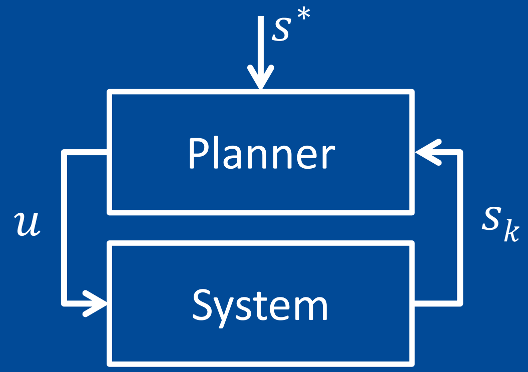
A Planning Based Framework for Controlling Hybrid Systems



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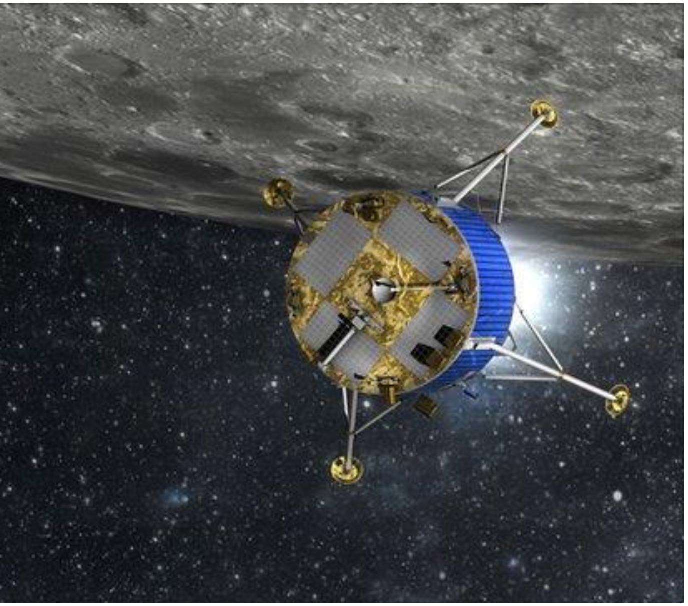
Outline

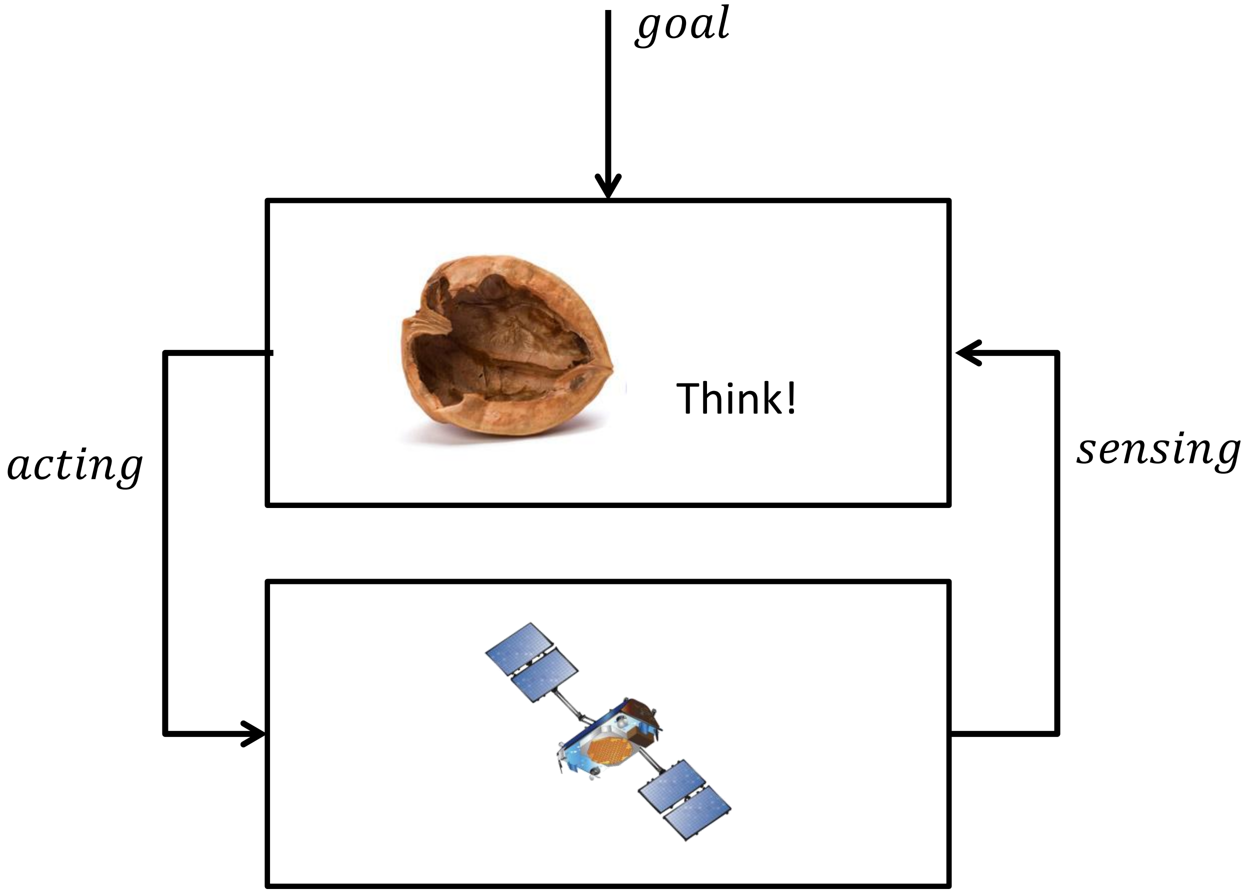
- Motivation
- From Continuous Dynamics…
- … to a Domain Model
- Domain Predictive Control
- Exemplary Simulation
- Discussion
- Outlook

Motivation



Lunar Lander ExoMars

Motivation



Motivation

- Key Aspects

Hybrid Systems
Continuous Dynamics
Boolean State Variables

Autonomy
Reduction of Computational Effort
Quick Decision Generation

Exogenous Events
Obstacles
Reactivity

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From a Hybrid System…

Hybrid System

$$\dot{\boldsymbol{x}}_n(t) = A(\boldsymbol{x}_l)\,\boldsymbol{x}_n(t) + B(\boldsymbol{x}_l)\,\boldsymbol{u}\,(t)$$

Planning Task

Find $\boldsymbol{u}(t),\ t \in [t_a, t_b]$ such that:

$$\mathbf{x}_n(t_a) \longrightarrow \mathbf{x}_n(t_b)$$

Initial State → Desired State

…to a Planning Action…

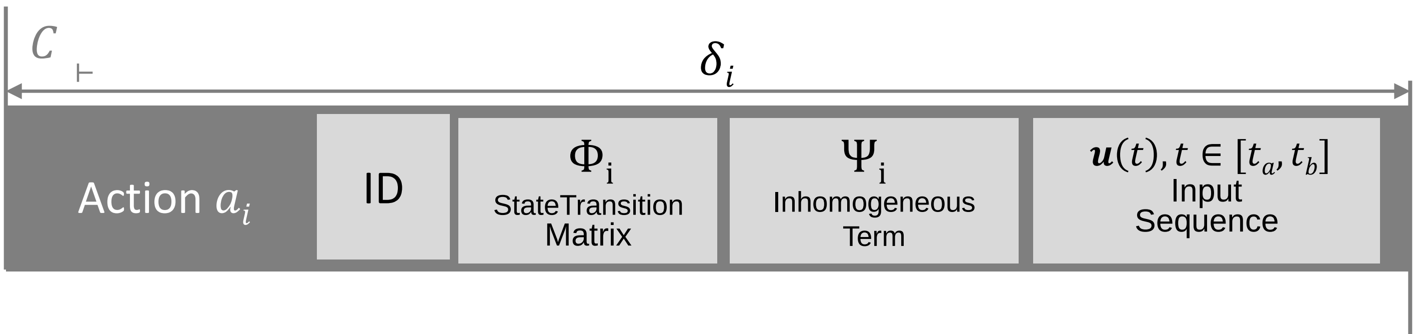
1. Anticipate some input fragments $\boldsymbol{u}_i(t), t \in [0, \delta_i]$

2. Solve the differential equations (preprocessing step)

$$\Phi = e^{A(\boldsymbol{x}_l)\,\delta_i}$$

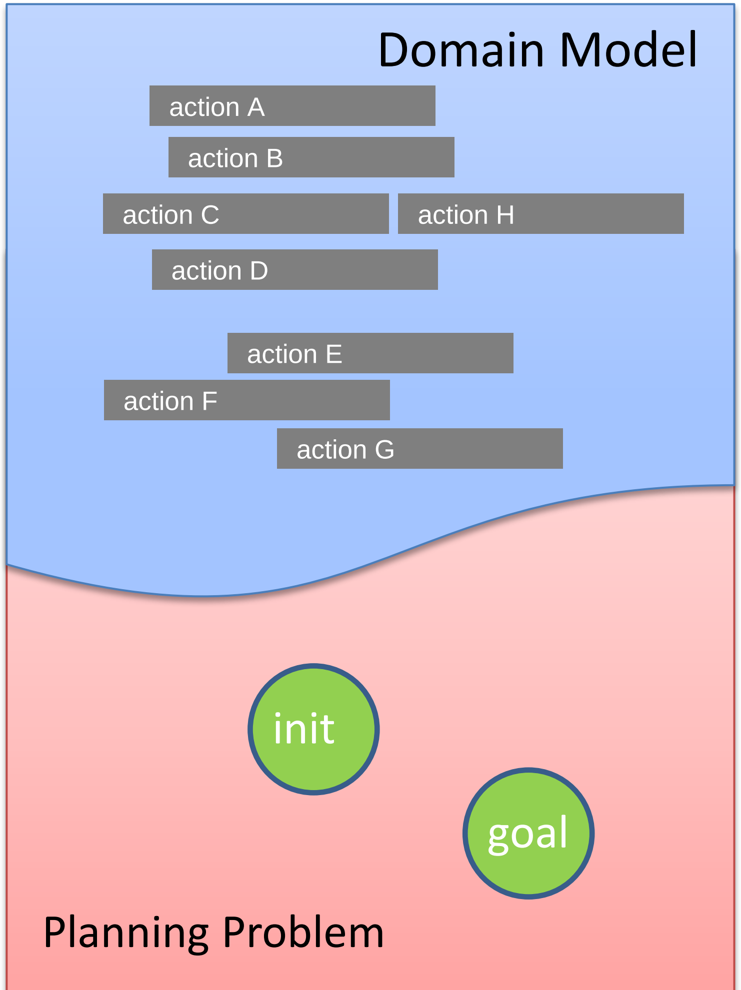
$$\Psi = \int_{t_0}^{t_0+\delta_i} e^{A(x_l)\cdot(t_0+\delta_i-\tau)}\, B(\boldsymbol{x}_l)\, \boldsymbol{u}(\tau)\, d\tau$$

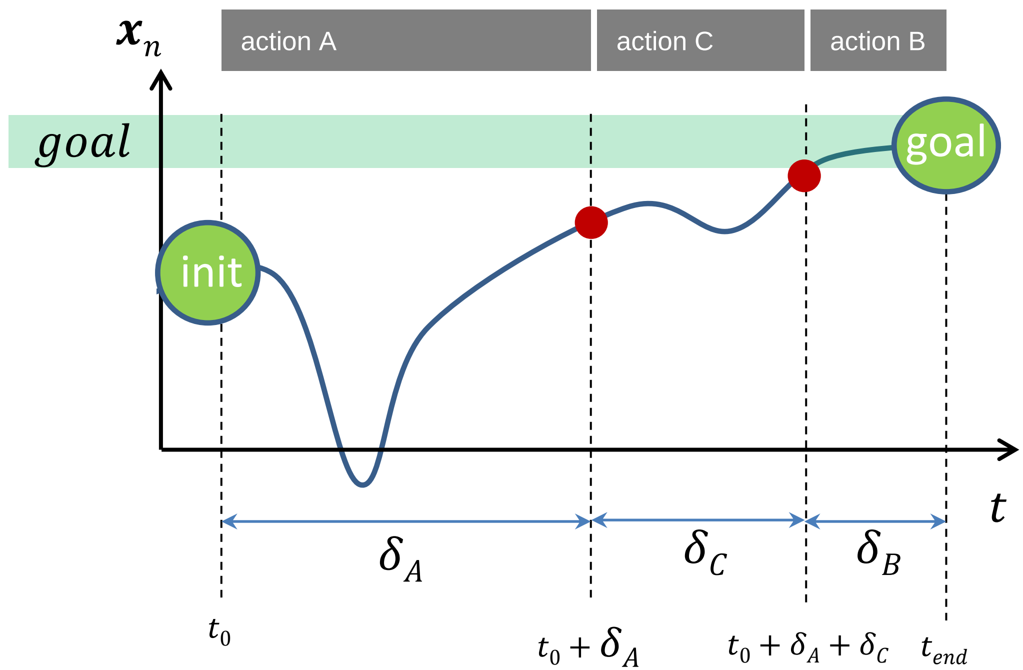
3. Generate planning action



$$E_{\dashv}: \quad \boldsymbol{x}_n(t_0 + \delta_i) = \Phi_i\, \boldsymbol{x}_n(t_0) + \Psi_i$$

… to the Domain Model





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- **Domain Predictive Control**
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Remember the Key Aspects

- Key Aspects

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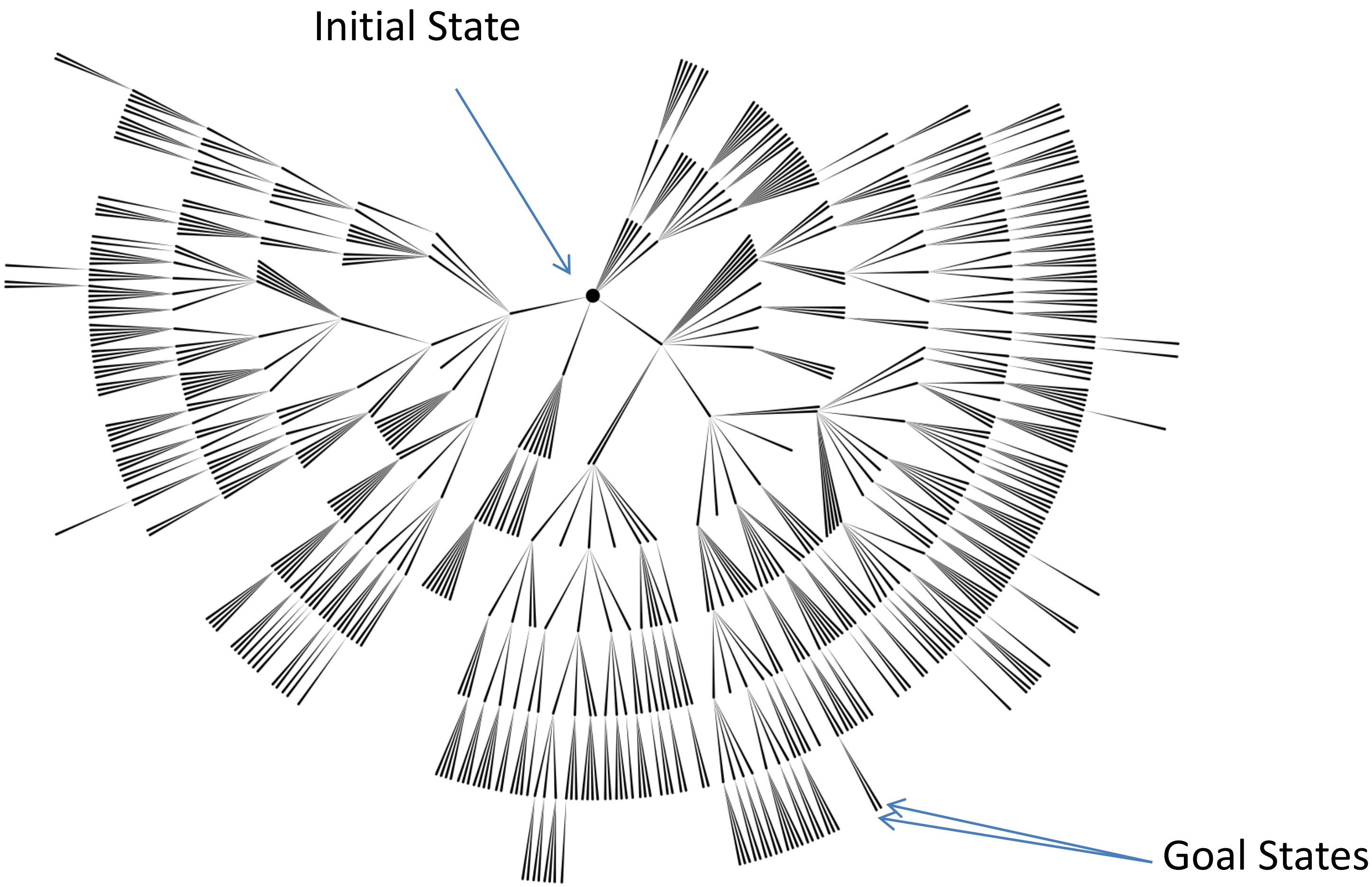
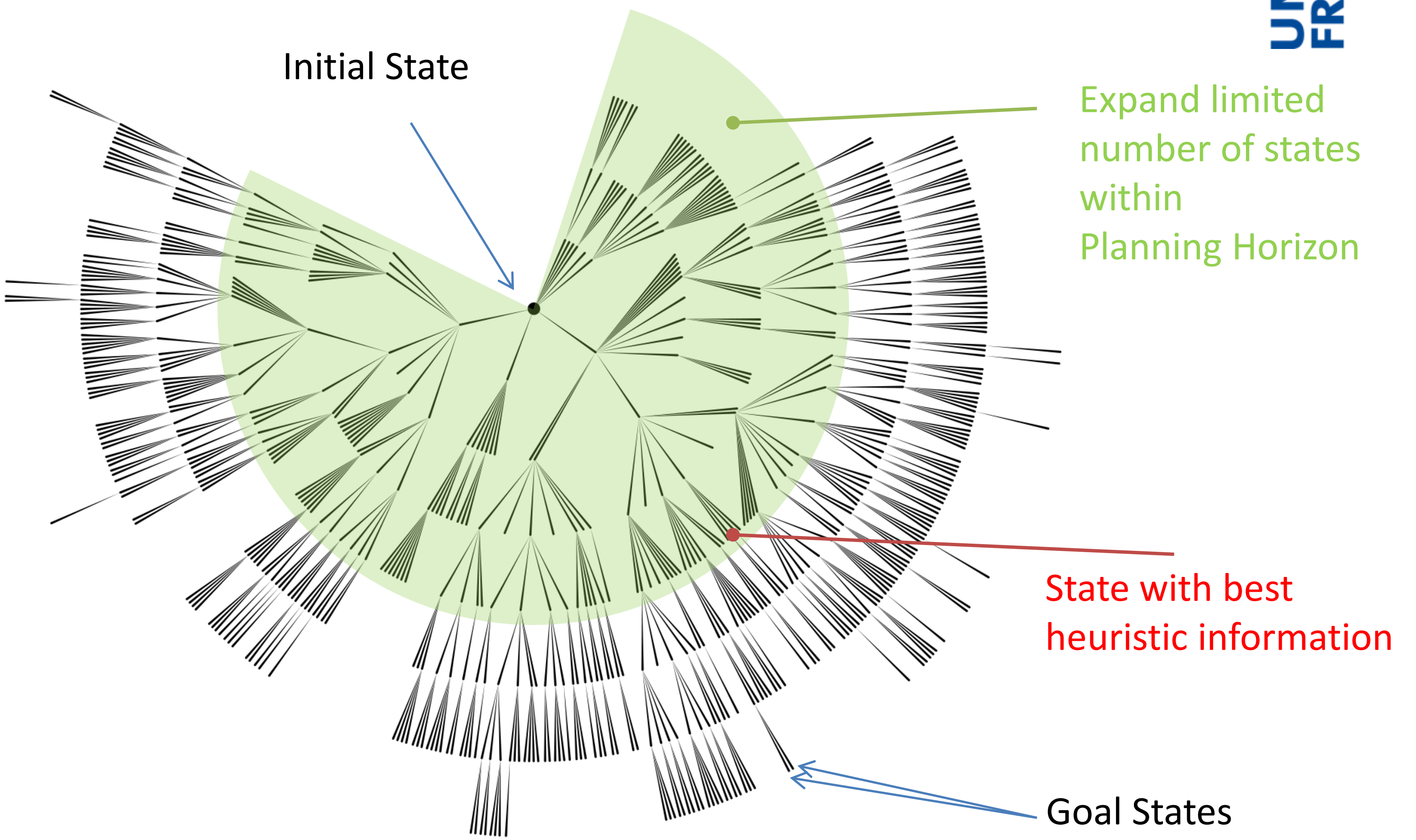
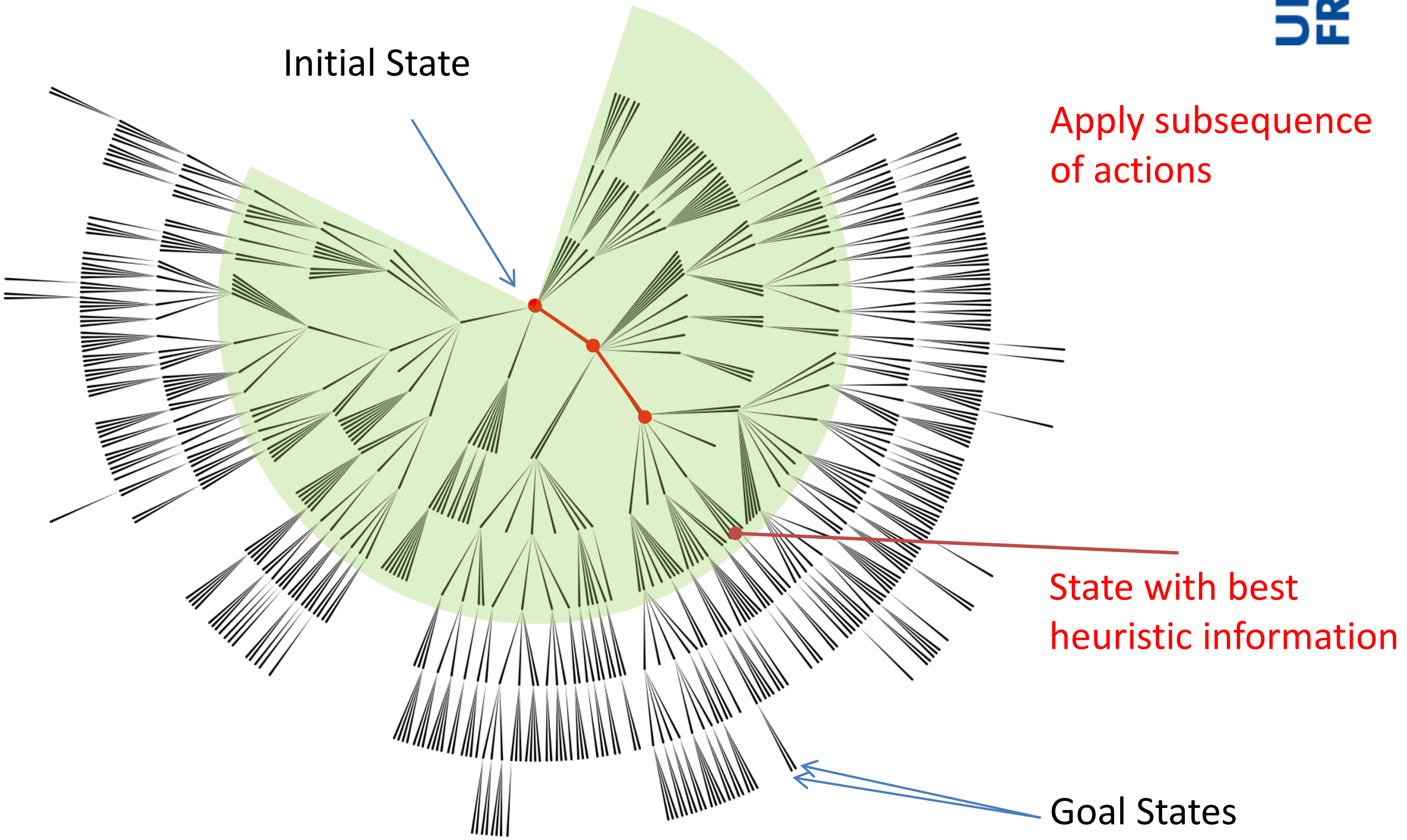
Domain Predictive Control



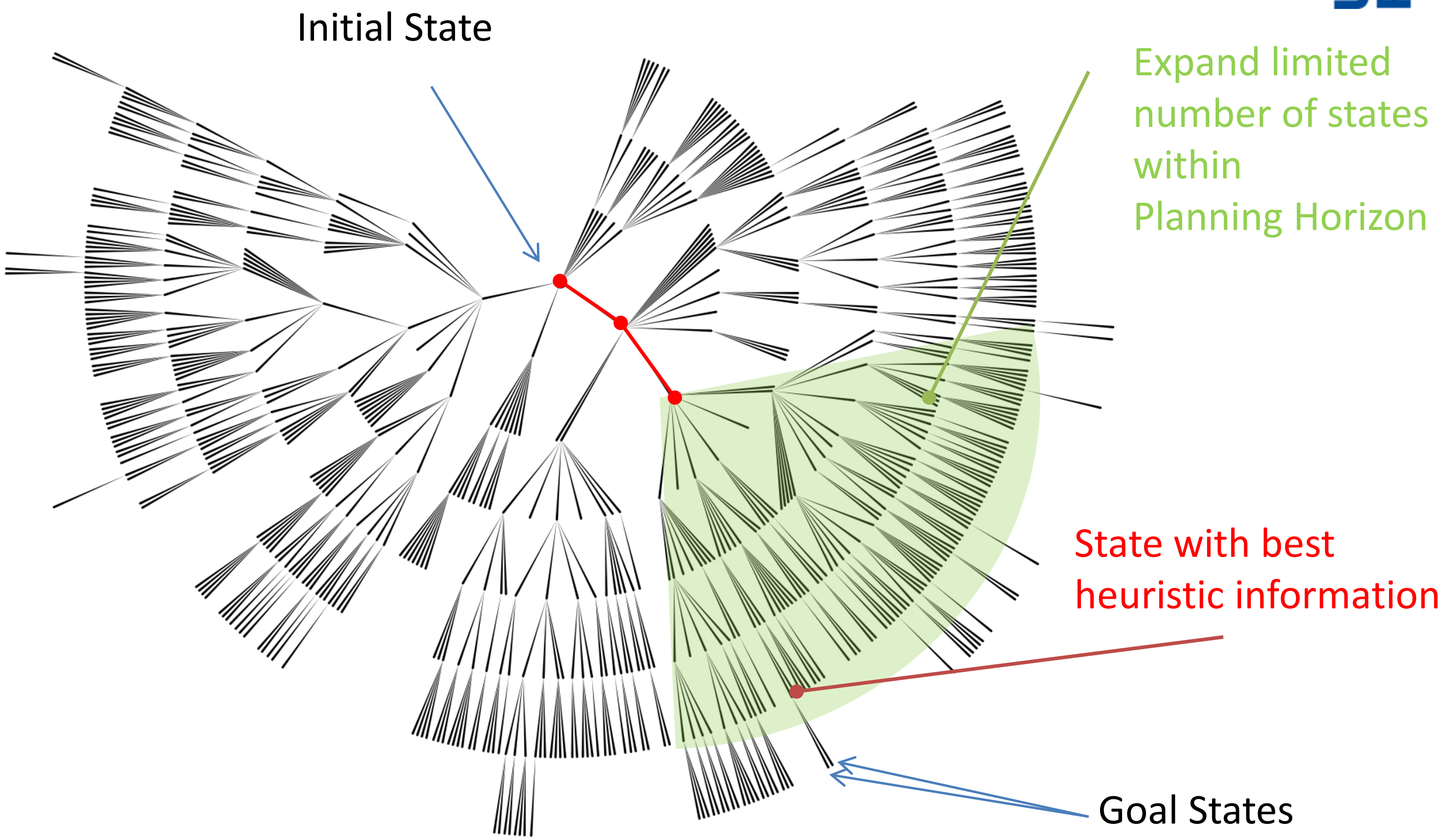
Domain Predictive Control



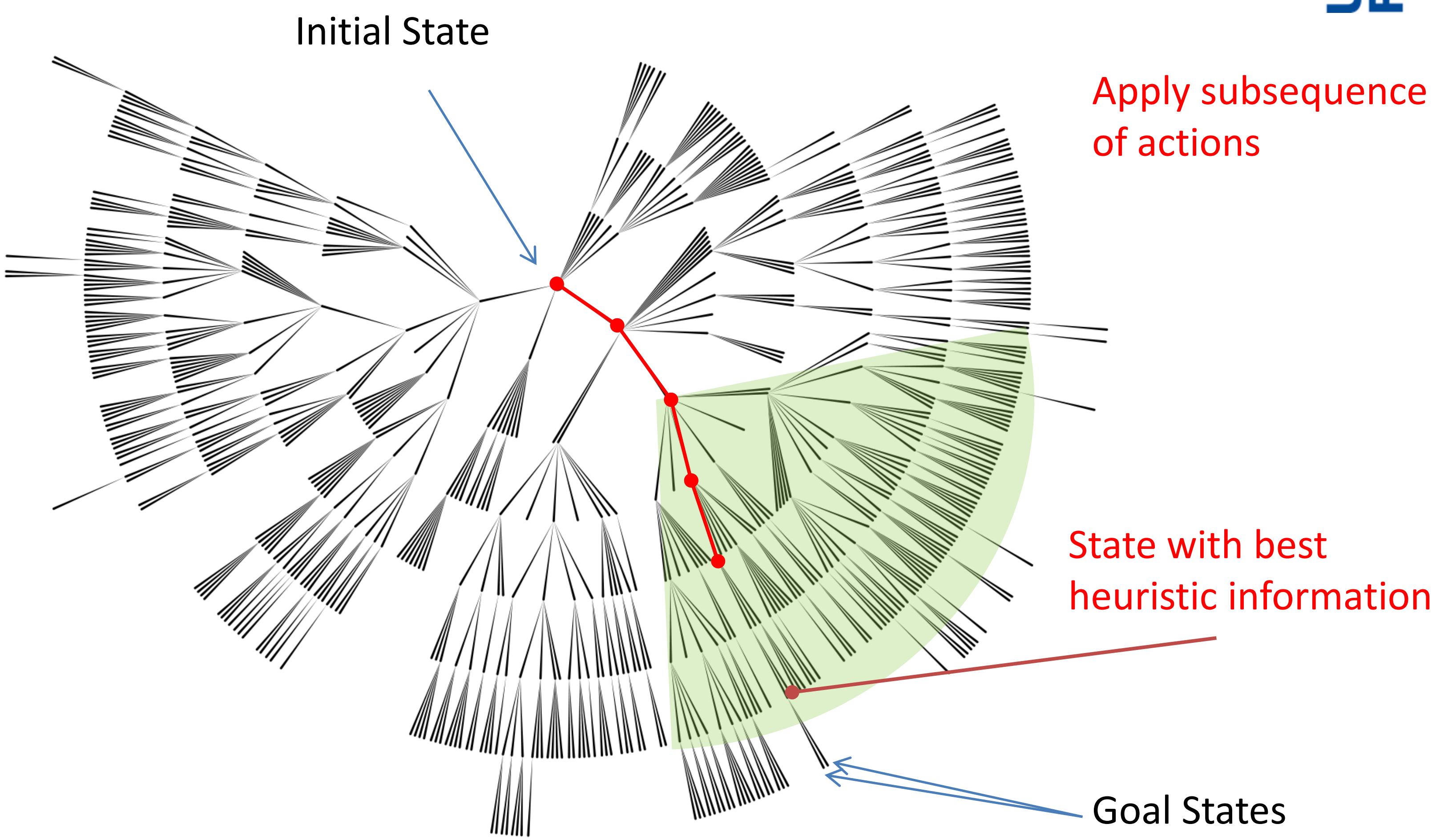
Domain Predictive Control



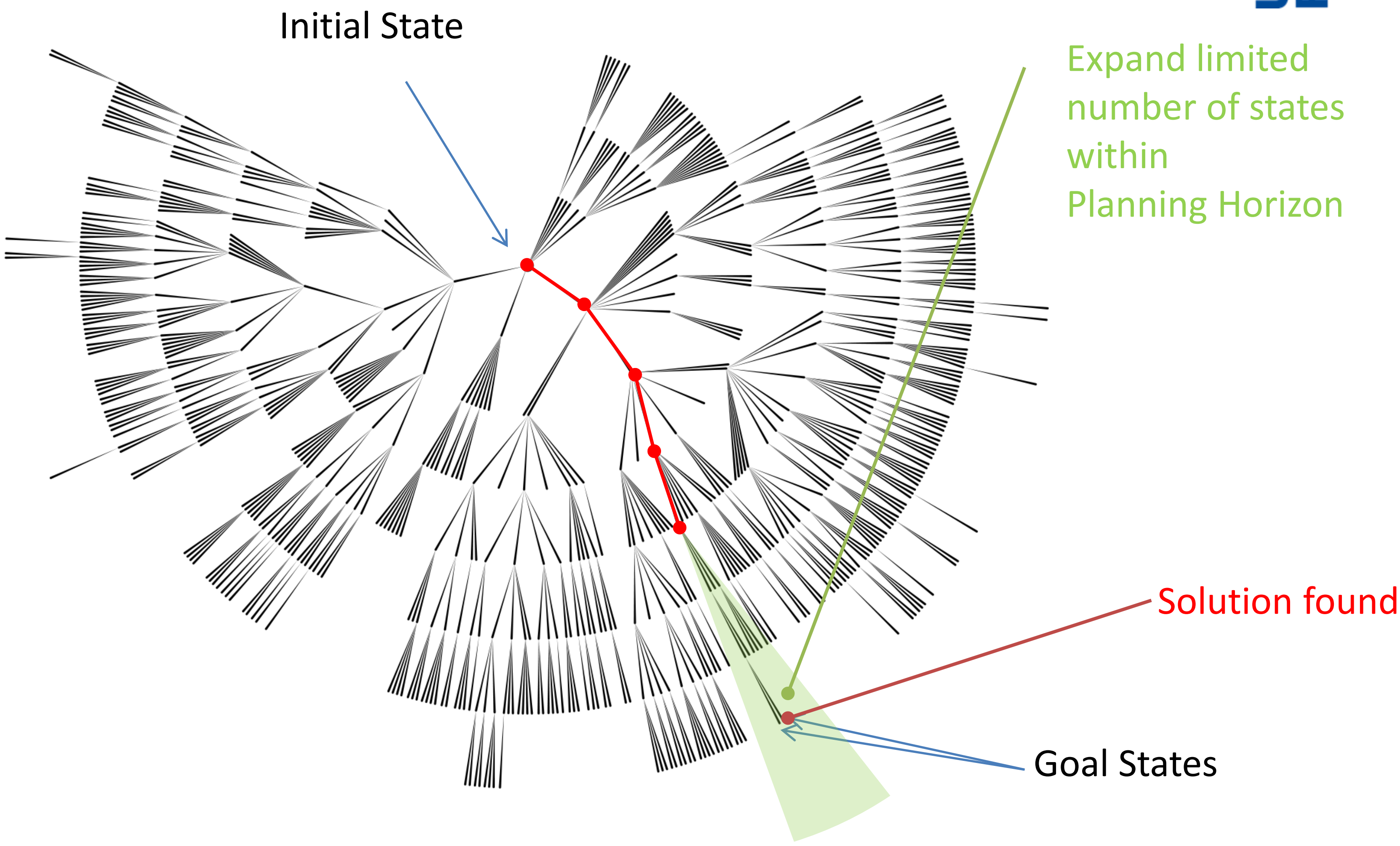
Domain Predictive Control



Domain Predictive Control



Domain Predictive Control



Domain Predictive Control

- Key Aspects

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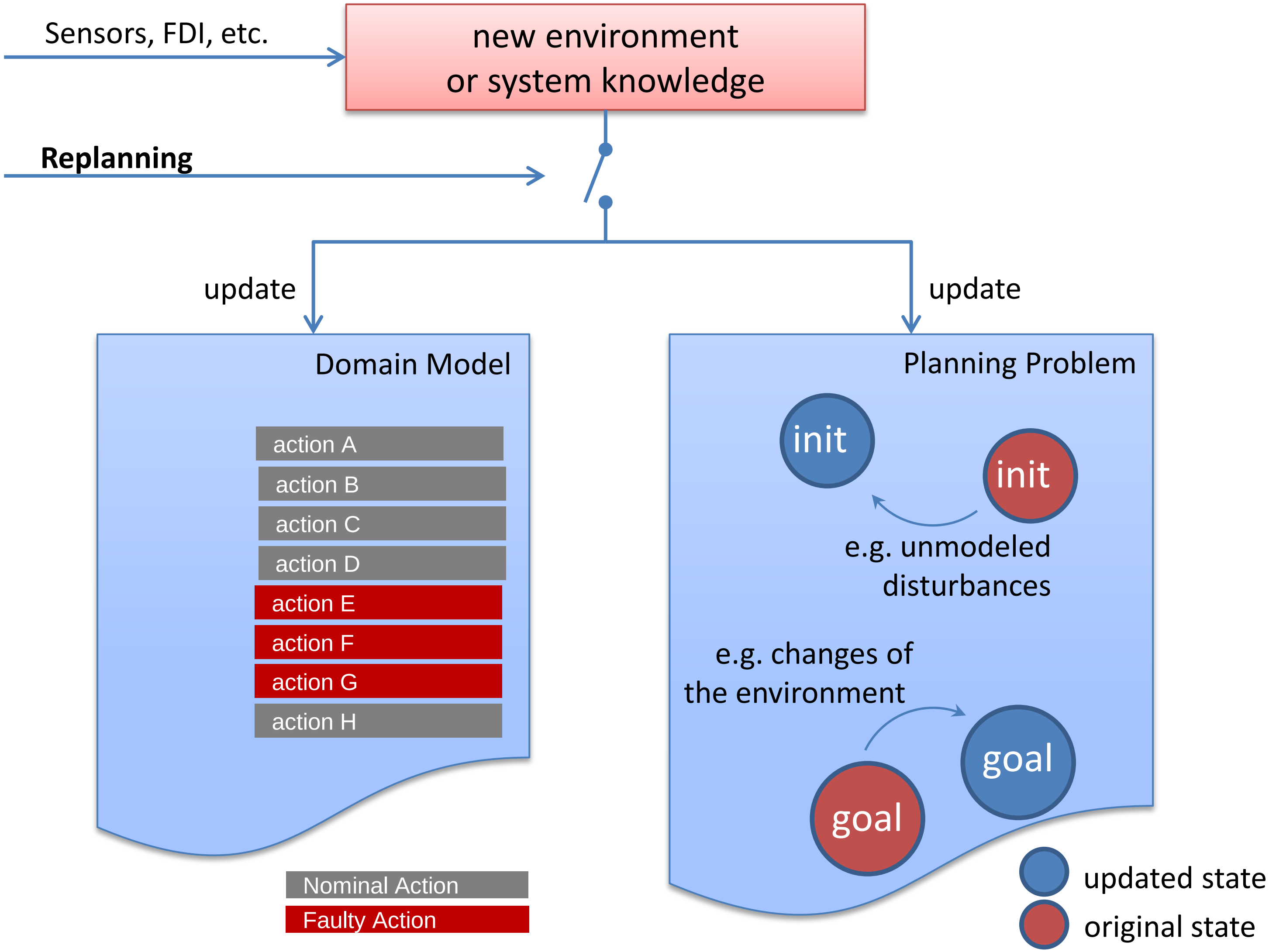
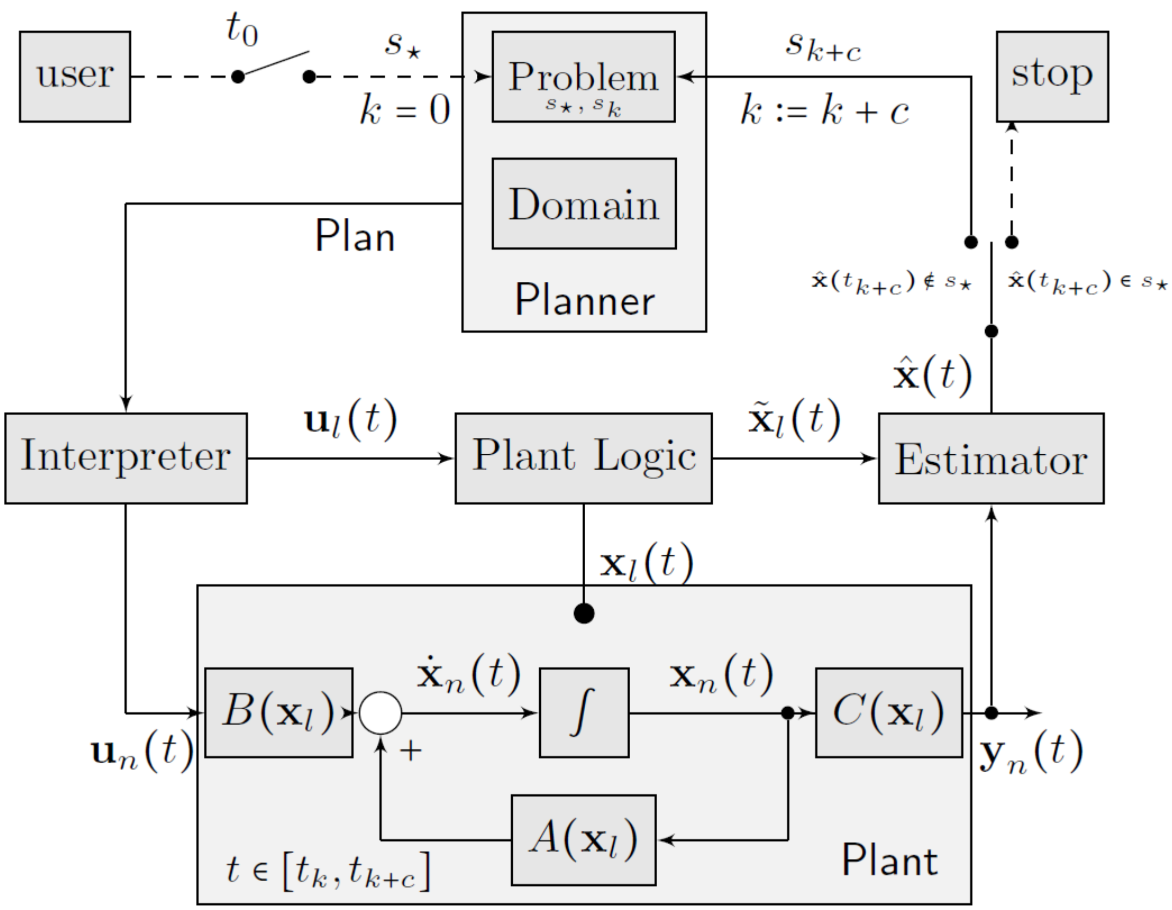
Domain Predictive Control



Domain Predictive Control Arcitecture



Outline

Motivation

From Continuous Dynamics…

… to a Domain Model

Domain Predictive Control

Exemplary Simulations

Discussion

Outlook

Exemplary Simulation

action 0	$\alpha_y = 0°$	$\alpha_x = 0°$
action 1	$\alpha_y = 0°$	$\alpha_x = 2.92°$
action 2	$\alpha_y = 0°$	$\alpha_x = -2.92°$
action 3	$\alpha_y = 2.92°$	$\alpha_x = 0°$
action 4	$\alpha_y = -2.92°$	$\alpha_x = 0°$
action 5	$\alpha_y = 2.92°$	$\alpha_x = -2.92°$
action 6	$\alpha_y = 2{,}92°$	$\alpha_x = 2.92°$
action 7	$\alpha_y = 2.92°$	$\alpha_x = -2.92°$
action 8	$\alpha_y = -2.92°$	$\alpha_x = -2.92°$

$$\delta_i = 0.5\, s, \forall\, i \in [0,8]$$

$p_{\vdash}$ =

$[(x > 8) \lor (x < 2) \lor (y > 3) \lor (y < 2)] \land$

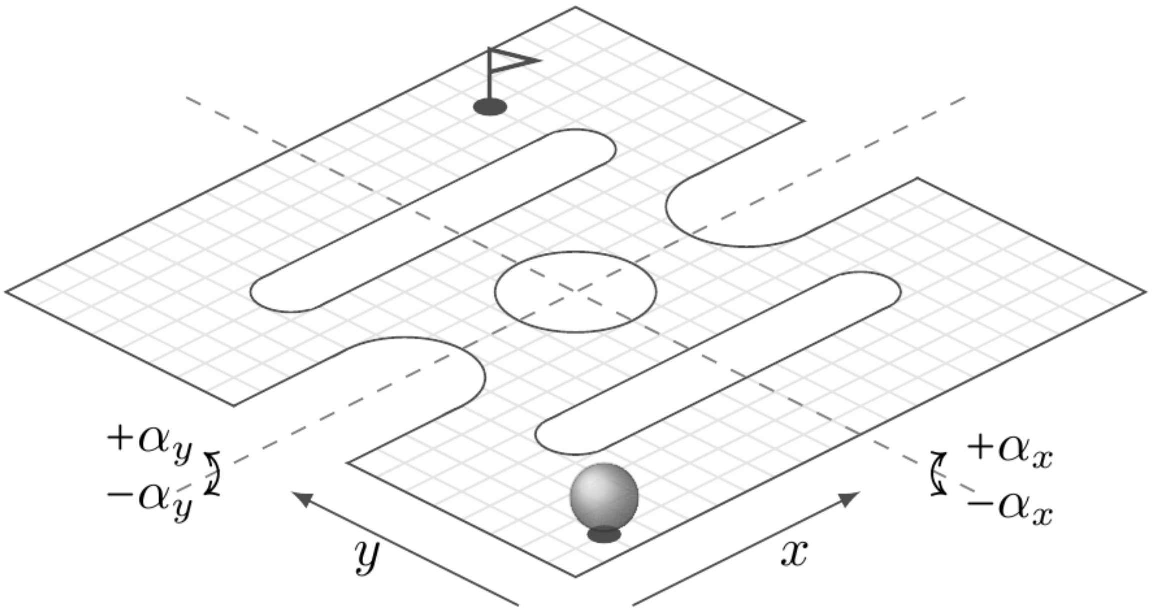
$[(x > 6) \lor (x < 4) \lor (y > 6) \lor (y < 4)] \land$

$[(x > 4) \lor (x < 0) \lor (y > 6) \lor (y < 4)] \land$

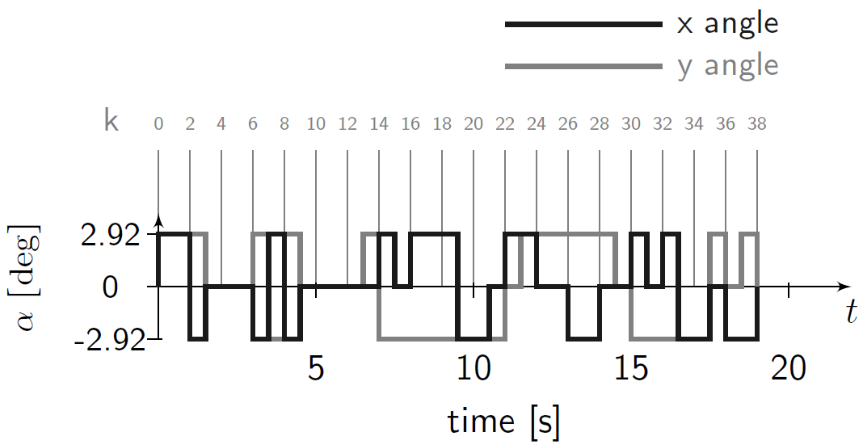
$[(x > 10) \lor (x < 6) \lor (y > 6) \lor (y < 4)] \land$

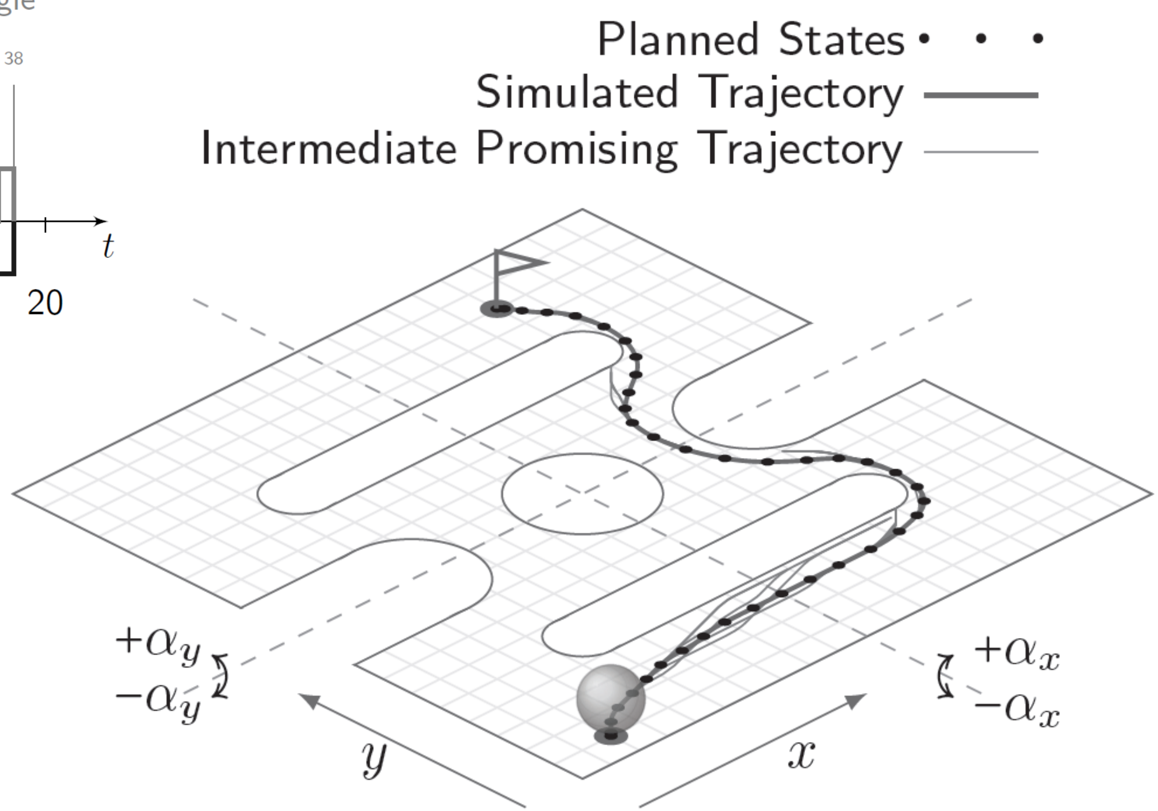
$[(x > 8) \lor (x < 2) \lor (y > 8) \lor (y < 7)] \land$

$[(x > 0) \land (x < 10) \land (y > 0) \land (y < 10)]$



Exemplary Simulation





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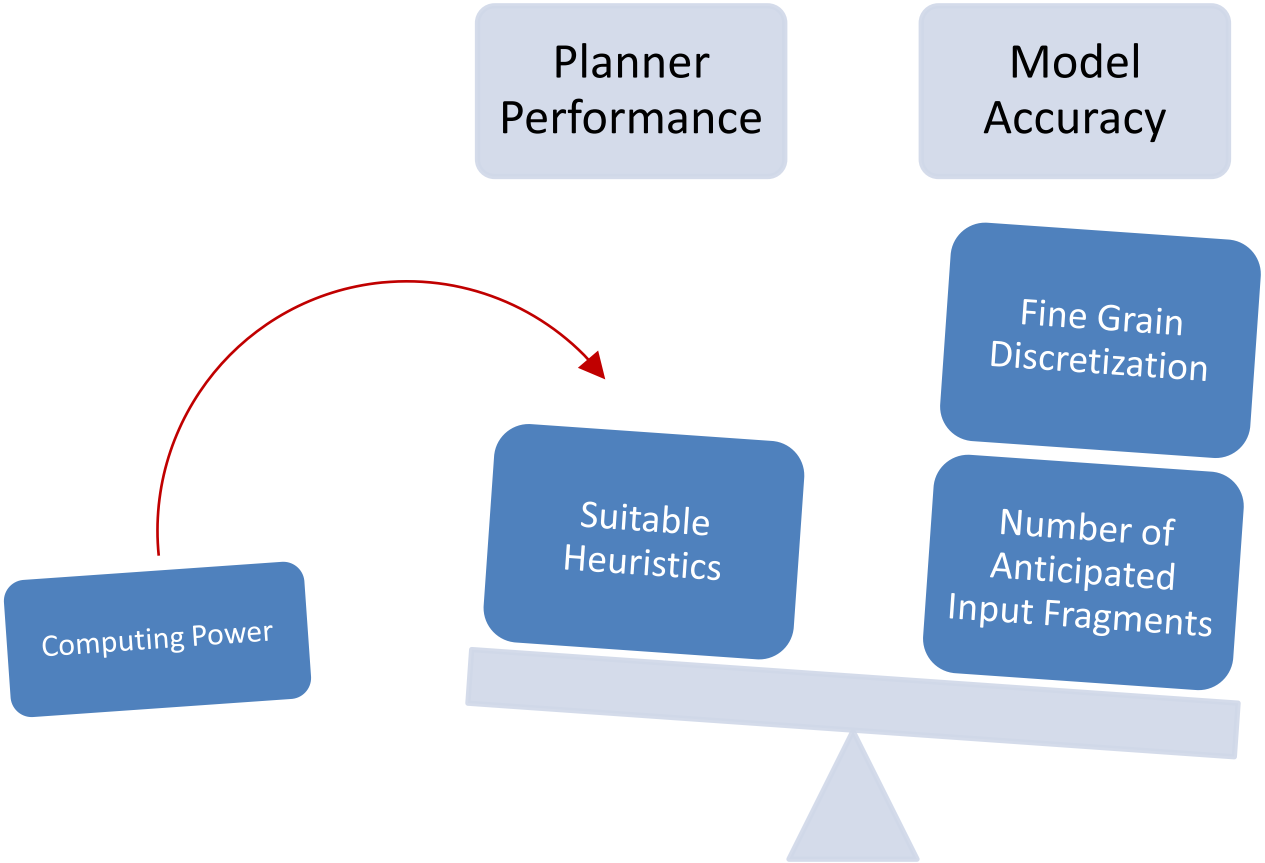
Discussion


Planner Performance
Model Accuracy
Fine Grain Discretization
Suitable Heuristics
Number of Anticipated Input Fragments
Computing Power

Summary and Conclusion

Pros

- **general** problem formulation
- **changing system configurations**
- restricted state space
- **failure tolerance**

Cons

- anticipated input fragments
- discrete system dynamics
- computational effort
- currently: linear systems only

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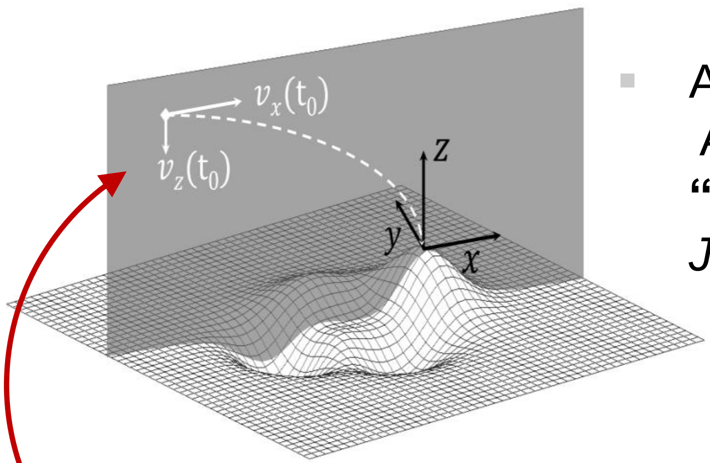
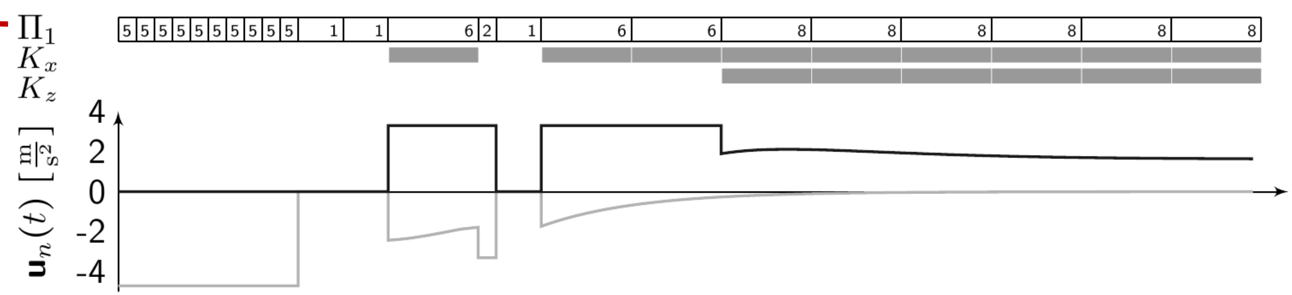
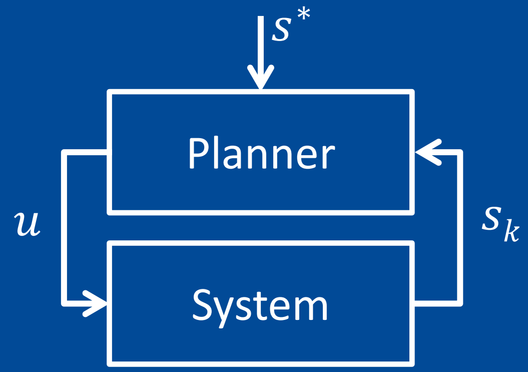
Outlook



- American Institute of Aeronautics and Astronautics Astrodynamics Specialist Conference (August 2012)
"Planning-based Autonomous Lander Control"
J. Löhr, B. Nebel, and S. Winkler



Planning Based Framework for Controlling Hybrid Systems



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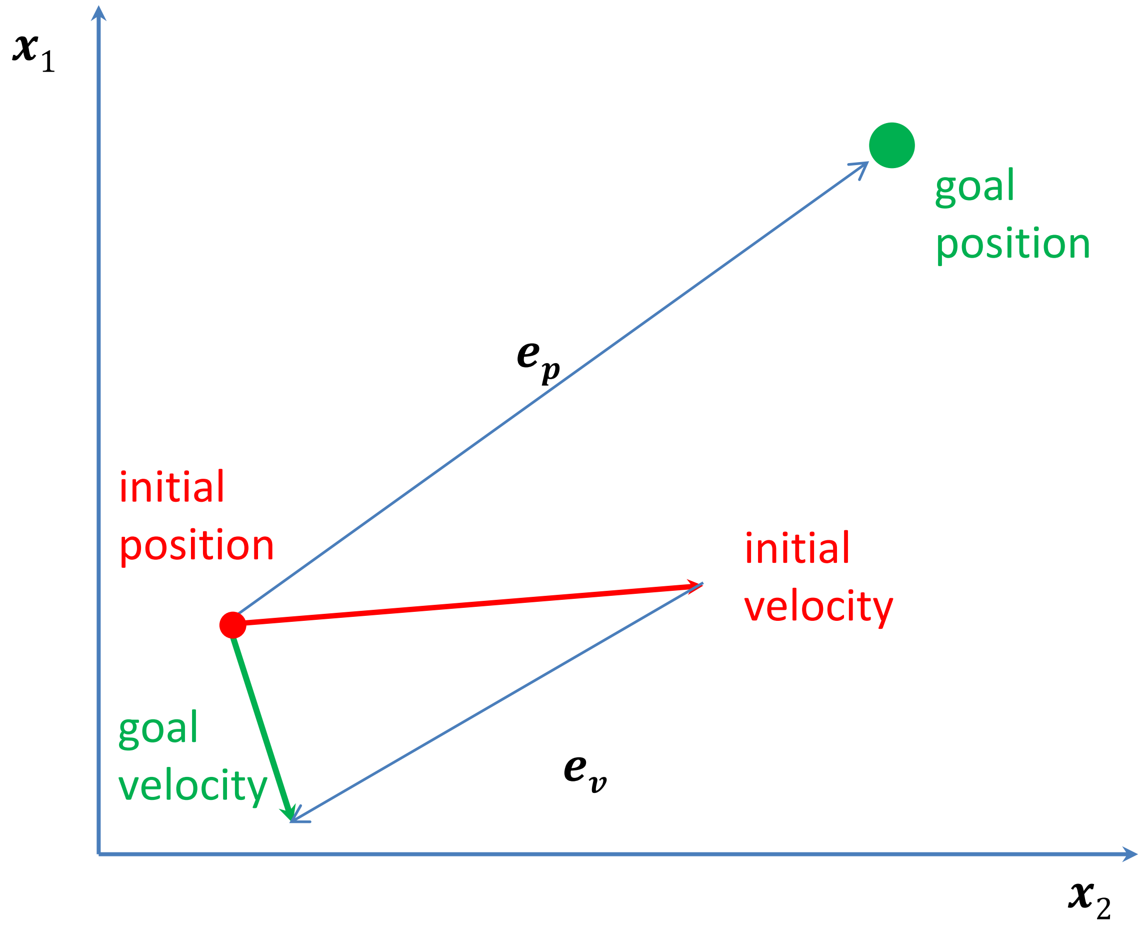
Heuristic

Error State Heuristic

$$h = \|\boldsymbol{e}_p + \boldsymbol{e}_v\|_1$$

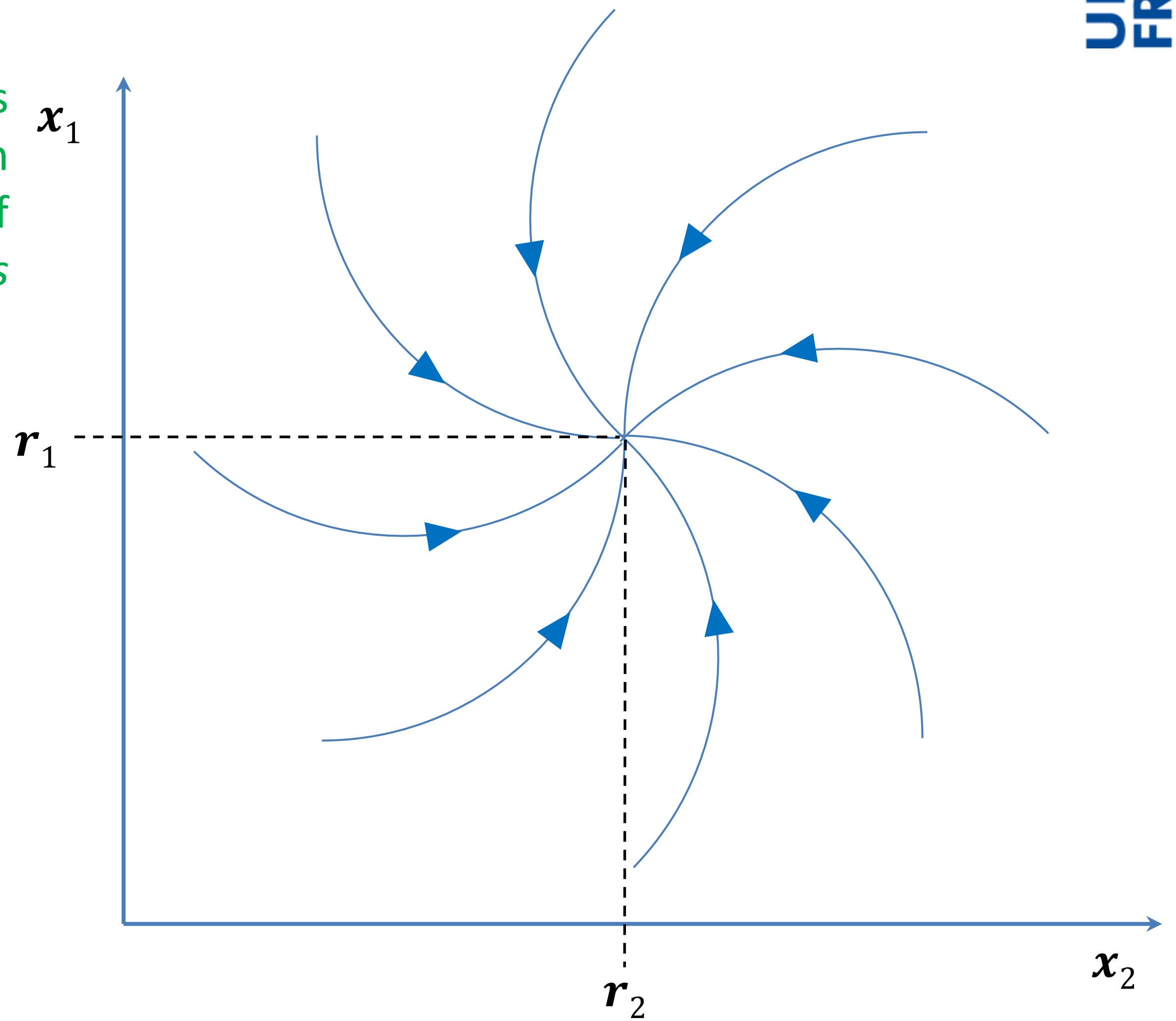
Open Heuristic Issues:

1. Weighting of numerical variables
2. Weighting between numerical and logical variables



Stable Dynamics

Homogeneous
Solution
of
Stable Dynamics



$\dot{x}_n(t) = A_{cl}\,x_n(t) + B u_n(t)$

A_{cl} state feedback controlled
$u_n(t) = -K\,x_n(t)$

closed loop dynamics
$A_{cl} = A - BK$

choose controller K such that
$Re(eig|A - B\,K|) < 0$

Stable Dynamics

Homogeneous
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$\dot{\boldsymbol{x}}_n(t) = A_{\boldsymbol{cl}}\,\boldsymbol{x}_n(t) + B\boldsymbol{u}_n(t)$

$A_{\boldsymbol{cl}}$ state feedback controlled
$\boldsymbol{u}_n(t) = -\mathrm{K}\,\boldsymbol{x}_n(t)$

closed loop dynamics
$A_{\boldsymbol{cl}} = \mathrm{A} - \mathrm{BK}$

choose controller K such that
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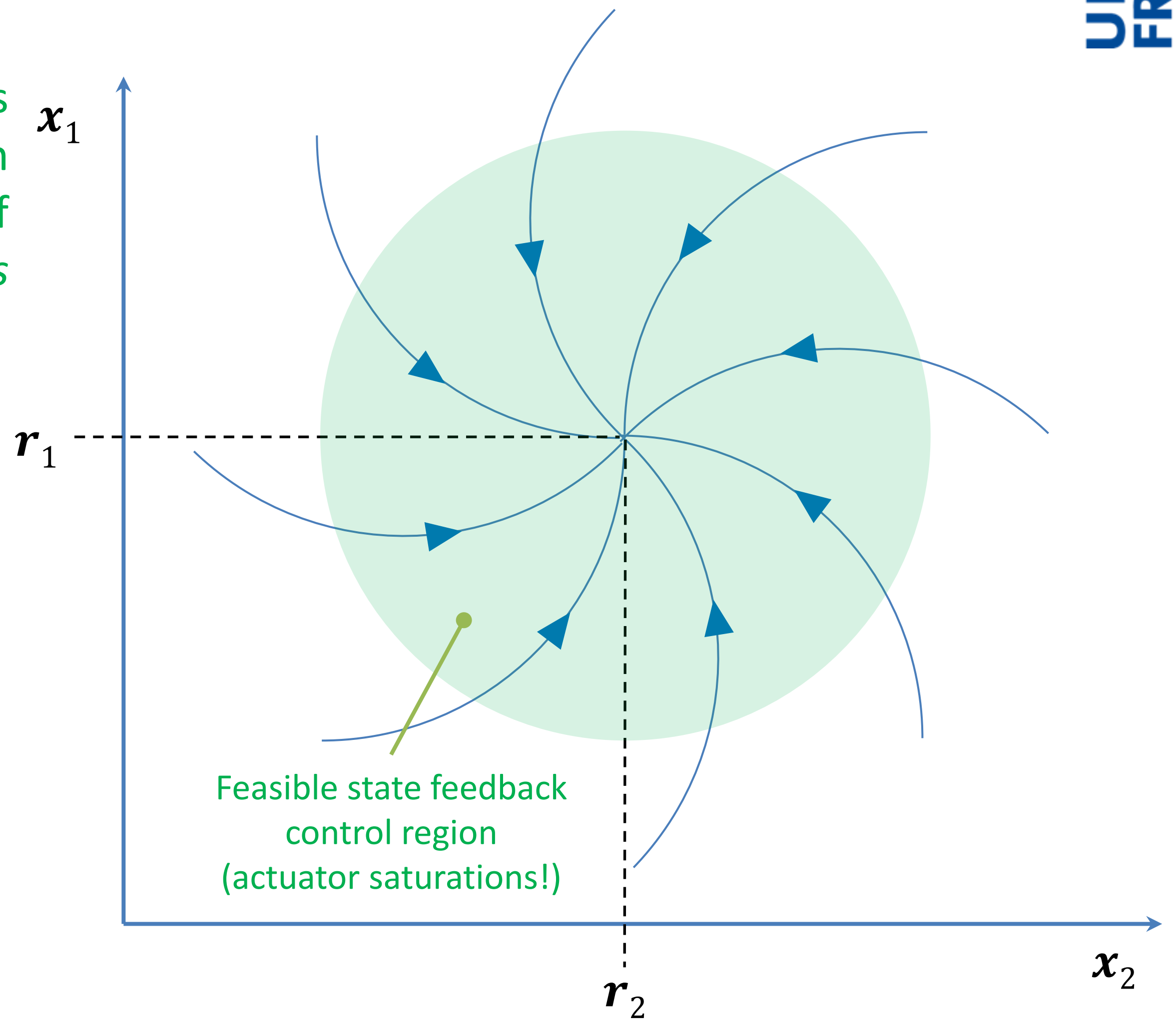
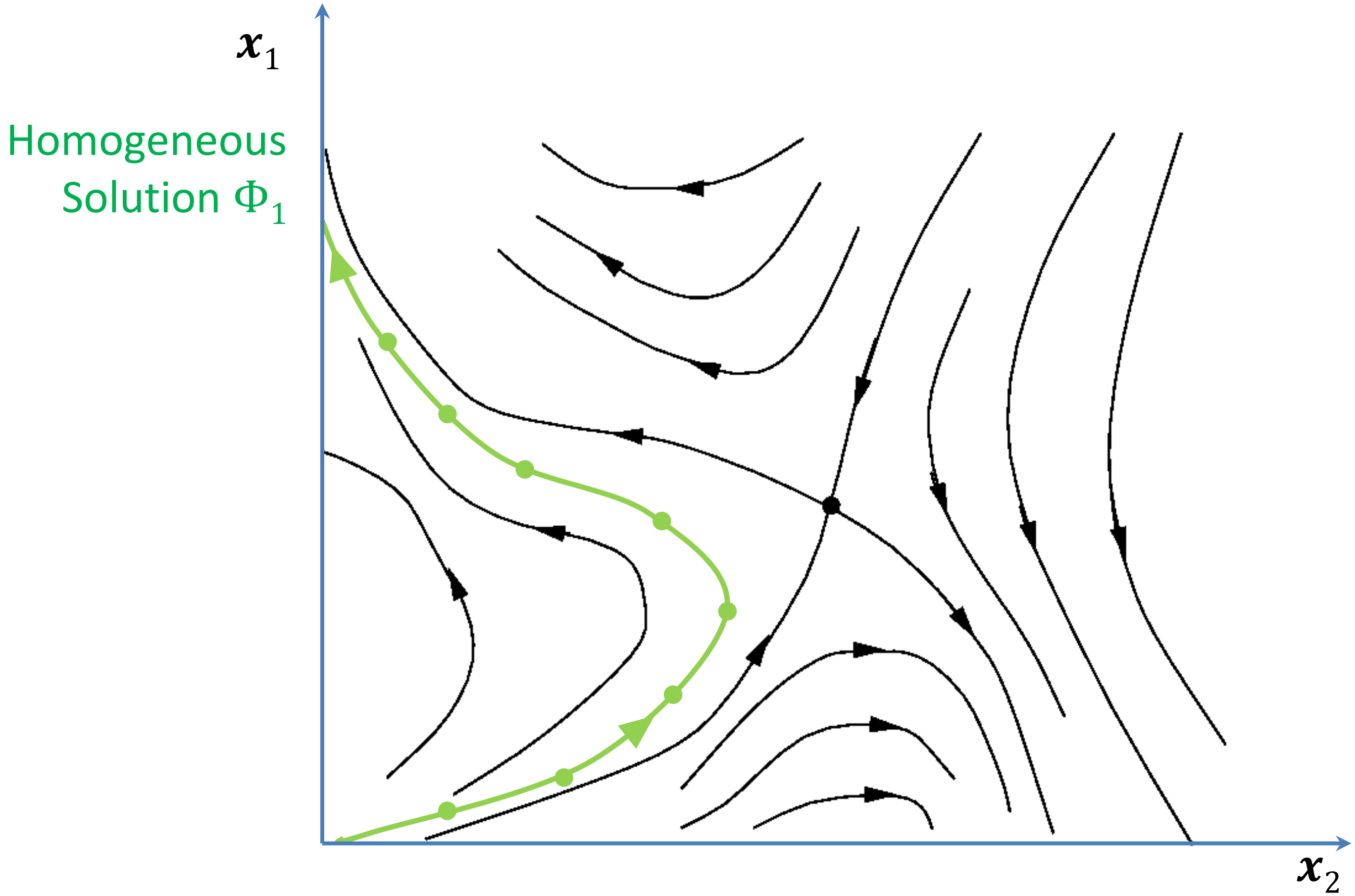
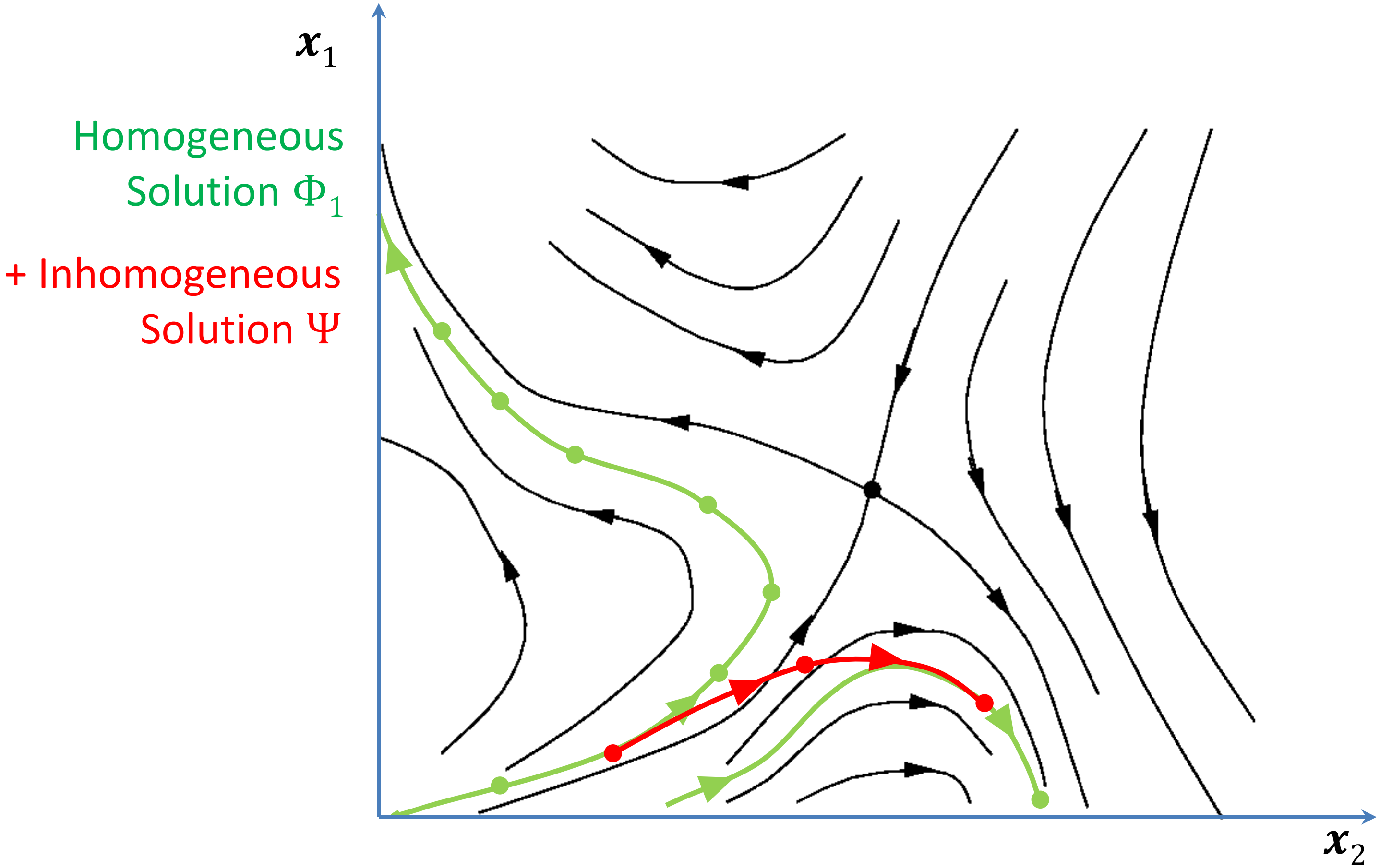


Discretized Dynamics

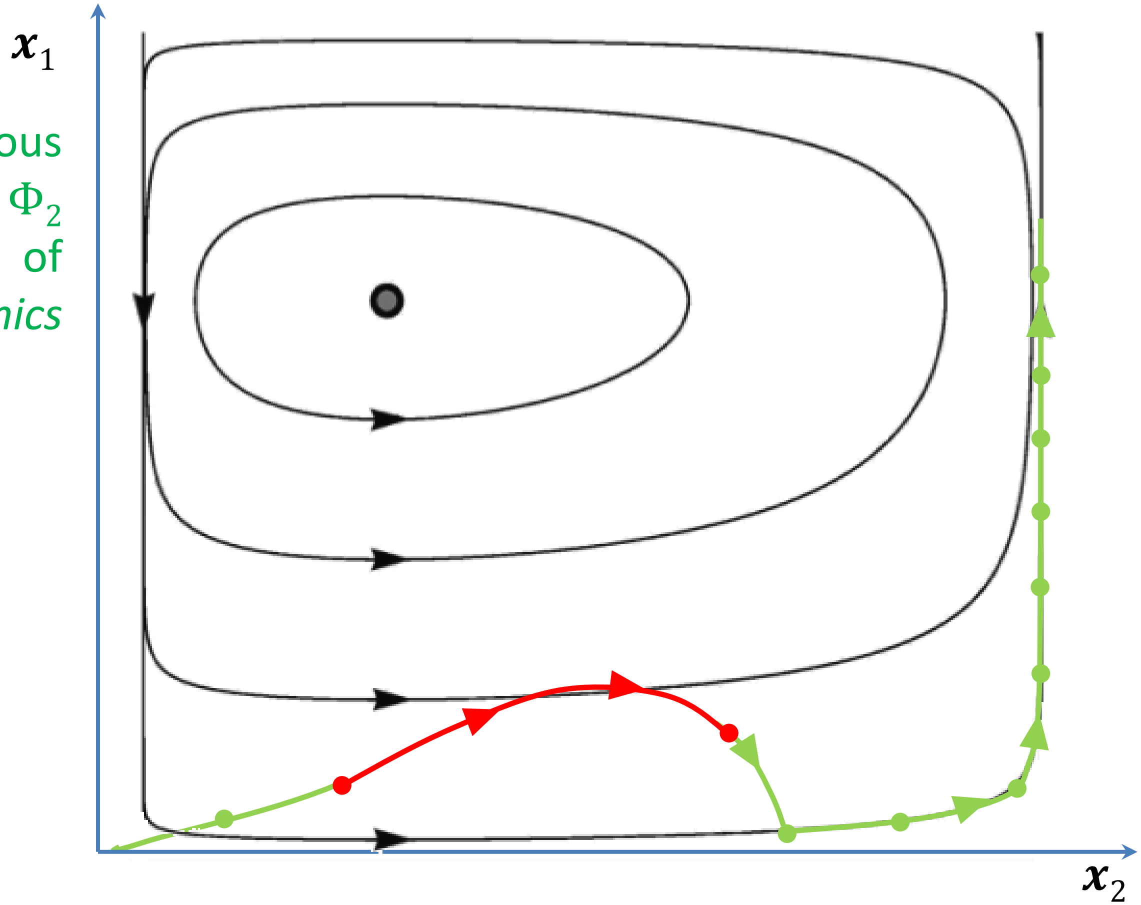


Discretized Dynamics

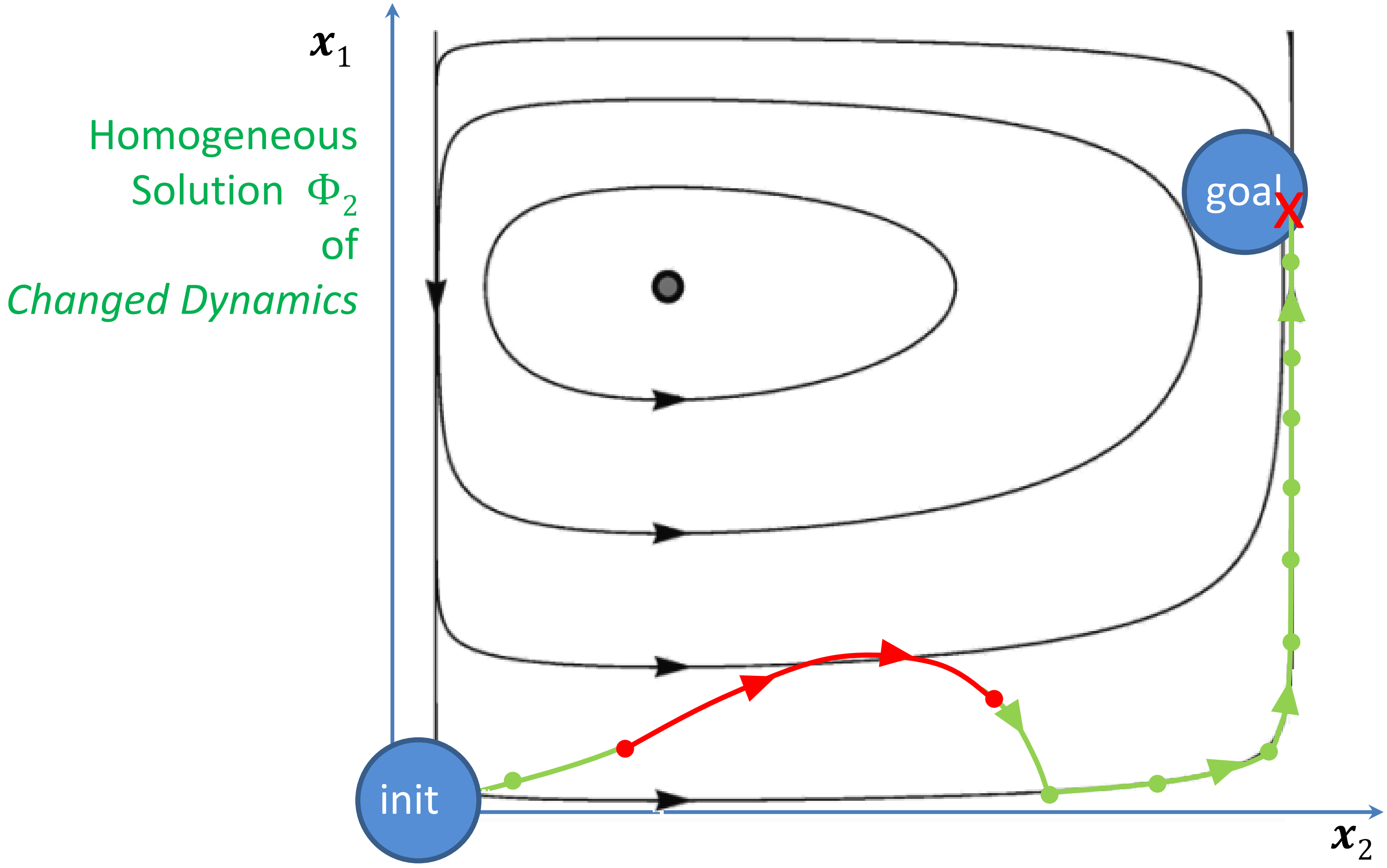


Discretized Dynamics

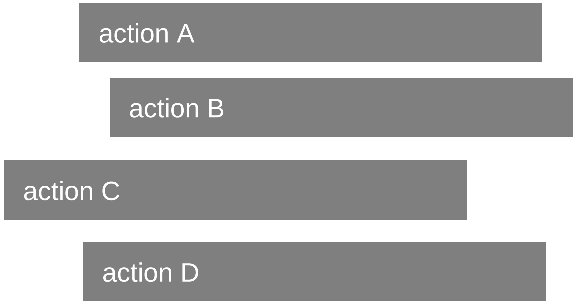
Homogeneous Solution Φ_2 of *Changed Dynamics*



Discretized Dynamics



The Domain Model
A Piecewise Affine System?



$$\boldsymbol{x}_n(k+1) = \Phi_i\, \boldsymbol{x}_n(k) + \Psi_i\;, \boldsymbol{x}_n \in \Omega_i$$

$$\Omega_i \cap \Omega_j = \emptyset, \qquad \forall\, i \neq j$$

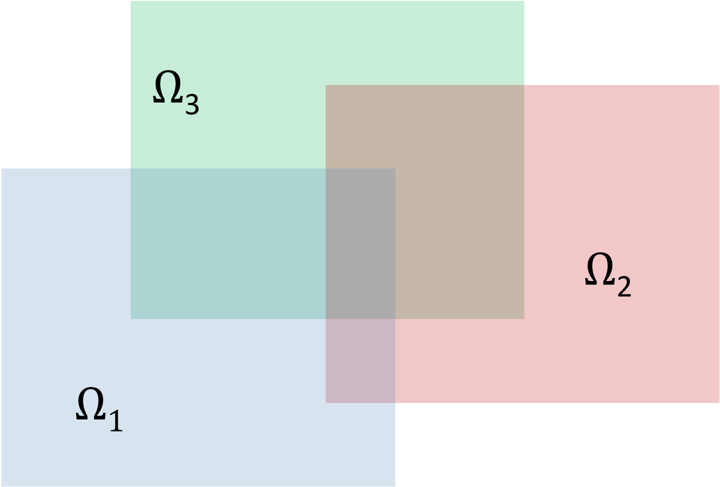
$$\Omega_i \cap \Omega_j = \mathcal{X}, \qquad \forall\, i \neq j$$

$\mathcal{X}$:

is not necessarily empty,

we explicitly allow for overlaps of Ω_i

Depicts the state space we can choose between actions



Time Discretization