Conference on Decision and Control
CDC2025

Duality between controllability and observability for target control and estimation in networks

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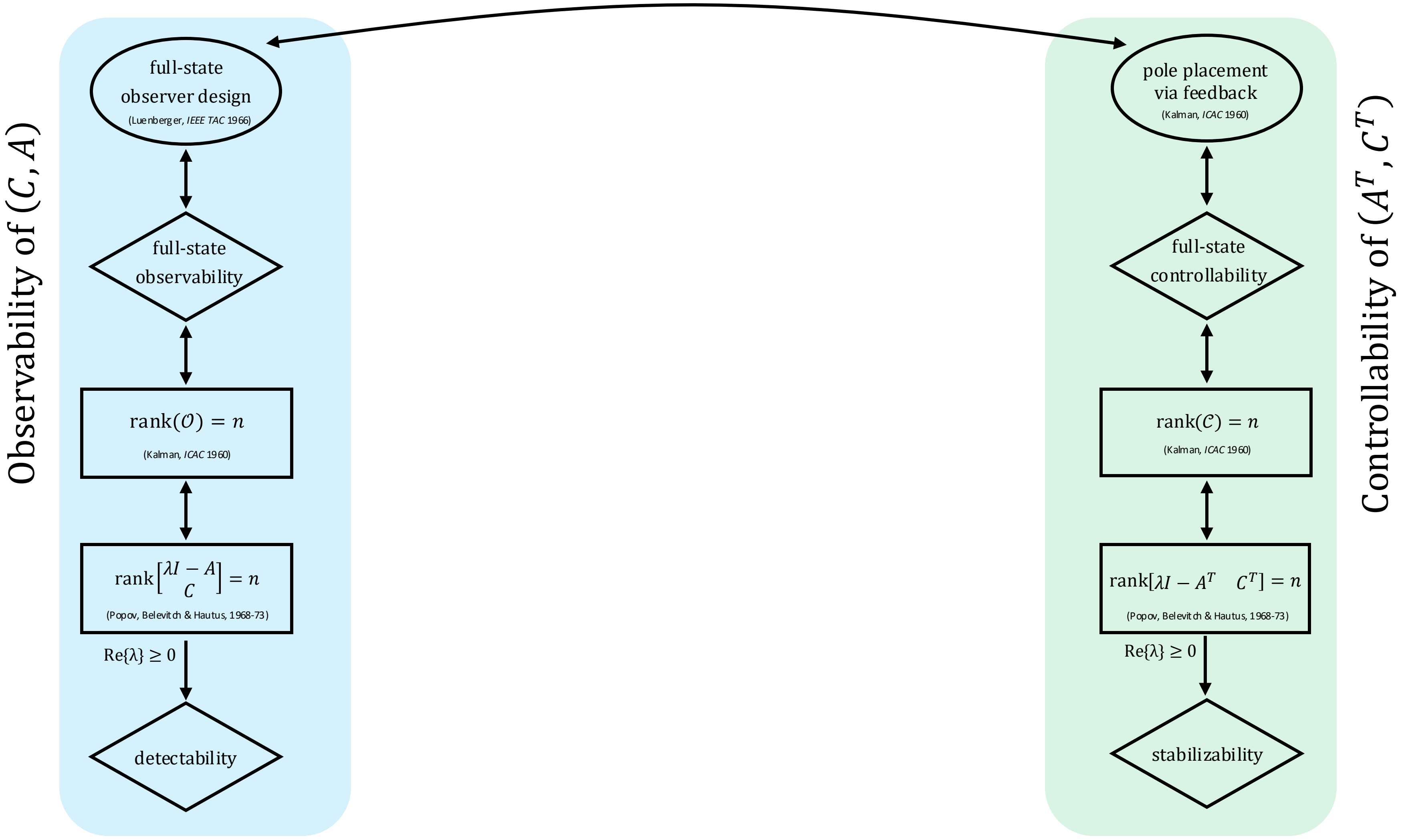
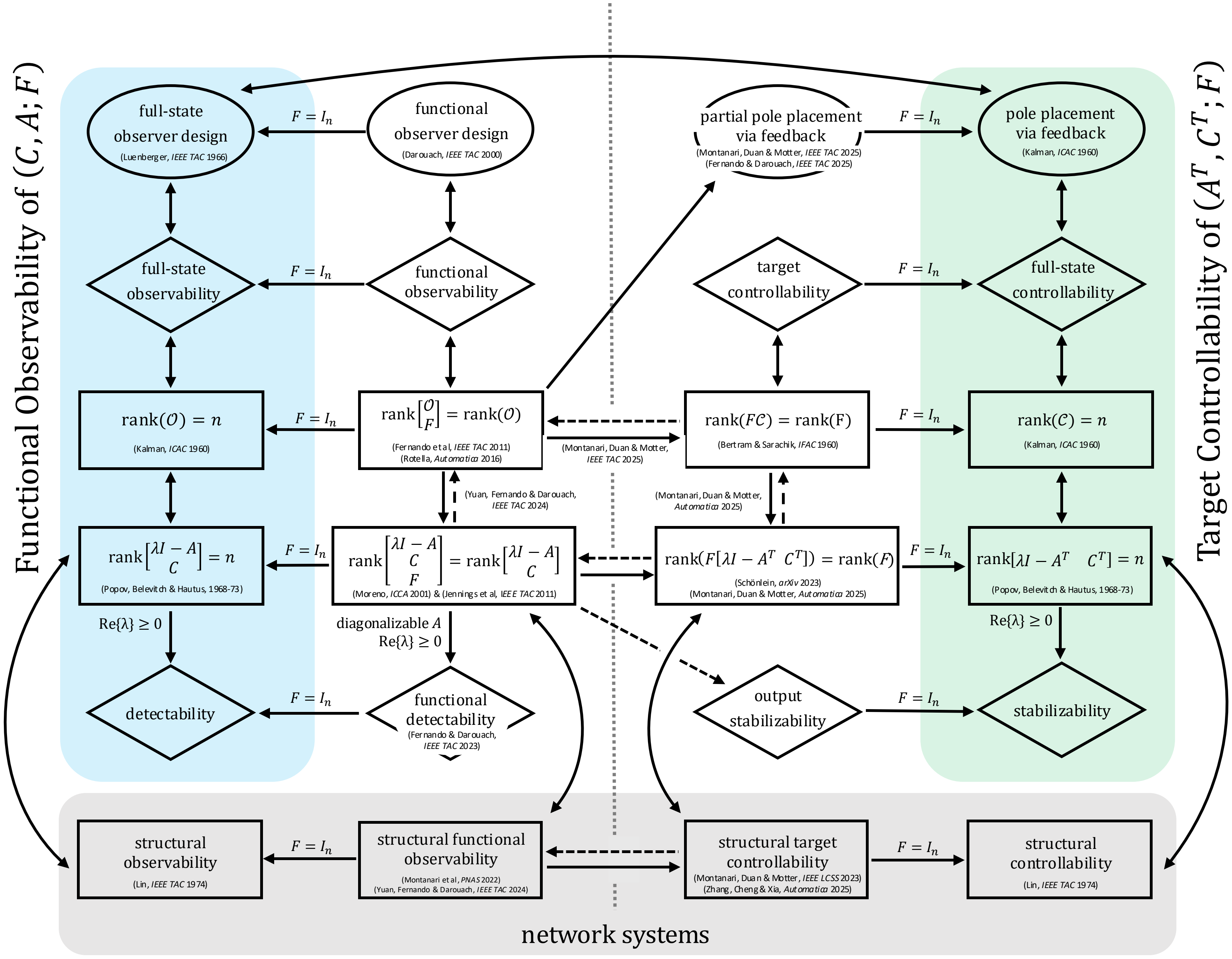


Observability of (C, A)
full-state observer design
(Luenberger, *IEEE TAC* 1966)
full-state observability
$\mathrm{rank}(\mathcal{O}) = n$
(Kalman, *ICAC* 1960)
$\mathrm{rank}\begin{bmatrix}\lambda I - A \\ C\end{bmatrix} = n$
(Popov, Belevitch & Hautus, 1968-73)
$\mathrm{Re}\{\lambda\} \geq 0$
detectability
Controllability of (A^T, C^T)
pole placement via feedback
(Kalman, *ICAC* 1960)
full-state controllability
$\mathrm{rank}(\mathcal{C}) = n$
(Kalman, *ICAC* 1960)
$\mathrm{rank}[\lambda I - A^T \quad C^T] = n$
(Popov, Belevitch & Hautus, 1968-73)
$\mathrm{Re}\{\lambda\} \geq 0$
stabilizability



Functional Observability of $(C, A; F)$
Target Controllability of $(A^T, C^T; F)$
full-state observer design
(Luenberger, *IEEE TAC* 1966)
$F = I_n$
functional observer design
(Darouach, *IEEE TAC* 2000)
partial pole placement via feedback
(Montanari, Duan & Motter, *IEEE TAC* 2025)
(Fernando & Darouach, *IEEE TAC* 2025)
$F = I_n$
pole placement via feedback
(Kalman, *ICAC* 1960)
full-state observability
$F = I_n$
functional observability
target controllability
$F = I_n$
full-state controllability
$\mathrm{rank}(\mathcal{O}) = n$
(Kalman, *ICAC* 1960)
$F = I_n$
$\mathrm{rank}\begin{bmatrix}\mathcal{O}\\ F\end{bmatrix} = \mathrm{rank}(\mathcal{O})$
(Fernando et al, *IEEE TAC* 2011)
(Rotella, *Automatica* 2016)
(Montanari, Duan & Motter, *IEEE TAC* 2025)
$\mathrm{rank}(F\mathcal{C}) = \mathrm{rank}(\mathrm{F})$
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$\mathrm{rank}\begin{bmatrix}\lambda I - A\\ C\\ F\end{bmatrix} = \mathrm{rank}\begin{bmatrix}\lambda I - A\\ C\end{bmatrix}$
(Moreno, *ICCA* 2001) & (Jennings et al, *IEEE TAC* 2011)
$\mathrm{rank}(F[\lambda I - A^T \quad C^T]) = \mathrm{rank}(F)$
(Schönlein, *arXiv* 2023)
(Montanari, Duan & Motter, *Automatica* 2025)
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diagonalizable A
$\mathrm{Re}\{\lambda\} \geq 0$
$\mathrm{Re}\{\lambda\} \geq 0$
detectability
$F = I_n$
functional detectability
(Fernando & Darouach, *IEEE TAC* 2023)
output stabilizability
$F = I_n$
stabilizability
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$F = I_n$
structural functional observability
(Montanari et al, *PNAS* 2022)
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structural target controllability
(Montanari, Duan & Motter, *IEEE LCSS* 2023)
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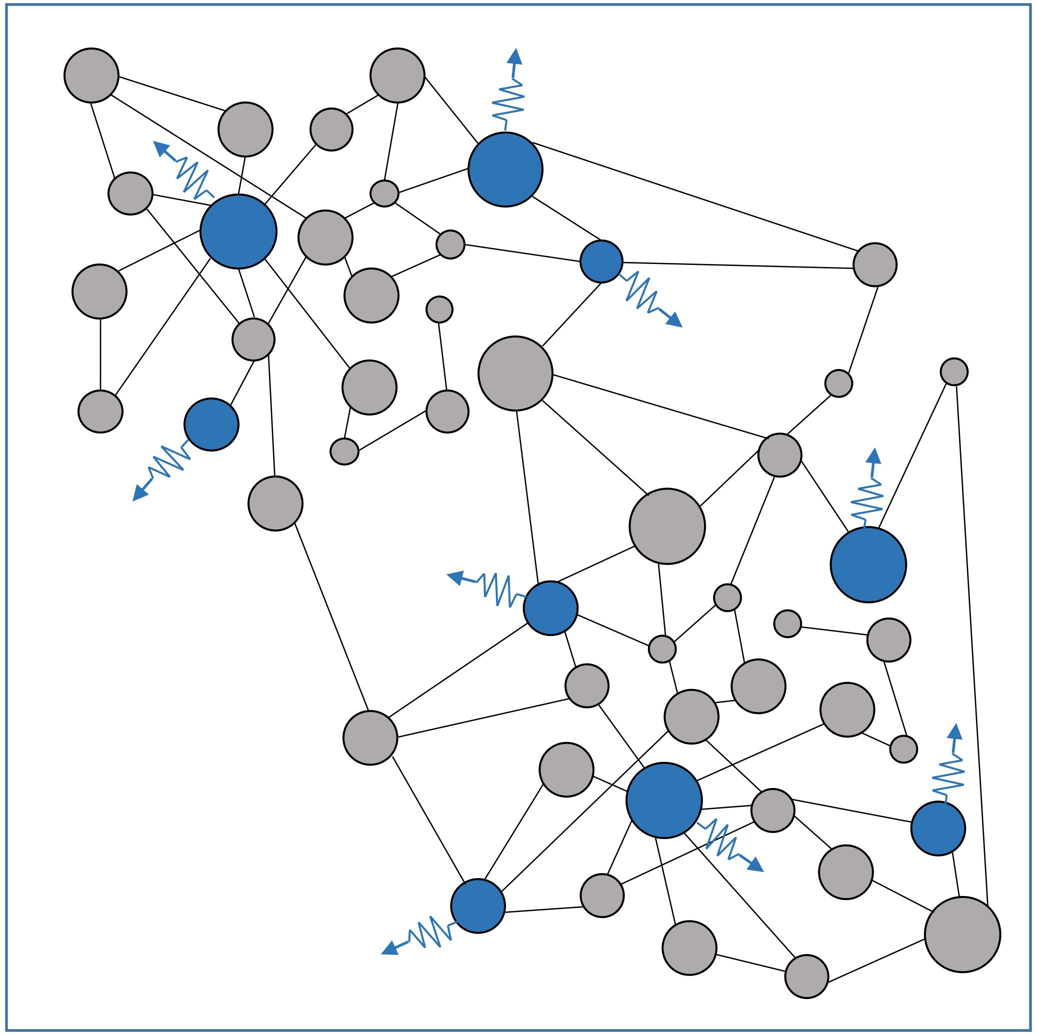
$F = I_n$
structural controllability
(Lin, *IEEE TAC* 1974)
network systems

Network system

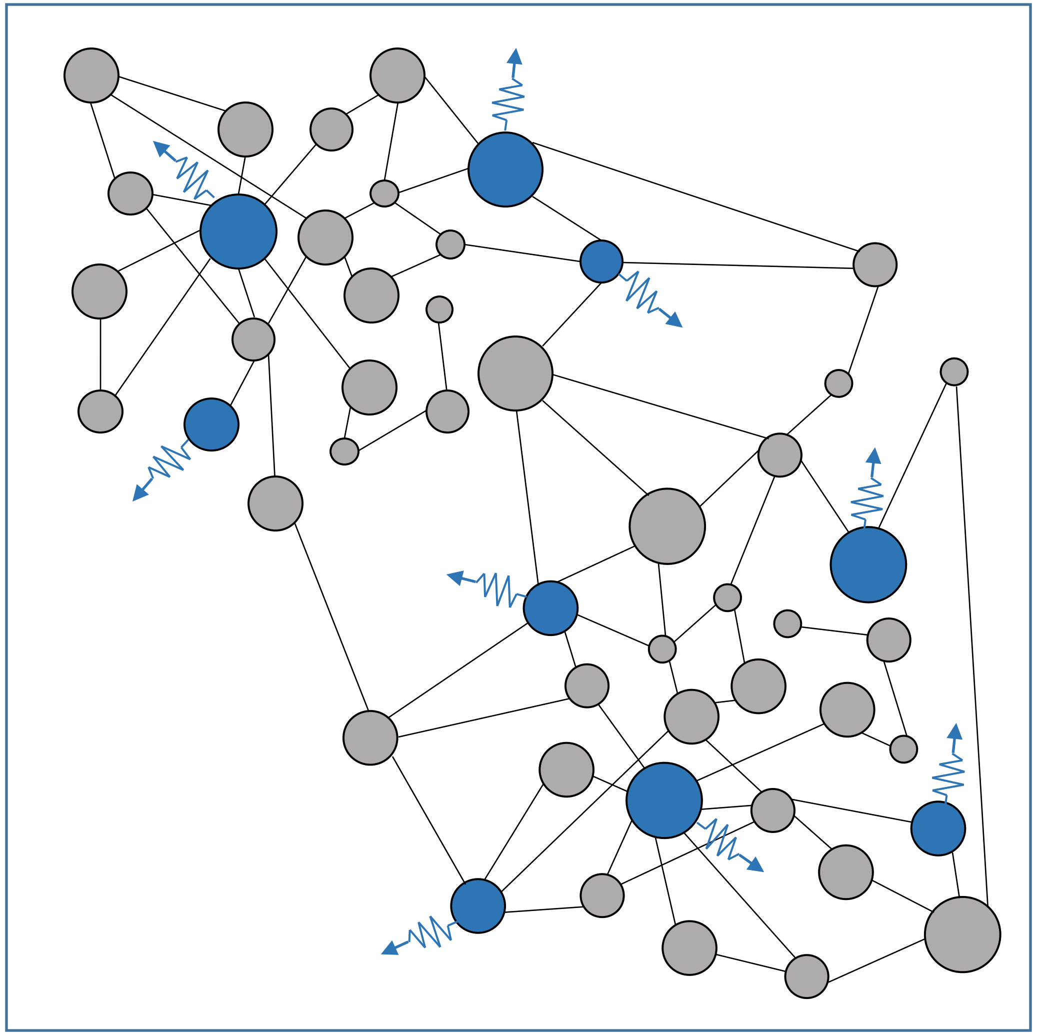


$$\begin{cases} \dot{\boldsymbol{x}} = A\boldsymbol{x} + B\boldsymbol{u} \\ \boldsymbol{y} = C\boldsymbol{x} \end{cases}$$

inference graph $\mathcal{G}(A)$
set of state variables $\mathcal{X}$
set of sensor nodes $\mathcal{S}$

$A_{ij} \neq 0$ -> draw an edge from x_j to x_i
$C_{ij} \neq 0$ -> node x_j is the ith sensor node

Network system



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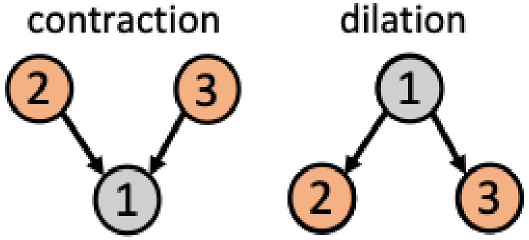
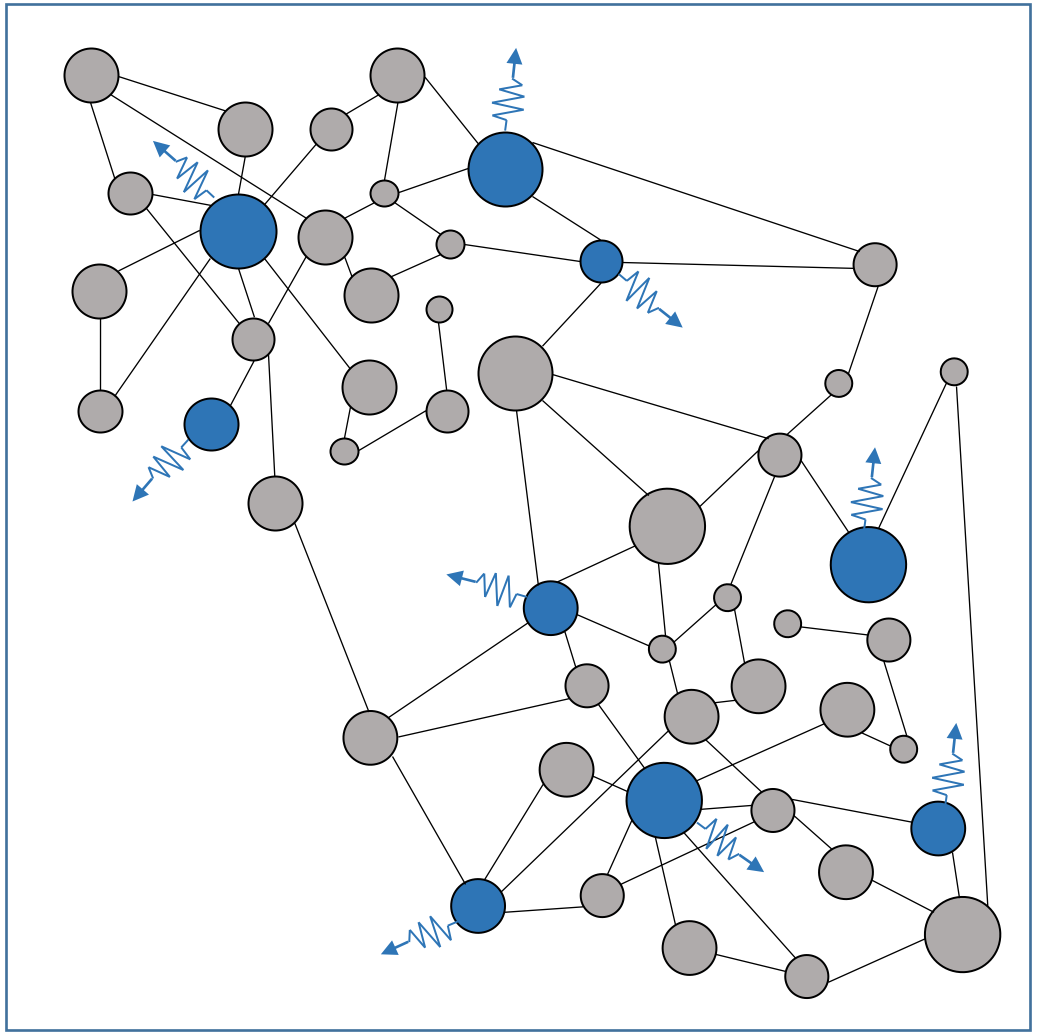


Observability of network systems



$$\begin{cases} \dot{\boldsymbol{x}} = A\boldsymbol{x} + Bu \\ \boldsymbol{y} = C\boldsymbol{x} \end{cases}$$

inference graph $\mathcal{G}(A)$
set of state variables $\mathcal{X}$
set of sensor nodes $\mathcal{S}$

pair (C, A) is observable

$$\mathcal{O} = \begin{bmatrix} C \\ CA \\ CA^2 \\ \vdots \\ CA^{n-1} \end{bmatrix}$$

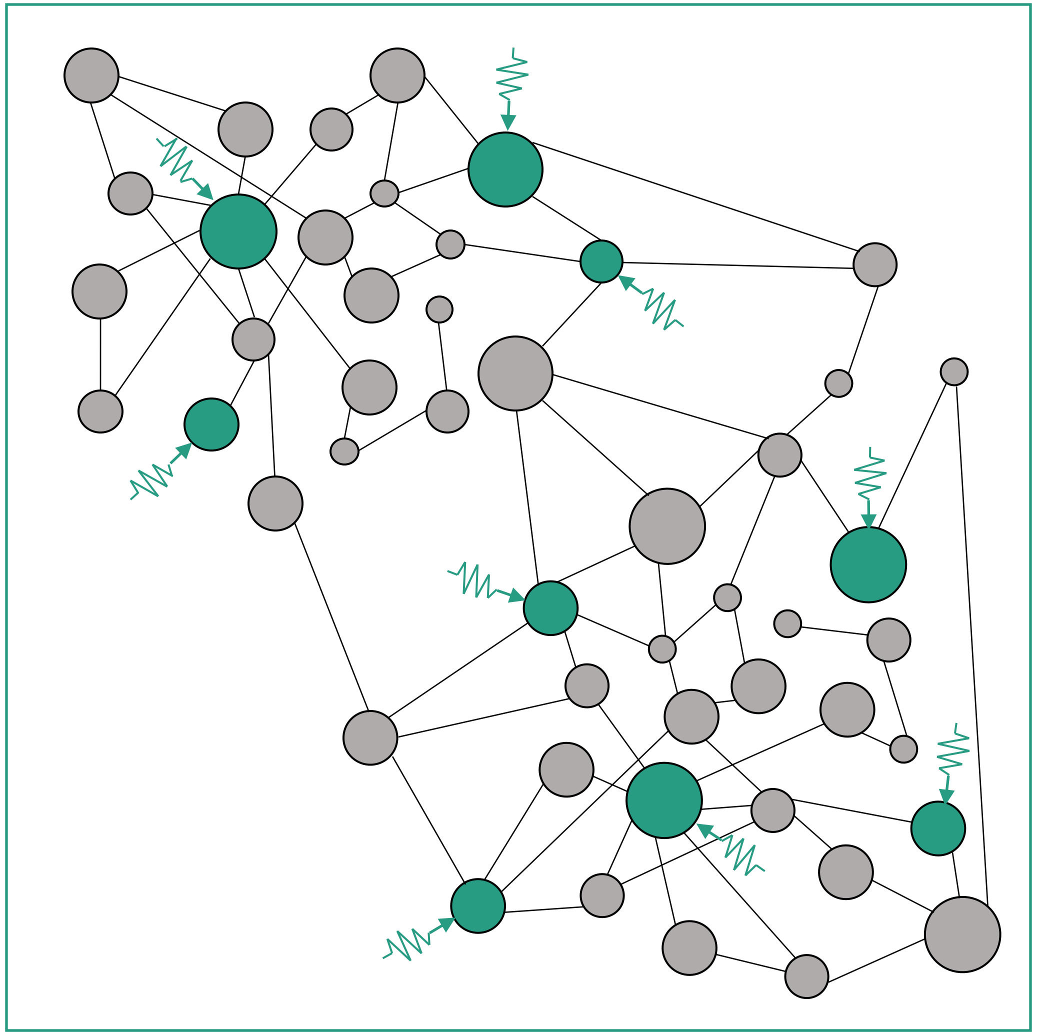
$$\operatorname{rank}(\mathcal{O}) = n$$

1) every node $x_i \in \mathcal{X}$ has a path to some sensor node $y_j \in \mathcal{S}$

2) graph has no contractions

CT Lin. Structural controllability. *IEEE Transactions on Automatic Control* (1974).

Controllability of network systems



$$\begin{cases} \dot{\boldsymbol{x}} = A\boldsymbol{x} + B\boldsymbol{u} \\ \boldsymbol{y} = C\boldsymbol{x} \end{cases}$$

inference graph $\mathcal{G}(A)$
set of state variables $\mathcal{X}$
set of driver nodes $\mathcal{D}$

pair (A, B) is controllable iff (A^T, C^T) is observable

$$\mathcal{C} = [B \;\; AB \;\; \dots \;\; A^{n-1}B]$$

$$\operatorname{rank}(\mathcal{C}) = n$$

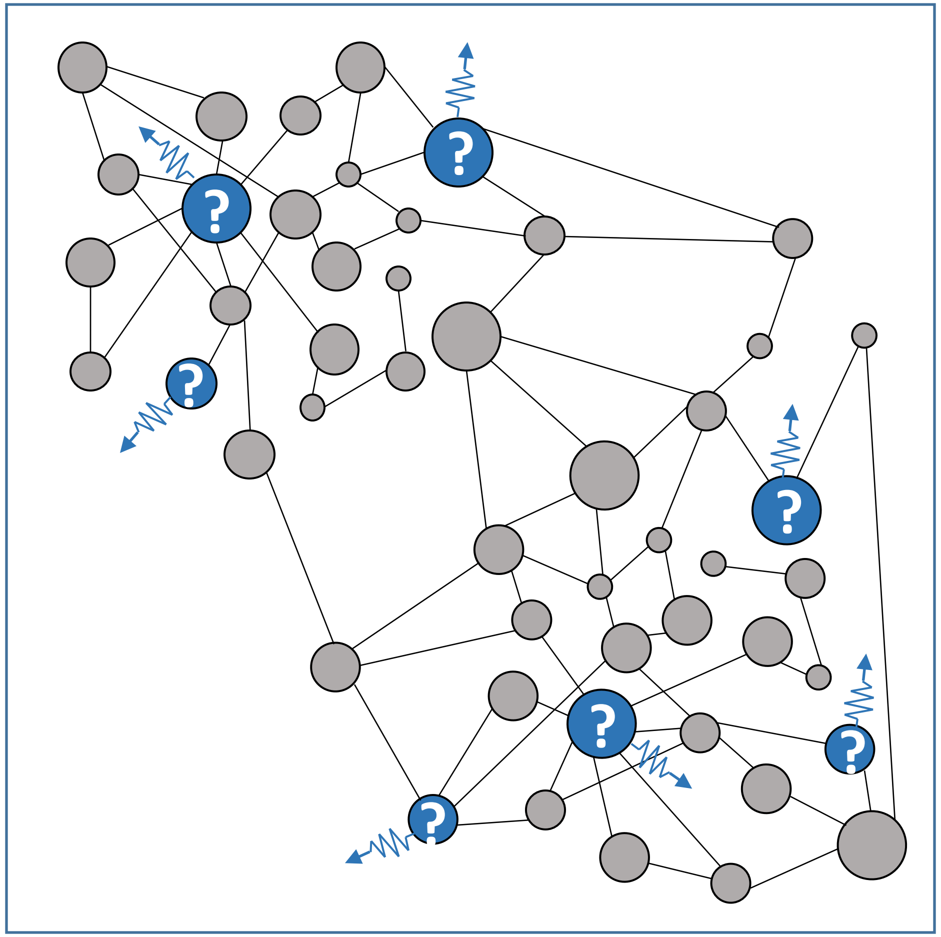
1) for every $x_i \in \mathcal{X}$, some driver node $u_j \in \mathcal{D}$ has a path to x_i

2) graph has no dilations

CT Lin. Structural controllability.
IEEE Transactions on Automatic Control (1974).

Challenges in large-scale networks

1) Minimum component placement



Challenges in large-scale networks

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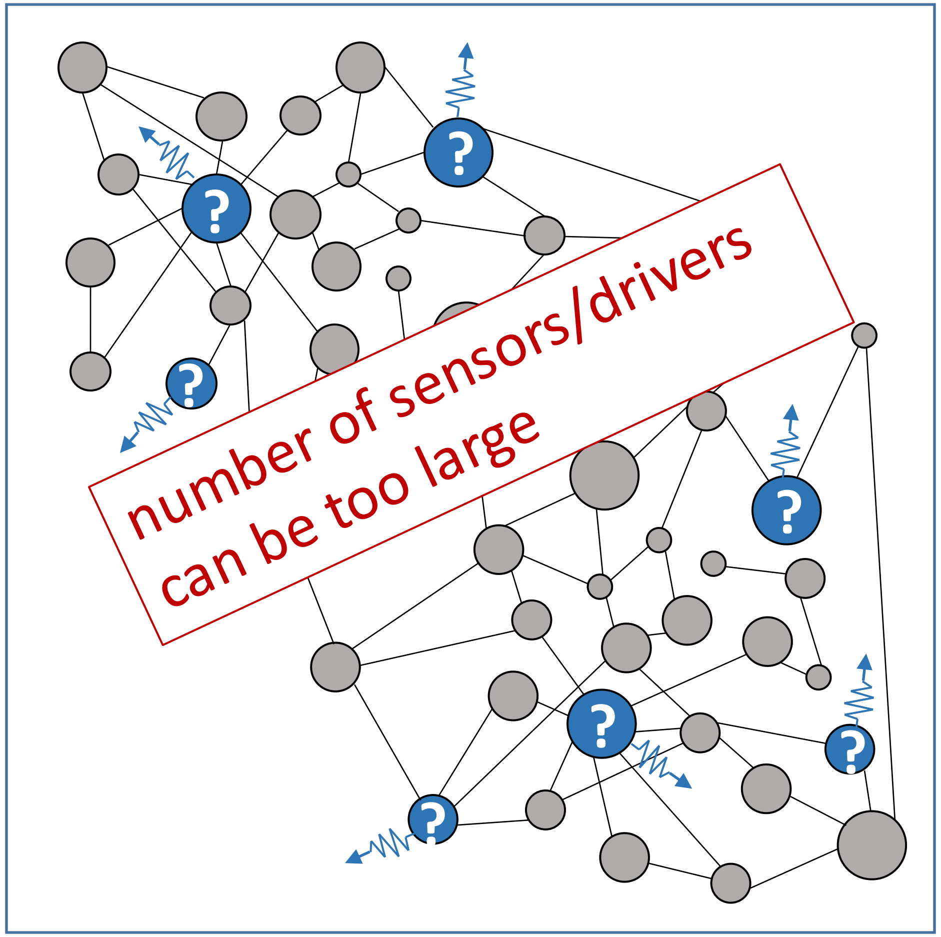

Challenges in large-scale networksv

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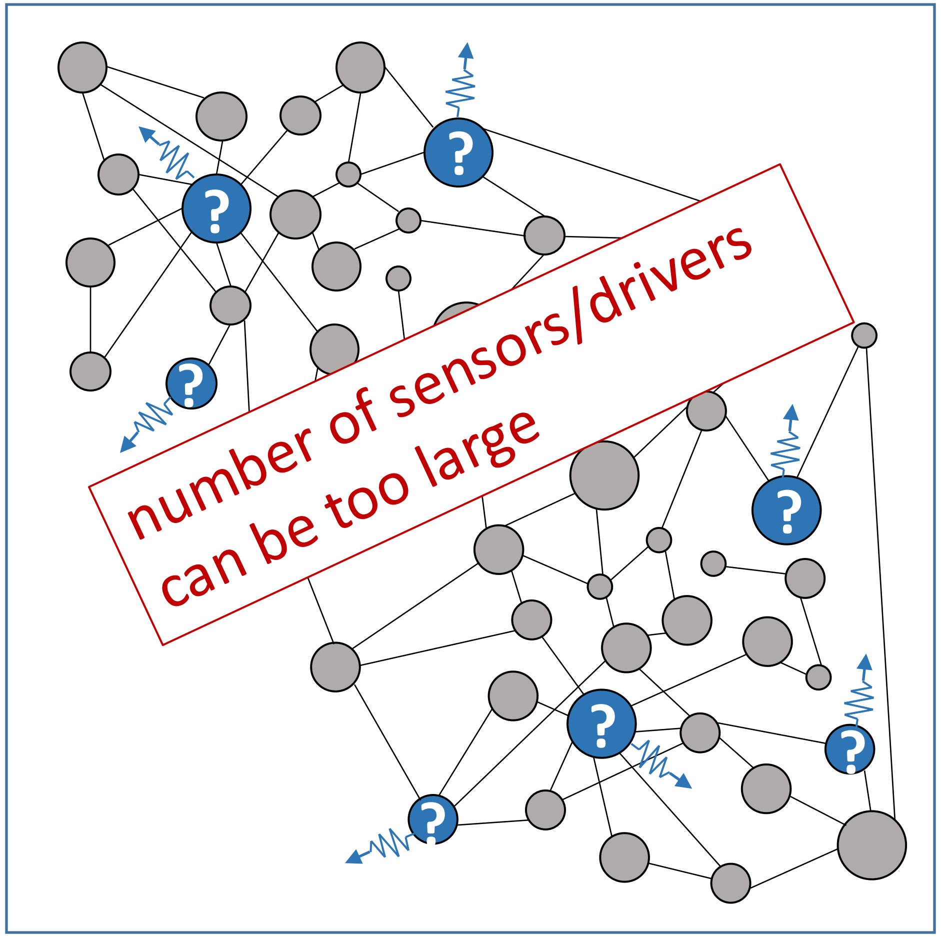
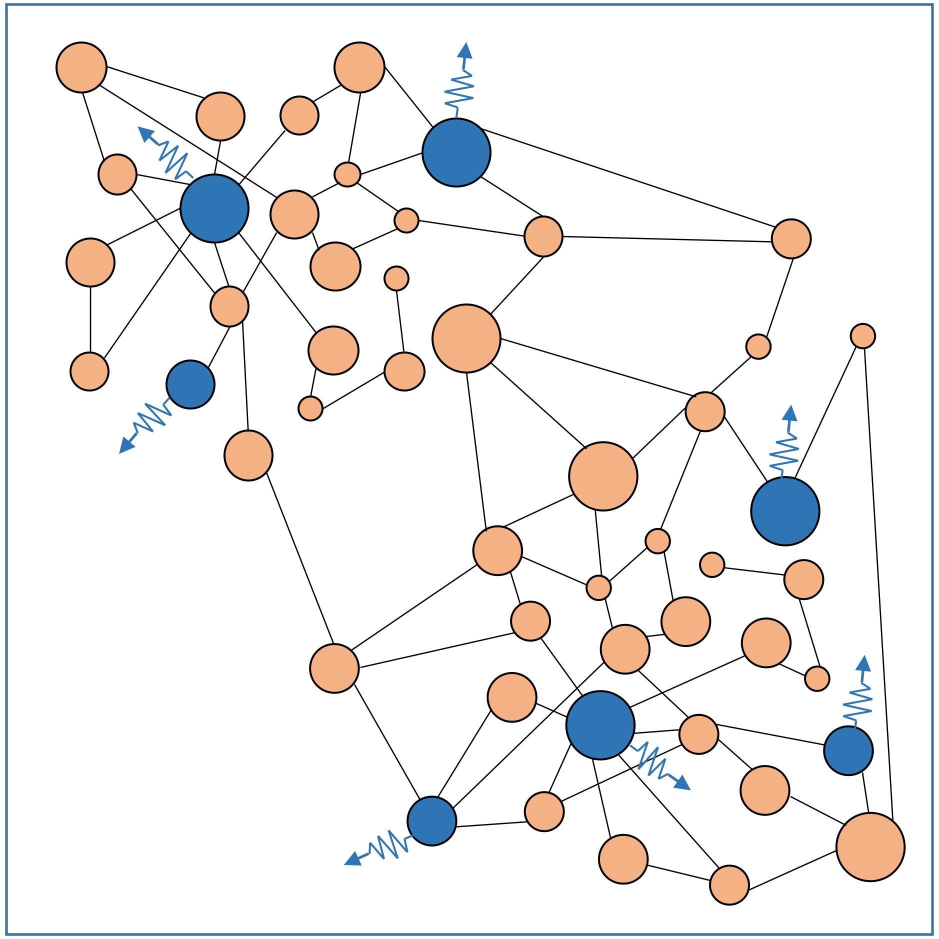


2) Observer or controller design



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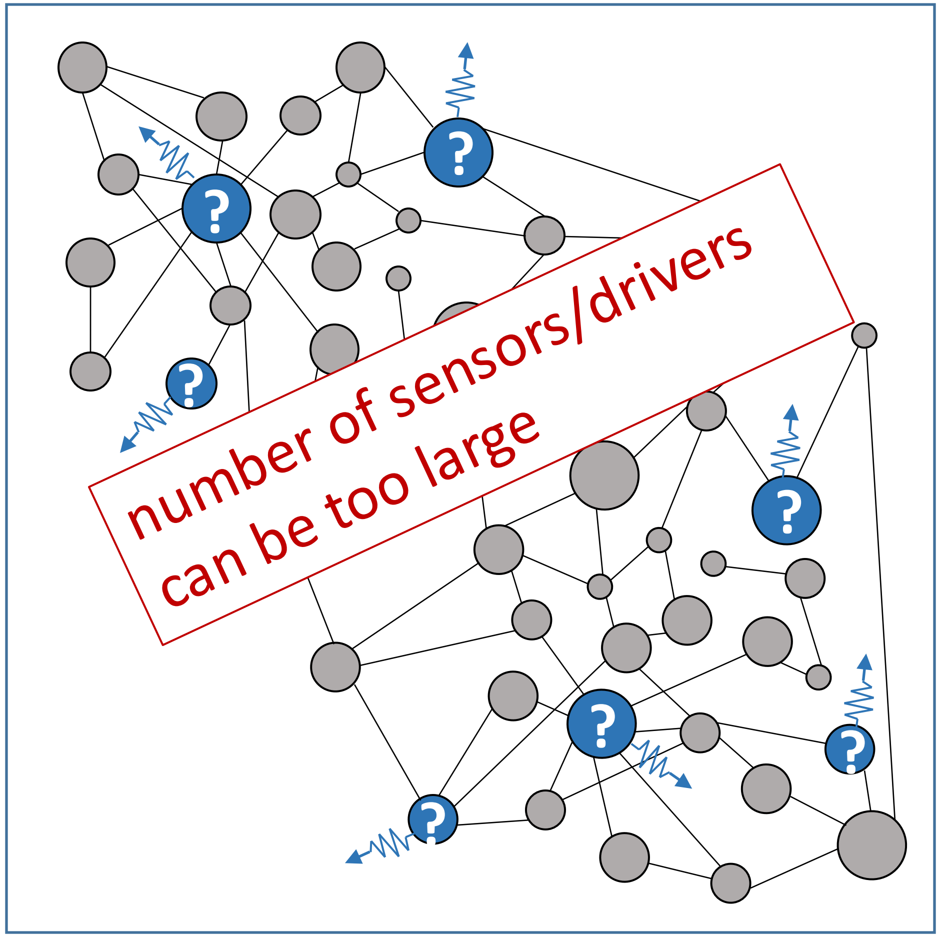

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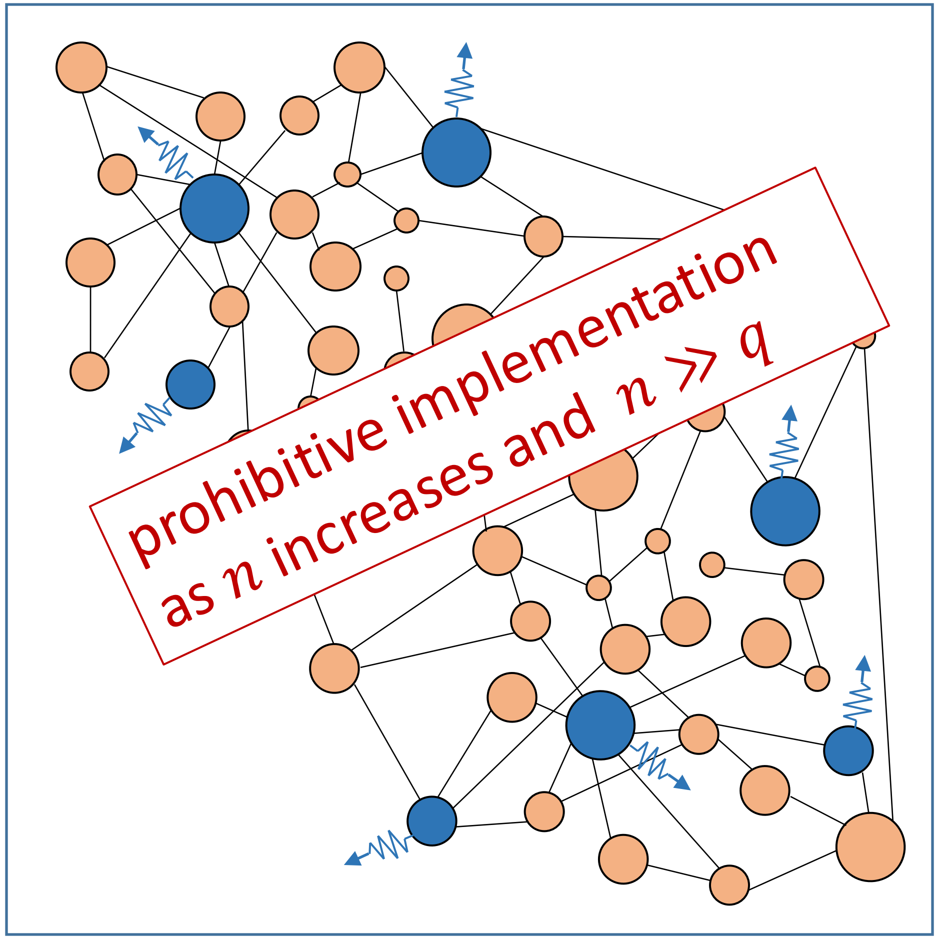


monitoring

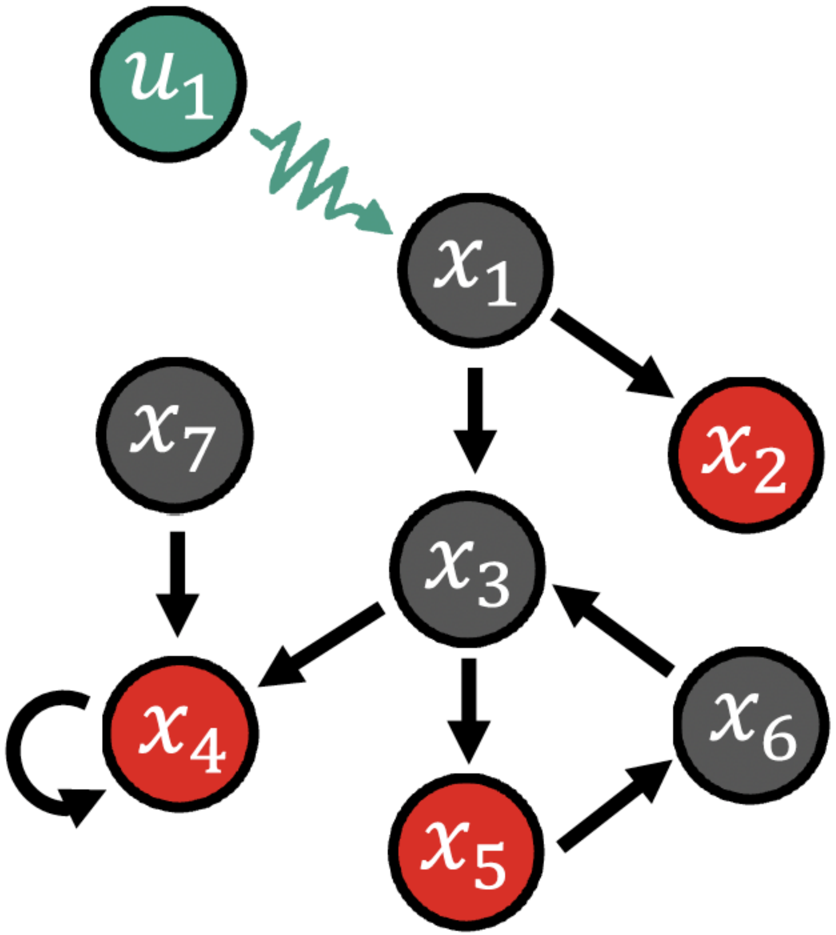
control

intervention

desired to control/estimate

only a target subset of state variables

Target (or output) controllability



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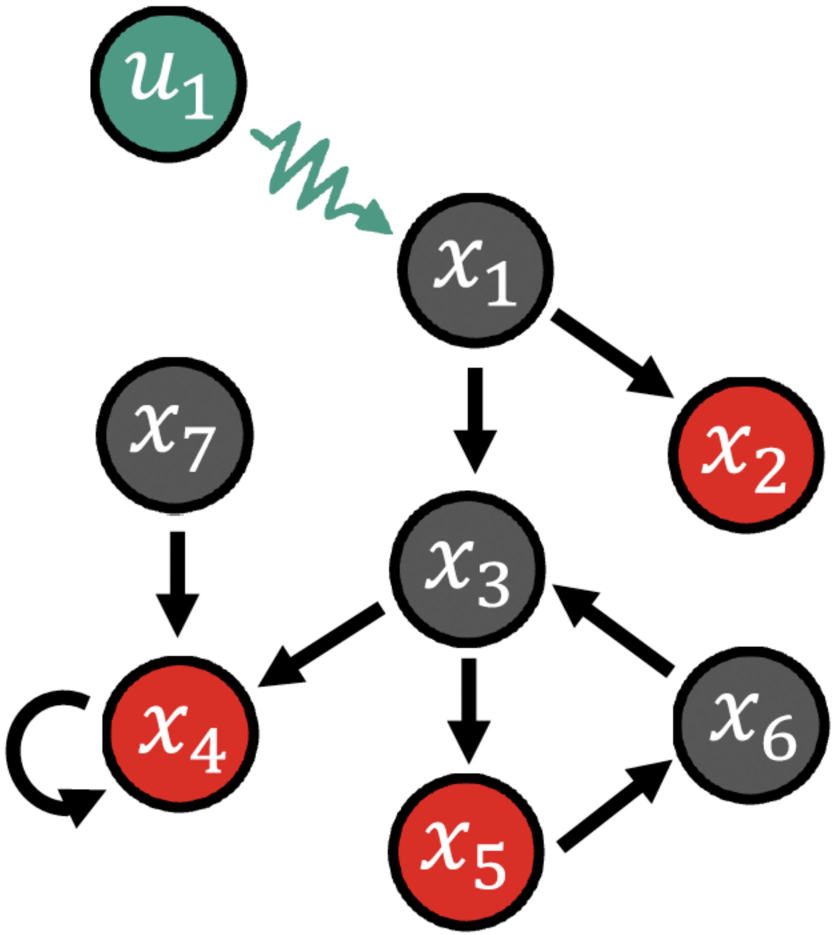
set of state variables $\mathcal{X}$
set of driver nodes $\mathcal{D}$
set of target nodes $\mathcal{T}$

Target (or output) controllability



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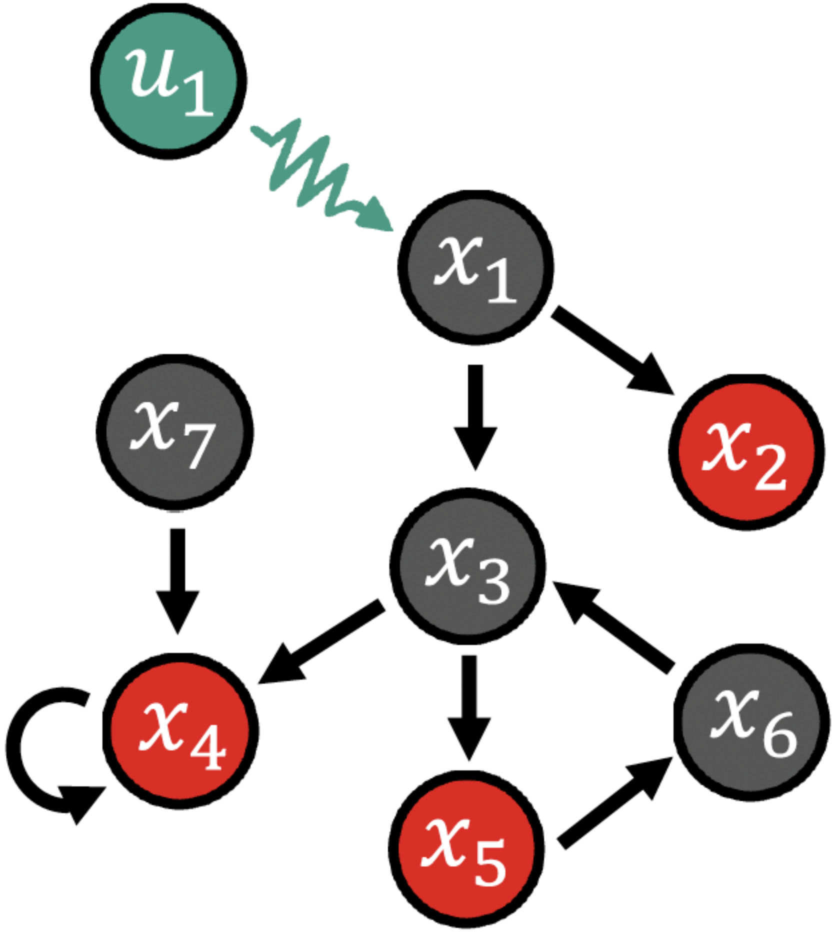
system $(A, B; F)$ is target controllable

condition

$$\mathrm{rank}(F\mathcal{C}) = \mathrm{rank}(F)$$

JE Bertram, PE Sarachik.
On optimal computer control.
IFAC Proceedings Volumes (1960).

Target (or output) controllability



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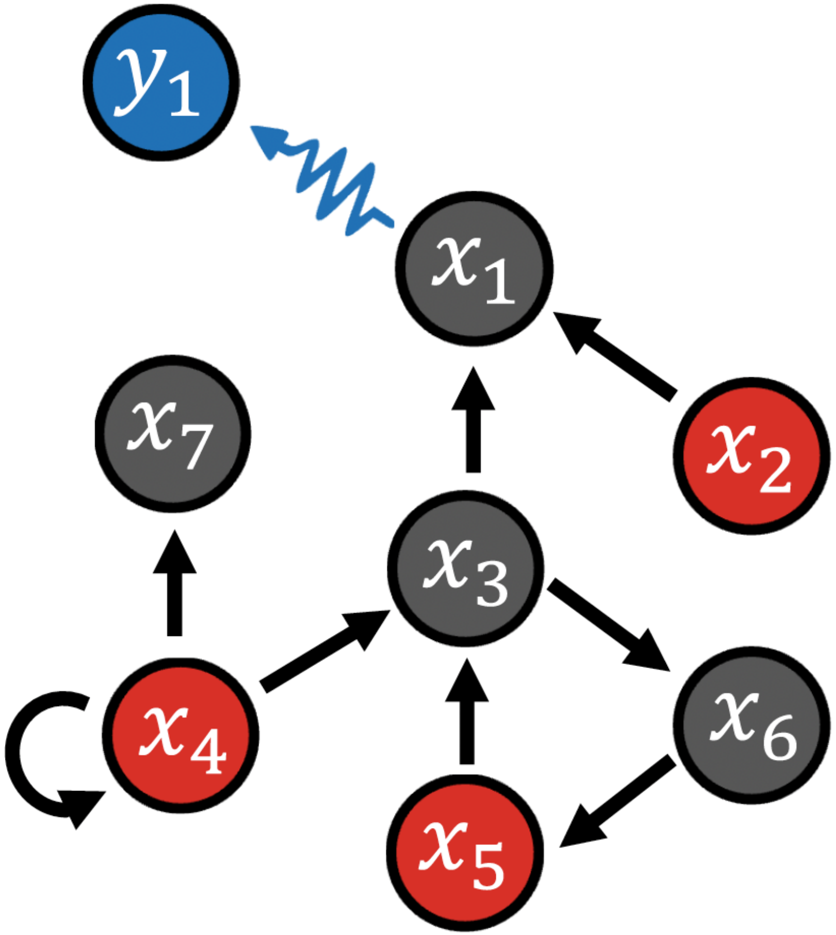
AN Montanari, C Duan, AE Motter.
Target controllability and target observability of structured network systems.
IEEE Control Systems Letters (2023).

Functional observability



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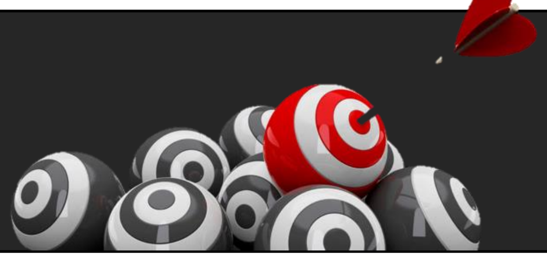
set of state variables $\mathcal{X}$
set of sensor nodes $\mathcal{S}$
set of target nodes $\mathcal{T}$

system $(C, A; F)$ is functionally observable

condition

$$\operatorname{rank}\left(\begin{bmatrix} \mathcal{O} \\ F \end{bmatrix}\right) = \operatorname{rank}(\mathcal{O})$$

LS Jennings, TL Fernando, HM Trinh.
Existence conditions for functional observability from an eigenspace perspective.
IEEE Transactions on Automatic Control (2011).



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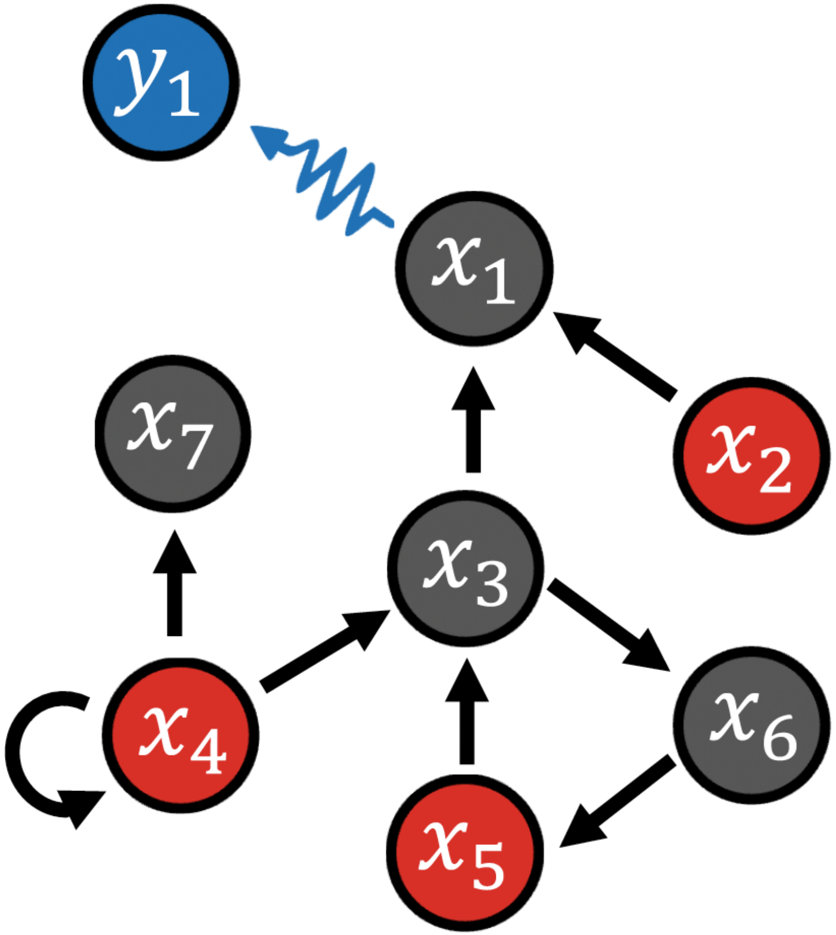

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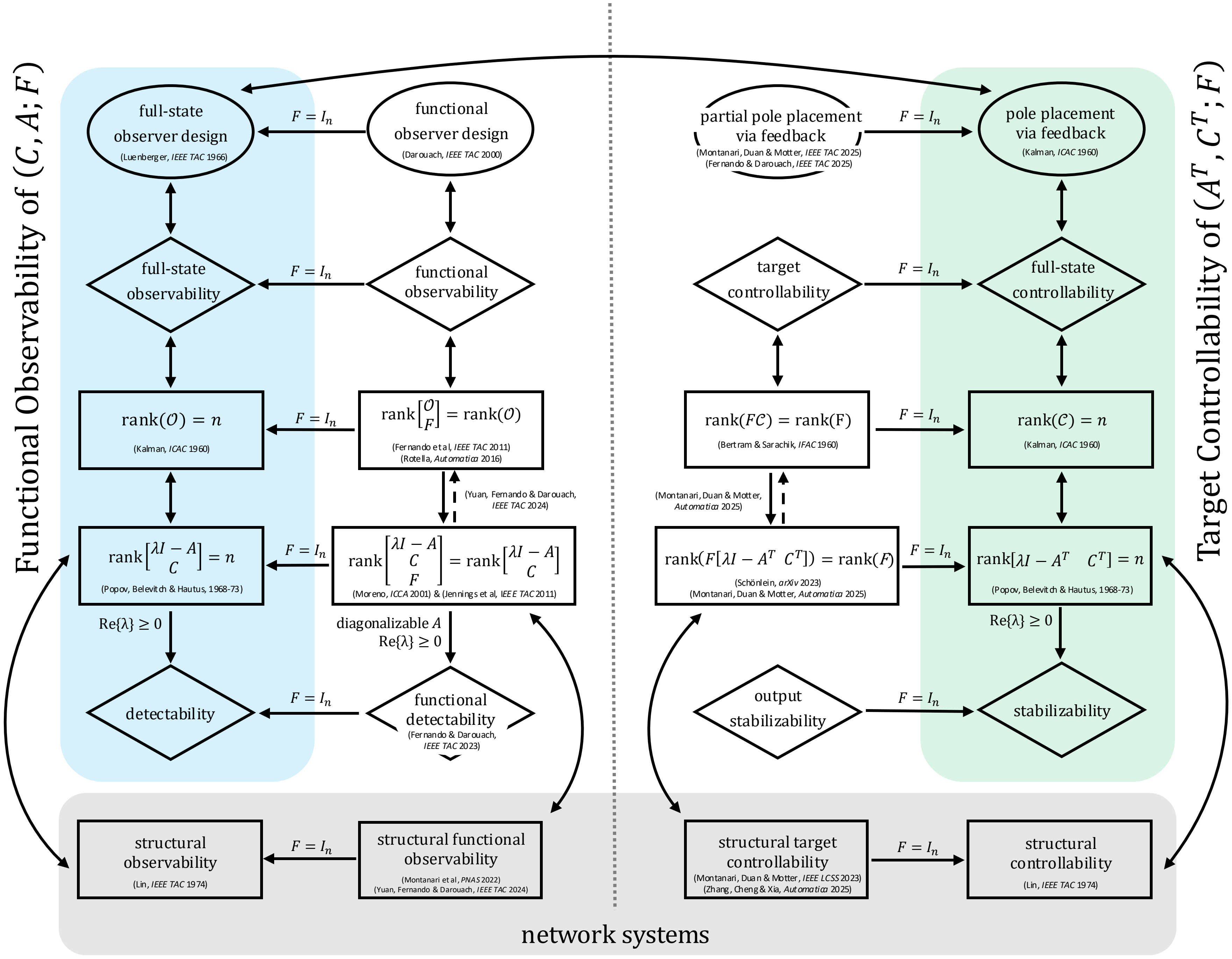
AN Montanari, C Duan, LA Aguirre, AE Motter. Functional observability and target state estimation in large-scale networks. *PNAS* (2022).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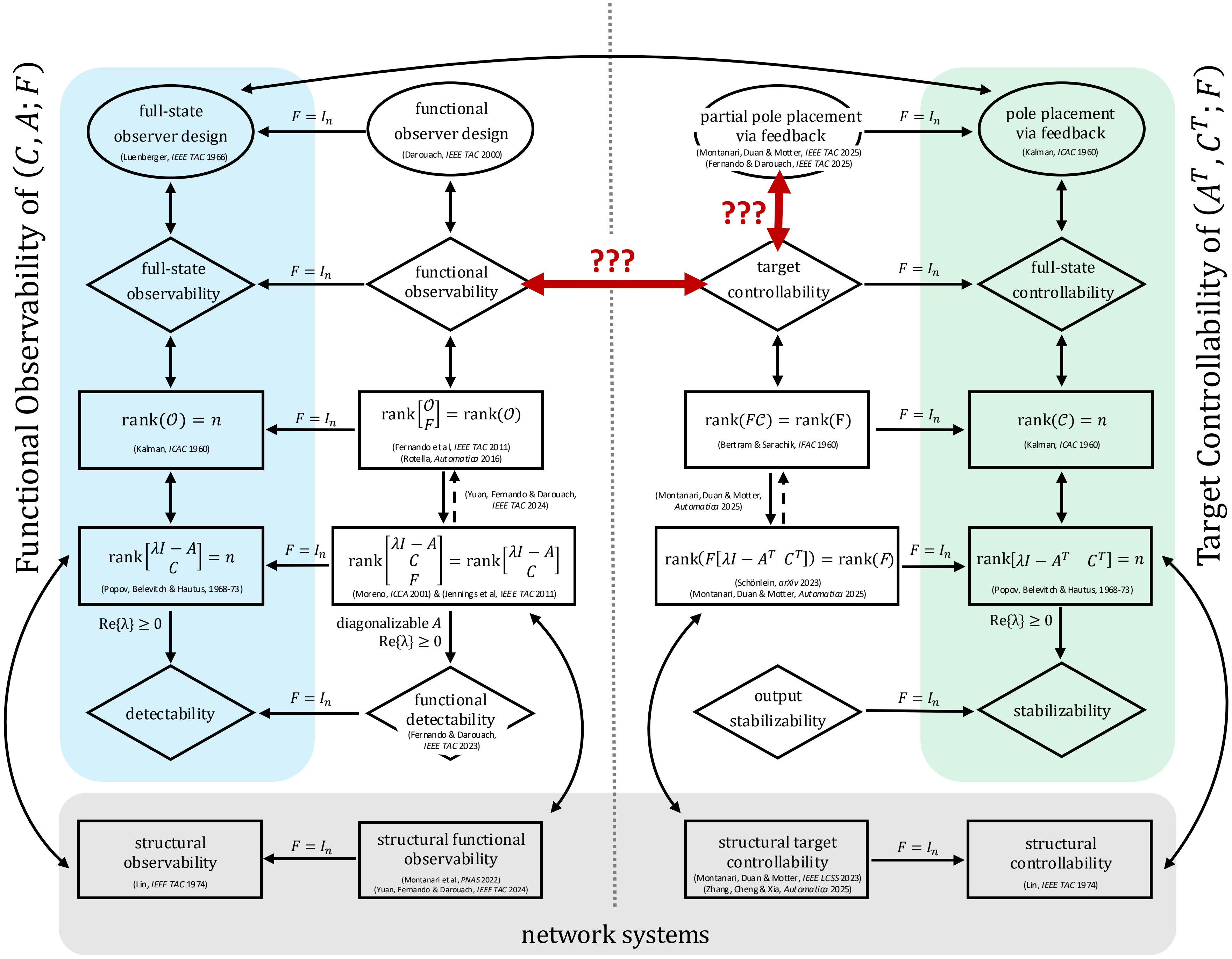
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Lack of duality

target controllability

$$\mathrm{rank}(F\mathcal{C}) = \mathrm{rank}(F)$$

1) for each target $x_i \in \mathcal{T}$, some driver node $u_j \in \mathcal{D}$ has a path to x_i

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functional observability

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Generalized duality principle

target controllability
subspace of target controllable states
$\boldsymbol{z}(t_f) \in \mathcal{C}_F$

functional observability
subspace of functionally observable states
$\boldsymbol{z}(0) \in \mathcal{O}_F$

Duality Principle

AN Montanari, C Duan, AE Motter. Duality between controllability and observability for target control and estimation in networks.
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Generalized duality principle

target controllability

subspace of target controllable states

$\boldsymbol{z}(t_f) \in \mathcal{C}_F$

functional observability

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Duality Principle

$(C, A; F)$ has a target observable space $\mathcal{O}_F$

$\mathcal{O}_F \subseteq \mathcal{C}_F$

$\mathcal{O}_F = \mathcal{C}_F$

$(A^T, C^T; F)$ has a target controllable space $\mathcal{C}_F$

$F\mathrm{Im}(W) \perp F\mathrm{Ker}(\mathrm{W})$

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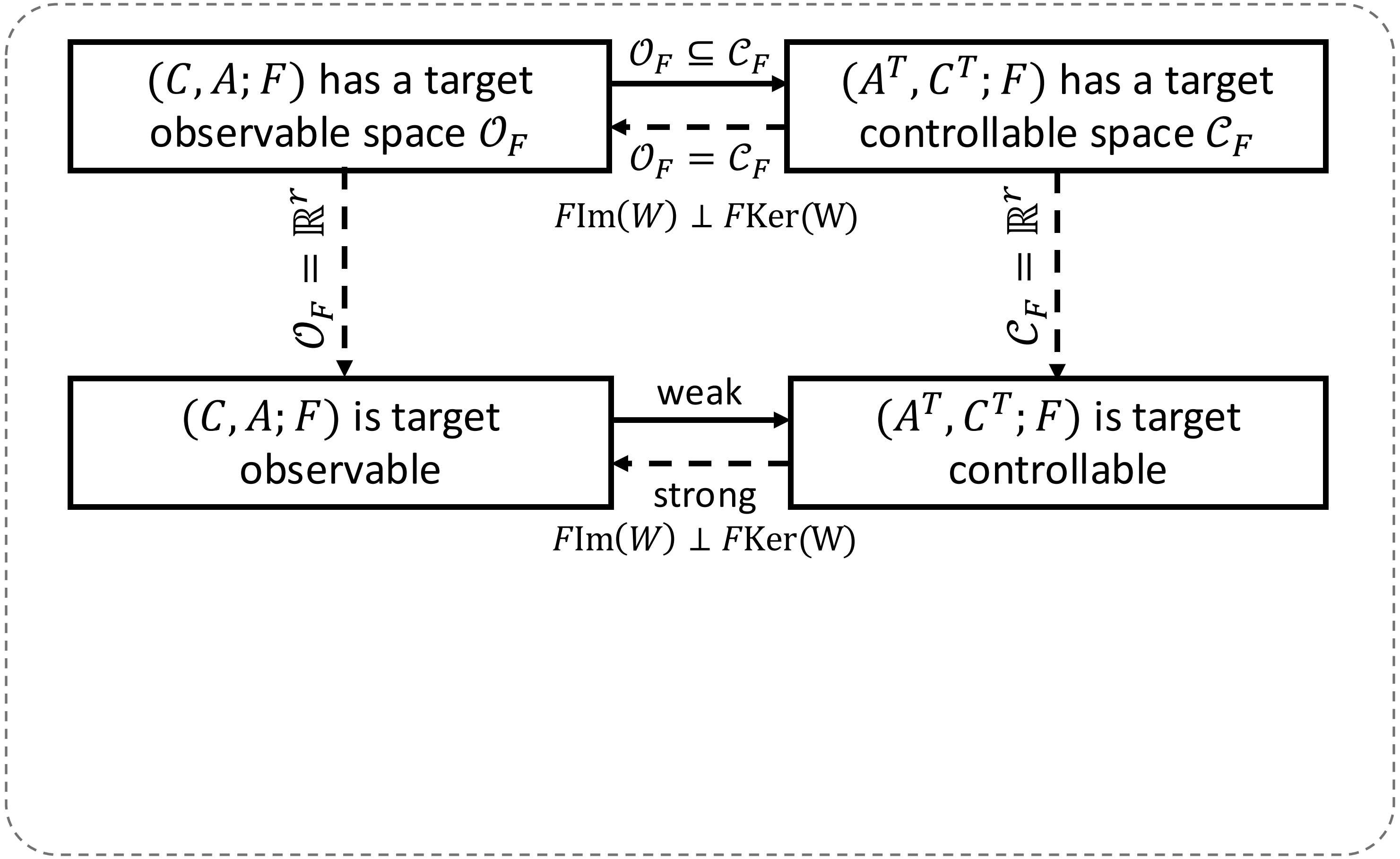

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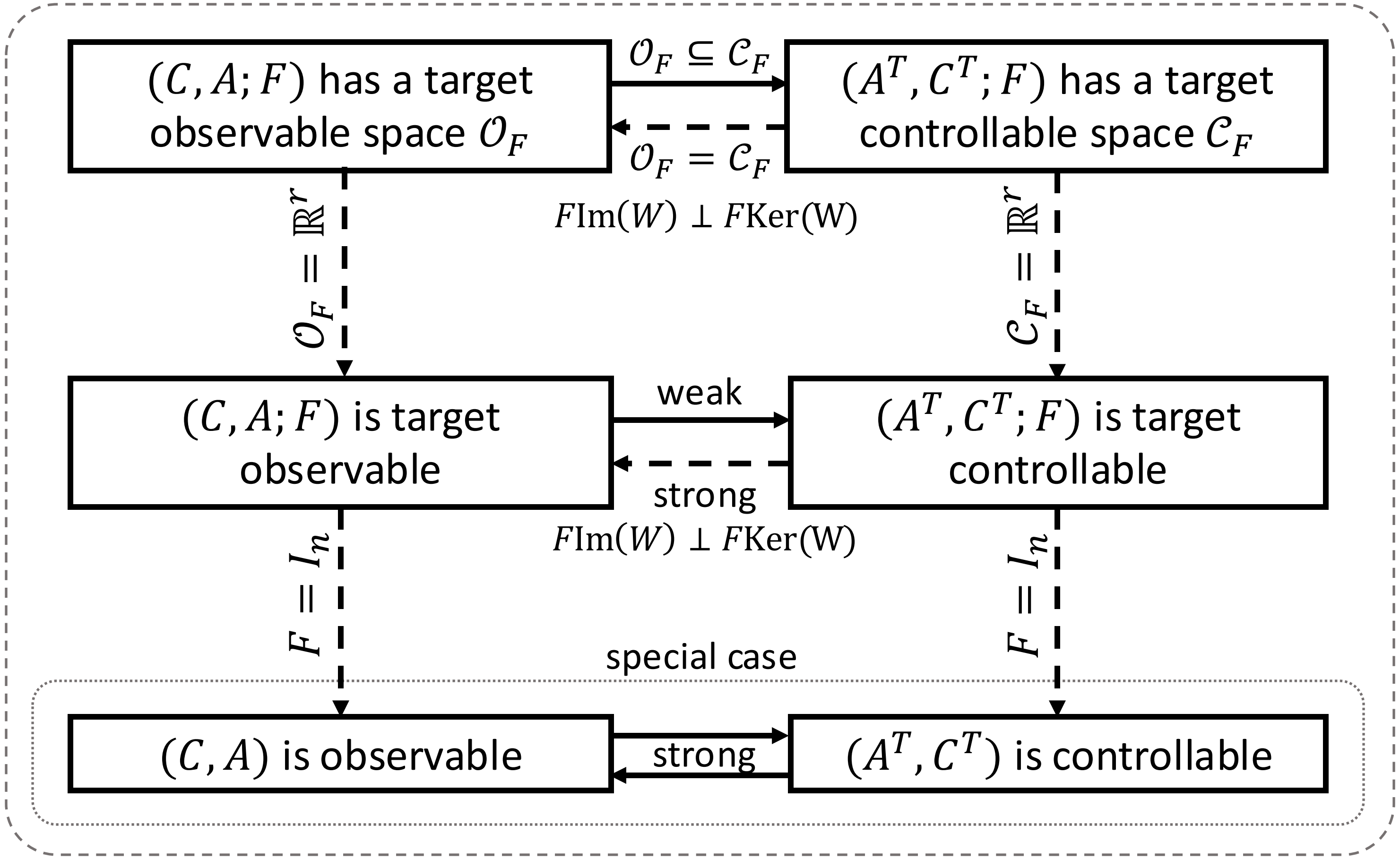

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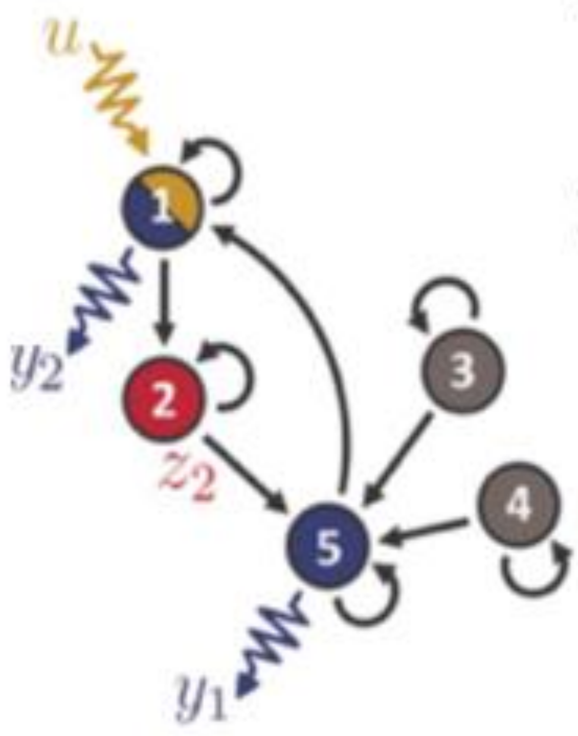
Partial state control via feedback



$\text{rank}[\mathcal{C}] < n$	uncontrollable system (A, B)	$\boldsymbol{x}(t)$ cannot be steered via feedback $\boldsymbol{u} = -K\boldsymbol{x}$
condition ???	functionally controllable system $(A, B; F)$	$\boldsymbol{z}(t)$ can be steered via feedback $\boldsymbol{u} = -K\boldsymbol{x}$

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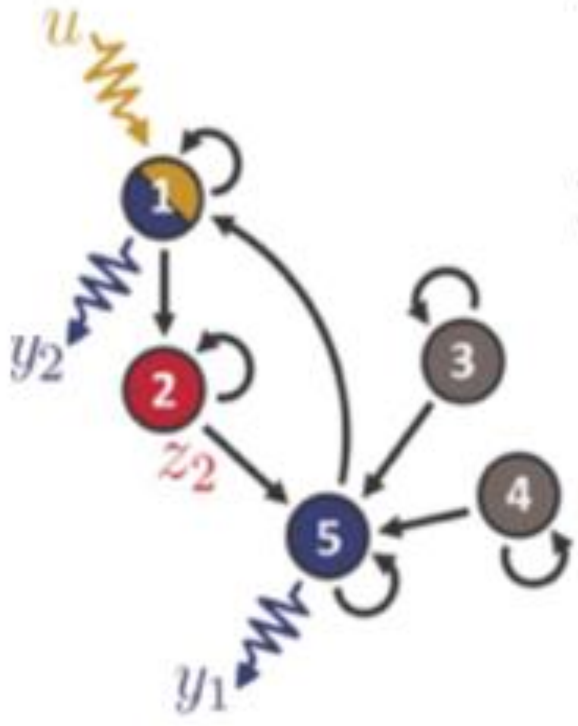
Partial state control via feedback



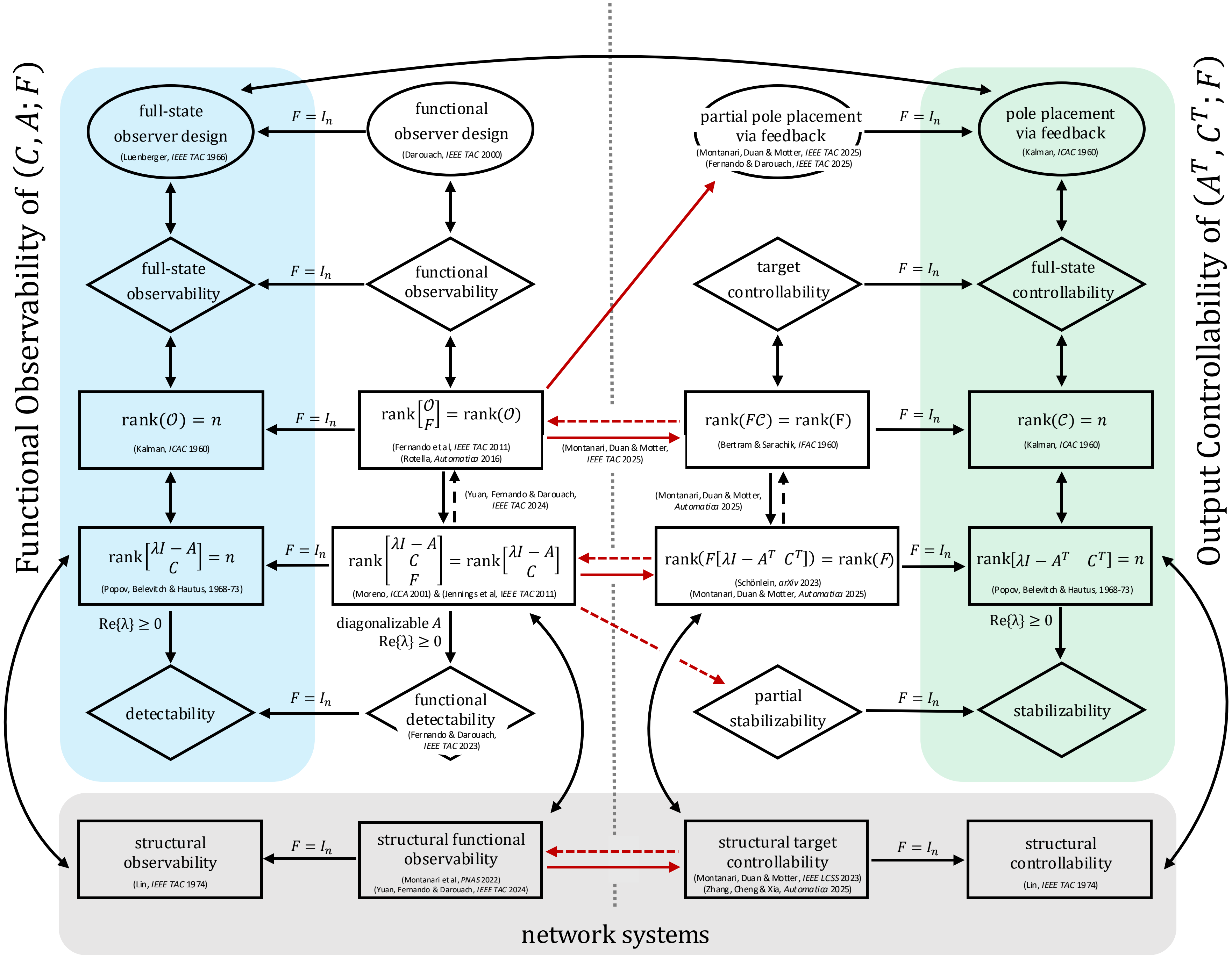
$\mathrm{rank}[\mathcal{C}] < n$ — uncontrollable system (A, B) — $\boldsymbol{x}(t)$ cannot be steered via feedback $\boldsymbol{u} = -K\boldsymbol{x}$

$\mathrm{rank}[\mathcal{C} \quad F] = \mathrm{rank}[\mathcal{C}]$ — functionally controllable system $(A, B; F)$ — $\boldsymbol{z}(t)$ can be steered via feedback $\boldsymbol{u} = -K\boldsymbol{x}$

duality by transposition

$\mathrm{rank}\begin{bmatrix}\mathcal{O} \\ F\end{bmatrix} = \mathrm{rank}[\mathcal{O}]$ — functionally observable dual system $(B^T, A^T; F)$

AN Montanari, C Duan, AE Motter. Duality between controllability and observability for target control and estimation in networks. *IEEE Transactions on Automatic Control* (2025).


Functional Observability of $(C, A; F)$
Output Controllability of $(A^T, C^T; F)$
full-state observer design
(Luenberger, IEEE TAC 1966)
$F = I_n$
functional observer design
(Darouach, IEEE TAC 2000)
partial pole placement via feedback
(Montanari, Duan & Motter, IEEE TAC 2025)
(Fernando & Darouach, IEEE TAC 2025)
$F = I_n$
pole placement via feedback
(Kalman, ICAC 1960)
full-state observability
$F = I_n$
functional observability
target controllability
$F = I_n$
full-state controllability
$\mathrm{rank}(\mathcal{O}) = n$
(Kalman, ICAC 1960)
$F = I_n$
$\mathrm{rank}\begin{bmatrix}\mathcal{O}\\F\end{bmatrix} = \mathrm{rank}(\mathcal{O})$
(Fernando et al, IEEE TAC 2011)
(Rotella, Automatica 2016)
(Montanari, Duan & Motter, IEEE TAC 2025)
$\mathrm{rank}(F\mathcal{C}) = \mathrm{rank}(\mathrm{F})$
(Bertram & Sarachik, IFAC 1960)
$F = I_n$
$\mathrm{rank}(\mathcal{C}) = n$
(Kalman, ICAC 1960)
(Yuan, Fernando & Darouach, IEEE TAC 2024)
(Montanari, Duan & Motter, Automatica 2025)
$\mathrm{rank}\begin{bmatrix}\lambda I - A\\C\end{bmatrix} = n$
(Popov, Belevitch & Hautus, 1968-73)
$F = I_n$
$\mathrm{rank}\begin{bmatrix}\lambda I - A\\C\\F\end{bmatrix} = \mathrm{rank}\begin{bmatrix}\lambda I - A\\C\end{bmatrix}$
(Moreno, ICCA 2001) & (Jennings et al, IEEE TAC 2011)
$\mathrm{rank}(F[\lambda I - A^T \;\; C^T]) = \mathrm{rank}(F)$
(Schönlein, arXiv 2023)
(Montanari, Duan & Motter, Automatica 2025)
$F = I_n$
$\mathrm{rank}[\lambda I - A^T \;\; C^T] = n$
(Popov, Belevitch & Hautus, 1968-73)
$\mathrm{Re}\{\lambda\} \geq 0$
diagonalizable A
$\mathrm{Re}\{\lambda\} \geq 0$
$\mathrm{Re}\{\lambda\} \geq 0$
detectability
$F = I_n$
functional detectability
(Fernando & Darouach, IEEE TAC 2023)
partial stabilizability
$F = I_n$
stabilizability
structural observability
(Lin, IEEE TAC 1974)
$F = I_n$
structural functional observability
(Montanari et al, PNAS 2022)
(Yuan, Fernando & Darouach, IEEE TAC 2024)
structural target controllability
(Montanari, Duan & Motter, IEEE LCSS 2023)
(Zhang, Cheng & Xia, Automatica 2025)
$F = I_n$
structural controllability
(Lin, IEEE TAC 1974)
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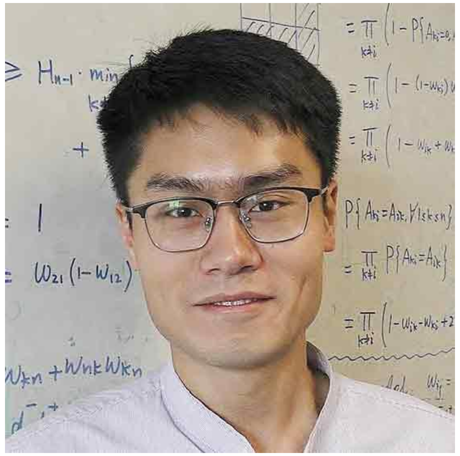

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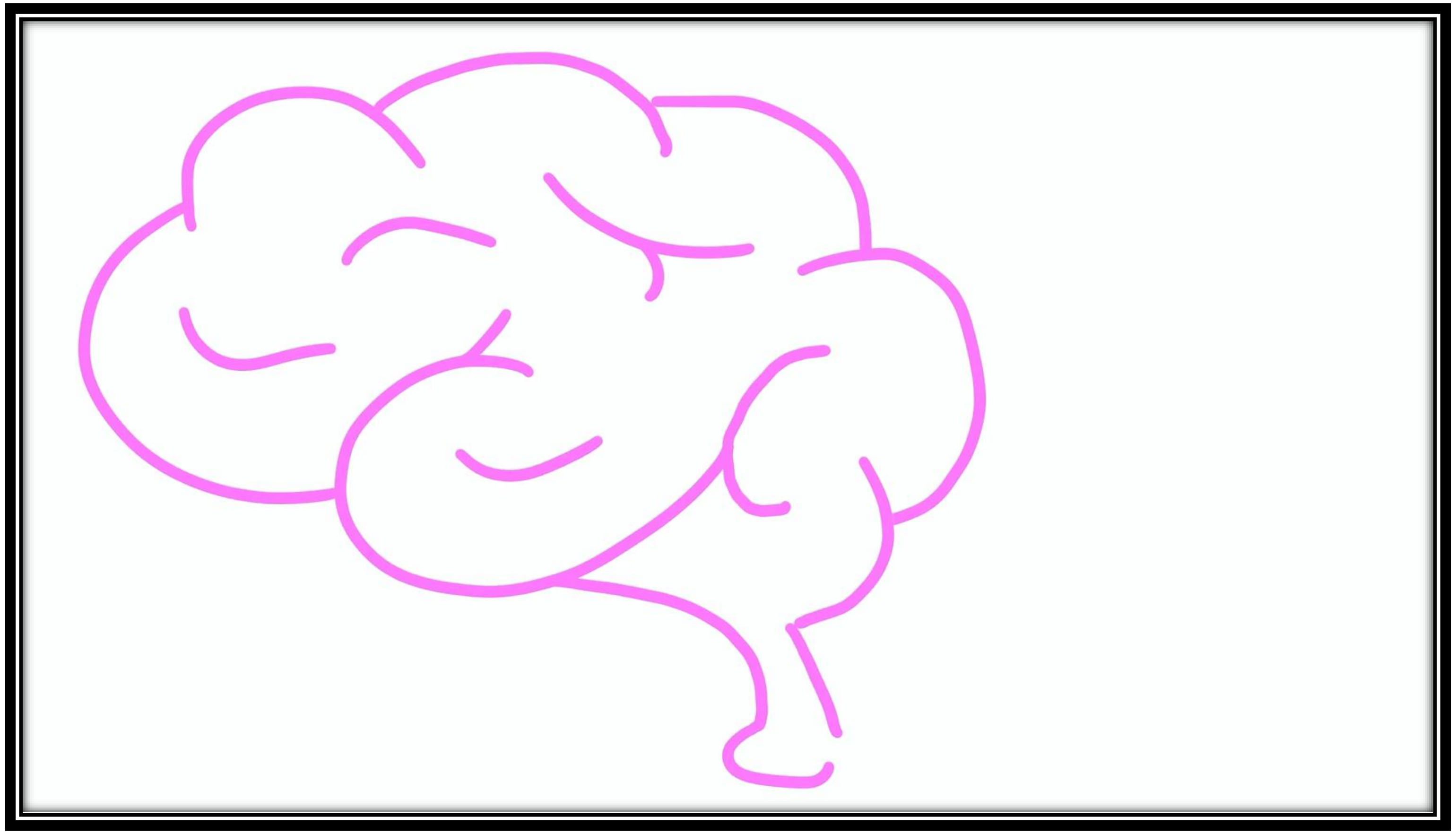
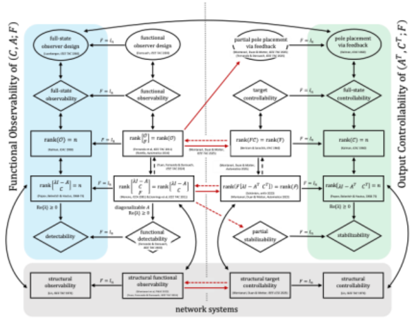


Thank you!

For slides and diagram on controllability-observability relation, see my webpage:

www.montanariarthur.com



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