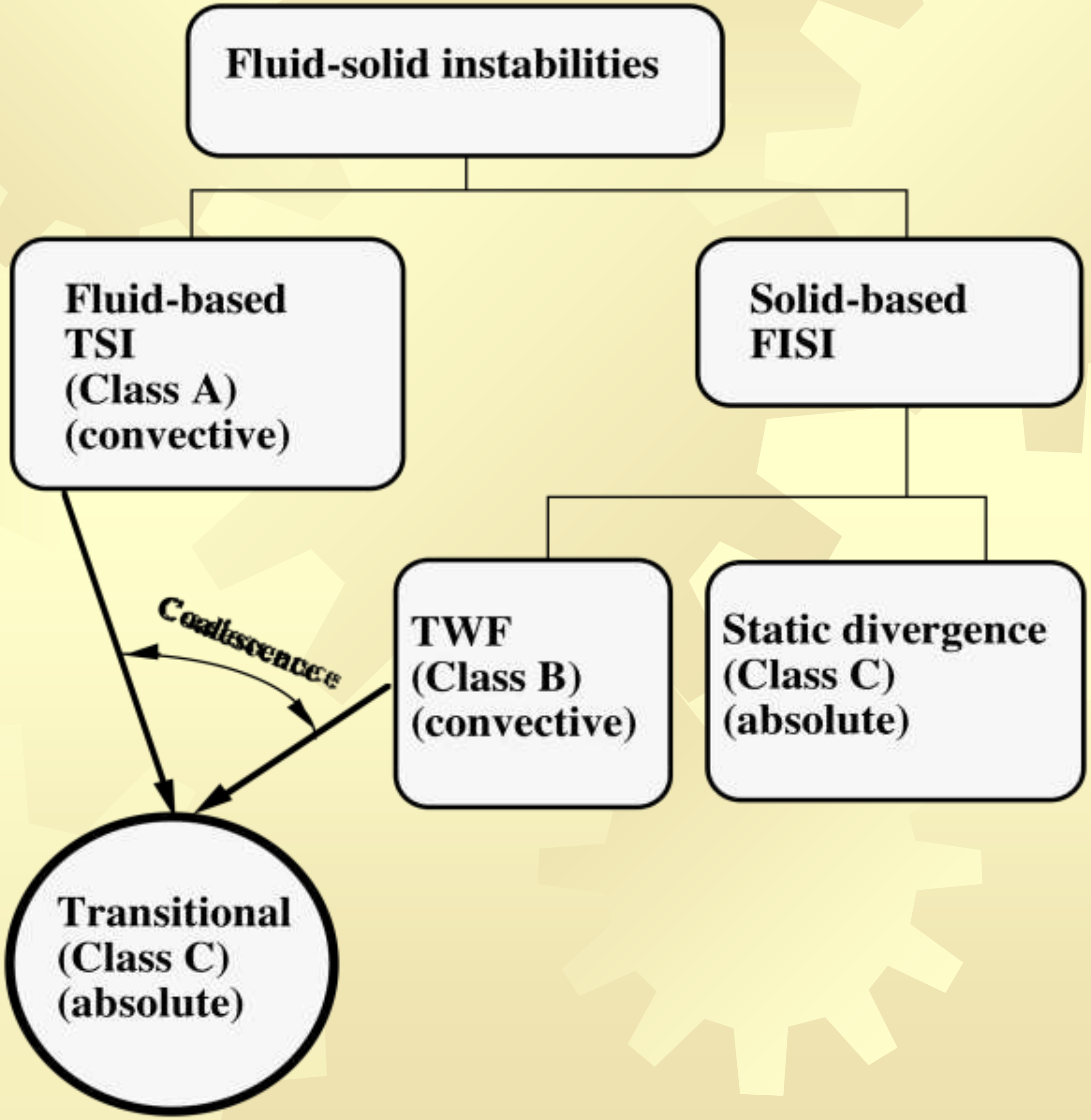
Compliant coating

- The *hope* is to find a coating that <u>may</u>:
  - Delay laminar-to-turbulence transition
  - Reduce skin friction in a TBL
  - Reduce noise/damp vibrations

The key issue

- Can compliant coatings inhibit/foster the dynamic instabilities in a wall-bounded flow?
  - Modification of mass, momentum and heat transfer
  - Change drag and acoustic properties
- Inhibiting fluid instabilities is a relatively easy task
  - Just make the coating *soft* enough
  - The challenge is to prevent instability waves in the coating itself from proliferating
  - FISI can trigger premature transition and act as roughness on the surface

Classification schemes of instabilities



The good news

- Compliant coatings can be rationally designed (optimized)
- Compliant surfaces can delay transition in both aerodynamic and hydrodynamic flows

$$Re_x = \mathcal{O}[10^7]$$

- Compliant coatings may favorably interact with turbulent boundary layers
  - Suppress turbulence
  - Reduce skin-friction drag??