Ceci n’est pas une pipe.
"There is nothing so practical as a good theory."

Ludwig Boltzman

$$S(Z) = k_B \ln \Omega(U,V,N)$$
 Orbit(t) = \sum_{i=0}^{n} a_i \sin(\omega_i t) 

Nonlinear Data Fitting
Physics

• Kepler’s Laws
• Newton’s Laws
Galileo Before The Papal Tribunal

<table>
<thead>
<tr>
<th>Name</th>
<th>Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copernicus</td>
<td>1473-1543</td>
</tr>
<tr>
<td>Tycho Brahe</td>
<td>1546-1601</td>
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<tr>
<td>Galileo</td>
<td>1564-1642</td>
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<tr>
<td>Kepler</td>
<td>1571-1630</td>
</tr>
<tr>
<td>Newton</td>
<td>1642-1727</td>
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</table>
IFAC World Congress Helsinki, Suomi-Finland 1978
4756 lines of assembly code

<table>
<thead>
<tr>
<th>Address</th>
<th>Value</th>
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<td>4ACC</td>
<td>2AEB41</td>
</tr>
<tr>
<td>4ACF</td>
<td>22F741</td>
</tr>
<tr>
<td>4B06</td>
<td>2AF741</td>
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<tr>
<td>4B09</td>
<td>23</td>
</tr>
<tr>
<td>4B0A</td>
<td>22F741</td>
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<td>3779</td>
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</tr>
</tbody>
</table>

CMU

Pitt
Titan IV Project with Martin Marietta

Adaptive Control Modifications:

- sigma modification
- parameter projection
- deadzone
- relative deadzone
- forgetting factor
- variable forgetting factor
- square root factorization
- normalization
- leakage
- ehc
- gmv
- gpc
- lqr
- pole-placement
- minimum variance control
- stochastic control
- simulations
- experiments
- theory
  - Stochastic
  - Robust
  - Deterministic
- ....
FIGURE 2.

The Adaptive Control Theoretician doing his mysterious work.

FIGURE 3.

The Adaptive Control Engineer trying to fathom the results and apply the ideas.
So-What Went Wrong?

Theorem (IEEE TAC 1992):

\[ \| y - y^{sp} \|_2 = \varepsilon_0 \| y^{sp} \|_2 + \varepsilon_1 \| d \|_2 \]
What is Process Control?
The Transfer Function

\[
\frac{dx}{dt} = f(x) + g(x,d,u)
\]
\[
y = h(x)
\]

- **Input** \((u)\)
- **Output** \((y)\)
- **Control System**
- **Cooling water in**
- **Cooling water out**

- **u** – input (deviation variable)
- **y** – output (deviation variable)
- **d** – disturbance (deviation variable)
- **e** – deviation (deviation)
- **r** – setpoint (deviation)
- **G(s)** – linear transfer function
- **s** – Laplace operator

Data fitting
- Step response
- Impulse response
- Frequency response
Feed

Input ($u$)

Output ($y$)

Control System

CT

TT

Cooling water in

Product out

Cooling water out

Feed

Input ($u$)

Output ($y$)

Control System

CT

TT

Cooling water in

Product out

Cooling water out
Feed

Input (u)

ST

Output (y)

Product out

Cooling water in

Cooling water out

Control System
IN A DISPLAY OF PERVERSE BRILLIANCE, CARL THE REPAIRMAN MISTAKES A ROOM HUMIDIFIER FOR A MID-RANGE COMPUTER BUT MANAGES TO TIE IT INTO THE NETWORK ANYWAY.
Thermodynamics (Irreversible) and Process Control
Passivity Theory

Two types of variables:
- Extensive
- Intensive

Current (flow): $u$
Force (effort): $y$
Power (supply): $u \cdot y$

Dissipation inequality

$$V(t) \geq 0$$
$$V(t) \leq V(0) + \int_0^t u \cdot y$$

Storage

Supply
Passivity Theory and Thermodynamics

\[ S(Z) = k_B \ln \Omega(U,V,N) \]

\[ u \rightarrow \text{Process} \rightarrow y \]

Extensive \hspace{1cm} Intensive

\[ V(t) \geq 0 \]

Storage

\[ V(t) \leq V(0) + \int_0^t u \cdot y \]

Supply

Dissipation inequality

\[ S(t) \geq 0 \]

\[ S(t) \geq S(0) + \int_1^2 \left( \frac{1}{T} \right) dQ \]

Clausius-Planck
Keenan’s Availability

Theorem: $A(Z_1, Z_2)$ is positive if the intensive variables corresponding to states $Z_1$ and $Z_2$ are different.

Entropy of Superheated Steam

$A(Z) = w_0^T Z - S(Z)$

Theorem: $A(Z_1, Z_2)$ is positive if the intensive variables corresponding to states $Z_1$ and $Z_2$ are different.
Theorem (J. Proc. Control 2007, Jillson)

\[
\frac{dA}{dt} = \sum \tilde{w}^T \tilde{p} + \sum \tilde{X}^T \tilde{f} + \sum \tilde{w}^T \tilde{f}
\]

Processes  Connections  Terminals
Why is Passivity so Precious?

Passive System: \[ \frac{dV_s}{dt} \leq u \cdot y \]

ISP Controller: \[ \frac{dV_c}{dt} \leq y \cdot u - ey^2 \]

Theorem (Automatica 2001, Alonso):
All Chemical Processes can be Controlled using PID Control
Temperature Control

Glass Quality Index

<table>
<thead>
<tr>
<th>PV</th>
<th>Control Method</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batch moisture</td>
<td>Minimum Variance</td>
<td>Variance Reduction 50%</td>
</tr>
<tr>
<td>Glass Level</td>
<td>Predictive</td>
<td>Variance Reduction 50%</td>
</tr>
<tr>
<td>Tweel Position</td>
<td>Machine Vision</td>
<td>Reduced distortion</td>
</tr>
<tr>
<td>Furnace pressure</td>
<td>Nonlinear adaptive</td>
<td>Stable pressure</td>
</tr>
<tr>
<td>Crown temperature</td>
<td>Multivariable MPC, Adaptive</td>
<td>Variance reduction 100%</td>
</tr>
<tr>
<td>Glass temperature, melter</td>
<td>PID</td>
<td>Standard deviation from 15°F to 1°F</td>
</tr>
<tr>
<td>Waist temperature</td>
<td>PID/Feedforward</td>
<td>Variance reduction 50%</td>
</tr>
<tr>
<td>Refiner temperature</td>
<td>PID</td>
<td>Variance reduction 50%</td>
</tr>
<tr>
<td>Conditioner temperature</td>
<td>PID</td>
<td>Variance reduction 100%</td>
</tr>
</tbody>
</table>
MODEL!

The “Sargant Program”

\[ \frac{dx}{dt} = f(x) + g(x, d, u) \]

\[ y = h(x) \]

State: \[ Z(x) = (U, V, M, A, \ldots) \]

(Entropy: \[ S(Z) = k_B \ln \Omega(Z) \])

Intensive variables: \[ w = \frac{\partial S}{\partial Z} \]

The Temple of Chemical Engineering (Paul Sides)

- Conservation Laws
- Dissipation

Dissipation and Invariants
Process Systems and Process Networks
Solar Grade Silicon
Christy White, G. Zeininger Fluor, P. Ege ReacTech

Particles are well-mixed
Integrate over time for particle size distribution

Plug flow reactor

Gas and powder are plug flow
Integrate over height for granular yield

Bed temperature
Bed density

Control fluidization regime
Simulate once to obtain model input

Population balance
Granular yield

Particle size

Computational fluid dynamics

SiH₄ → Si

Slow
Fast

Mass Profile

SiH₄
Granular Product Mean Diameter \( D_{ap} \) vs Yield and Seed Size

\[
D_{ap} = \sqrt[3]{1 + \frac{Y}{S}}
\]

\[y = 0.332x + 0.002 \]

\[R^2 = 1.000\]
This is not my research group
Trust is Good But Control is Better

Vladimir Lenin

"Let's face it—I'm a bit of a control freak."