Switched differential algebraic equations: Jumps and impulses

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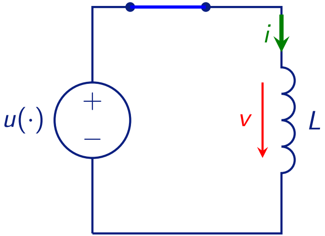
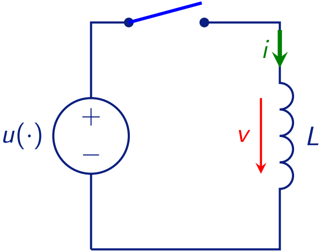
Motivating example

$t < 0$ $t \geq 0$

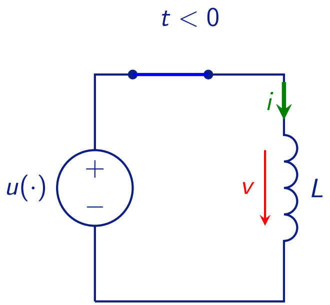




inductivity law: $L\frac{\mathrm{d}}{\mathrm{d}t}i = v$

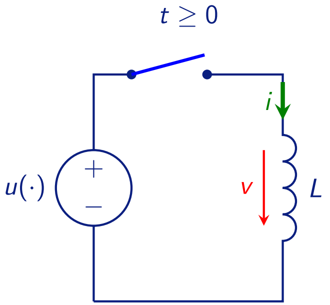
switch dependent: $0 = v - u$ $0 = i$

Motivating example



$x = [i, v]^\top$

$$\begin{bmatrix} L & 0 \\ 0 & 0 \end{bmatrix} \dot{x} = \begin{bmatrix} 0 & 1 \\ 0 & 1 \end{bmatrix} x + \begin{bmatrix} 0 \\ -1 \end{bmatrix} u$$



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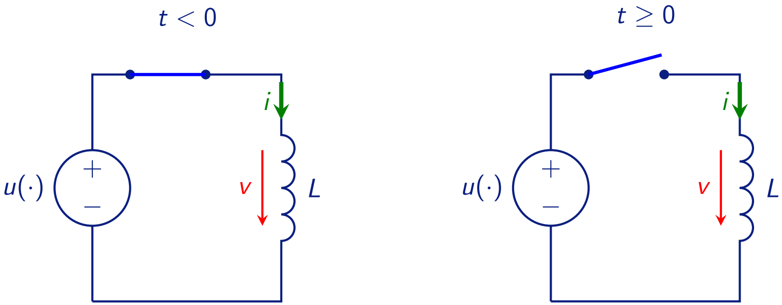
Motivating example



$E_1\dot{x} = A_1 x + B_1 u$
on $(-\infty, 0)$

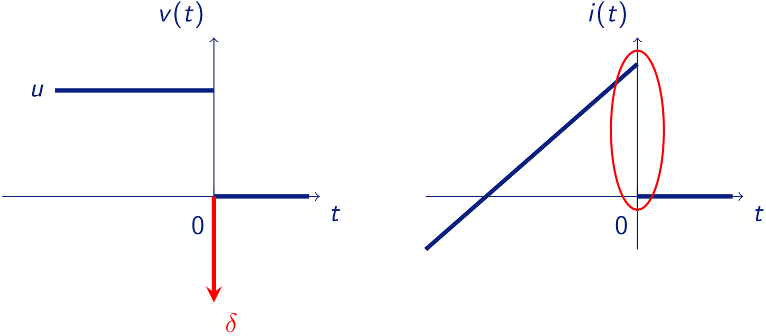
$E_2\dot{x} = A_2 x + B_2 u$
on $[0, \infty)$

$\rightarrow$ switched differential-algebraic equation

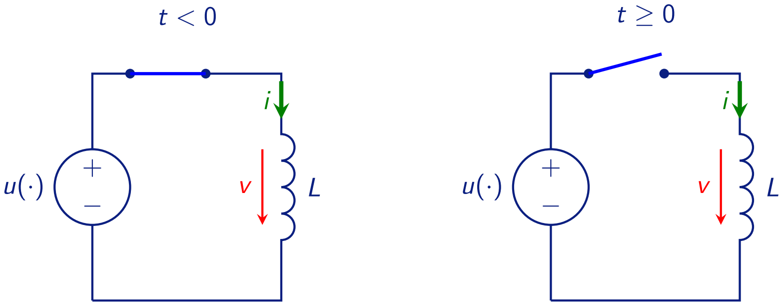
Solution of circuit example

$t < 0$	$t \geq 0$
$v = u$	$i = 0$
$L\frac{\mathrm{d}}{\mathrm{d}t}i = v$	$v = L\frac{\mathrm{d}}{\mathrm{d}t}i$

Solution (assume constant input u):



Observations



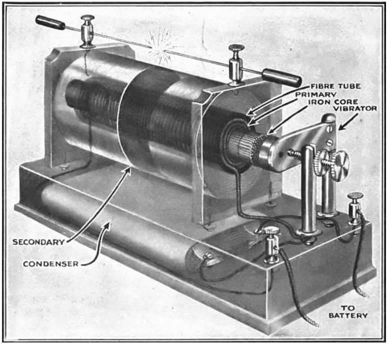
Observations

- $x(0^-) \neq 0$ inconsistent for $E_2\dot{x} = A_2 x + B_2 u$
- unique jump from $x(0^-)$ to $x(0^+)$
- derivative of jump = Dirac impulse appears in solution

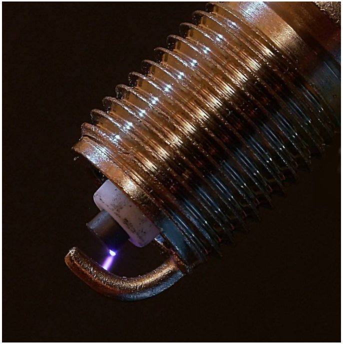
Dirac impulse is "real"

Dirac impulse

Not just a mathematical artifact!



Drawing: Harry Winfield Secor, public domain



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Definition

Switch → Different DAE models (=modes)
depending on time-varying position of switch

Definition (Switched DAE)

Switching signal $\sigma : \mathbb{R} \to \{1, \ldots, N\}$ picks mode at each time $t \in \mathbb{R}$:

$$\begin{aligned} E_{\sigma(t)}\dot{x}(t) &= A_{\sigma(t)}x(t) + B_{\sigma(t)}u(t) \\ y(t) &= C_{\sigma(t)}x(t) + D_{\sigma(t)}u(t) \end{aligned} \qquad \text{(swDAE)}$$

Attention

Each mode might have different consistency spaces
⇒ inconsistent initial values at each switch
⇒ Dirac impulses, in particular distributional solutions

Definition

Switch $\rightarrow$ Different DAE models (=modes)
depending on time-varying position of switch

Definition (Switched DAE)

Switching signal $\sigma : \mathbb{R} \rightarrow \{1, \ldots, N\}$ picks mode at each time $t \in \mathbb{R}$:

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$\Rightarrow$ inconsistent initial values at each switch
$\Rightarrow$ Dirac impulses, in particular distributional solutions

Distribution theory - basic ideas

Distributions - overview

- Generalized functions
- Arbitrarily often differentiable
- Dirac-Impulse δ is "derivative" of Heaviside step function $\mathbb{1}_{[0,\infty)}$

Two different formal approaches

1. Functional analytical: Dual space of the space of test functions (L. Schwartz 1950)
2. Axiomatic: Space of all "derivatives" of continuous functions (J. Sebastião e Silva 1954)

Distributions - formal

Definition (Test functions)

$\mathcal{C}_0^\infty := \{ \ \varphi : \mathbb{R} \to \mathbb{R} \ | \ \varphi \text{ is smooth with compact support } \}$

Definition (Distributions)

$\mathbb{D} := \{ \ D : \mathcal{C}_0^\infty \to \mathbb{R} \ | \ D \text{ is linear and continuous } \}$

Definition (Regular distributions)

$f \in L_{1,\text{loc}}(\mathbb{R} \to \mathbb{R})$: $\quad f_\mathbb{D} : \mathcal{C}_0^\infty \to \mathbb{R}, \ \varphi \mapsto \int_\mathbb{R} f(t)\varphi(t)\mathrm{d}t \in \mathbb{D}$

Definition (Derivative)

$D'(\varphi) := -D(\varphi')$

Dirac Impulse at $t_0 \in \mathbb{R}$

$\delta_{t_0} : \mathcal{C}_0^\infty \to \mathbb{R}, \quad \varphi \mapsto \varphi(t_0)$

Multiplication with functions

Definition (Multiplication with smooth functions)

$\alpha \in \mathcal{C}^\infty : \quad (\alpha D)(\varphi) := D(\alpha\varphi)$

$$\begin{aligned} E_\sigma \dot{x} &= A_\sigma x + B_\sigma u \\ y &= C_\sigma x + D_\sigma u \end{aligned} \qquad \text{(swDAE)}$$

Coefficients not smooth

Problem: $E_\sigma, A_\sigma, C_\sigma \notin \mathcal{C}^\infty$

Observation, for $\sigma_{[t_i,t_{i+1})} \equiv p_i$, $i \in \mathbb{Z}$:

$$\begin{aligned} E_\sigma \dot{x} &= A_\sigma x + B_\sigma u \\ y &= C_\sigma x + D_\sigma u \end{aligned} \quad \Leftrightarrow \quad \forall i \in \mathbb{Z} : \begin{aligned} (E_{p_i}\dot{x})_{[t_i,t_{i+1})} &= (A_{p_i}x + B_{p_i}u)_{[t_i,t_{i+1})} \\ y_{[t_i,t_{i+1})} &= (C_{p_i}x + D_{p_i}u)_{[t_i,t_{i+1})} \end{aligned}$$

New question: Restriction of distributions

Desired properties of distributional restriction

Distributional restriction:

$$\{\ M \subseteq \mathbb{R} \mid M \text{ interval }\ \} \times \mathbb{D} \to \mathbb{D}, \quad (M, D) \mapsto D_M$$

and for each interval $M \subseteq \mathbb{R}$

1. $D \mapsto D_M$ is a projection (linear and idempotent)
2. $\forall f \in L_{1,\text{loc}}: \quad (f_{\mathbb{D}})_M = (f_M)_{\mathbb{D}}$
3. $\forall \varphi \in \mathcal{C}_0^\infty: \quad \begin{bmatrix} \operatorname{supp}\varphi \subseteq M & \Rightarrow & D_M(\varphi) = D(\varphi) \\ \operatorname{supp}\varphi \cap M = \emptyset & \Rightarrow & D_M(\varphi) = 0 \end{bmatrix}$
4. $(M_i)_{i\in\mathbb{N}}$ pairwise disjoint, $M = \bigcup_{i\in\mathbb{N}} M_i$:

$$D_M = \sum_{i\in\mathbb{N}} D_{M_i}, \quad D_{M_1 \dot\cup M_2 = D_{M_1} + D_{M_2}}, \quad (D_{M_1})_{M_2} = 0$$

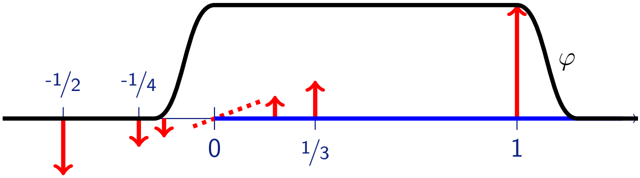
Theorem ([T. 2009])

Such a distributional restriction does not exist.

Proof of non-existence of restriction

Consider the following (well defined!) distribution:

$$D := \sum_{i\in\mathbb{N}} d_i \, \delta_{d_i}, \quad d_i := \frac{(-1)^i}{i+1}$$



Restriction should give

$$D_{[0,\infty)} = \sum_{k\in\mathbb{N}} d_{2k} \, \delta_{d_{2k}}$$

Choose $\varphi \in \mathcal{C}_0^\infty$ such that $\varphi_{[0,1]} \equiv 1$:

$$D_{[0,\infty)}(\varphi) = \sum_{k\in\mathbb{N}} d_{2k} = \sum_{k\in\mathbb{N}} \frac{1}{2k+1} = \infty$$

Dilemma

Switched DAEs

- Examples: distributional solutions
- Multiplication with non-smooth coefficients
- Or: Restriction on intervals

Distributions

- Distributional restriction not possible
- Multiplication with non-smooth coefficients not possible
- *Initial value problems cannot be formulated*

Underlying problem

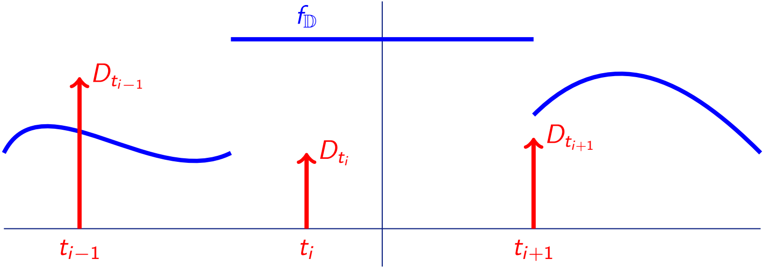
Space of distributions too big.

Piecewise smooth distributions

Define a suitable smaller space:

Definition (Piecewise smooth distributions $\mathbb{D}_{\mathrm{pw}\mathcal{C}^\infty}$, [T. 2009])

$$\mathbb{D}_{\mathrm{pw}\mathcal{C}^\infty} := \left\{ f_{\mathbb{D}} + \sum_{t \in T} D_t \;\middle|\; \begin{array}{l} f \in \mathcal{C}^\infty_{\mathrm{pw}}, \\ T \subseteq \mathbb{R} \text{ locally finite}, \\ \forall t \in T : D_t = \sum_{i=0}^{n_t} a_i^t \delta_t^{(i)} \end{array} \right\}$$



Properties of $\mathbb{D}_{\mathrm{pw}\mathcal{C}^\infty}$

- $\mathcal{C}^\infty_{\mathrm{pw}}$ "$\subseteq$" $\mathbb{D}_{\mathrm{pw}\mathcal{C}^\infty}$
- $D \in \mathbb{D}_{\mathrm{pw}\mathcal{C}^\infty} \Rightarrow D' \in \mathbb{D}_{\mathrm{pw}\mathcal{C}^\infty}$
- Well definded restriction $\mathbb{D}_{\mathrm{pw}\mathcal{C}^\infty} \to \mathbb{D}_{\mathrm{pw}\mathcal{C}^\infty}$

$$D = f_{\mathbb{D}} + \sum_{t \in T} D_t \quad \mapsto \quad D_M := (f_M)_{\mathbb{D}} + \sum_{t \in T \cap M} D_t$$

- Multiplication with $\alpha = \sum_{i \in \mathbb{Z}} \alpha_{i[t_i, t_{i+1})} \in \mathcal{C}^\infty_{\mathrm{pw}}$ well defined:

$$\alpha D := \sum_{i \in \mathbb{Z}} \alpha_i D_{[t_i, t_{i+1})}$$

- Evaluation at $t \in \mathbb{R}$: $D(t^-) := f(t^-)$, $D(t^+) := f(t^+)$
- Impulses at $t \in \mathbb{R}$: $D[t] := \begin{cases} D_t, & t \in T \\ 0, & t \notin T \end{cases}$

Application to (swDAE)

(x, u) solves (swDAE) $\quad :\Leftrightarrow \quad$ (swDAE) holds in $\mathbb{D}_{\mathrm{pw}\mathcal{C}^\infty}$

Relevant questions

$$\begin{aligned} E_\sigma \dot{x} &= A_\sigma x + B_\sigma u \\ y &= C_\sigma x + D_\sigma u \end{aligned} \qquad \text{(swDAE)}$$

Piecewise-smooth distributional solution framework

$x \in \mathbb{D}^n_{\text{pw}\mathcal{C}^\infty}$, $u \in \mathbb{D}^m_{\text{pw}\mathcal{C}^\infty}$, $y \in \mathbb{D}^p_{\text{pw}\mathcal{C}^\infty}$

- Existence and uniqueness of solutions?
- Jumps and impulses in solutions?
- Conditions for impulse free solutions?
- Control theoretical questions
  - Stability and stabilization
  - Observability and observer design
  - Controllability and controller design

Existence and uniqueness of solutions for (swDAE)

$$E_\sigma \dot{x} = A_\sigma x + B_\sigma u \qquad \text{(swDAE)}$$

Basic assumptions

- $\sigma \in \Sigma_0 := \left\{ \sigma : \mathbb{R} \to \{1, \ldots, N\} \;\middle|\; \begin{array}{l} \sigma \text{ is piecewise constant and} \\ \sigma\big|_{(-\infty,0)} \text{ is constant} \end{array} \right\}.$
- (E_p, A_p) is regular $\forall p \in \{1, \ldots, N\}$, i.e. $\det(sE_p - A_p) \not\equiv 0$

Theorem (T. 2009)

Consider (swDAE) *with regular* (E_p, A_p). *Then*

$$\forall\ u \in \mathbb{D}^m_{\text{pw}\mathcal{C}^\infty}\ \forall\ \sigma \in \Sigma_0\ \exists \textit{ solution } x \in \mathbb{D}^n_{\text{pw}\mathcal{C}^\infty}$$

and $x(0^-)$ *uniquely determines* x.

Inconsistent initial values

$$E\dot{x} = Ax + Bu, \quad x(0) = x^0 \in \mathbb{R}^n$$

Inconsistent initial value = special switched DAE

$$\dot{x}_{(-\infty,0)} = 0, \qquad x(0^-) = x^0$$
$$(E\dot{x})_{[0,\infty)} = (Ax + Bu)_{[0,\infty)}$$

Corollary (Consistency projector)

Exist unique consistency projector $\Pi_{(E,A)}$ such that

$$x(0^+) = \Pi_{(E,A)} x^0$$

$\Pi_{(E,A)}$ can easily be calculated via the Wong sequences [T. 2009].

Sufficient conditions for impulse-freeness

Question

When are all solutions of homogenous (swDAE) $E_\sigma \dot{x} = A_\sigma x$ impulse free?

Note: Jumps are OK.

Lemma (Sufficient conditions)

- *(E_p, A_p) all have index one (i.e. $(sE - A)^{-1}$ is proper)*
  $\Rightarrow$ (swDAE) impulse free
- *all consistency spaces of (E_p, A_p) coincide*
  $\Rightarrow$ (swDAE) impulse free

Characterization of impulse-freeness

Theorem (Impulse-freeness, [T. 2009])

The switched DAE $E_\sigma \dot{x} = A_\sigma x$ is impulse free $\forall \sigma \in \Sigma_0$

$$\Leftrightarrow \quad E_q(I - \Pi_q)\Pi_p = 0 \quad \forall p, q \in \{1, \ldots, N\}$$

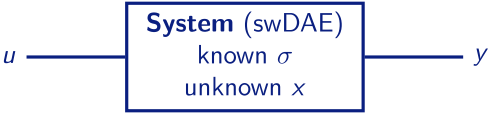
where $\Pi_p := \Pi_{(E_p, A_p)}$, $p \in \{1, \ldots, N\}$ is the p-th consistency projector.

Remark

- Index-1-case $\Rightarrow$ $E_q(I - \Pi_q) = 0 \ \forall q$
- Consistency spaces equal $\Rightarrow$ $(I - \Pi_q)\Pi_p = 0 \ \forall p, q$

Contents

Global Observability of Switched DAEs



Definition (Global observability)

(swDAE) with given σ is (globally) observable $:\Leftrightarrow$
$\forall$ solutions $(u_1, x_1, y_1), (u_2, x_2, y_2)$: $\quad (u_1, y_1) \equiv (u_2, y_2) \;\Rightarrow\; x_1 \equiv x_2$

Lemma (0-distinguishability)

(swDAE) *is observable if, and only if,*

$$y \equiv 0 \text{ and } u \equiv 0 \quad \Rightarrow \quad x \equiv 0.$$

Hence consider in the following (swDAE) without inputs:

$$\begin{aligned} E_\sigma \dot{x} &= A_\sigma x \\ y &= C_\sigma x \end{aligned}$$ and observability question: $$y \equiv 0 \overset{?}{\Rightarrow} x \equiv 0$$

Motivating example

System 1:

$$\begin{bmatrix}1&0&0\\0&0&0\\0&0&1\end{bmatrix}\dot{x}=\begin{bmatrix}0&0&0\\0&1&0\\0&0&0\end{bmatrix}x$$

$$y=\begin{bmatrix}0&0&1\end{bmatrix}x$$

$y=x_3,\ \dot{y}=\dot{x}_3=0,\ x_2=0,\ \dot{x}_1=0$

$\Rightarrow x_1$ unobservable

System 2:

$$\begin{bmatrix}0&0&0\\0&1&0\\1&0&0\end{bmatrix}\dot{x}=\begin{bmatrix}1&0&0\\0&0&0\\0&0&1\end{bmatrix}x$$

$$y=\begin{bmatrix}0&0&1\end{bmatrix}x$$

$y=x_3=\dot{x}_1,\ x_1=0,\ \dot{x}_2=0$

$\Rightarrow x_2$ unobservable

$\sigma(\cdot):1\to 2$

Jump in x_1 produces impulse in y
$\Rightarrow$ Observability

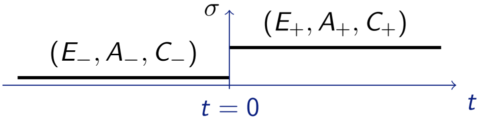
$\sigma(\cdot):2\to 1$

Jump in x_2 no influence in y
$\Rightarrow x_2$ remains unobservable

Question

$$\begin{aligned}E_p\dot{x}&=A_px+B_pu\\ y&=C_px+D_pu\end{aligned}\quad \text{not observable} \quad \overset{?}{\Rightarrow} \quad \begin{aligned}E_\sigma\dot{x}&=A_\sigma x+B_\sigma u\\ y&=C_\sigma x+D_\sigma u\end{aligned}\quad \text{observable}$$

The single switch result



Theorem (Unobservable subspace, Tanwani & T. 2010)

For (swDAE) *with* **a single switch** *the following equivalence holds*

$$y \equiv 0 \quad \Leftrightarrow \quad x(0^-) \in \mathcal{M}$$

where

$$\boxed{\mathcal{M} := \mathfrak{C}_- \cap \ker O_- \cap \ker O_+^- \cap \ker O_+^{\text{imp}}}$$

In particular: (swDAE) *observable* $\Leftrightarrow$ $\mathcal{M} = \{0\}$.

What are these four subspace?

The four subspaces

Unobservable subspace: $\mathcal{M} := \mathfrak{C}_- \cap \ker O_- \cap \ker O_+^- \cap \ker O_+^{\text{imp}}$, i.e.

$$x(0^-) \in \mathcal{M} \quad \Leftrightarrow \quad y_{(-\infty,0)} \equiv 0 \ \wedge \ y[0] = 0 \ \wedge \ y_{(0,\infty)} \equiv 0$$

The four spaces

- Consistency: $x(0^-) \in \mathfrak{C}_-$
- Left unobservability: $y_{(-\infty,0)} \equiv 0 \ \Leftrightarrow \ x(0^-) \in \ker O_-$
- Right unobservability: $y_{(0,\infty)} \equiv 0 \ \Leftrightarrow \ x(0^-) \in \ker O_+^-$
- Impulse unobervability: $y[0] = 0 \ \Leftrightarrow \ x(0^-) \in \ker O_+^{\text{imp}}$

Question

How to calculate these four spaces?

Wong sequences

Definition

Let $E, A \in \mathbb{R}^{m\times n}$. The corresponding Wong sequences of the pair (E, A) are:

$$\mathcal{V}_0 := \mathbb{R}^n, \qquad \mathcal{V}_{i+1} := A^{-1}(E\mathcal{V}_i), \qquad i = 0, 1, 2, 3, \dots$$
$$\mathcal{W}_0 := \{0\}, \qquad \mathcal{W}_{j+1} := E^{-1}A(\mathcal{W}_j), \qquad j = 0, 1, 2, 3, \dots$$

Note: $M^{-1}\mathcal{S} := \{\ x \mid Mx \in \mathcal{S}\ \}$ and $M\mathcal{S} := \{\ Mx \mid x \in \mathcal{S}\ \}$

Clearly, $\exists i^*, j^* \in \mathbb{N}$

$$\mathcal{V}_0 \supset \mathcal{V}_1 \supset \dots \supset \mathcal{V}_{i^*} = \mathcal{V}_{i^*+1} = \mathcal{V}_{i^*+2} = \dots$$
$$\mathcal{W}_0 \subset \mathcal{W}_1 \subset \dots \subset \mathcal{W}_{j^*} = \mathcal{W}_{j^*+1} = \mathcal{W}_{j^*+2} = \dots$$

Wong limits:

$$\boxed{\mathcal{V}^* := \bigcap_{i\in\mathbb{N}} \mathcal{V}_i = \mathcal{V}_{i^*}} \qquad \boxed{\mathcal{W}^* = \bigcup_{j\in\mathbb{N}} \mathcal{W}_j = \mathcal{W}_{j^*}}$$

Wong sequences and the QWF

Theorem (QWF [Berger, Ilchmann & T. 2012])

The following statements are equivalent for square $E, A \in \mathbb{R}^{n\times n}$:

(i) (E, A) *is regular*

(ii) $\mathcal{V}^* \oplus \mathcal{W}^* = \mathbb{R}^n$

(iii) $E\mathcal{V}^* \oplus A\mathcal{W}^* = \mathbb{R}^n$

In particular, with $\operatorname{im} V = \mathcal{V}^*$, $\operatorname{im} W = \mathcal{W}^*$

$$(E, A) \text{ regular} \quad \Rightarrow \quad T := [V, W] \text{ and } S := [EV, AW]^{-1} \text{ invertible}$$

and S, T yield quasi-Weierstrass form (QWF):

$$(SET, SAT) = \left(\begin{bmatrix} I & \\ & N \end{bmatrix}, \begin{bmatrix} J & \\ & I \end{bmatrix} \right), \quad N \text{ nilpotent}$$

Calculation of Wong sequences

Remark

Wong sequences can easily be calculated with Matlab even when the matrices still contain symbolic entries (like “R”, “L”, “C”).

```
function V=getPreImage(A,S)
% returns a basis of the preimage of A of the linear space spanned by
% the columns of S, i.e. im V = { x | Ax \in im S }

[m1,n1]=size(A); [m2,n2]=size(S);
if m1==m2
    H=null([A,S]);
    V=colspace(H(1:n1,:));
else
    error('Both matrices must have same number of rows');
end;
```

Consistency space

$$x(0^-) \in \mathfrak{C}_- \cap \ker O_- \cap \ker O_+^- \cap \ker O_+^{\mathrm{imp}-} \quad \Leftrightarrow \quad y \equiv 0$$

Corollary from QWF

$$\mathfrak{C}_- = \mathcal{V}_-^*$$

where $\mathcal{V}_-^*$ is the first Wong limit of (E_-, A_-).

The differential projector

For regular (E, A) let $(SET, SAT) = \left(\begin{bmatrix} I & 0 \\ 0 & N \end{bmatrix}, \begin{bmatrix} J & 0 \\ 0 & I \end{bmatrix} \right)$.

Definition (Differential "projector")

$$\Pi^{\text{diff}}_{(E,A)} := T \begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} S \quad \text{and} \quad \boxed{A^{\text{diff}} := \Pi^{\text{diff}}_{(E,A)} A}$$

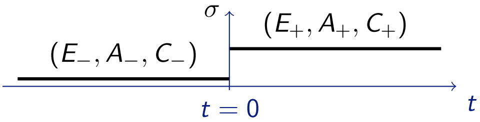
Following Implication holds:

$$x \text{ solves } E\dot{x} = Ax \quad \Rightarrow \quad \dot{x} = A^{\text{diff}} x$$

Hence, with $y = Cx$,

$$y \equiv 0 \quad \Rightarrow \quad x(0) \in \ker[C / CA^{\text{diff}} / C(A^{\text{diff}})^2 / \cdots / C(A^{\text{diff}})^{n-1}]$$

The spaces O_- and O_+



Hence

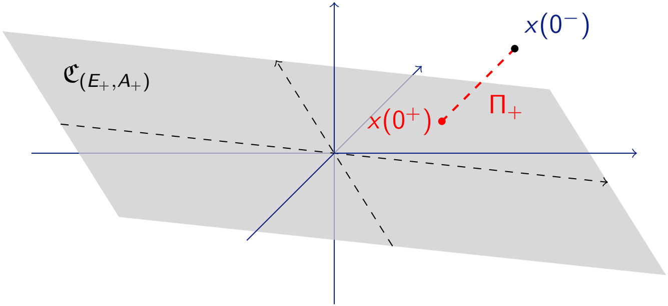
$$y_{(-\infty,0)} \equiv 0 \quad \Rightarrow \quad x(0^-) \in \ker \underbrace{[C_-/C_-A_-^{\text{diff}}/C_-(A_-^{\text{diff}})^2/\cdots/C_-(A_-^{\text{diff}})^{n-1}]}_{:= O_-}$$

and

$$y_{(0,\infty)} \equiv 0 \quad \Rightarrow \quad x(0^+) \in \ker \underbrace{[C_+/C_+A_+^{\text{diff}}/C_+(A_+^{\text{diff}})^2/\cdots/C_+(A_+^{\text{diff}})^{n-1}]}_{:= O_+}$$

Question: $x(0^+) \in \ker O_+ \quad \Rightarrow \quad x(0^-) \in \ ?$

Consistency projector and O_+^-



Assume $(S_+E_+T_+, S_+A_+T_+) = \left(\left[\begin{smallmatrix} I & 0 \\ 0 & N_+ \end{smallmatrix}\right], \left[\begin{smallmatrix} J_+ & 0 \\ 0 & I \end{smallmatrix}\right]\right)$:

Consistency projector

$x(0^+) = \Pi_+ x(0^-)$ where

$$\Pi_+ := T_+ \begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} T_+^{-1}$$

$x(0^+) \in \ker O_+$

$$\Rightarrow \quad x(0^-) \in \Pi_+^{-1} \ker O_+ = \ker \underbrace{O_+ \Pi_+}_{=: \, O_+^-}$$

The impulsive effect

Assume $(S_+ E_+ T_+, S_+ A_+ T_+) = \left(\begin{bmatrix} I & 0 \\ 0 & N_+ \end{bmatrix}, \begin{bmatrix} J_+ & 0 \\ 0 & I \end{bmatrix}\right)$:

Definition (Impulse "projector")

$$\Pi_+^{\text{imp}} := T_+ \begin{bmatrix} 0 & 0 \\ 0 & I \end{bmatrix} S_+ \quad \text{and} \quad \boxed{E_+^{\text{imp}} := \Pi_+^{\text{imp}} E_+}$$

Impulsive part of solution:

$$x[0] = -\sum_{i=0}^{n-1} (E_+^{\text{imp}})^{i+1} x(0^-)\, \delta_0^{(i)}$$

Dirac impulses

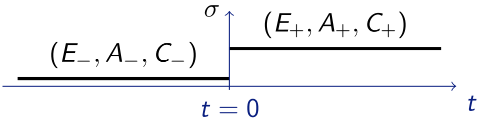
Conclusion:

$$y[0] = 0 \quad \Rightarrow \quad C_+ x[0] = 0 \quad \Rightarrow \quad \boxed{x(0^-) \in \ker O_+^{\text{imp}}}$$

where

$$O_+^{\text{imp}} := [C_+ E_+^{\text{imp}} \,/\, C_+ (E_+^{\text{imp}})^2 \,/\, \cdots \,/\, C_+ (E_+^{\text{imp}})^{n-1}]$$

Observability summary



$$y \equiv 0 \quad \Leftrightarrow \quad x(0^-) \in \mathfrak{C}_- \cap \ker O_- \cap \ker O_+^- \cap \ker O_+^{\text{imp}-}$$

with

- $\mathfrak{C}_- = \mathcal{V}_-^*$ (first Wong limit)
- $O_- = [C_-/C_-A_-^{\text{diff}}/C_-(A_-^{\text{diff}})^2/\cdots/C_-(A_-^{\text{diff}})^{n-1}]$
- $O_+^- = [C_+/C_+A_+^{\text{diff}}/C_+(A_+^{\text{diff}})^2/\cdots/C_+(A_+^{\text{diff}})^{n-1}]\Pi_+$
- $O_+^{\text{imp}} = [C_+E_+^{\text{imp}} \,/\, C_+(E_+^{\text{imp}})^2 \,/\, \cdots \,/\, C_+(E_+^{\text{imp}})^{n-1}]$

Example revisited

System 1:

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \dot{x} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} x$$

$$y = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix} x$$

$\sigma(\cdot) : 1 \to 2$ gives

$$\begin{aligned} \mathfrak{C}_- &= \operatorname{span}\{e_1, e_3\}, \\ \ker O_- &= \operatorname{span}\{e_1, e_2\} \\ \ker O_+^- &= \operatorname{span}\{e_1, e_2, e_3\}, \\ \ker O_+^{\text{imp}} &= \operatorname{span}\{e_2, e_3\} \end{aligned}$$

$$\Rightarrow \quad \mathcal{M} = \{0\}$$

System 2:

$$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{bmatrix} \dot{x} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} x$$

$$y = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix} x$$

$\sigma(\cdot) : 2 \to 1$ gives

$$\begin{aligned} \mathfrak{C}_- &= \operatorname{span}\{e_2\}, \\ \ker O_- &= \operatorname{span}\{e_1, e_2\} \\ \ker O_+^- &= \operatorname{span}\{e_1, e_2\}, \\ \ker O_+^{\text{imp}} &= \operatorname{span}\{e_1, e_2, e_3\} \end{aligned}$$

$$\Rightarrow \quad \mathcal{M} = \operatorname{span}\{e_2\}$$

Overall summary

$$\begin{aligned} E_\sigma \dot{x} &= A_\sigma x + B_\sigma u \\ y &= C_\sigma x + D_\sigma u \end{aligned} \qquad \text{(swDAE)}$$

Piecewise-smooth distributional solution framework

$x \in \mathbb{D}^n_{\mathrm{pw}\mathcal{C}^\infty}$, $u \in \mathbb{D}^m_{\mathrm{pw}\mathcal{C}^\infty}$, $y \in \mathbb{D}^p_{\mathrm{pw}\mathcal{C}^\infty}$

- Existence and uniqueness of solutions? ✓
- Jumps and impulses in solutions? ✓
- Conditions for impulse free solutions? ✓
- Control theoretical questions
  - Stability ✓ and stabilization
  - Observability ✓ and observer design ✓
  - Controllability ✓ and controller design

Major future challenge

Extension to nonlinear case.