CONTROLLABILITY & OBSERVABILITY

in a

NEW PERSPECTIVE

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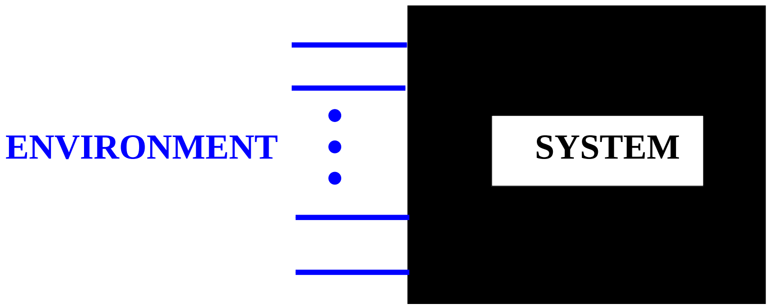
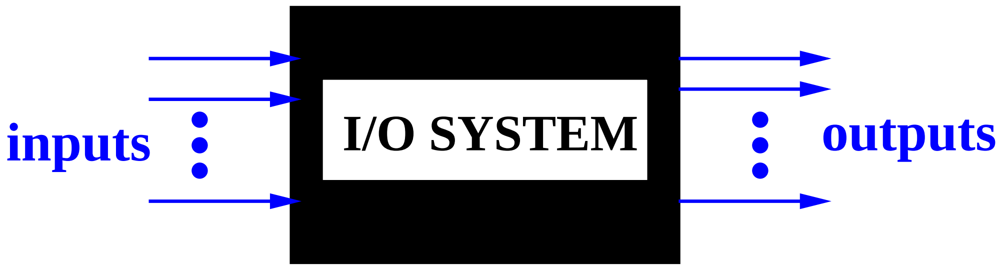
Motivation

Open and Connected



In system theory, we are accustomed to view a dynamical system as an input/output map



Open and Connected

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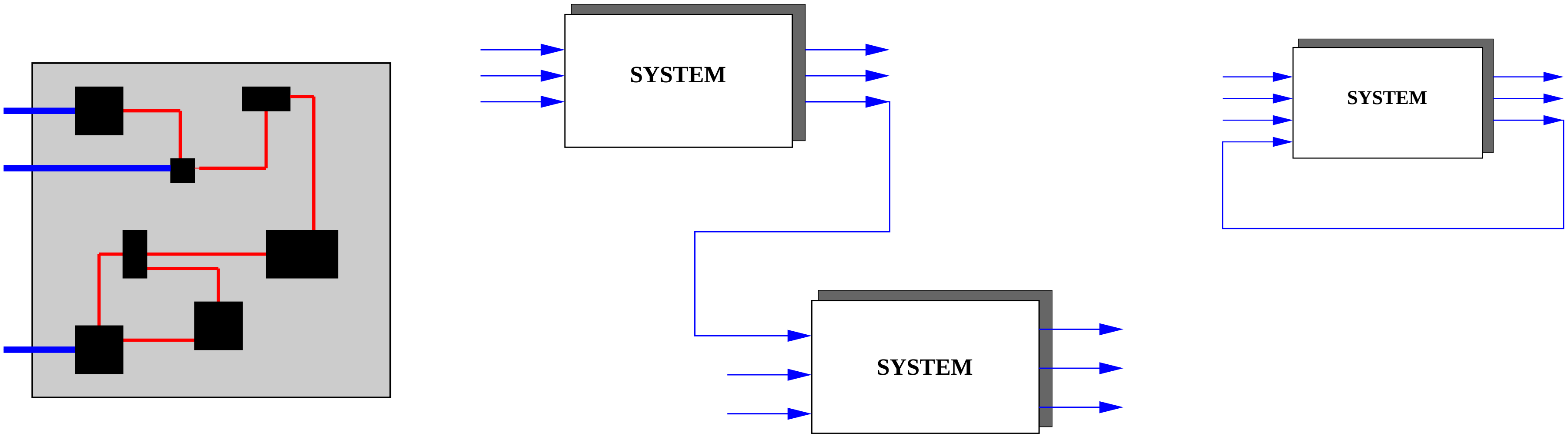
and an interconnection as a output-to-input assignment.



Open and Connected

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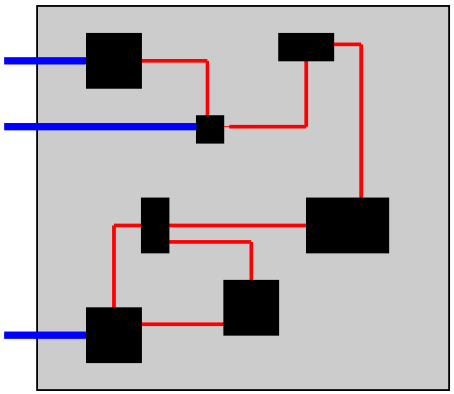
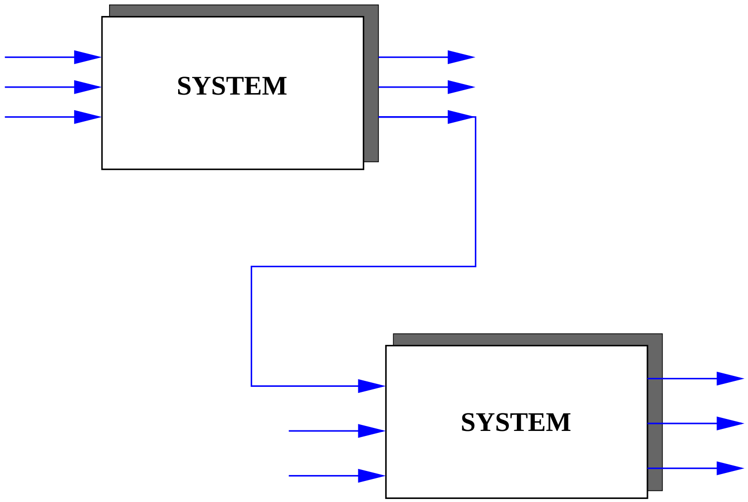
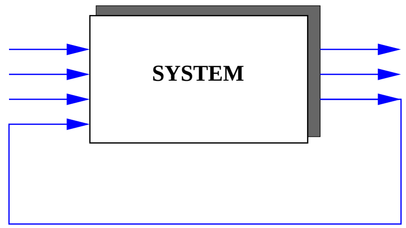
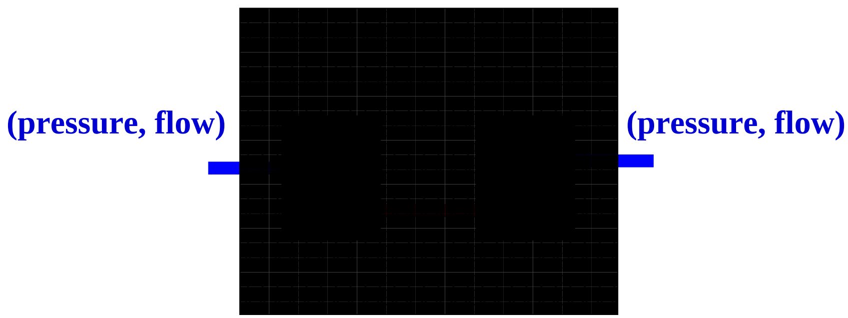


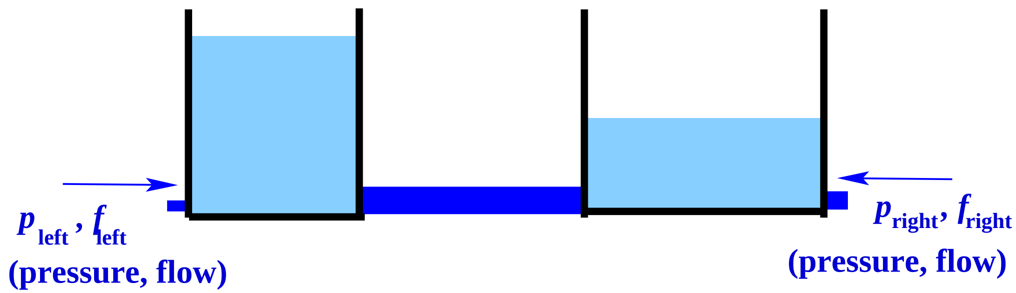


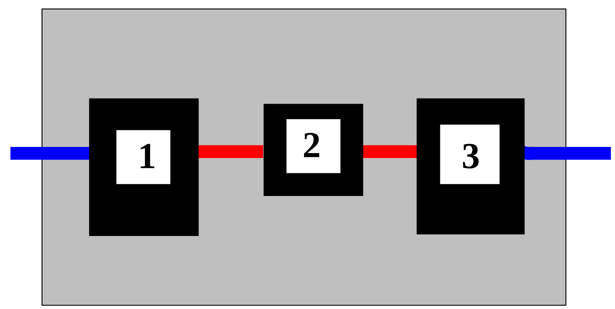


Is this appropriate for modeling physical systems?
If not, how should we proceed instead?

Example

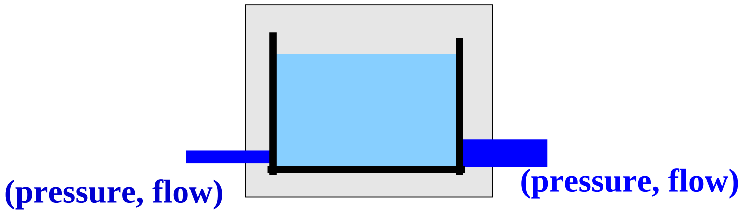

(pressure, flow)
(pressure, flow)

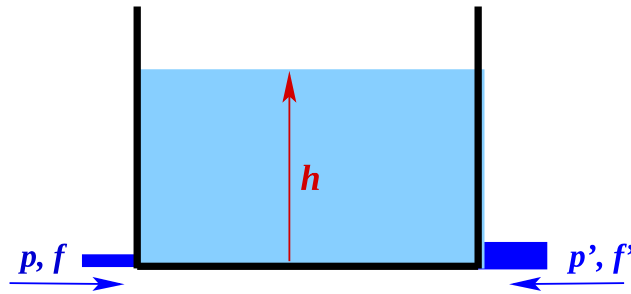

p_{left}, f_{left}
(pressure, flow)
p_{right}, f_{right}
(pressure, flow)


1
2
3

Example

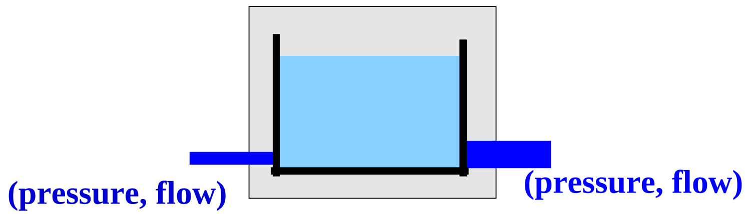
Subsystems 1 and 3:

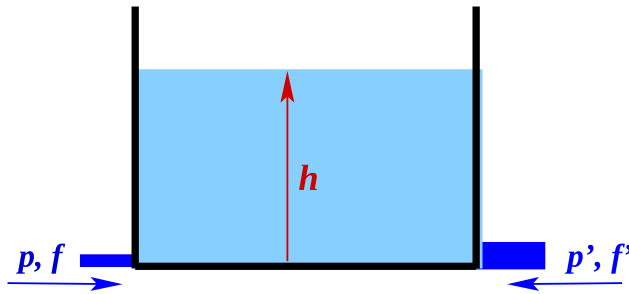




Example

Subsystems 1 and 3:

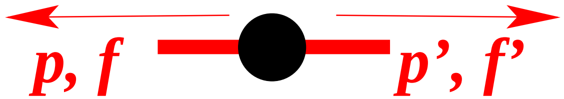




Subsystem 2:

Example

Interconnection laws:



$$p = p', \qquad f + f' = 0.$$

$$A_1 \frac{d}{dt} h_1 = f_1 + f_1',$$

$$B_1 f_1 = \begin{cases} \sqrt{|p_1 - p_0 - \rho h_1|} & \text{if } p_1 - p_0 \geq \rho h_1, \\ -\sqrt{|p_1 - p_0 - \rho h_1|} & \text{if } p_1 - p_0 \leq \rho h_1, \end{cases} \tag{1}$$

$$C f_1' = \begin{cases} \sqrt{|p_1' - p_0 - \rho h_1|} & \text{if } p_1' - p_0 \geq \rho h_1, \\ -\sqrt{|p_1' - p_0 - \rho h_1|} & \text{if } p_1' - p_0 \leq \rho h_1, \end{cases}$$

$$f_2 = -f_2', \quad p_2 - p_2' = \alpha f_2, \tag{2}$$

$$A_3 \frac{d}{dt} h_3 = f_3 + f_3',$$

$$C f_3 = \begin{cases} \sqrt{|p_3 - p_0 - \rho h_3|} & \text{if } p_3 - p_0 \geq \rho h_3, \\ -\sqrt{|p_3 - p_0 - \rho h_3|} & \text{if } p_3 - p_0 \leq \rho h_3, \end{cases} \tag{3}$$

$$C_3 f_3' = \begin{cases} \sqrt{|p_3' - p_0 - \rho h_3|} & \text{if } p_3' - p_0 \geq \rho h_3, \\ -\sqrt{|p_3' - p_0 - \rho h_3|} & \text{if } p_3' - p_0 \leq \rho h_3, \end{cases}$$

$$p_1' = p_2, \; f_1' + f_2 = 0, \; p_2' = p_3, \; f_2' + f_3 = 0. \tag{4}$$

$$p_{\text{left}} = p_1, \; f_{\text{left}} = f_1, \; p_{\text{right}} = p_3', \; f_{\text{right}} = f_3'. \tag{5}$$

Conclusion

- **Unclear input/output structure for terminal variables**
- **Many variables, indivisibly, at the same terminal**
- **Interconnection = variable sharing**
- **...**

Conclusion

- Unclear input/output structure for terminal variables
- Many variables, indivisibly, at the same terminal
- Interconnection = variable sharing
- ...

“Block diagrams unsuitable for serious physical modeling
- the control/physics barrier”

“Behavior based (declarative) modeling is a good alternative”

from K.J. Åström
Present Developments in Control Applications
IFAC 50-th Anniversary Celebration
Heidelberg, September 12, 2006.

Remedy

A dynamical system

:$\Leftrightarrow$ a family of time functions, ‘*the behavior*’.

Interconnection :$\Leftrightarrow$ ‘*variable sharing*’.

Even though modeling of interconnected physical systems may be the strongest case for ‘behaviors’, I will not deal with this today.

Concepts

Models

A dynamical system $:\Leftrightarrow$ $(\mathbb{T}, \mathbb{W}, \mathfrak{B})$

$\mathbb{T} \subseteq \mathbb{R}$ **'time set'**

$\mathbb{W}$ **'signal space'**

$\mathfrak{B} \subseteq \mathbb{W}^{\mathbb{T}}$ **the 'behavior'**

a family of trajectories $\mathbb{T} \longrightarrow \mathbb{W}$

henceforth, today, $\mathbb{T} = \mathbb{R}$, $\mathbb{W} = \mathbb{R}^{\mathtt{w}}$.

Hence today $\mathfrak{B}$ is a family of vector-valued continuous-time trajectories

$w : \mathbb{R} \longrightarrow \mathbb{R}^{\mathtt{w}} \in \mathfrak{B}$ **means "w is compatible with the model"**

$w : \mathbb{R} \longrightarrow \mathbb{R}^{\mathtt{w}} \notin \mathfrak{B}$ **means "the models forbids w"**

Models

The dynamical system $(\mathbb{R}, \mathbb{R}^{\mathtt{w}}, \mathfrak{B})$ $\quad \leadsto \quad \mathfrak{B}$

linear $:\Leftrightarrow$ $w_1, w_2 \in \mathfrak{B}, \alpha \in \mathbb{R}$, **imply** $\alpha w_1 + w_2 \in \mathfrak{B}$

time-invariant $:\Leftrightarrow$ $w \in \mathfrak{B}$, σ **any shift, imply** $\sigma w \in \mathfrak{B}$

differential $:\Leftrightarrow$ **'described' by an ODE. 'LTIDS'**

$$R_0 w + R_1 \frac{d}{dt} w + \cdots + R_{\mathtt{n}} \frac{d^{\mathtt{n}}}{dt^{\mathtt{n}}} w = 0.$$

$\leadsto$ $\quad R\left(\frac{d}{dt}\right) w = 0$ $\quad R$ **typically 'wide'** $\boxed{}$ **LTIDS**

$R = R_0 + R_1 \xi + \cdots + R_{\mathtt{n}} \xi^{\mathtt{n}}$ **polynomial matrix.**

Defines $\mathfrak{B} = \text{kernel}\left(R\left(\frac{d}{dt}\right)\right)$ ***'kernel representation'*** **of** $\mathfrak{B}$

Models

For example,

$$P\left(\frac{d}{dt}\right)y = Q\left(\frac{d}{dt}\right)u, \quad w = \begin{bmatrix} u \\ y \end{bmatrix}, \quad P, Q \text{ polynomial matrices}$$

$$\frac{d}{dt}x = Ax + Bu, y = Cx + Du, \quad w = \begin{bmatrix} u \\ y \\ x \end{bmatrix} \text{ or } w = \begin{bmatrix} u \\ y \end{bmatrix}$$

$$y = G\left(\frac{d}{dt}\right)u, w = \begin{bmatrix} u \\ y \end{bmatrix}, \quad P, Q \text{ matrices of rational f'ns}$$

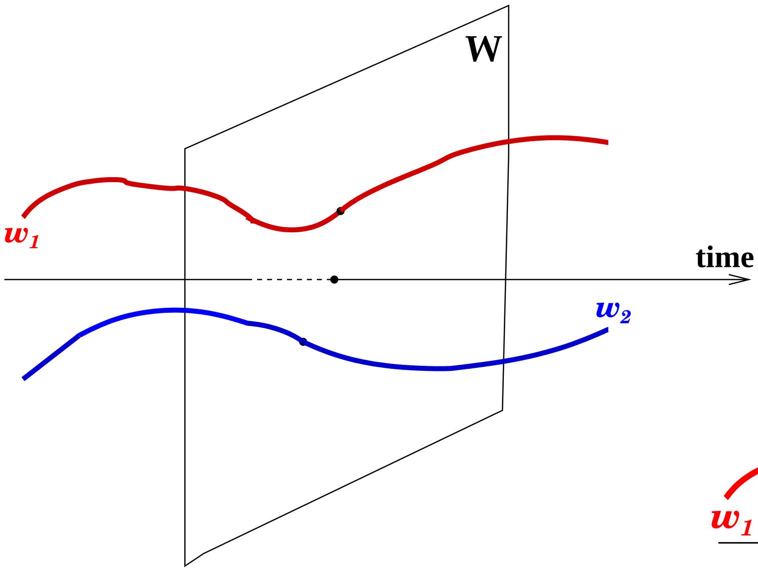
DAE's $\quad F\frac{d}{dt}x + Gx + Hw = 0$

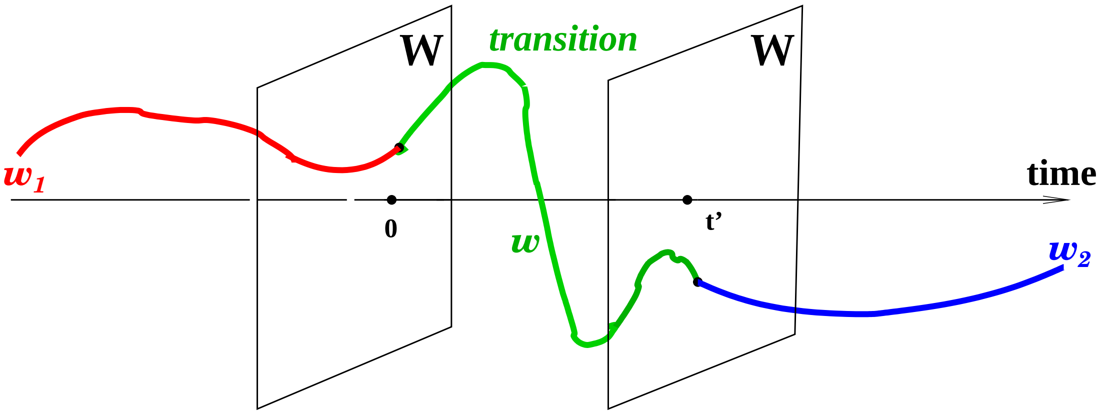
etc.

Controllability

The time-invariant system $(\mathbb{R}, \mathbb{R}^{\mathtt{w}}, \mathfrak{B})$ $\rightsquigarrow$ $\mathfrak{B} \subseteq (\mathbb{R}^{\mathtt{w}})^{\mathbb{R}}$

controllable $:\Leftrightarrow$
for all $w_1, w_2 \in \mathfrak{B}$, **exists** $w \in \mathfrak{B}$ **and** $T \geq 0$ **such that**

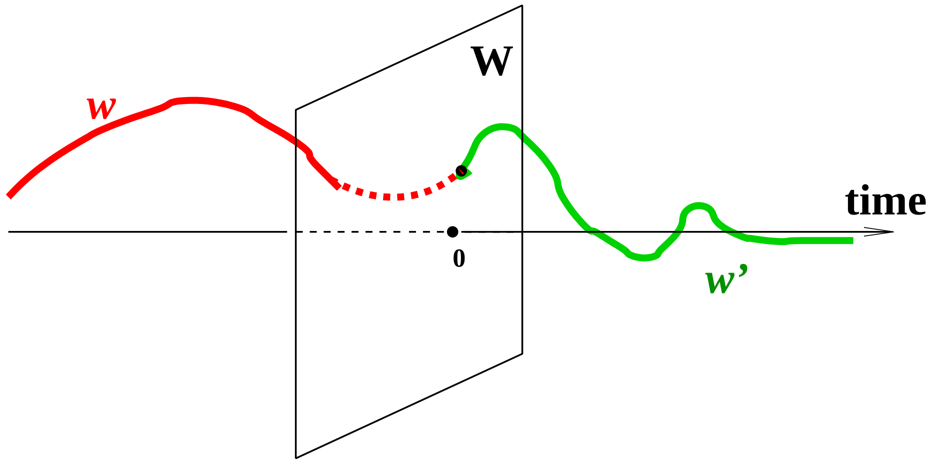




Controllability

The time-invariant system $(\mathbb{R}, \mathbb{R}^{\mathtt{w}}, \mathfrak{B})$ $\quad \rightsquigarrow \quad \mathfrak{B} \subseteq (\mathbb{R}^{\mathtt{w}})^{\mathbb{R}}$

stabilizable $:\Leftrightarrow$ **for all** $w \in \mathfrak{B}$, **exists** $w' \in \mathfrak{B}$ **such that**



stable $:\Leftrightarrow$ $w \in \mathfrak{B}$ **implies** $w(t) \rightarrow 0$ **for** $t \rightarrow \infty$

autonomous $:\Leftrightarrow$

$$w_1, w_2 \in \mathfrak{B}, w_1(t) = w_2(t) \text{ for } t < 0 \text{ implies } w_1 = w_2$$

Controllability

The time-invariant system $(\mathbb{R}, \mathbb{R}^{\mathtt{w}}, \mathfrak{B})$ $\quad \rightsquigarrow \quad \mathfrak{B} \subseteq (\mathbb{R}^{\mathtt{w}})^{\mathbb{R}}$

$$R\left(\frac{d}{dt}\right) w = 0$$

defines a controllable system iff

$R(\lambda)$ **has the same rank for all** $\lambda \in \mathbb{C}$**.**

a stabilizable system iff

$R(\lambda)$ **has the same rank for all** $\lambda \in \bar{\mathbb{C}}_+$**.**

Observability

Consider the dynamical system $\left(\mathbb{R}, \mathbb{R}^{\mathtt{w}_1 \times \mathtt{w}_2}, \mathfrak{B}\right)$

w_2 observable from w_1 :⇔

$$(w_1, w_2), (w_1, w_2') \in \mathfrak{B} \Rightarrow w_2 = w_2'$$

w_2 detectable from w_1 :⇔

$$(w_1, w_2), (w_1, w_2') \in \mathfrak{B} \Rightarrow w_2(t) - w_2'(t) \longrightarrow 0 \text{ for } t \longrightarrow \infty$$

Observability

Consider the dynamical system $(\mathbb{R}, \mathbb{R}^{\mathtt{w}_1 \times \mathtt{w}_2}, \mathfrak{B})$

w_2 **observable from** w_1 :⇔

$$(w_1, w_2), (w_1, w_2') \in \mathfrak{B} \Rightarrow w_2 = w_2'$$

w_2 **detectable from** w_1 :⇔

$$(w_1, w_2), (w_1, w_2') \in \mathfrak{B} \Rightarrow w_2(t) - w_2'(t) \longrightarrow 0 \text{ for } t \longrightarrow \infty$$

There exists a map $F : w_1 \mapsto w_2$ **such that**
$(w_1, w_2) \in \mathfrak{B} \Rightarrow w_2 = F(w_1)$ **recovers** w_2 **(asymptotically)**

There are tests for

$$R_1\left(\frac{d}{dt}\right) w_1 = R_2\left(\frac{d}{dt}\right) w_2$$

LTIDS: Basic results

LTIDS

Recall

$$R\left(\frac{d}{dt}\right)w = 0$$

R **a polynomial matrix** $R \in \mathbb{R}[\xi]^{\bullet \times \mathtt{w}} \quad \rightsquigarrow \mathfrak{L}^{\mathtt{w}}, \mathfrak{L}^{\bullet}$

Fact 1: $\mathfrak{L}^{\bullet}$ **closed under addition, intersection, & projection**

LTIDS

Fact 1: $\mathfrak{L}^\bullet$ **closed under addition, intersection, & projection**

Consider

$$R_1\left(\frac{d}{dt}\right)w_1 + R_2\left(\frac{d}{dt}\right)w_2 = 0 \;\rightsquigarrow\; \textbf{behavior } \mathfrak{B}$$

Define

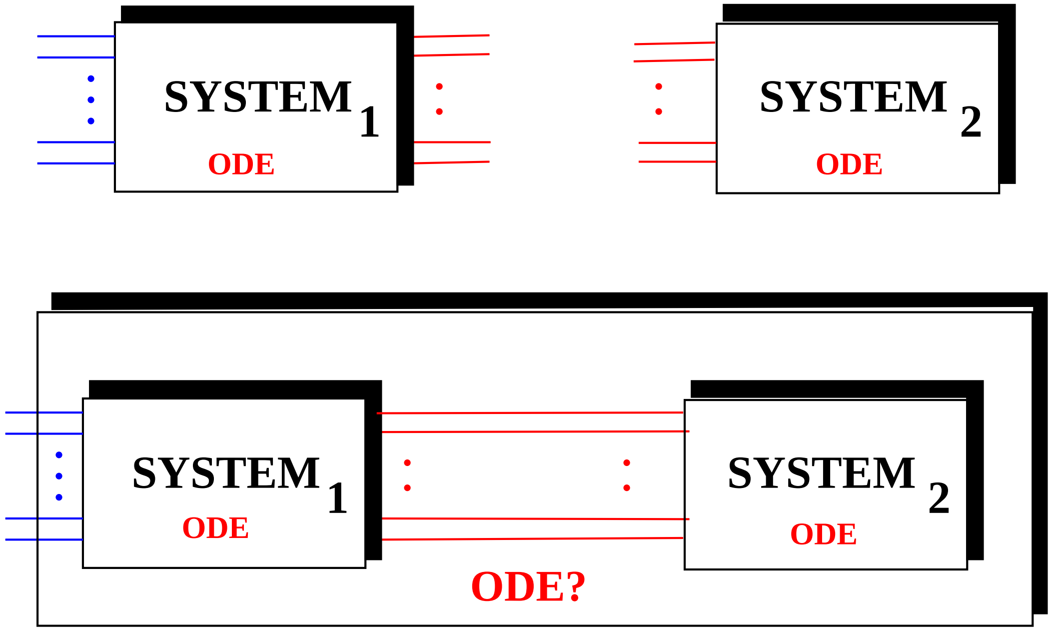
$$\mathfrak{B}_1 := \{w_1 \mid \exists\, w_2 \textbf{ such that } (w_1, w_2) \in \mathfrak{B}\}$$

Elimination thm $\exists R$ **such that** $\mathfrak{B}_1 = \text{kernel}\left(R\left(\frac{d}{dt}\right)\right)$**!**

E.g. $\frac{d}{dt}x = Ax + Bu, y = Cx + Du \;\Rightarrow\; P(\frac{d}{dt})y = Q(\frac{d}{dt})u$
linear DAE's always allow elimination of nuisance variables

LTIDS

<u>Fact 1</u>: $\mathfrak{L}^\bullet$ closed under addition, intersection, & projection



In LTIDS described by ODE if systems 1 and 2 are.
In nonlinear case, very unlikely described by ODE, even if systems 1 and 2 are!

Why are ODE's so common?

LTIDS

Fact 1: $\mathfrak{L}^\bullet$ closed under addition, intersection, & projection

Fact 2: Consequences of $\mathfrak{B} \in \mathfrak{L}^{\mathtt{w}}$: $\mathbb{R}[\xi]$-submodule of $\mathbb{R}[\xi]^{\mathtt{w}}$

$n \in \mathbb{R}[\xi]^{\mathtt{w}}$ is a consequence of $\mathfrak{B}$ $:\Leftrightarrow n^\top\left(\frac{d}{dt}\right)\mathfrak{B} = 0$.

E.g. Observability of

$$R_1\left(\frac{d}{dt}\right)w_1 = R_2\left(\frac{d}{dt}\right)w_2$$

equivalent to existence of consequences

$$w_2 = F\left(\frac{d}{dt}\right)w_1$$

LTIDS

Fact 1: $\mathfrak{L}^\bullet$ closed under addition, intersection, & projection

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$n \in \mathbb{R}[\xi]^{\mathtt{w}}$ is a consequence of $\mathfrak{B}$ $:\Leftrightarrow n^\top\left(\frac{d}{dt}\right)\mathfrak{B} = 0$.

E.g. detectability of

$$R_1\left(\frac{d}{dt}\right)w_1 = R_2\left(\frac{d}{dt}\right)w_2$$

equivalent to existence of consequences

$$H\left(\frac{d}{dt}\right)w_1 = F\left(\frac{d}{dt}\right)w_2, \qquad H \text{ Hurwitz}$$

LTIDS

<u>Fact 1</u>: $\mathfrak{L}^\bullet$ closed under addition, intersection, & projection

<u>Fact 2</u>: Consequences of $\mathfrak{B} \in \mathfrak{L}^{\mathtt{w}}$: $\mathbb{R}[\xi]$-submodule of $\mathbb{R}[\xi]^{\mathtt{w}}$

<u>Fact 3</u>: Controllability of $\mathfrak{B} \in \mathfrak{L}^{\mathtt{w}} \Leftrightarrow \exists$ *image repr'ion*

Consider $w = M\left(\frac{d}{dt}\right)\ell$

i.e., w-behavior $\mathfrak{B} = \mathrm{image}\left(M\left(\frac{d}{dt}\right)\right)$.

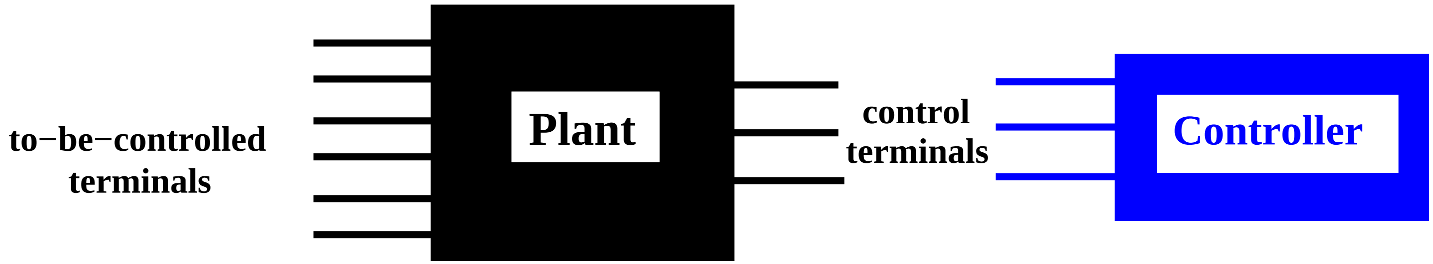
Elimination thm $\Rightarrow \mathfrak{B} = \mathrm{kernel}\left(R\left(\frac{d}{dt}\right)\right)$, **for some R.**

So, all images are kernels, but what kernels are images?

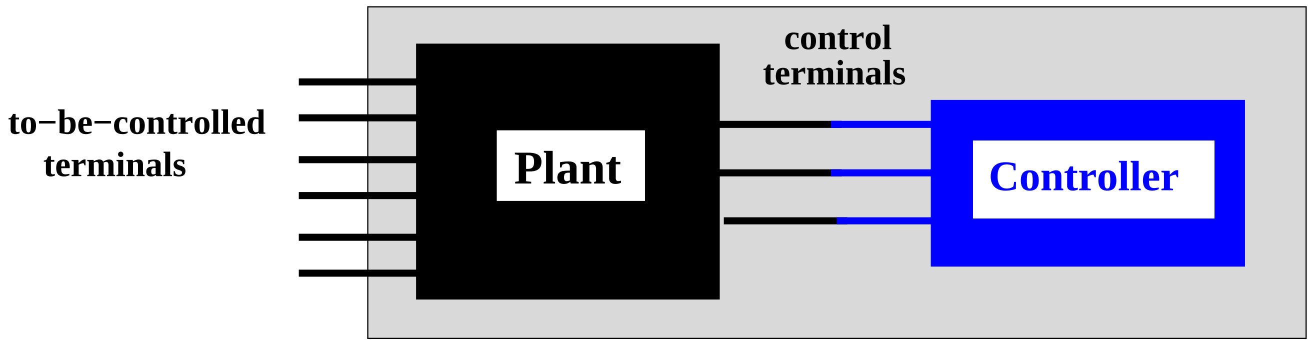
$\Leftrightarrow \mathfrak{B}$ is controllable

Control

Control as Interconnection

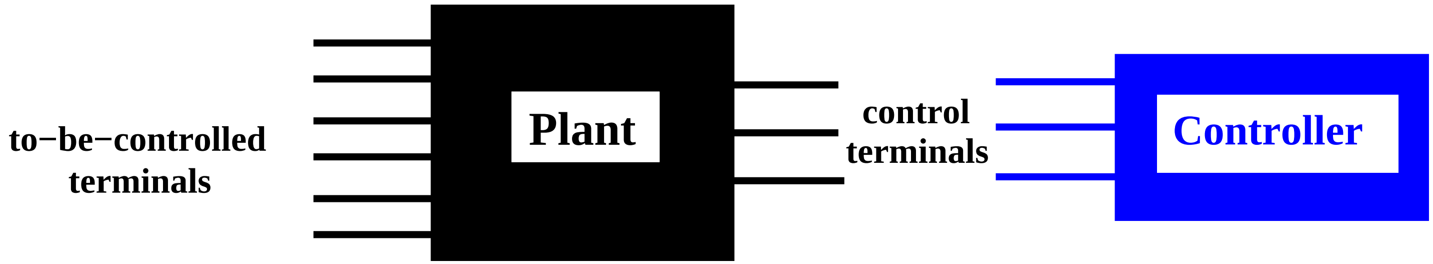


Interconect via control terminals:



Controlled system

Control as Interconnection



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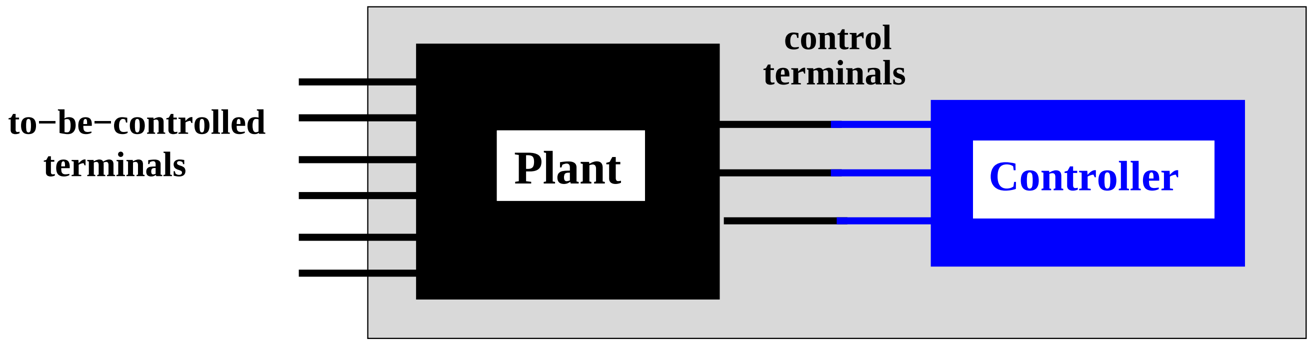
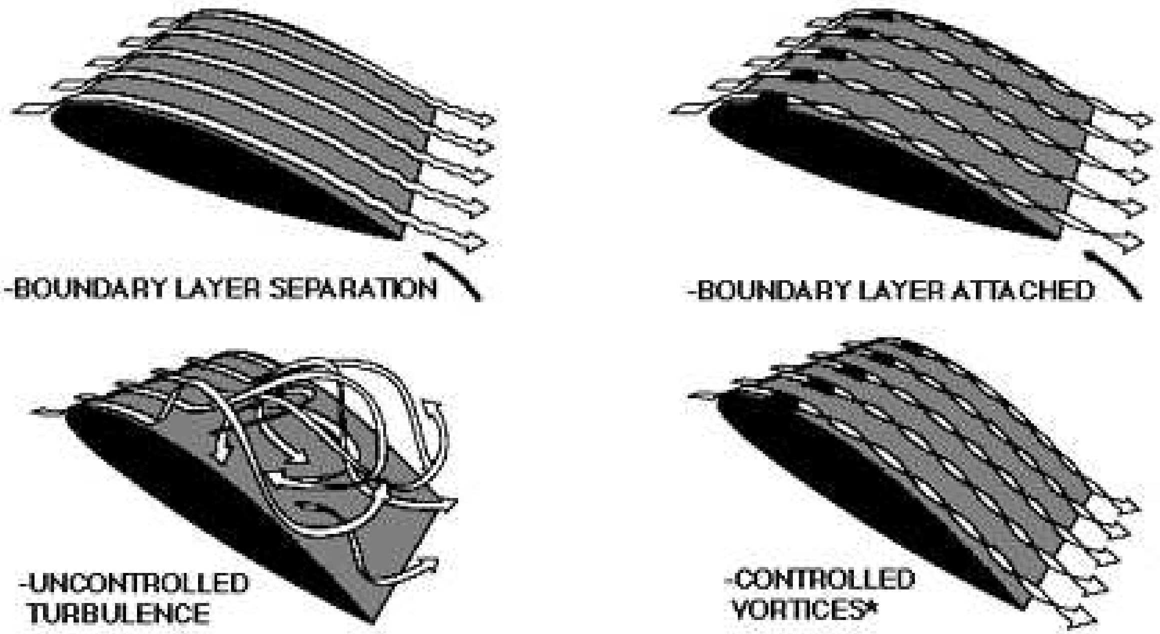


Controlled system

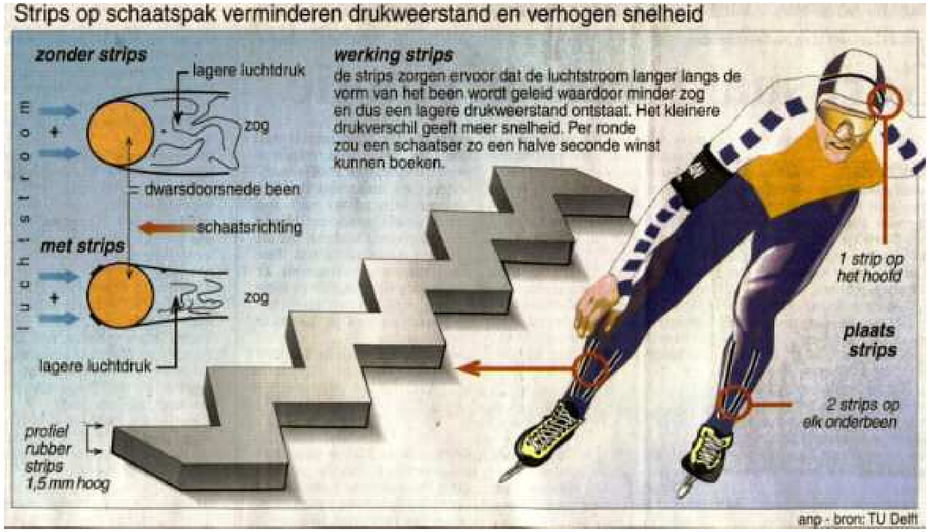
- **Are all interconnections ‘reasonable’?**
- **Which controlled behaviors can be achieved?**
- **Parametrize all stabilizing controllers**

Many controllers are not sensor-to-actuator

Controlling turbulence:

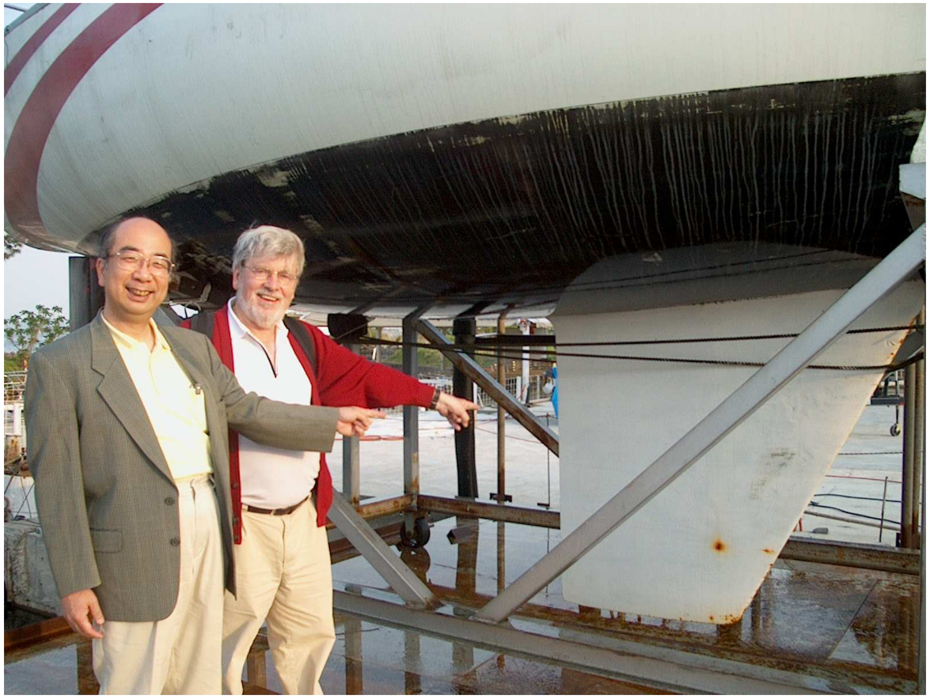


Many controllers are not sensor-to-actuator



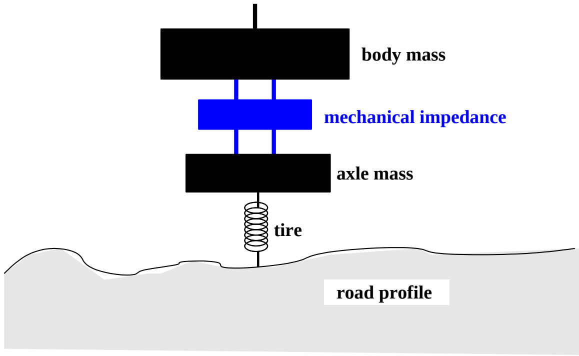
Many controllers are not sensor-to-actuator

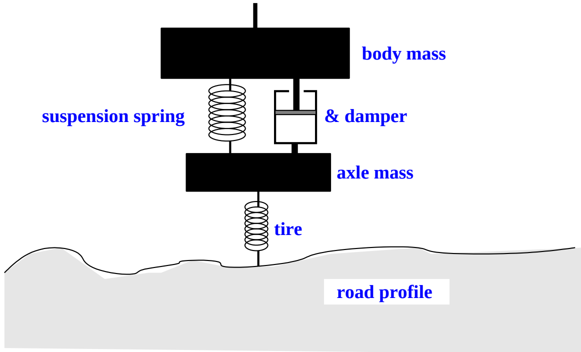
Stabilization:

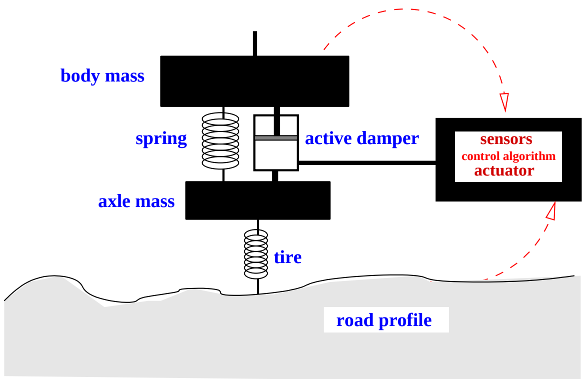


Many controllers are not sensor-to-actuator

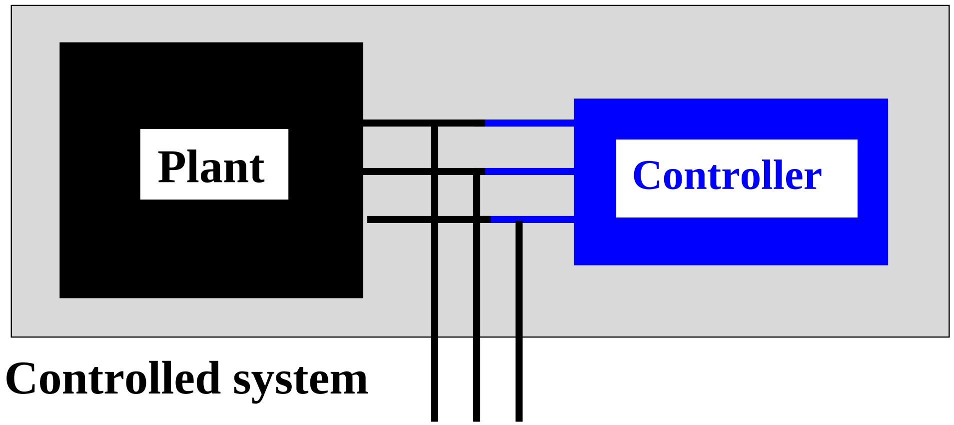
Disturbance attenuation:







Full Control



Let $\mathfrak{B}$ be the plant behavior, $\mathfrak{C}$ the controller behavior,

Then the controlled behavior $\mathfrak{K} = \mathfrak{B} \cap \mathfrak{C} \subseteq \mathfrak{B}$

Control means finding a subbehavior of the plant behavior

Henceforth, $\mathfrak{B} \in \mathfrak{L}^{\mathtt{w}}$, $\mathfrak{C} \in \mathfrak{L}^{\mathtt{w}} \Rightarrow \mathfrak{K} = \mathfrak{B} \cap \mathfrak{C} \in \mathfrak{L}^{\mathtt{w}}$

How to generate subbehaviors?

Plant & controller in kernel repr'ion. R **is 'wide'**

$$\boxed{R}\left(\frac{d}{dt}\right)w = 0 \quad \Rightarrow \quad \begin{bmatrix} R \\ C \end{bmatrix}\left(\frac{d}{dt}\right)w = 0$$

Plant in kernel & controller in image representation

$$\boxed{R}\left(\frac{d}{dt}\right)w = 0 \quad \Rightarrow \quad RC\left(\frac{d}{dt}\right)\ell = 0$$

Plant & controller in image representation. M **is 'tall'**

$$w = \boxed{M}\left(\frac{d}{dt}\right)\ell \quad \Rightarrow \quad \begin{bmatrix} M & C \end{bmatrix}\left(\frac{d}{dt}\right)\ell' = 0$$

'Squaring' $\sim$ **creating autonomous behavior**

$\Rightarrow$ **pole placement, stabilization, ...**

Regularity

2 notions of 'well behaved' controllers:

'regular' and 'superregular'.

$\mathfrak{C}$ **is a regular controller for** $\mathfrak{B}$ **:⇔**

$$\boxed{\mathtt{p}(\mathfrak{K}) = \mathtt{p}(\mathfrak{B}) + \mathtt{p}(\mathfrak{C})}$$

$\mathtt{p} :=$ **number of eq'ns, of output variables.**

$\mathfrak{C}$ **is a superregular controller for** $\mathfrak{B}$ **:⇔, in addition,**

$$\boxed{\mathtt{n}(\mathfrak{K}) = \mathtt{n}(\mathfrak{B}) + \mathtt{n}(\mathfrak{C})}$$

$\mathtt{n} :=$ **number of state variables, 'McMillan degree'.**

Regularity

$\mathfrak{C}$ is a regular controller for $\mathfrak{B}$:⇔

$$\boxed{\mathtt{p}(\mathfrak{K}) = \mathtt{p}(\mathfrak{B}) + \mathtt{p}(\mathfrak{C})}$$

(±) allows proper and improper controller transfer functions. The states need to be 'prepared' before interconnection.

$\mathfrak{C}$ is a superregular controller for $\mathfrak{B}$:⇔, in addition,

$$\boxed{\mathtt{n}(\mathfrak{K}) = \mathtt{n}(\mathfrak{B}) + \mathtt{n}(\mathfrak{C})}$$

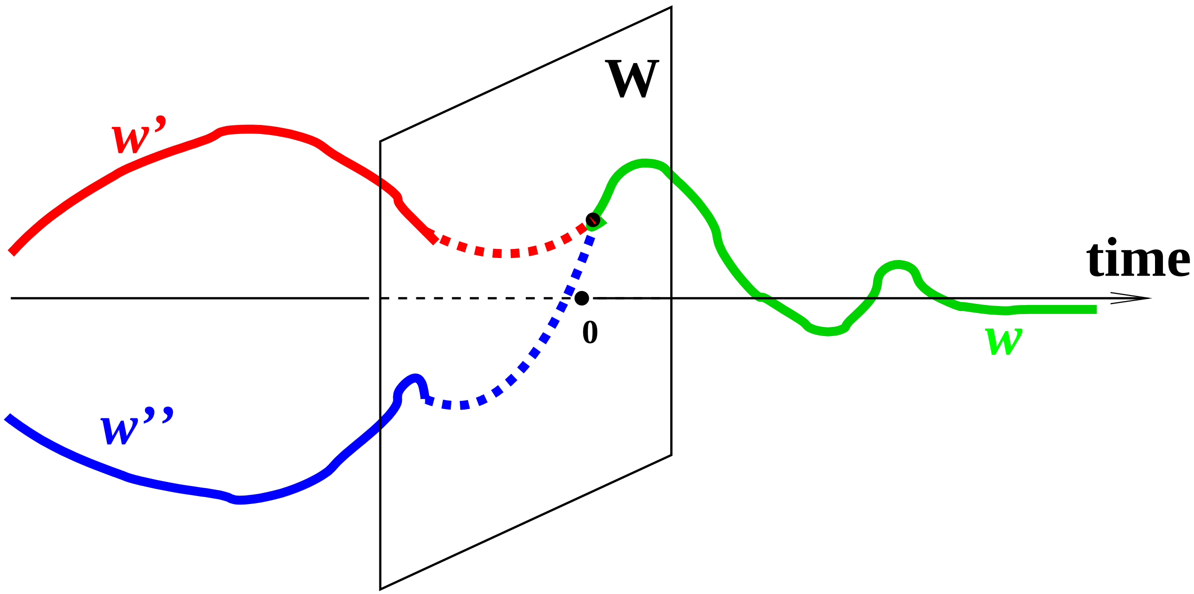
(±) allows only proper transfer functions in the controller. It is equivalent to feedback control.

Regularity

Superregularity also means:

'the controller can take effect at any time'

$$\forall w' \in \mathfrak{B}, w'' \in \mathfrak{C}, \exists w \in \mathfrak{B} \cap \mathfrak{C} \text{ such that}$$



On regular controllers: Madhu Belur & Harry Trentelman, IEEE AC, 2002

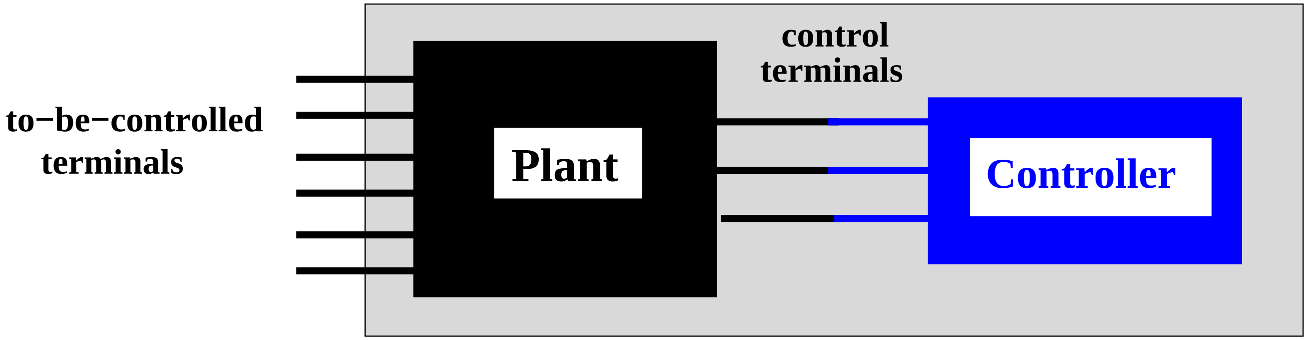
Implementability

Assume that the plant $\mathfrak{B} \in \mathfrak{L}^{\mathtt{w}}$ is controllable, then **any** $\mathfrak{K} \subseteq \mathfrak{B}$ is implementable by a regular controller, i.e.

$$\forall\, \mathfrak{K} \in \mathfrak{L}^{\mathtt{w}},\ \exists\, \mathfrak{C} \in \mathfrak{L}^{\mathtt{w}} \text{ such that } \mathfrak{K} = \mathfrak{B} \cap \mathfrak{C}$$

In order to be implementable by a superregular controller, we need $\mathtt{n}(\mathfrak{K})$ to be sufficiently high.

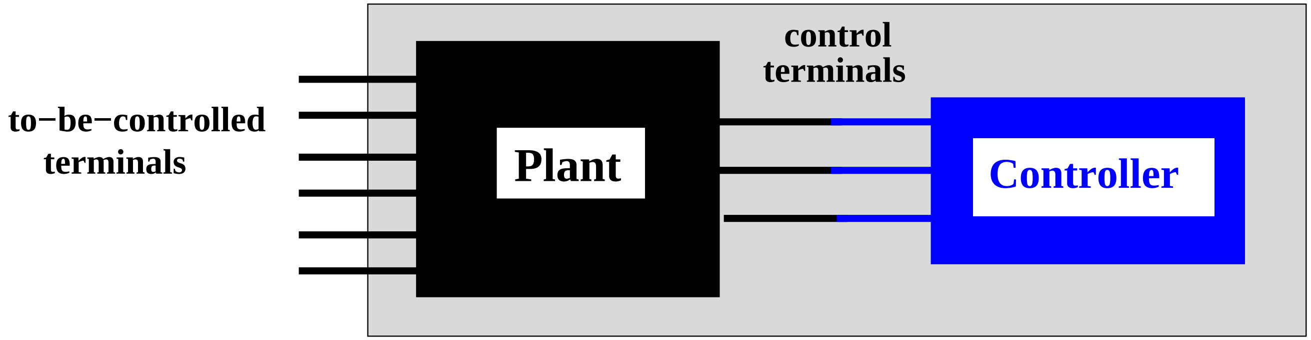
Implementability



Controlled system

w to-be-controlled variables, c control variables.
Assume behavior of plant, before control, $\in \mathfrak{L}^{\mathtt{w}+\mathtt{c}}$.

Implementability



Controlled system

Let $\mathfrak{P} \in \mathfrak{L}^{\mathtt{w}}$ be the **plant behavior**, the behavior of to-be-controlled variables before the controller is applied.

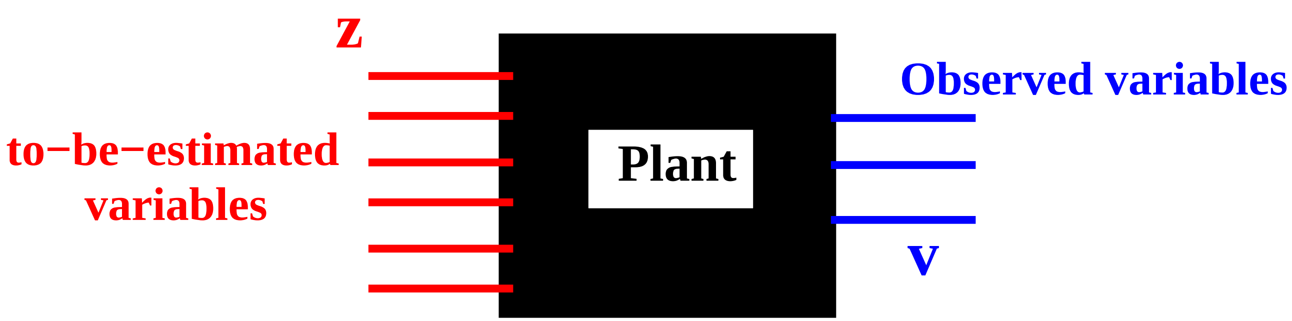
Let $\mathfrak{N} \in \mathfrak{L}^{\mathtt{w}}$ be the **hidden behavior**, the behavior of to-be-controlled variables compatible with $w = 0$.

Assume $\mathfrak{P}$ controllable. $\mathfrak{K}$ is regularly implementable iff

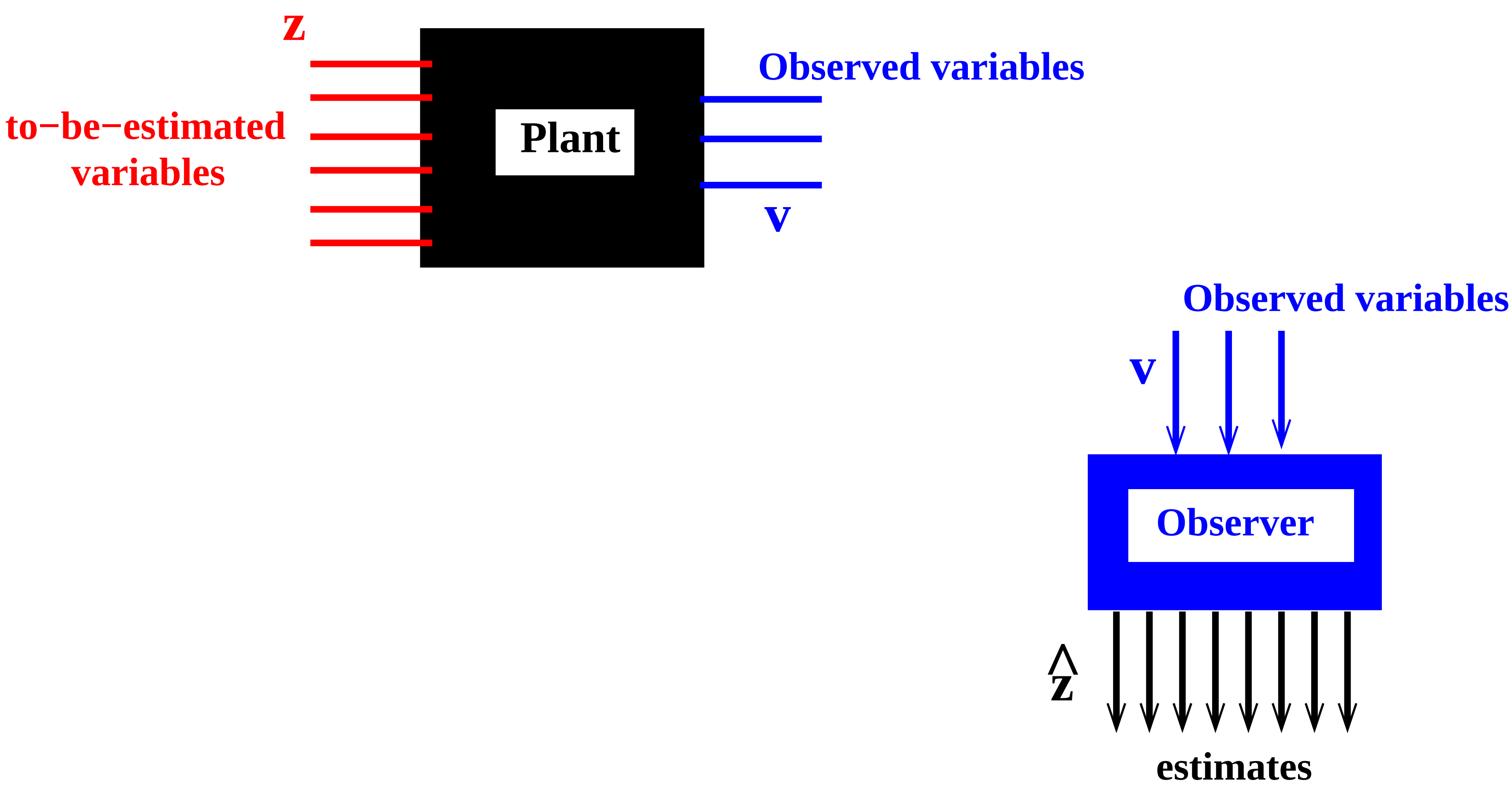
$$\mathfrak{N} \subseteq \mathfrak{K} \subseteq \mathfrak{P}$$

Observers: Joint work with Jochen

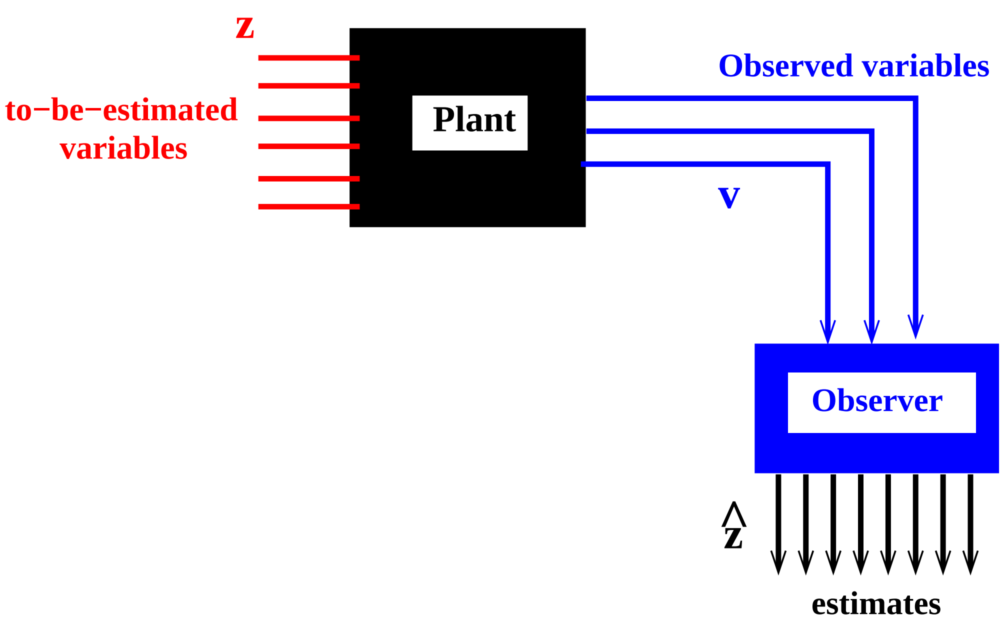
Observer Architecture



Observer Architecture



Observer Architecture



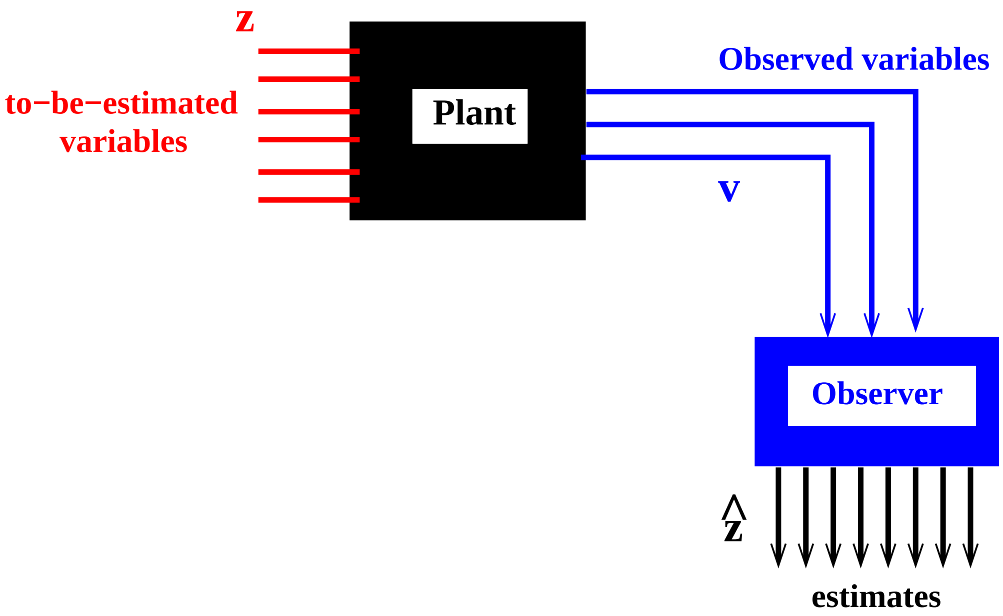
Plant var.: (v, z): v observed, z to-be-estimated var.

Observer variables: $(v, \hat{z})$: v observed, $\hat{z}$ estimates

Interconnected system variables: $v, z, \hat{z}$.

Estimation error:

$$e = z - \hat{z}$$



Plant behavior: $\mathfrak{B}$, Observer behavior: $\hat{\mathfrak{B}}$, Error behavior: $\mathfrak{E}$

Call $\hat{\mathfrak{B}}$ a replicator of $\mathfrak{B}$ if for all $(y, z) \in \mathfrak{B}$, there exists $(y, \hat{z}) \in \hat{\mathfrak{B}}$ such that $z = \hat{z}$, i.e. $\mathfrak{B} \subseteq \hat{\mathfrak{B}}$

tracking if the error behavior $\mathfrak{E}$ is autonomous.

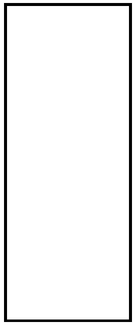
Thm: Assume plant $\mathfrak{B}$ controllable, y 'free' in observer $\hat{\mathfrak{B}}$.

$\hat{\mathfrak{B}}$ is tracking iff it is a replicator

Observers means finding a supbehavior of the plant behavior

How to generate supbehaviors?

Plant in kernel representation. $\quad\quad\quad$ R **is 'tall'**



Plant:

$$R\left(\frac{d}{dt}\right) z = H\left(\frac{d}{dt}\right) v$$

How to generate supbehaviors?

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Plant:

$$R\left(\frac{d}{dt}\right) z = H\left(\frac{d}{dt}\right) v$$

Observer:

$$F\left(\frac{d}{dt}\right) R\left(\frac{d}{dt}\right) \hat{z} = F\left(\frac{d}{dt}\right) H\left(\frac{d}{dt}\right) v$$

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Observer:

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Error dynamics: $e = z - \hat{z}$ $\quad$ **'eliminate'** $v, z, \hat{z} \ \Rightarrow$

$$F\left(\frac{d}{dt}\right) R\left(\frac{d}{dt}\right) e = 0$$

So, squaring up $\boxed{R}$ **to** FR

$\Rightarrow$ **error autonomous, desired input structure.**

Pole placement, stabilization, ...

Example

Plant equations in 'observability' canonical form:

$$V\left(\frac{d}{dt}\right)v = 0, \quad z = Z\left(\frac{d}{dt}\right)v$$

This canonical form exists iff z observable from v in the plant.

Example

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Observer:

$$P\left(\frac{d}{dt}\right)\hat{z} = P\left(\frac{d}{dt}\right)Z\left(\frac{d}{dt}\right)v + S\left(\frac{d}{dt}\right)V\left(\frac{d}{dt}\right)v$$

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Error dynamics:

$$P\left(\frac{d}{dt}\right)e = 0$$

Choose P for stability, S for high frequency roll-off, etc.

Conclusion

The barrier

"Block diagrams unsuitable for serious physical modeling
- the control/physics barrier"

"Behavior based (declarative) modeling is a good alternative"

from K.J. Åström

Present Developments in Control Applications

IFAC 50-th Anniversary Celebration

Heidelberg, September 12, 2006.

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Block diagrams are indeed unsuitable for serious physical modeling. Block diagrams also exclude many controllers!

Behaviors respect the physics, easier, more general concepts, block diagrams are a very important special case, ...

Details & copies of the lecture frames are available from/at

`Jan.Willems@esat.kuleuven.be`

`http://www.esat.kuleuven.be/∼jwillems`

Thank you

Thank you

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