Cyber-Physical Systems

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Lecture 15: STL applications

[Many Slides due to J. Deshmukh, S. Silvetti]

Falsification re-framed

Given:

- Set of all such input signals : U
- Input signal $\mathbf{u} : \mathbb{T} \rightarrow D_1 \times \cdots \times D_m$, where $\mathbb{T} \subseteq [0, T], D_i \subset \mathbb{R}$ compact set
- Model M s.t. $M(\mathbf{u}) = \mathbf{y}, \quad \mathbf{y}: \mathbb{T} \rightarrow \mathbb{R}^n$
  M maps $\mathbf{u}$ to some signal $\mathbf{y}$ with the same domain as $\mathbf{u}$, and co-domain some subset of $\mathbb{R}^n$
- Property φ that can be evaluated to true/false over given $\mathbf{u}$ and $\mathbf{y}$

Check: $\exists \mathbf{u} \in U : \left(\mathbf{y} = M(\mathbf{u})\right) \vDash \neg\varphi(\mathbf{u}, \mathbf{y})$

Input/Output Properties for Closed-loop Models

- Properties/Specifications/Requirements are rarely monolithic formulas $\varphi(\mathbf{u}, \mathbf{y})$
- Typically specified as a pair: a pre-condition φ_I on the inputs, and a post-condition φ_O on the outputs
- Verification problem then stated as:

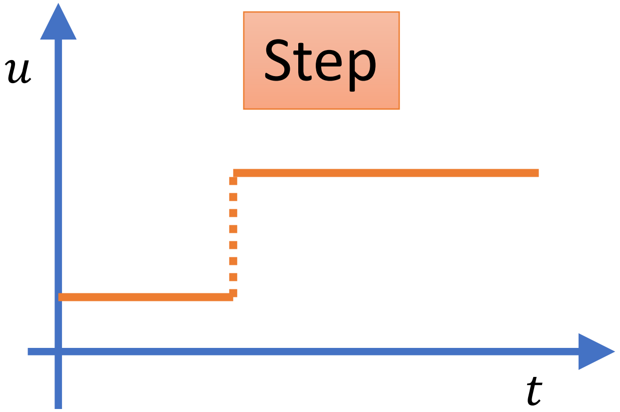
  Prove that: $\forall \mathbf{u} \in U : (\mathbf{u} \vDash \varphi_I) \wedge \left(\mathbf{y} = M(\mathbf{u})\right) \Rightarrow (\mathbf{y} \vDash \varphi_O)$
- Testing problem stated as:

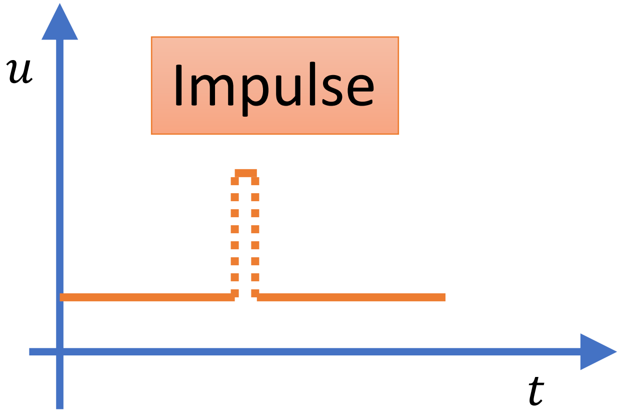
  Find u such that $(\mathbf{u} \vDash \varphi_I) \wedge \left(\mathbf{y} = M(\mathbf{u})\right) \wedge (\mathbf{y} \nvDash \varphi_O)$

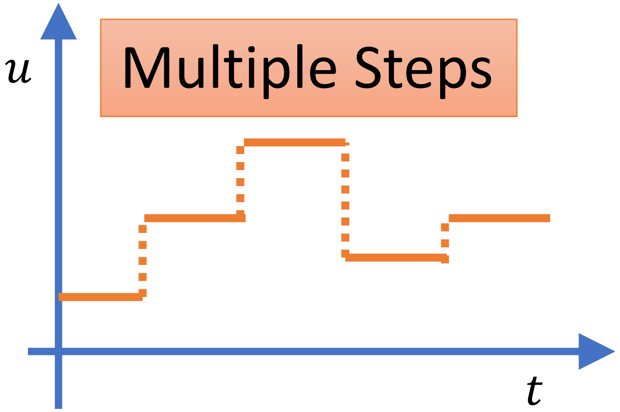
Input Properties/Pre-conditions

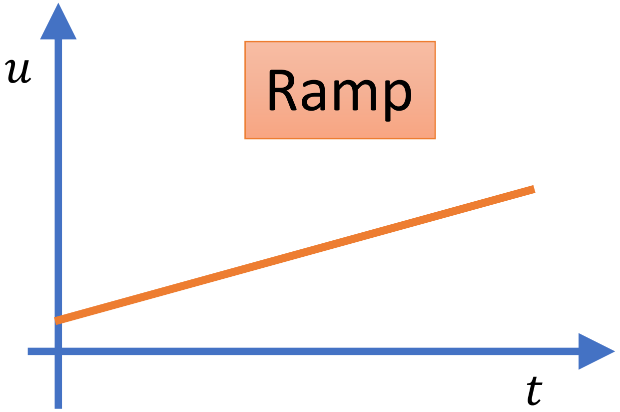
- Common practice in control theory to excite closed-loop models with input signals of certain special shapes
- Motivation comes from theory of linear systems, where a *step-response* or *impulse-response* are enough to characterize all behaviors of the system
- Such special shapes do not provide comprehensive information for nonlinear closed-loop systems, yet, it is still common to excite these systems with a few common patterns
- Frequently, input signal patterns come from engineering insights or application-specific domain expertise

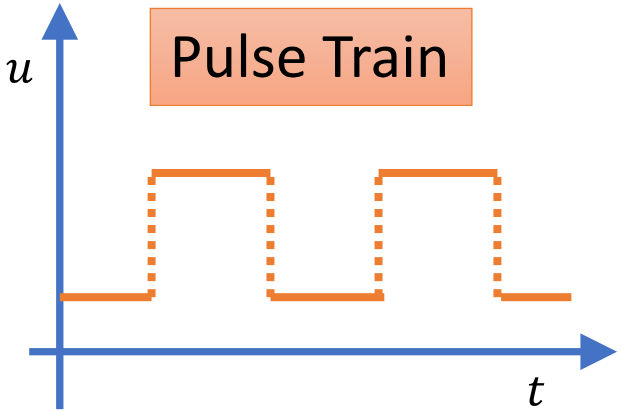
Common input patterns used for testing

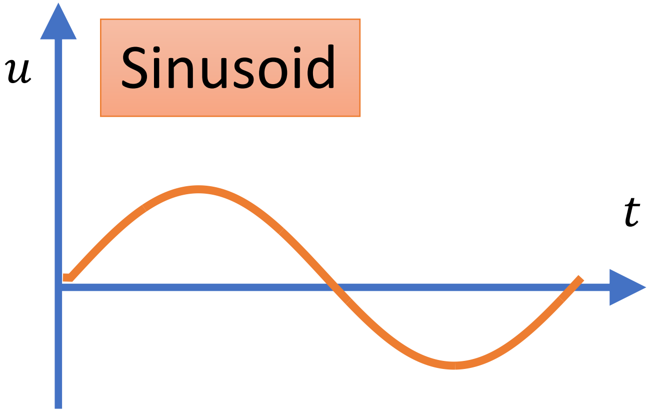












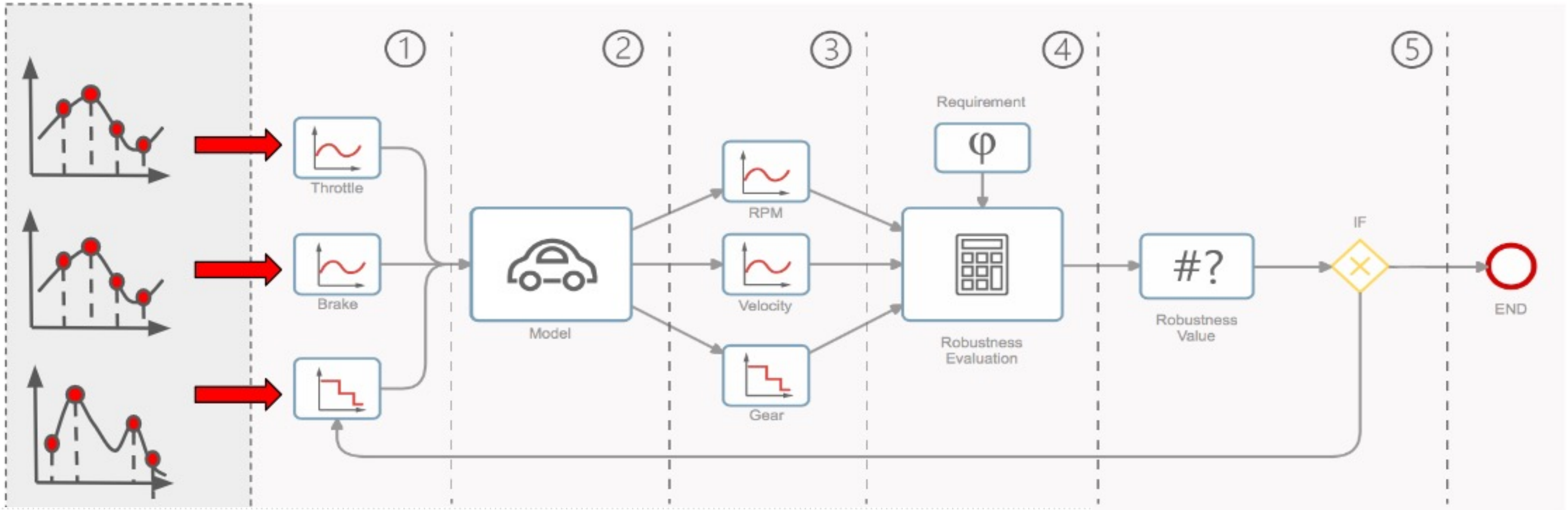
Testing in practice

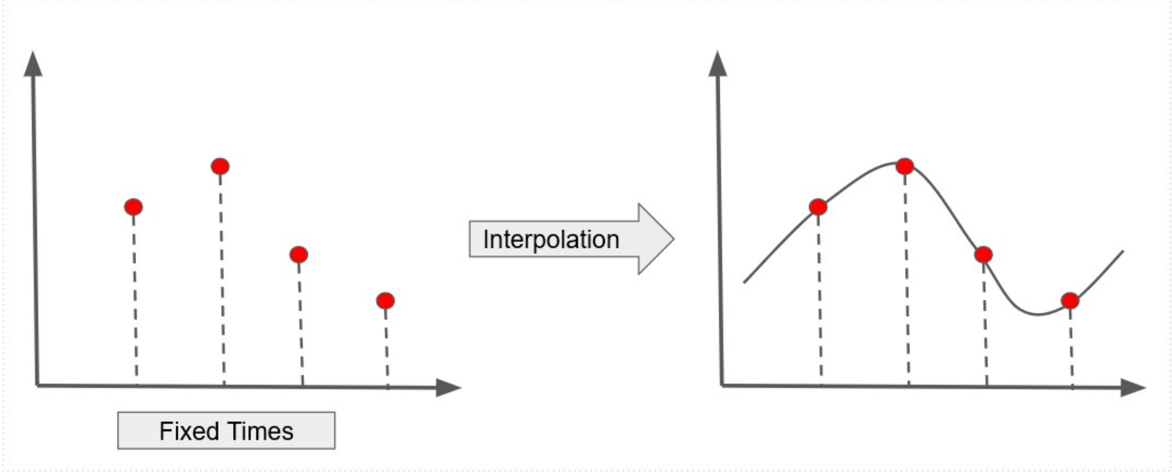
- Each time-point in a signal is an independent dimension, i.e. the signal can change arbitrarily at each time-point in the signal
- Number of independent domains is infinite (e.g. consider a signal defined over rational time-points)
- Typical testing approach is to find a *test-suite:* This is a **finite** number of test input signals (satisfying φ_I) and then obtain output behaviors using these signals as test inputs.
- If each corresponding output signal satisfies the output property φ_0, then testing concludes, indicating that the model is correct for the given test-suite (i.e. no output in the test-suite satisfies φ_0).

Signal Generation

- Find a *signal generator* for the property φ_I
  - Function that uses random-ness to generate an input signal that satisfies φ_I (hopefully, an input signal different from previously generated ones!)
- Signal generation usually relies on defining a *finite parameterization* for the input signal
  - For the chosen class of signals, find parameters that define the shape
  - Define acceptable ranges for the parameters
  - Define a generation function that takes the *parameter values* as inputs and generates an input signal

Finite Parameterization





N Control points

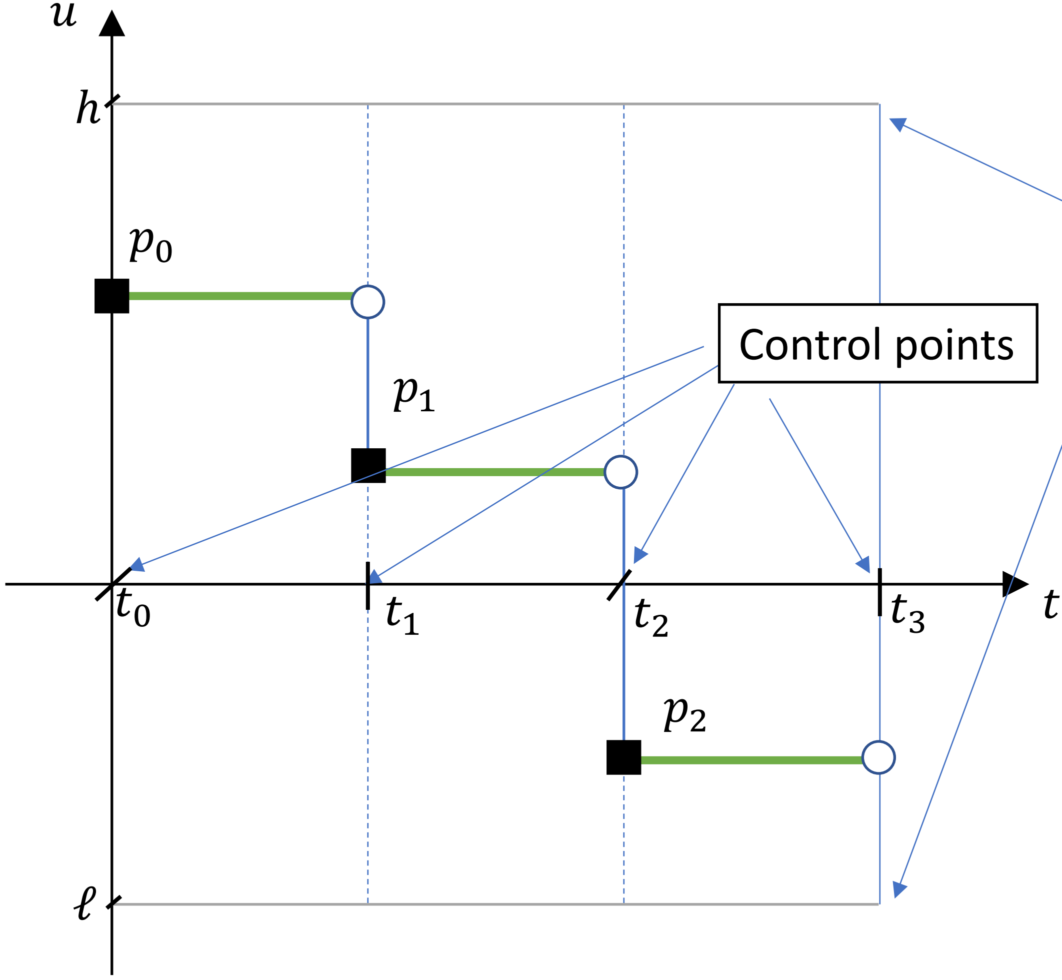
↓

N variable

Finite parameterization using control points

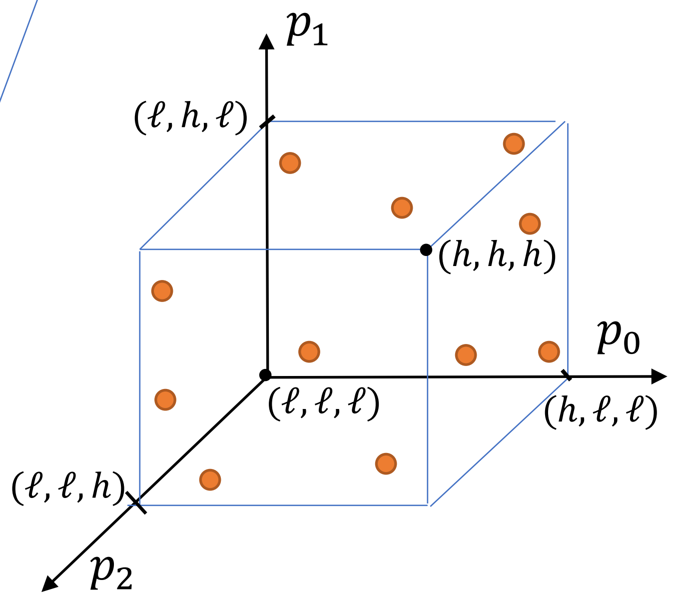
Finite Parameterization of $u(t)$:

$$u(t) = \begin{cases} p_0 \text{ if } \mathrm{t}_0 \leq t < t_1 \\ p_1 \text{ if } \mathrm{t}_1 \leq t < t_2 \\ p_2 \text{ if } \mathrm{t}_2 \leq t < t_3 \end{cases}$$



Control points

Acceptable ranges on parameters (control points)



We can view this as values of u are picked for (fixed) time points (determined *a priori*), and then $u(t)$ is generated using constant interpolation

Finite parameterization using control points

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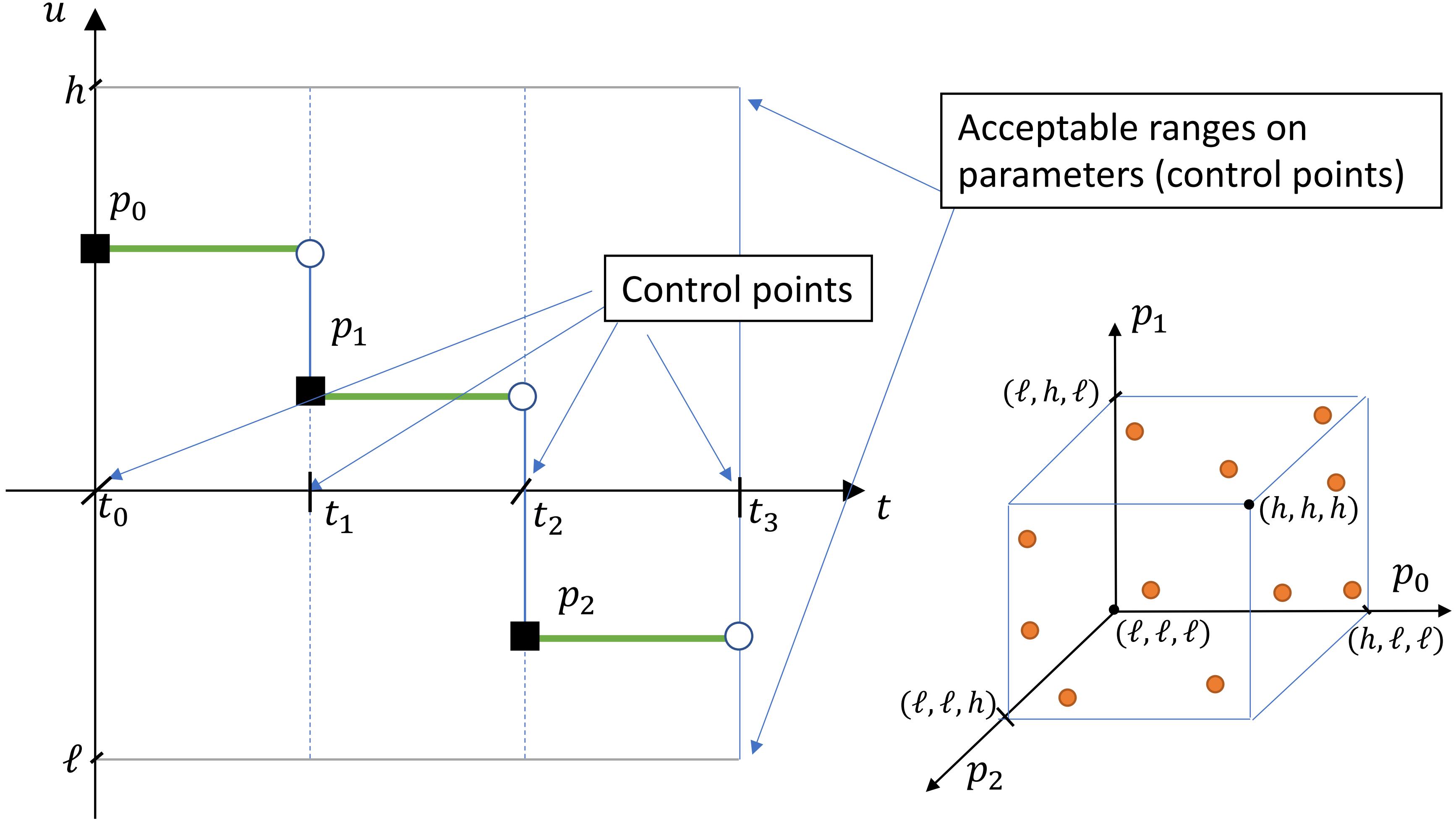

Acceptable ranges on parameters (control points)

Control points

Finite parameterization using linear interpolation

Finite Parameterization of $u(t)$:

$$u(t) = \begin{cases} p_0 + (t - t_0) \cdot \dfrac{p_1 - p_0}{t_1 - t_0} & \text{if } t_0 \leq t < t_1 \\ p_1 + (t - t_1) \cdot \dfrac{p_2 - p_1}{t_2 - t_1} & \text{if } t_1 \leq t < t_2 \\ p_2 + (t - t_2) \cdot \dfrac{p_3 - p_2}{t_3 - t_2} & \text{if } t_2 \leq t < t_3 \end{cases}$$

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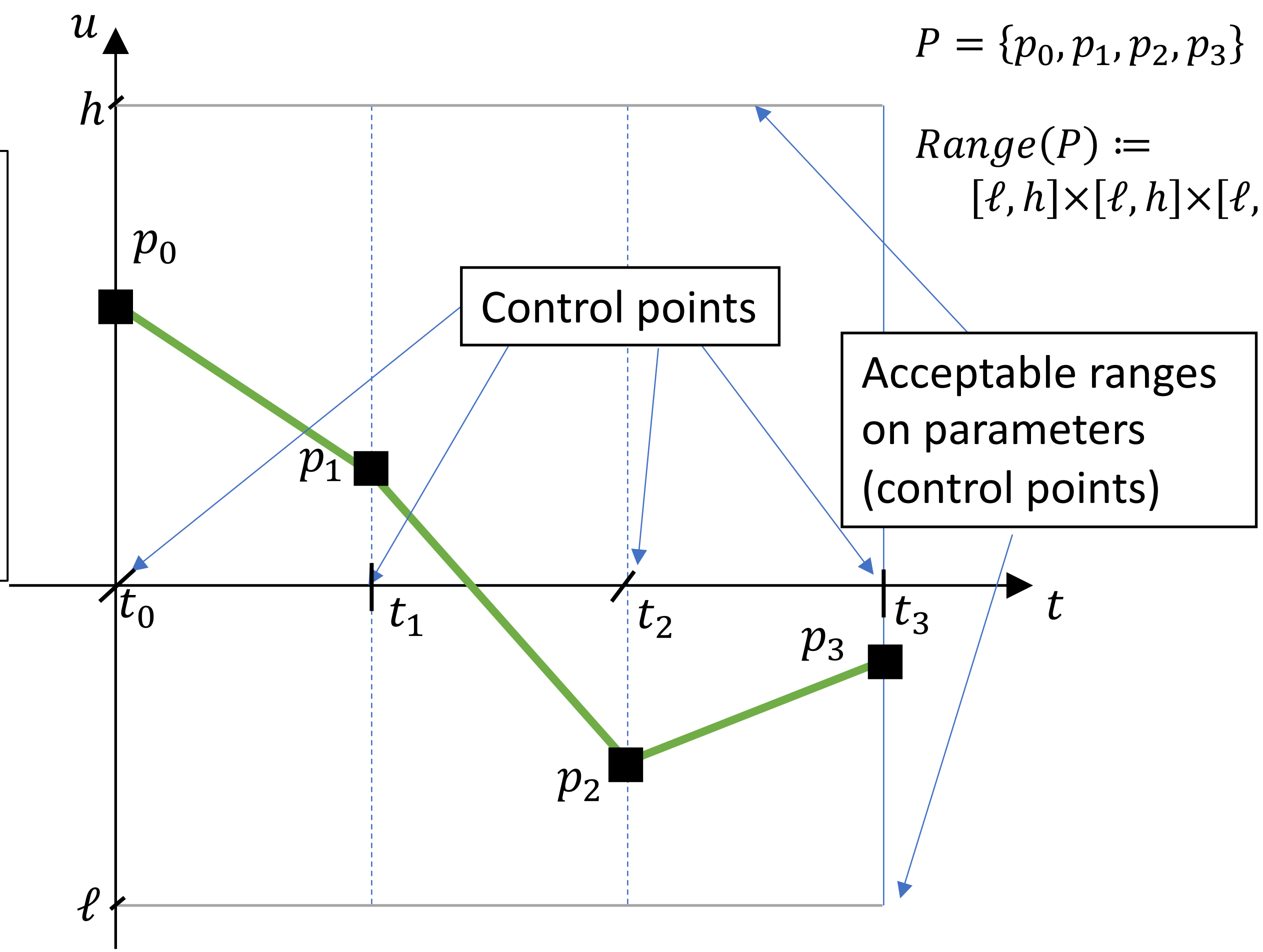


Control points

Acceptable ranges on parameters (control points)

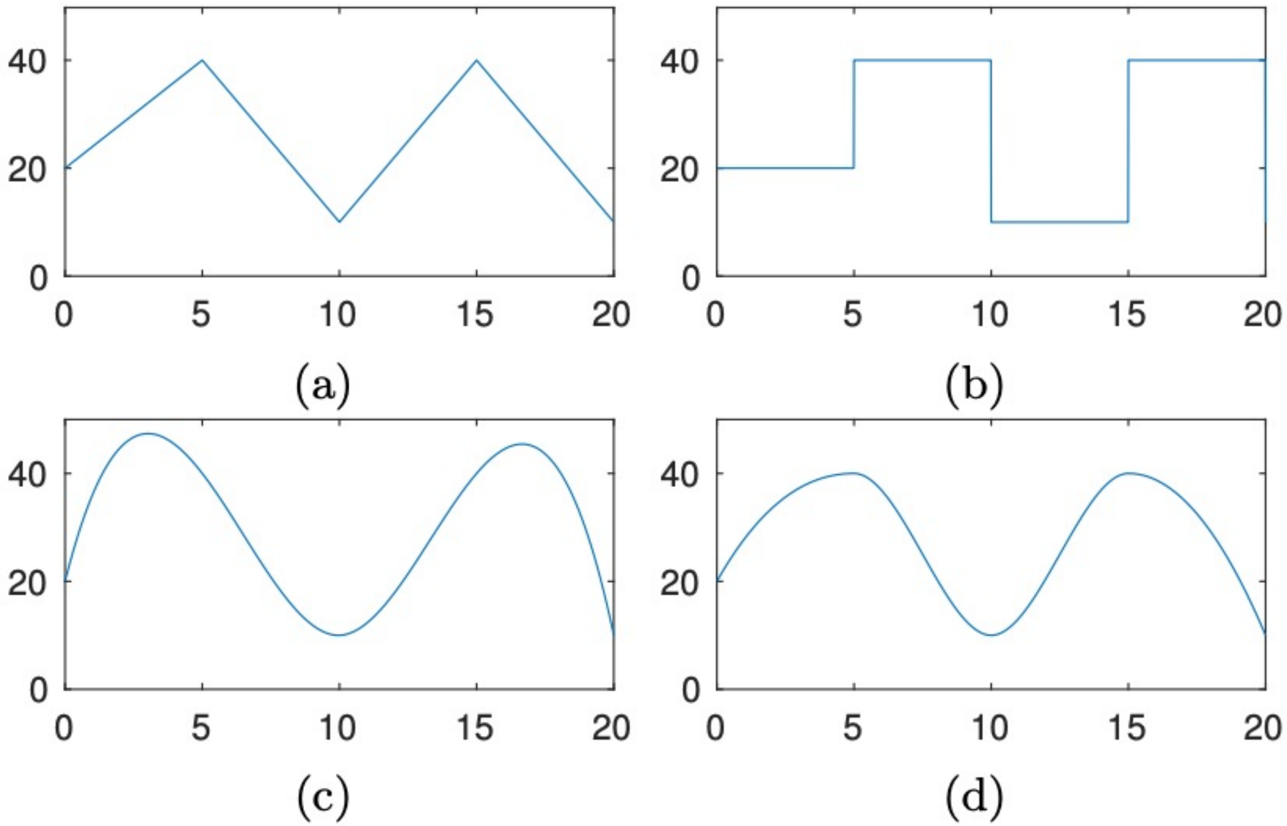
$P = \{p_0, p_1, p_2, p_3\}$

$Range(P) \coloneqq [\ell, h] \times [\ell, h] \times [\ell, h] \times [\ell, h]$

Finite parameterization using interpolation

Linear

Piecewise constant



(a) (b)

(c) (d)

Spline

Piecewise cubic interpolation

λ = [20, 40, 10, 40, 10]

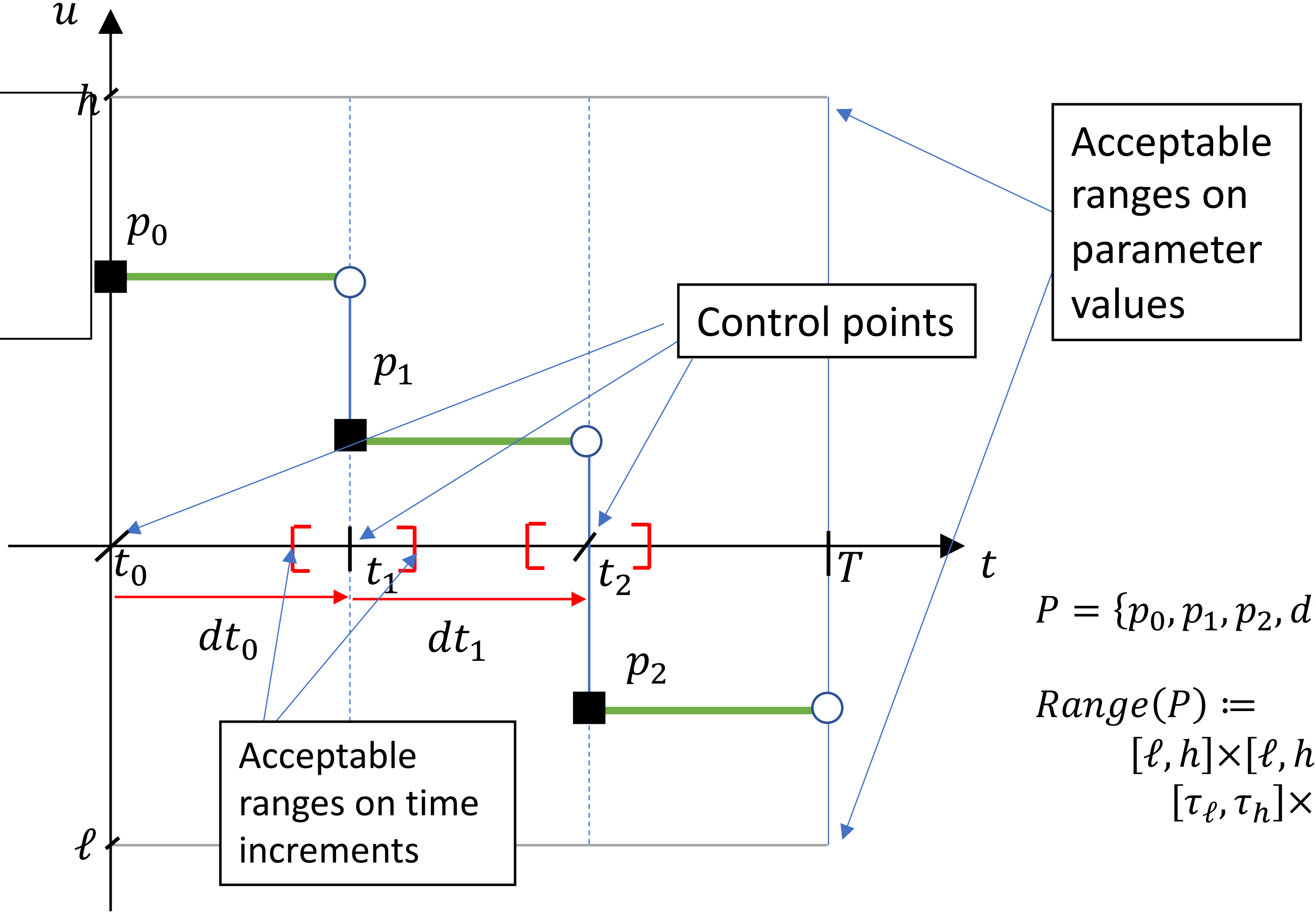
t = [0, 5, 10, 15, 20]

Finite parameterization variable control point times

Finite Parameterization of $u(t)$:

$$u(t) = \begin{cases} p_0 \text{ if } t_0 \leq t < t_0 + dt_0 \\ p_1 \text{ if } t_1 \leq t < t_1 + dt_1 \\ p_2 \text{ if } t_2 \leq t < T \end{cases}$$

We can view this as values of u and time increments in u are both picked, and then $u(t)$ is generated using constant interpolation



Control points

Acceptable ranges on parameter values

Acceptable ranges on time increments

$P = \{p_0, p_1, p_2, dt_0, dt_1\}$

$$Range(P) \coloneqq [\ell, h] \times [\ell, h] \times [\ell, h] \times [\tau_\ell, \tau_h] \times [\tau_\ell, \tau_h]$$

Finite parameterization variable control point times

Finite Parameterization of $u(t)$:

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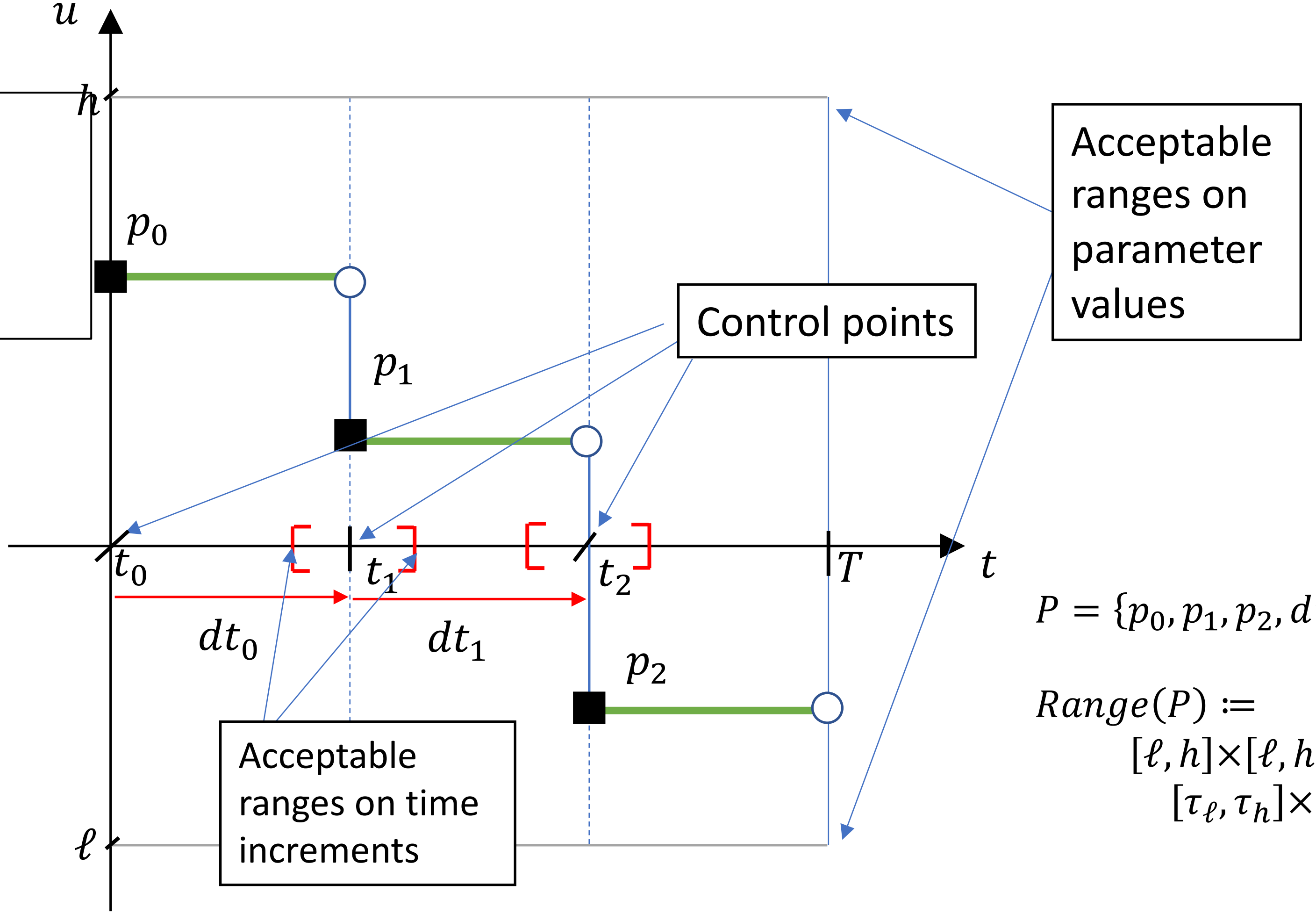

Control points

Acceptable ranges on parameter values

Acceptable ranges on time increments

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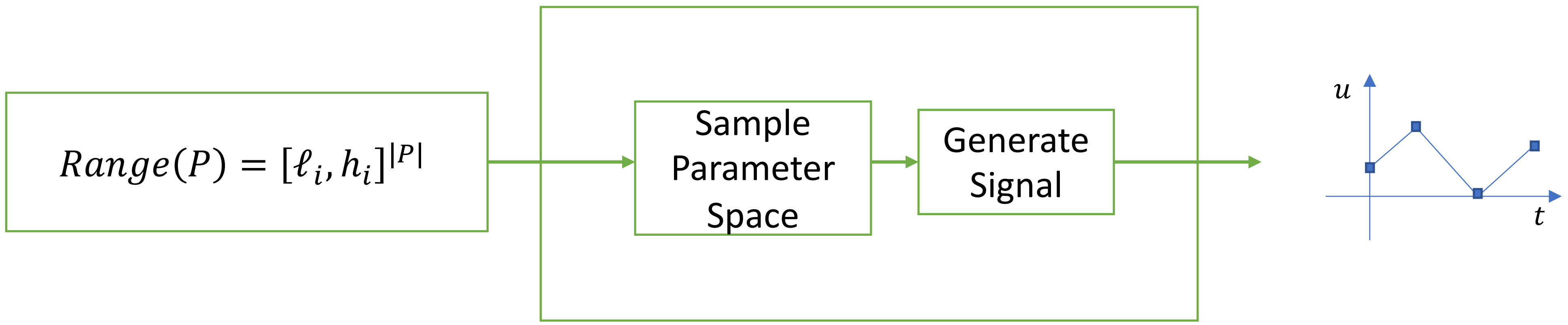
Signal Generator



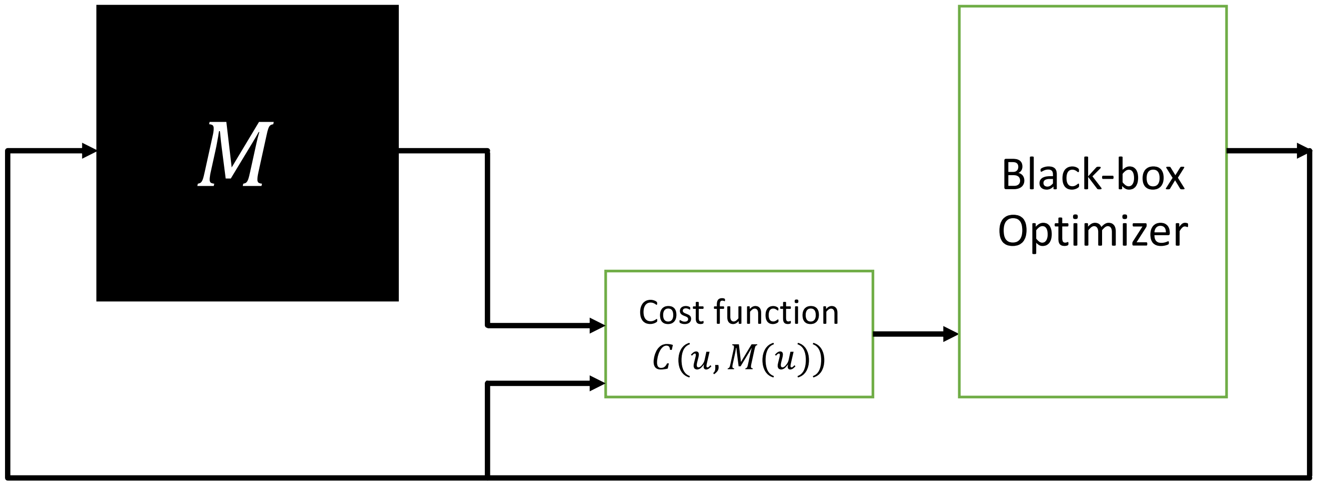
$Range(P) = [\ell_i, h_i]^{|P|}$

Sample Parameter Space

Generate Signal

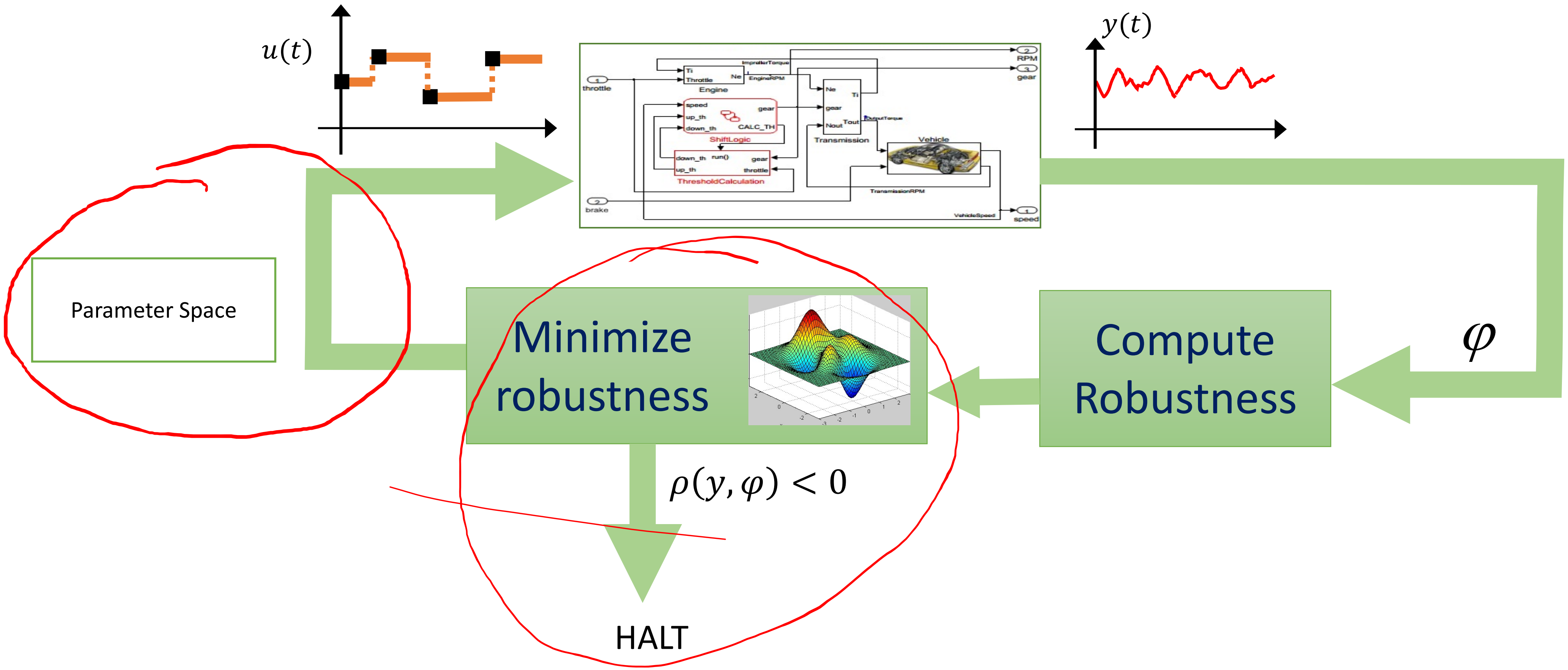
- Signal Generation controlled by the testing algorithm
  - Parameter space could be sampled all at once
  - Parameter space could be sampled in a sequential fashion, e.g. using a method such as Markov Chain Monte Carlo
  - Sampling scheme could be application-specific: uniform random, quasi-random (more evenly spread out), truncated normal, grid-based sampling (points from a fixed grid), etc.

Black-box Optimization



- Given:
  - Function $M: U \rightarrow Y$ with unknown symbolic representation
  - Ability to query the value of M at any given u; query will return some y
  - Cost function $C: X \times Y \rightarrow \mathbb{R}$
- Objective of black-box optimizer
  - Let $x^* = \min_{x \in X} C(x, f(x))$
  - Find $\hat{x}$ such that $\|\hat{x} - x^*\|$ is small
- Let $\widehat{x_i}$ be the best answer found by optimizer in its i^{th} iteration
- Ideally, $\lim_{i \rightarrow \infty} \| \widehat{x_i} - x^* \| = 0$

Falsification using Optimization



Parameter Space

Minimize robustness

Compute Robustness

φ

$\rho(y, \varphi) < 0$

HALT

Step-by-step of how falsification works

- Given: a finite parameterization for input signals, a model that can be simulated and an STL property
- While the number of allowed iterations is not exhausted do:
  - pick values for the signal parameters
  - generate an input signal
  - run simulation with generated input signal to get output signal
  - compute robustness value of given property w.r.t. the input/output signals
  - if robustness value is negative, **HALT**
  - pick a new set of values for the signal parameters based on certain heuristics

Picking new parameter values to explore

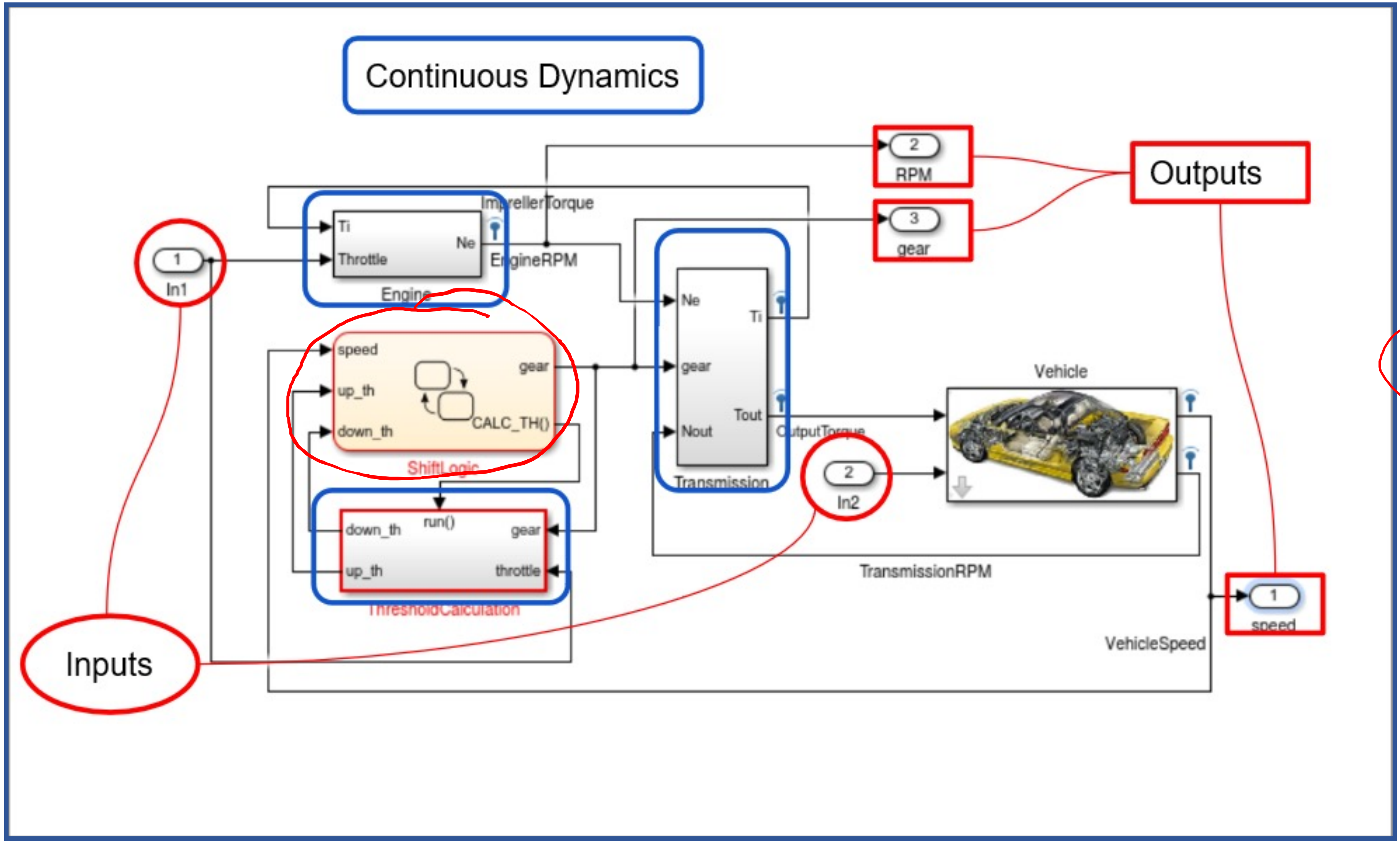
- Pick random sampling as a (not very good) strategy!
- Basic method: locally approximate the gradient of the function ρ locally, and chose the direction of steepest descent (greedy heuristic to take you quickly close to a local optimum)
- Challenge 1: cost surface may not be convex, thus you could have many local optima
- Challenge 2: cost surface may be highly nonlinear and even discontinuous, using just gradient-based methods may not work well
- Heuristics rely on:
  - combining gradient-based methods with perturbing the search strategy (e.g. simulated annealing, stochastic local search with random restarts)
  - evolutionary strategies: Covariance Matrix Adaptation Evolution Strategy (CMA-ES), genetic algorithms etc.
  - probabilistic techniques: Ant Colony Optimization, Cross-Entropy optimization, Bayesian optimization

Model

Inputs:

Throttle

Brake



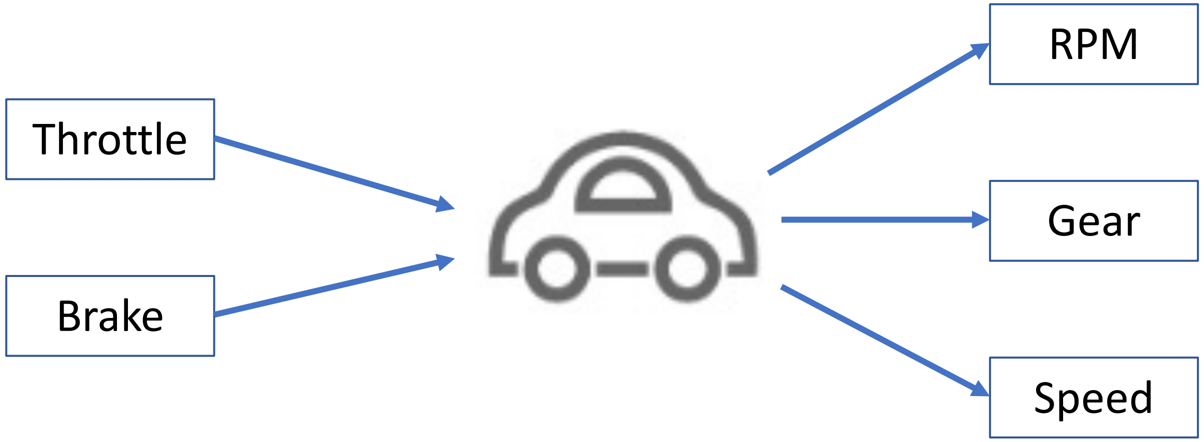
Outputs:

RPM

Gear

Speed

Model



Throttle

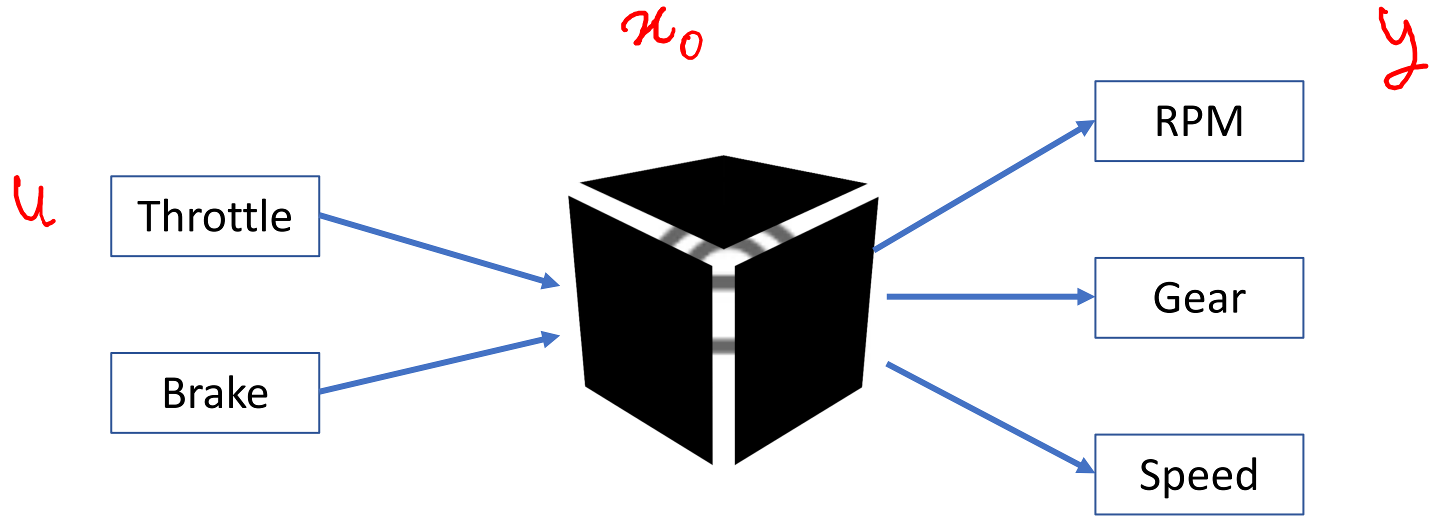
Brake

RPM

Gear

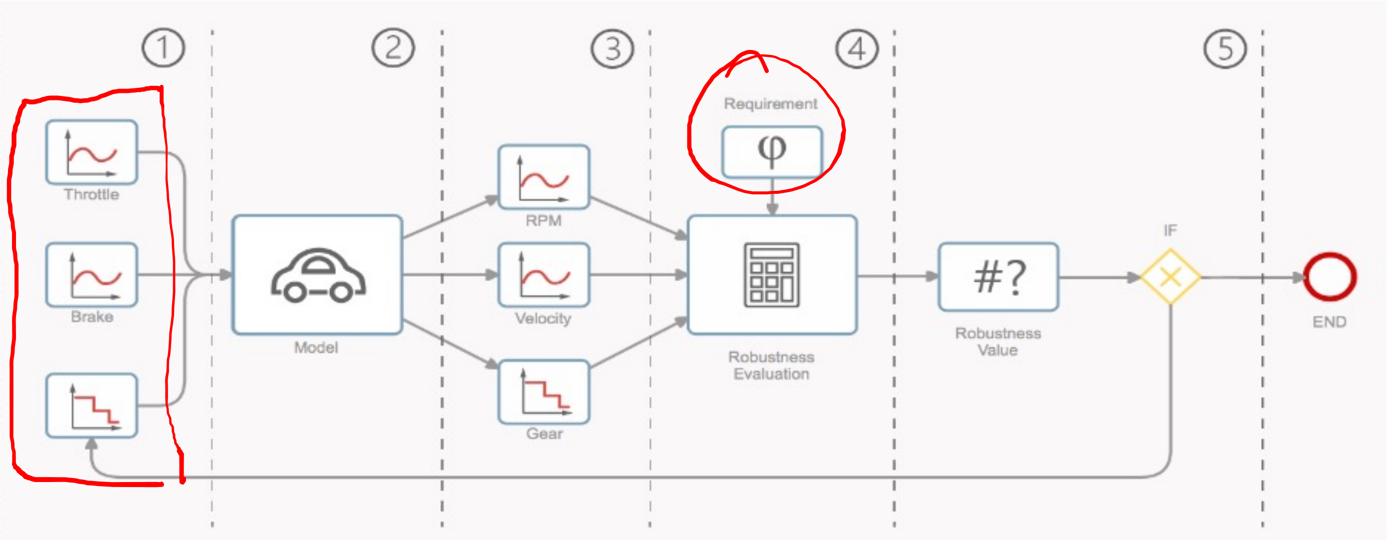
Speed

Black Box Assumption



- Less information
- A more general Approach (interesting for industries)

Falsification of CPS



Goal:

Find the inputs (1) which falsify the requirements (4)

Problems:

- Falsify with a low number of simulations ⇒ Active Learning
- Functional Input Space ⇒ Adaptive Parameterization

Gaussian Processes

Definition

$$f \sim GP(m, k) \iff (f(t_1), f(t_2), \dots, f(t_n)) \sim N(m, K)$$

where $m = (m(t_1), m(t_2), \dots, m(t_n))$ is the vector mean

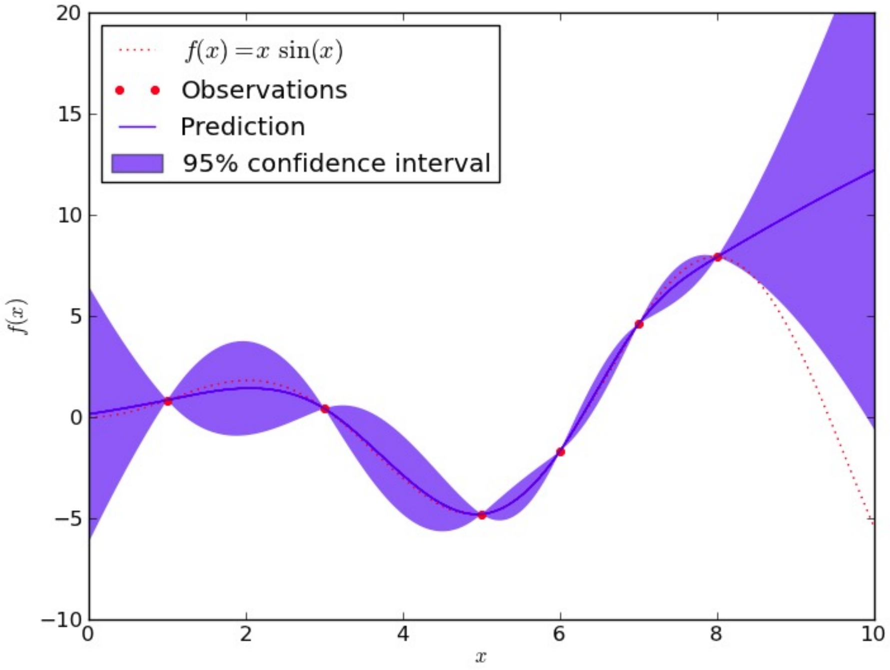
$K \in \mathbb{R}^{n \times n}$ is the covariance matrix, such that $K_{ij} = k(f(t_i), f(t_j))$

Prediction

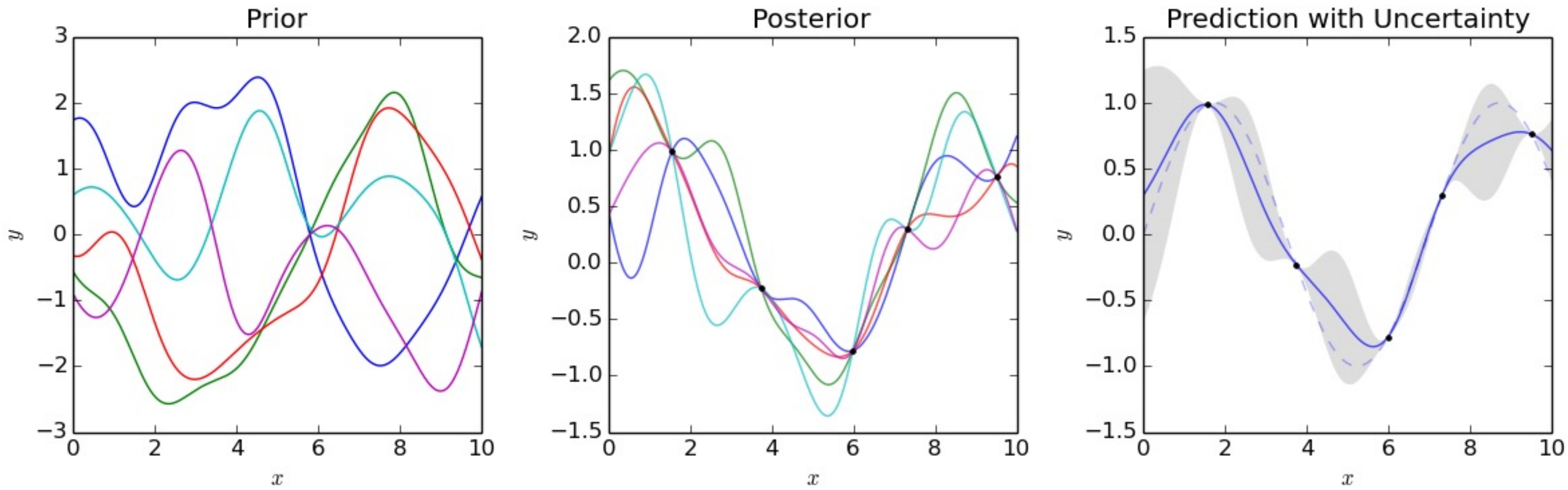
$$\{\underbrace{f(\theta_1), \dots, f(\theta_n)}_{\mathbf{f}}, f(\theta')\} \sim \mathcal{N}(\mathbf{m}', K')$$

$$\mathbb{E}(f(\theta')) = \underbrace{(k(\theta_1, \theta'), \dots, k(\theta_N, \theta',))}_{\mathbf{k}} \cdot K^{-1} \cdot \mathbf{f}$$

$$var(f(\theta')) = k(\theta', \theta') - \mathbf{k} \cdot K^{-1} \cdot \mathbf{k}^T$$



Gaussian Processes



$$(f(\theta_1),\ldots,f(\theta_n)) \xrightarrow{\text{GP}} \tilde{f}$$

Training set

- Mean
- Variance
- $p(\tilde{f} \in I)$

Domain Estimation Problem

Finding the trajectories which falsify the requirements, finding $\boldsymbol{u} \in B$

$$B = \{\boldsymbol{u} \in \mathrm{U} \mid \rho(\phi, \boldsymbol{u}, 0) < 0\} \subseteq U$$

- **Training Set**: K= $\{\boldsymbol{u}_{\mathrm{i}}, \rho(\phi, \boldsymbol{u}_i, 0))\}_{i \leq n}$ (the partial knowledge after n iterations)
- **Gaussian Process**: $\rho_K(\boldsymbol{u}) \sim GP(m_K(\boldsymbol{u}), \sigma_K(\boldsymbol{u}))$ (the partial model)

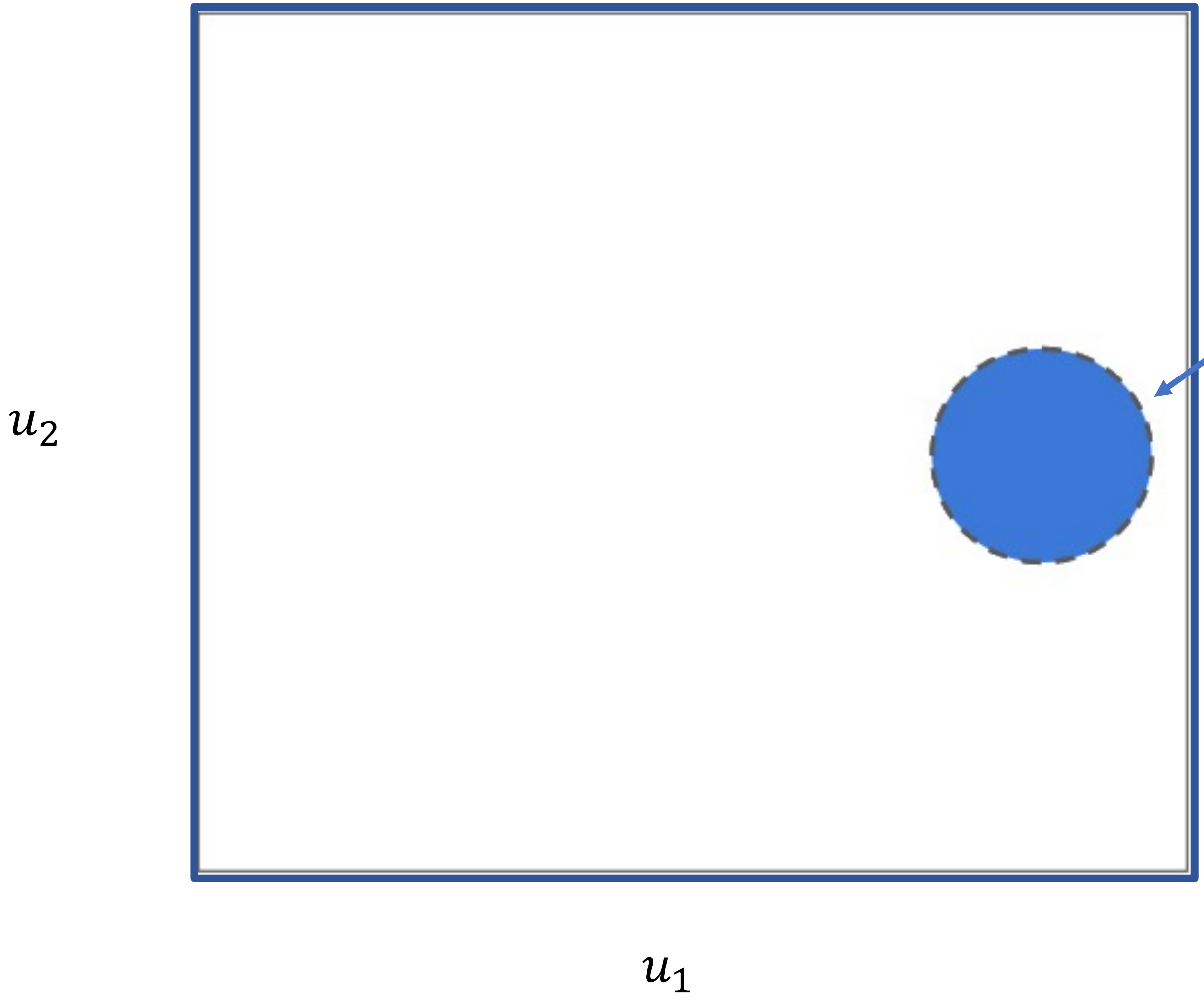
$$P(\rho_K(\boldsymbol{u}) < 0) = CDF\left(\frac{0 - m_K(\boldsymbol{u})}{\sigma_K(\boldsymbol{u})}\right)$$

Idea: implementing an iterative sample strategy in order to increase the probability to sample a point in B, as the number of iterations increases.

Algorithm 1

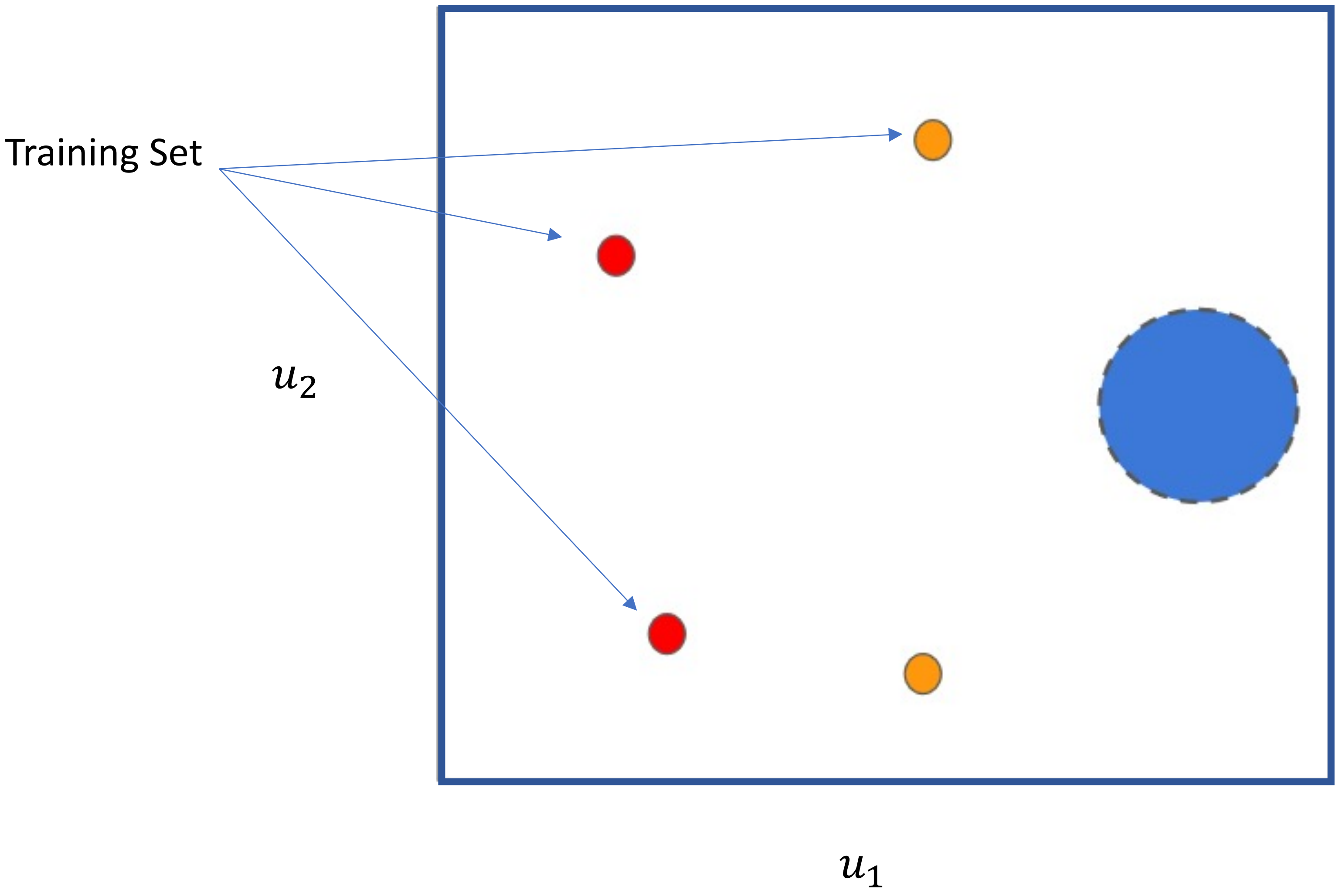
```
procedure $[B, d\ ] =$ domainEstimation($maxIter, ce, m, f, I$)
    $i \leftarrow 0,\ B \leftarrow \emptyset,\ d \leftarrow +\infty$
    initialize($K(f)$)
    while ( $|B| \leq ce$ and $i \leq \text{maxIter}$) do
        $f_{K(f)} \sim$ trainGaussianProcess($K(f)$)
        $D_{grid} \leftarrow$ lhs($m$)
        $x_{new} \leftarrow$ sample$\{(x, P(x \in \mathcal{B})), x \in D_{grid}\}$
        $f_{new} \leftarrow f(x_{new})$
        $d \leftarrow \min(d,$ distance$(f_{new}, I))$
        $K(f) \leftarrow K(f) \cup \{(x_{new}, f_{new})\}$
        if $f_{new} \in I$ then
            $B = B \cup \{x_{new}\}$
        end if
        $i \leftarrow i + 1$
    end while
end procedure
```

Domain Estimation Algorithm (DEA)



B= $\{\boldsymbol{u} \in \mathrm{U} \mid \rho(\,M(\boldsymbol{u}), \phi) < 0\}$

Domain Estimation Algorithm (DEA)

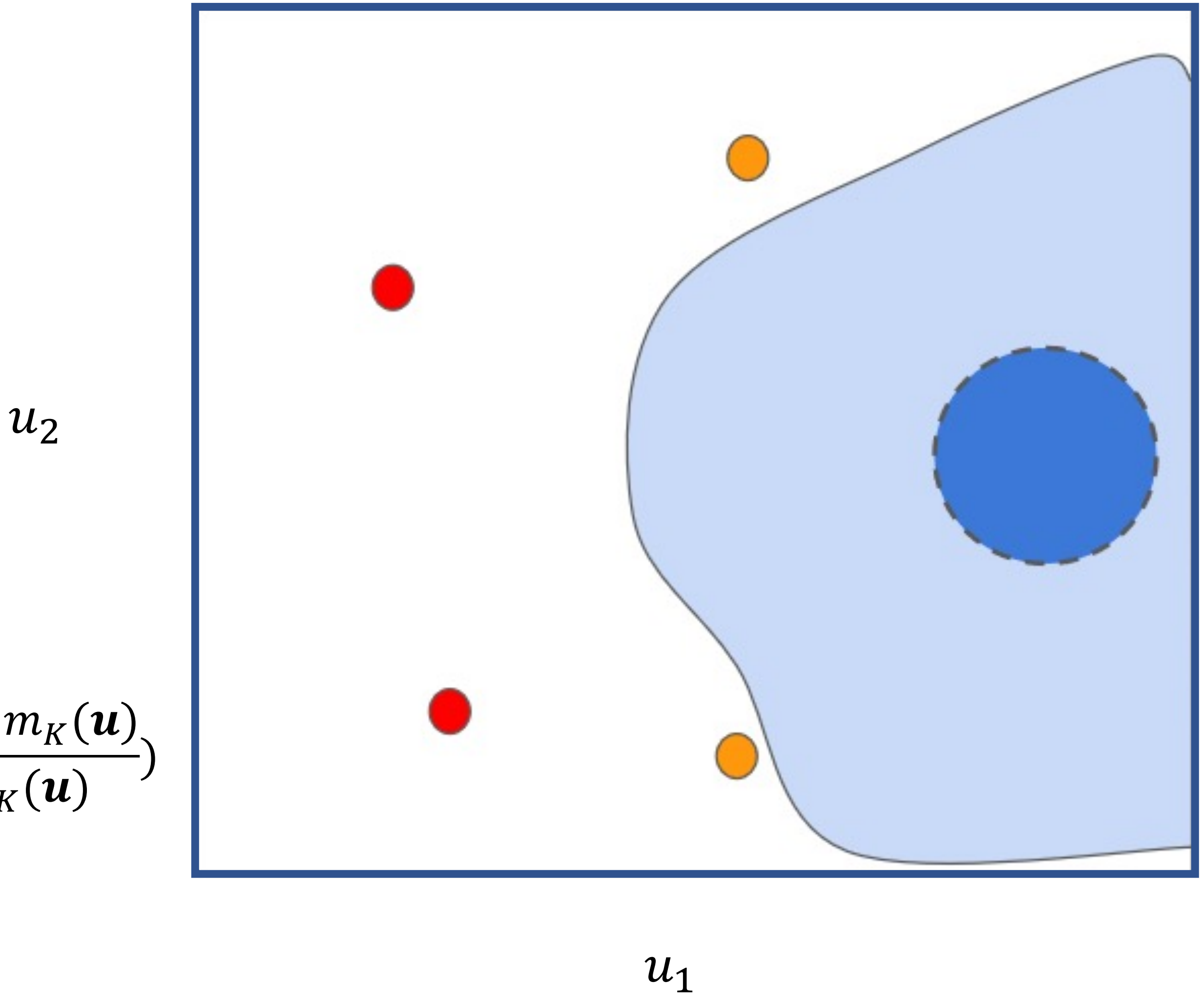


Training Set

u_2

u_1

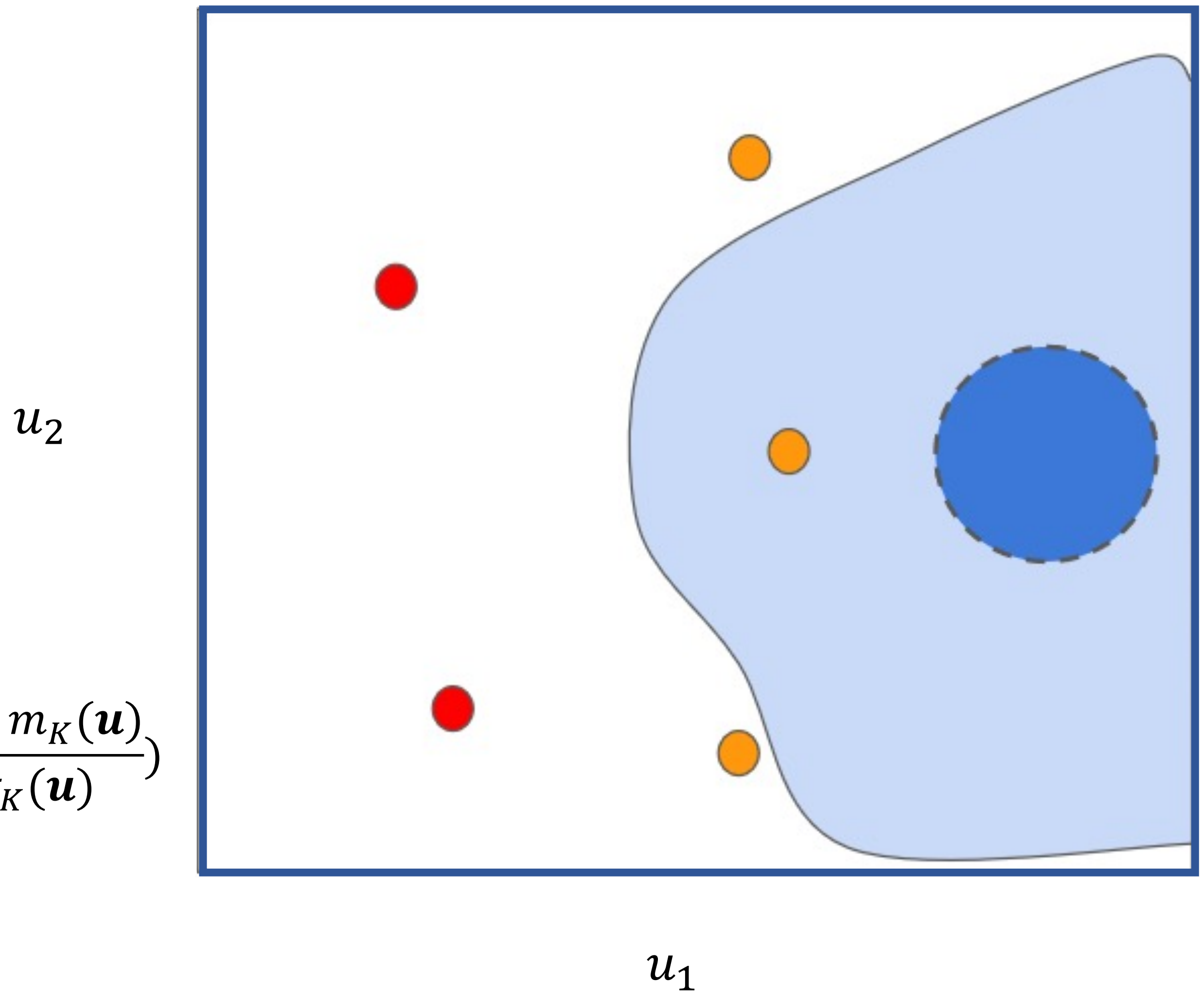
Domain Estimation Algorithm (DEA)



Sample a new point accordingly to:

$$P(\rho_K(\boldsymbol{u}) < 0) = CDF(\frac{0 - m_K(\boldsymbol{u})}{\sigma_K(\boldsymbol{u})})$$

Domain Estimation Algorithm (DEA)



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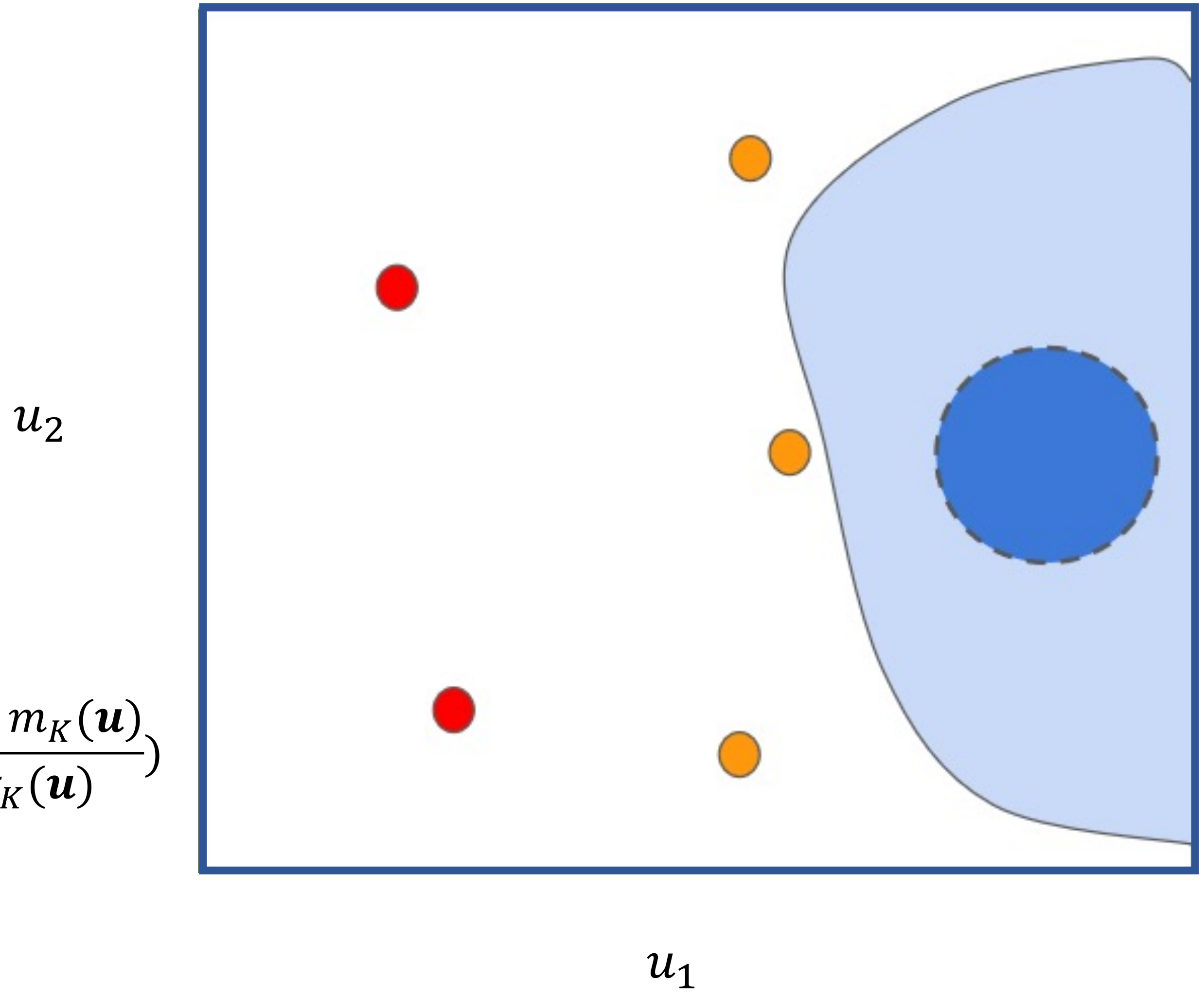

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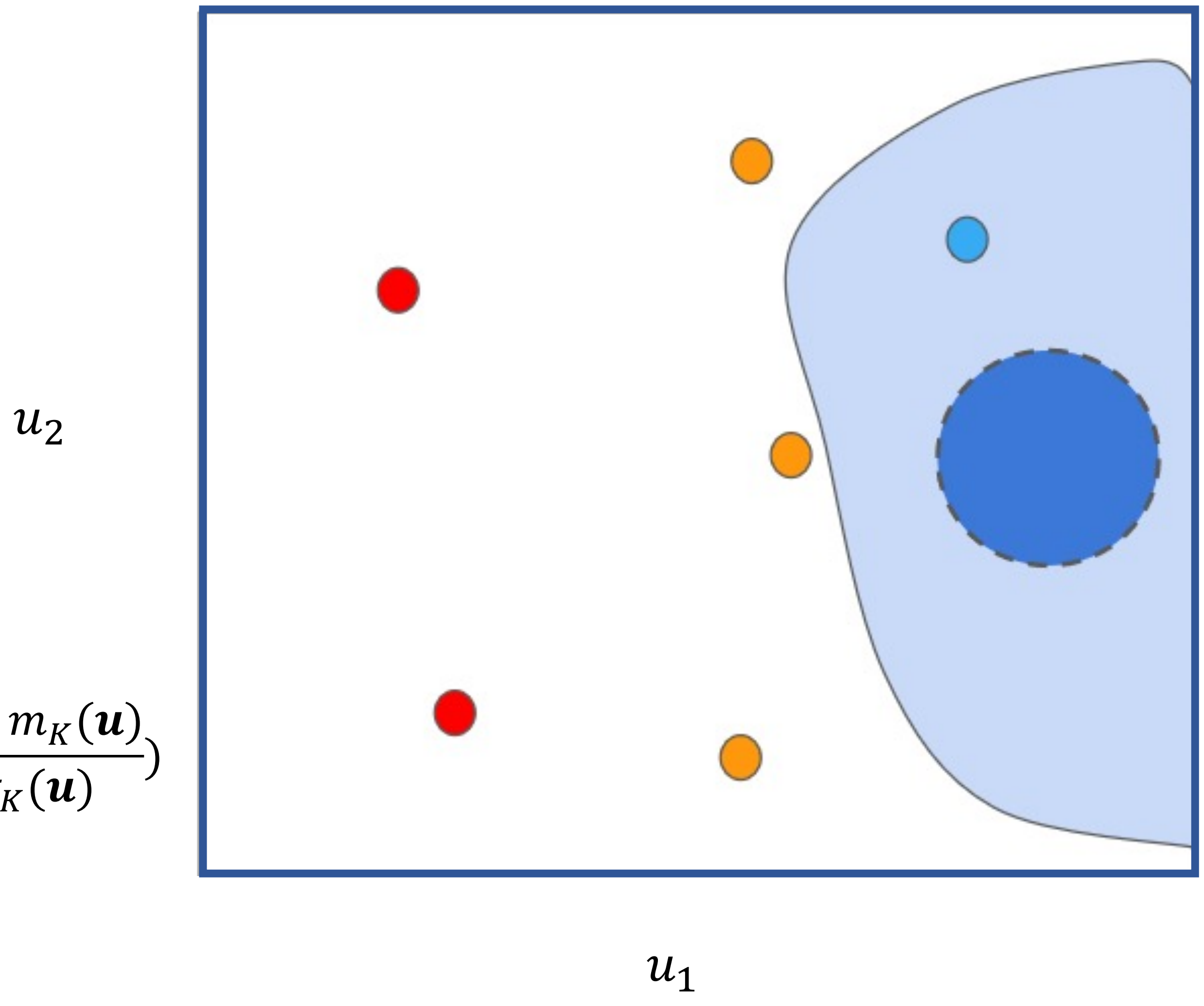

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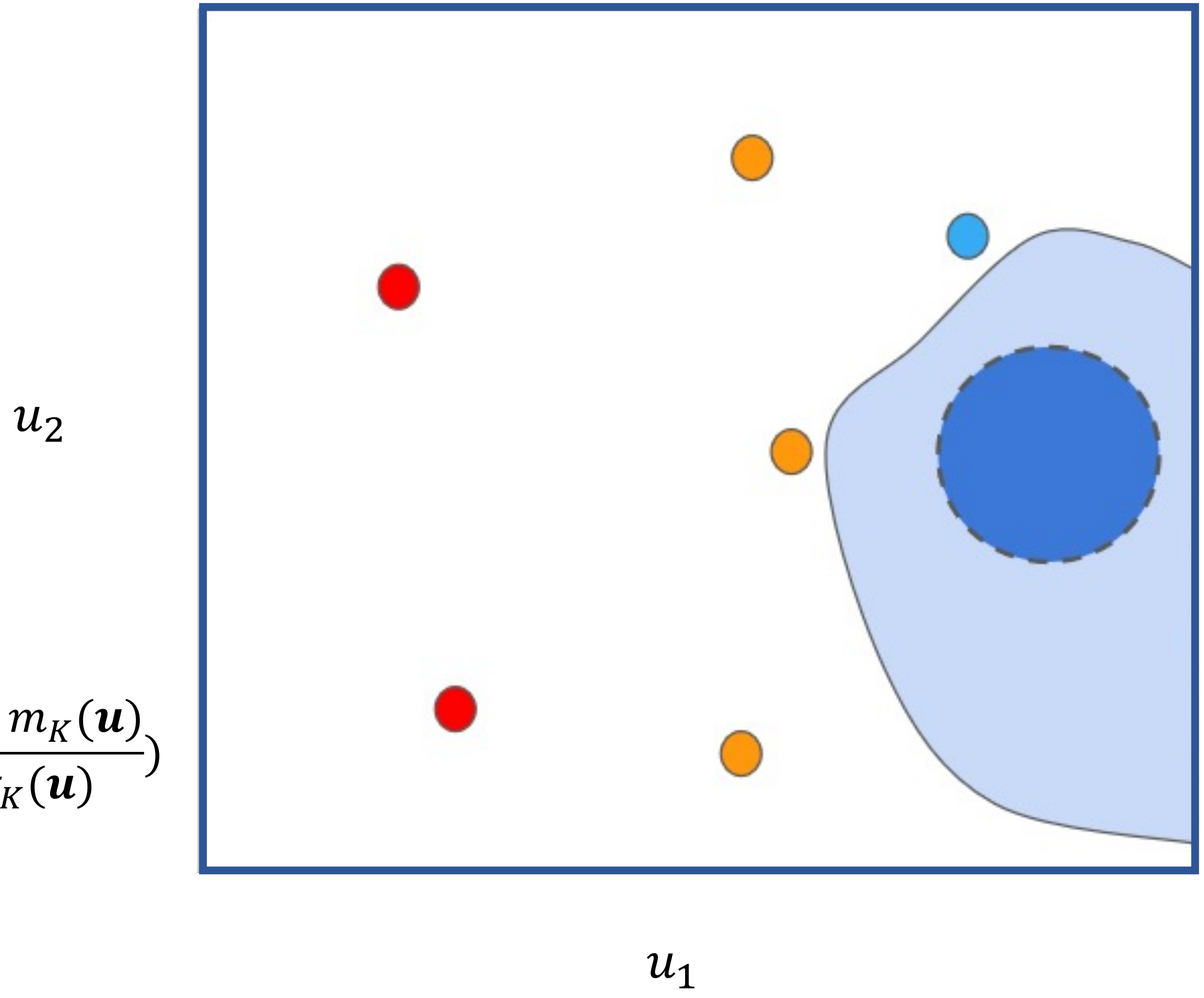

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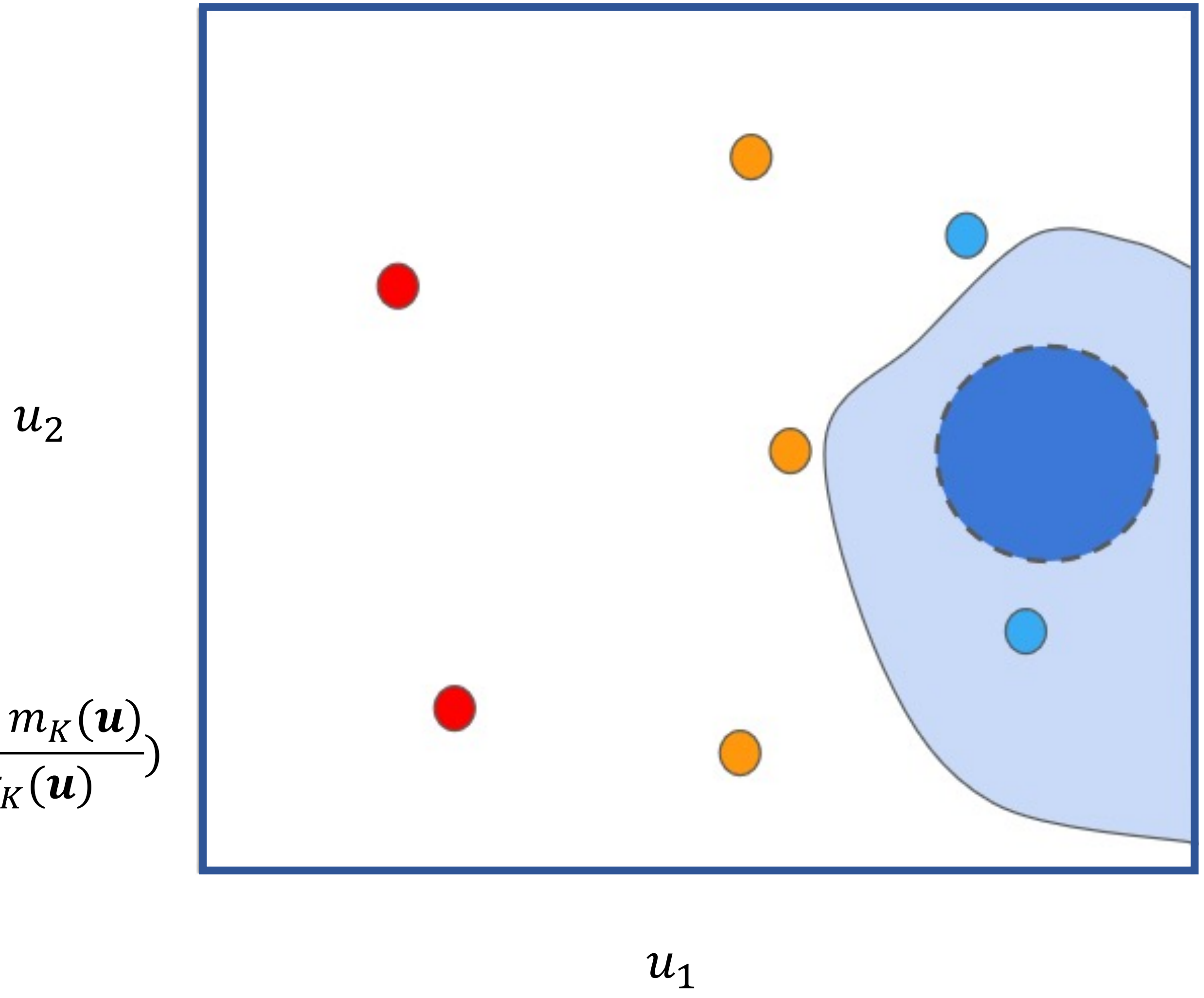

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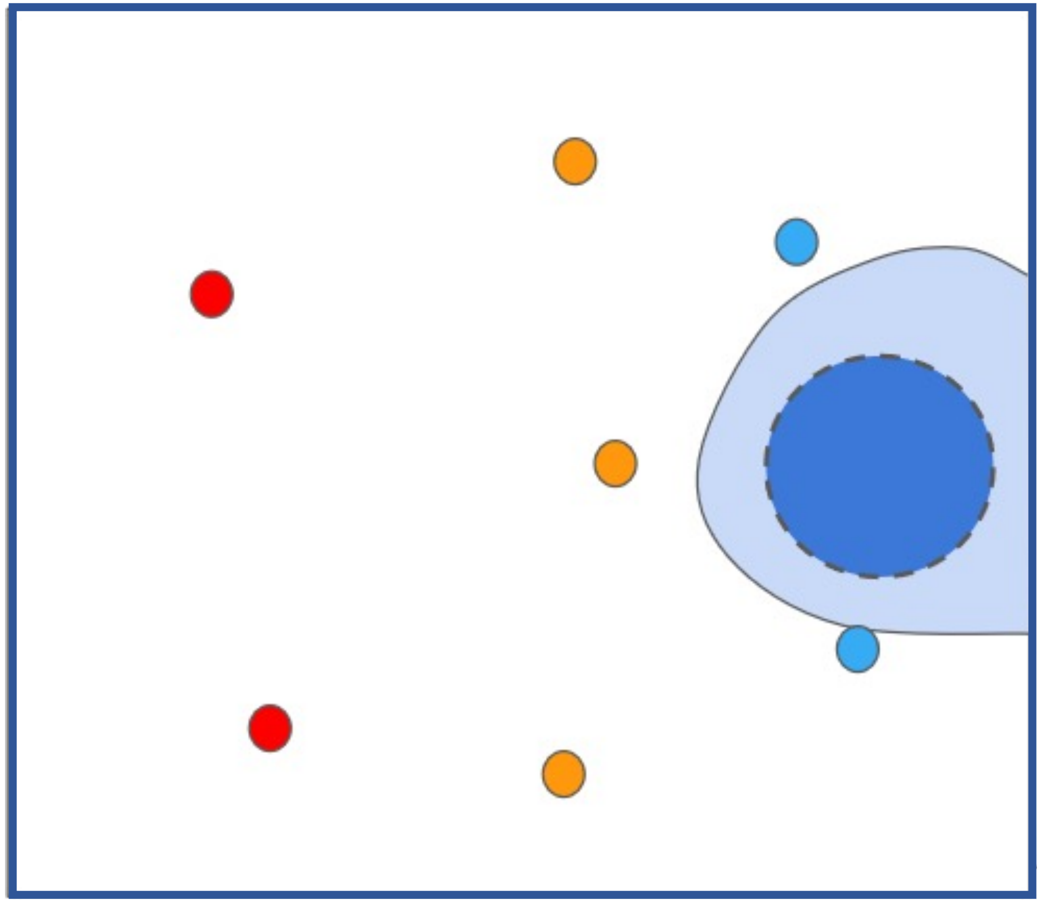

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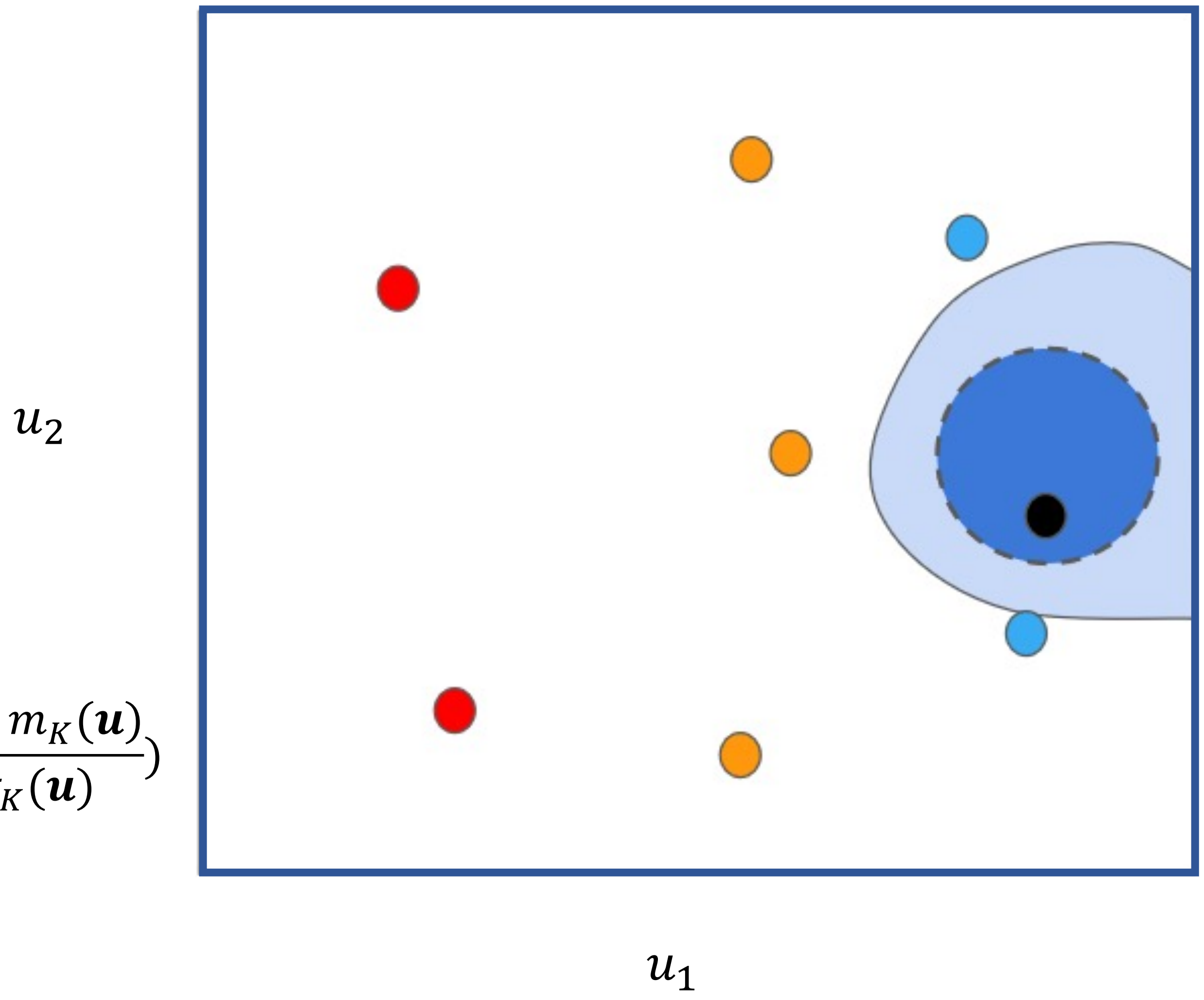

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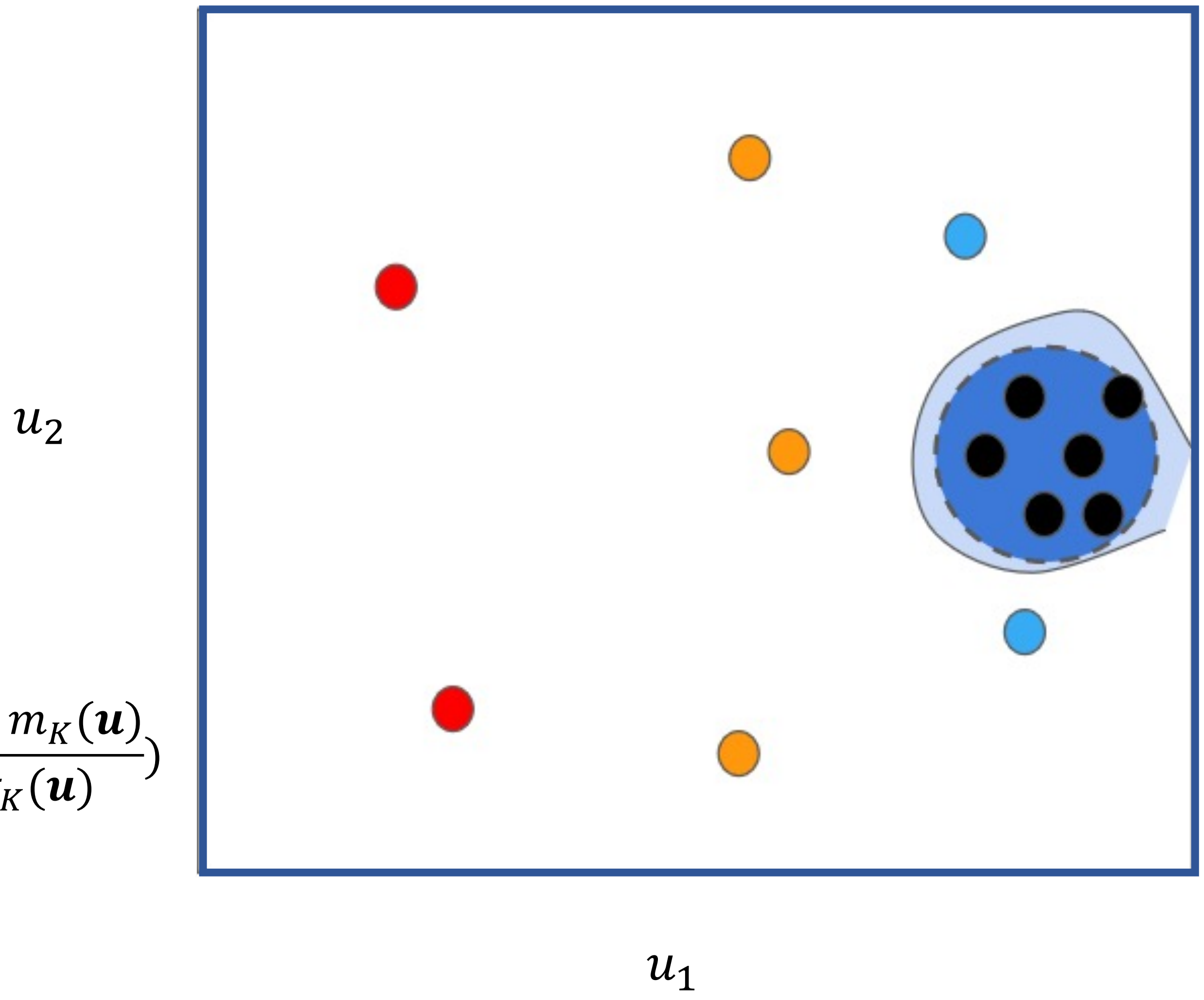

Sample a new point accordingly to:

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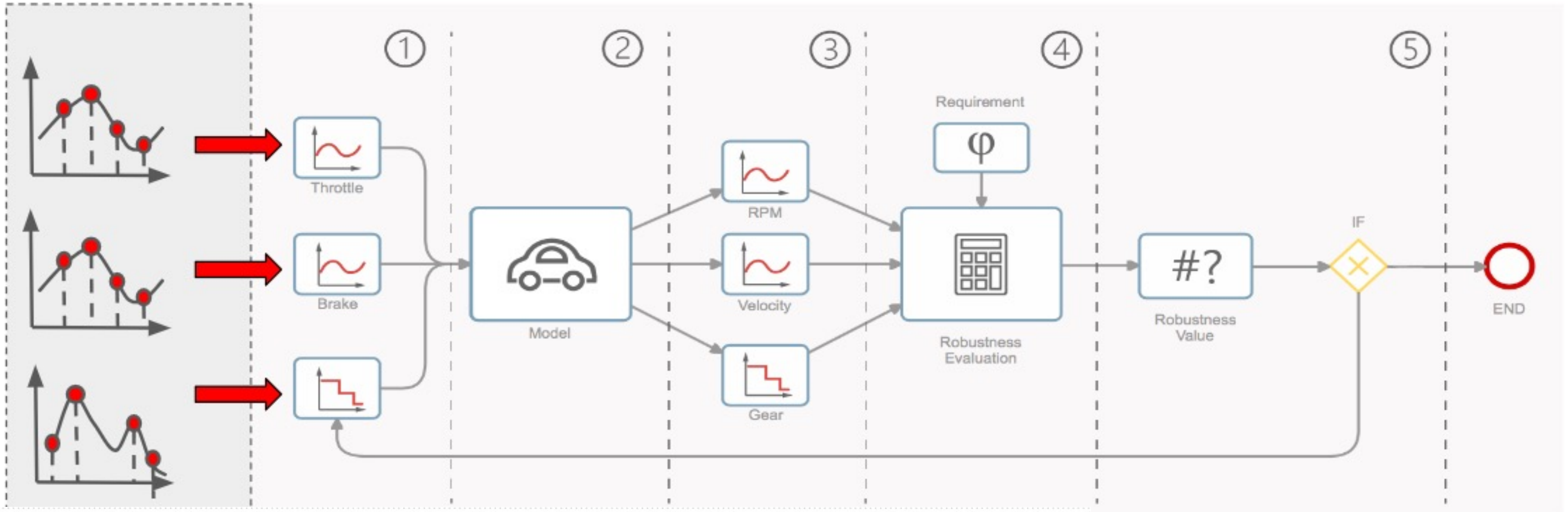
$$\mathrm{B} = \{\boldsymbol{u} \in \mathrm{U} \mid \rho(\phi, \boldsymbol{u}, 0) < 0\} \subseteq U$$

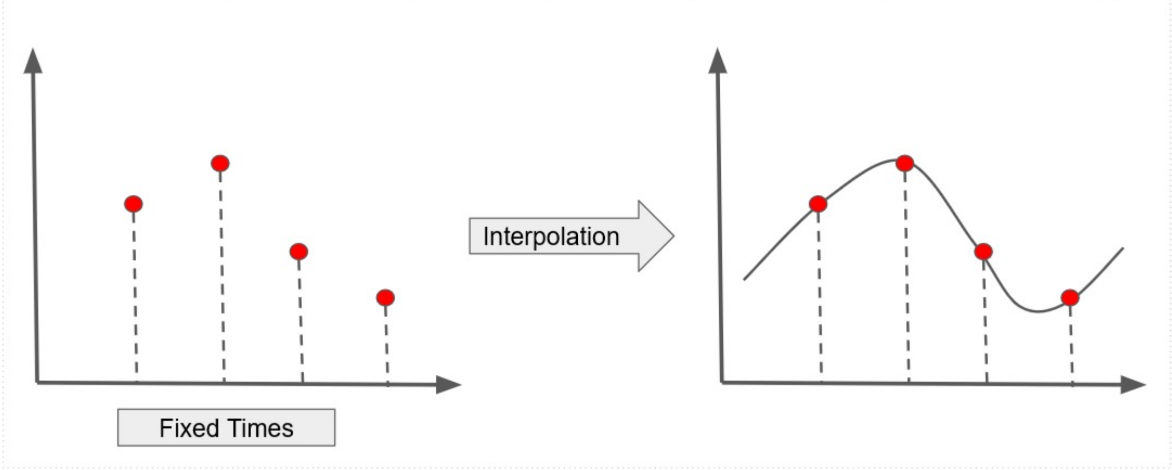
We call B the counterexample set and its elements counterexamples

If B is empty then $\rho(\phi, \boldsymbol{u}, 0) \geq 0$

Solving the domain estimation problem could be extremely difficult because of the infinite dimensionality of the input space, which is a space of functions

Finite Parameterization





N Control points

N variable

Domain Estimation Problem

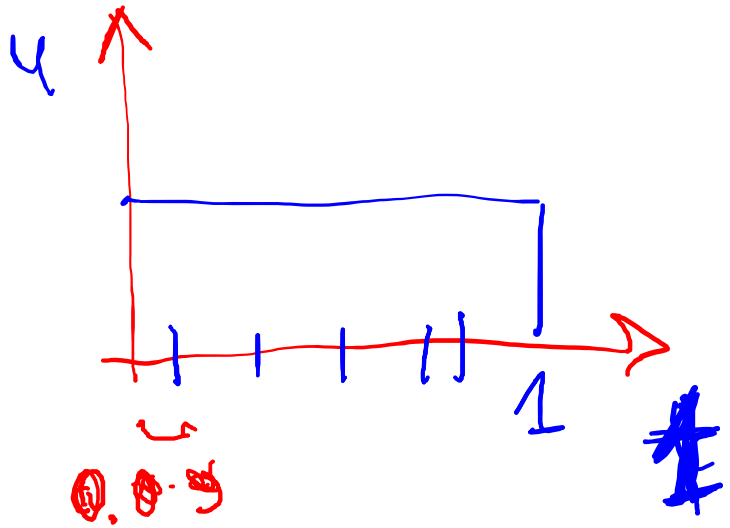
Finding the trajectories which falsify the requirements, finding $\hat{c} \in \hat{B}$

$$\hat{B} = \{ \hat{c} \in U_{n_1} \times \cdots \times U_{n_{|U|}} \mid \rho(\phi, P_{\boldsymbol{n}}(\hat{c}), 0)) < 0 \}$$

Where $c_k = \{(t_1^k, u_{n_k}^k), \ldots, (t_{n_k}^k, u_{k_n})\}$ and $P_{\boldsymbol{n}} = (P_{n_1}, \ldots, P_{n_{|U|}})$

Piecewise linear or polynomial functions are known to be dense in the space of continuous functions!

Then, B has at least one element $\Longleftrightarrow \exists n \in \omega^{|U|}$, $\hat{B}$ has at least one element.



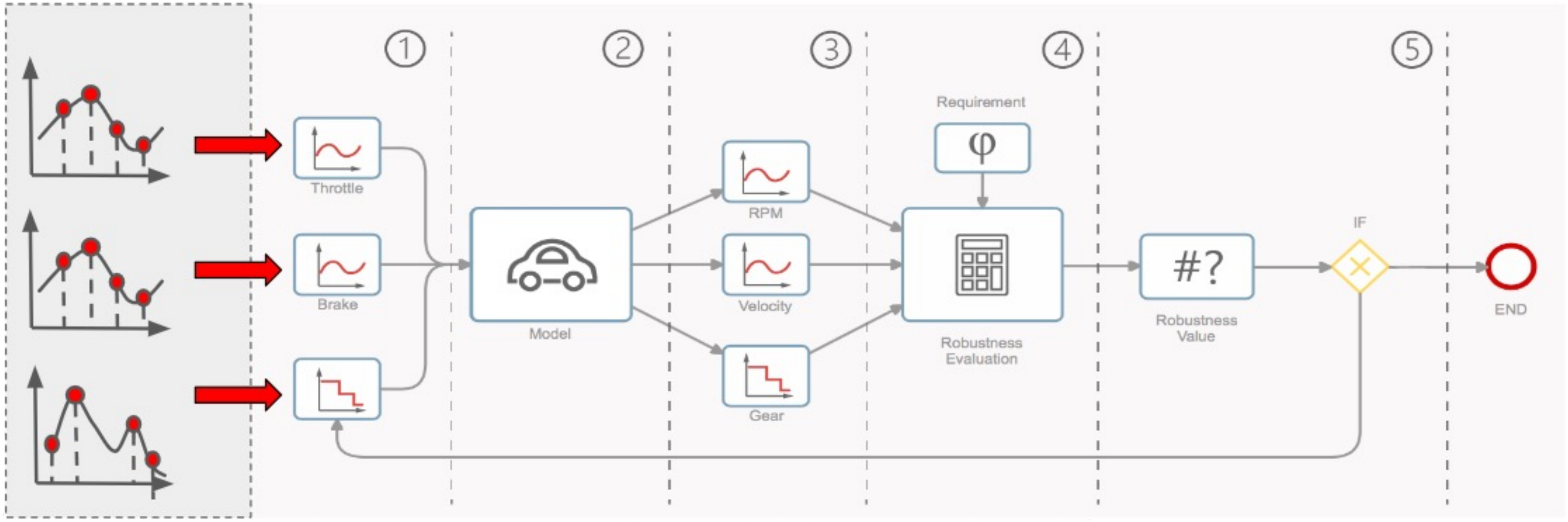
$$u : [0,1] \to [0,1]$$

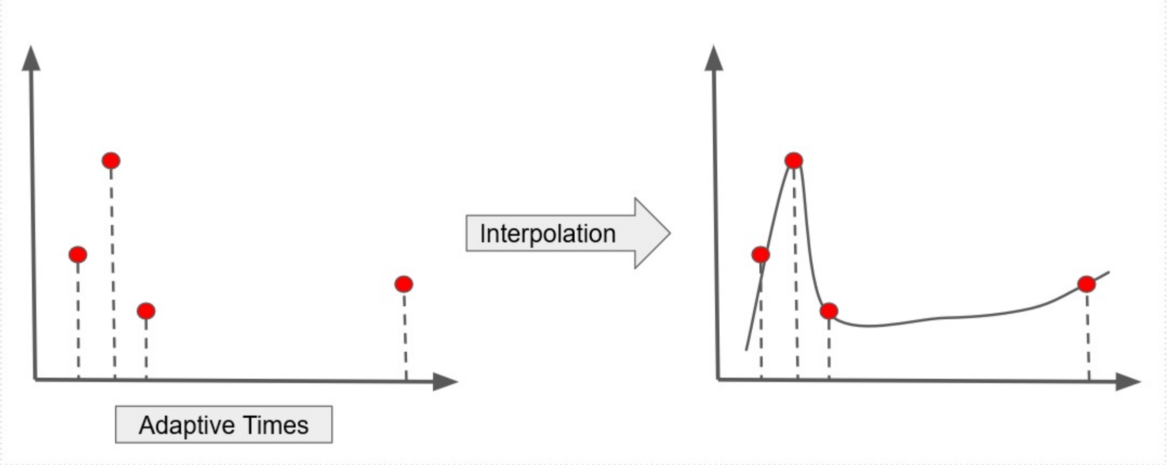
$$t \longmapsto k$$

$$\boxed{\varphi = \neg\Big(\underbrace{G_{[0,0.51]}(x<0.2)} \wedge \underbrace{G_{[0.58,1]}(x>0.8)}\Big)}$$

0.1 $u=0.5$

Adaptive Parameterization



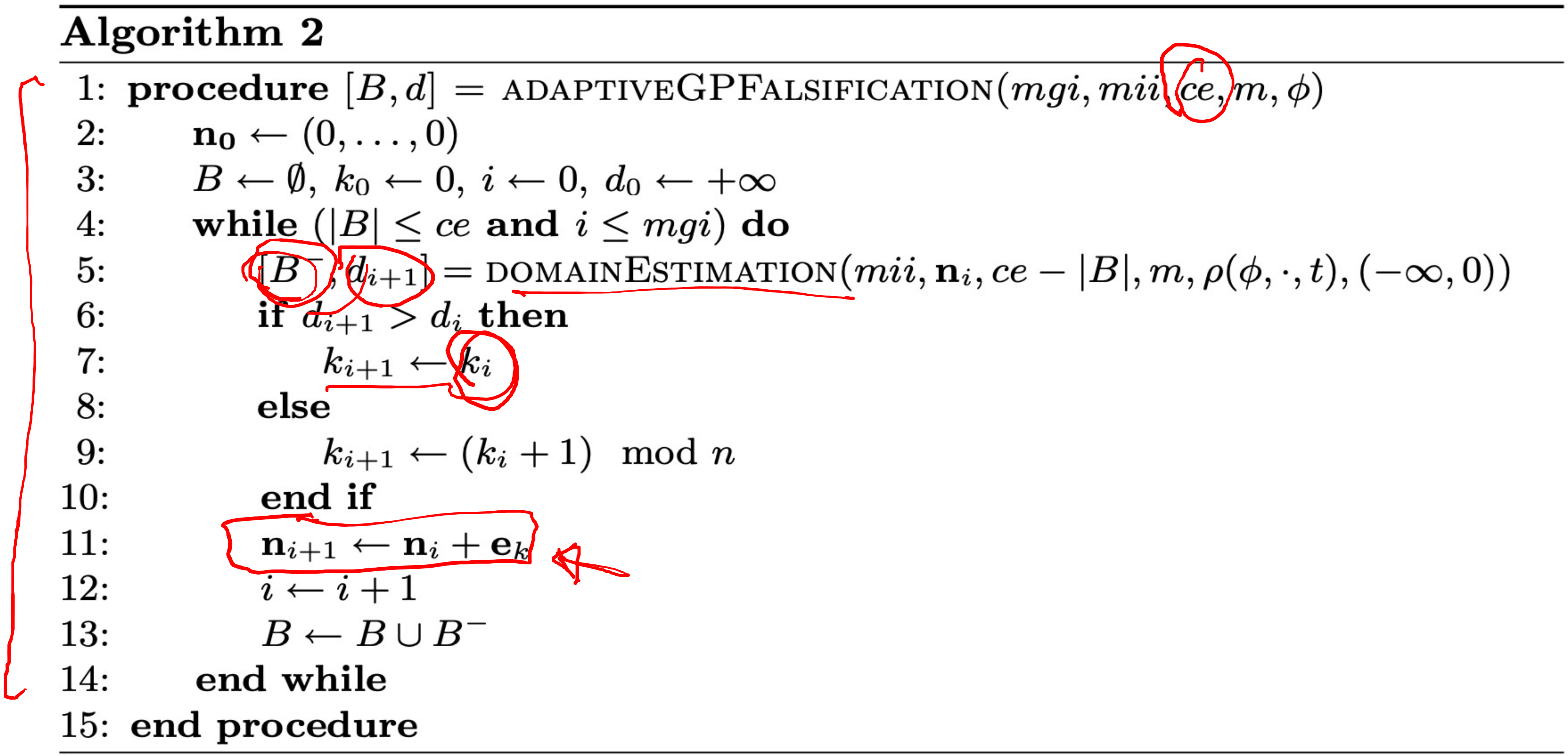


N Control points

↓

2N variable

Adaptive Parameterization

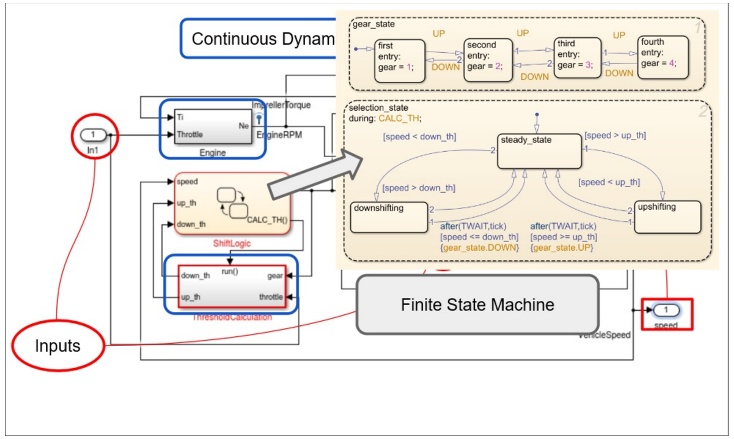


Algorithm 2

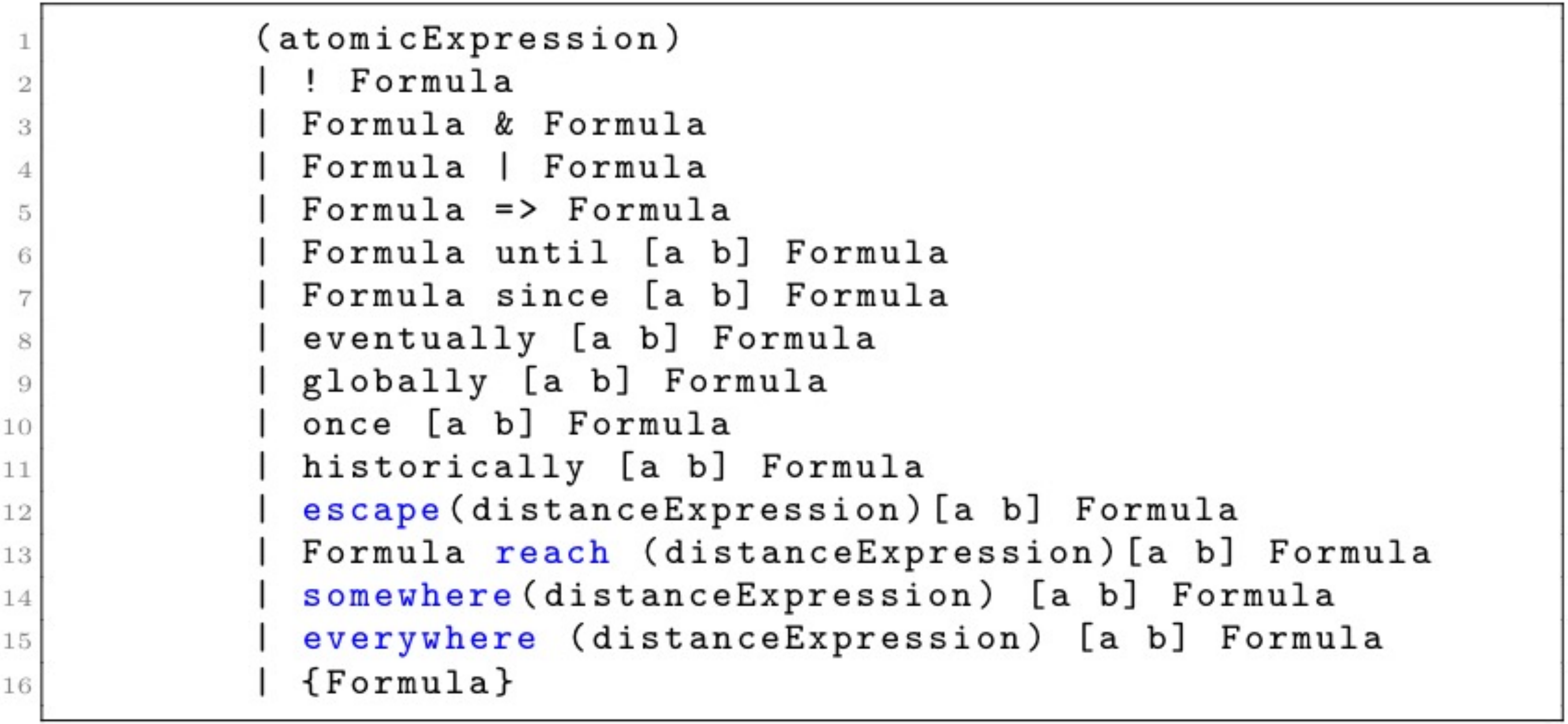
```
procedure $[B, d]$ = ADAPTIVEGPFALSIFICATION($mgi, mii, ce, m, \phi$)
    $\mathbf{n}_0 \leftarrow (0, \ldots, 0)$
    $B \leftarrow \emptyset,\ k_0 \leftarrow 0,\ i \leftarrow 0,\ d_0 \leftarrow +\infty$
    while ($|B| \leq ce$ and $i \leq mgi$) do
        $[B^-, d_{i+1}]$ = DOMAINESTIMATION($mii, \mathbf{n}_i, ce - |B|, m, \rho(\phi, \cdot, t), (-\infty, 0)$)
        if $d_{i+1} > d_i$ then
            $k_{i+1} \leftarrow k_i$
        else
            $k_{i+1} \leftarrow (k_i + 1) \mod n$
        end if
        $\mathbf{n}_{i+1} \leftarrow \mathbf{n}_i + \mathbf{e}_k$
        $i \leftarrow i + 1$
        $B \leftarrow B \cup B^-$
    end while
end procedure
```

Tests Case & Results

- $\phi_1(\bar{v},\bar{\omega}) = \mathbf{G}_{[0,30]}(v \leq \bar{v} \wedge \omega \leq \bar{\omega})$ (in the next 30 seconds the engine and vehicle speed never reach $\bar{\omega}$ rpm and $\bar{v}$ km/h, respectively)
- $\phi_2(\bar{v},\bar{\omega}) = \mathbf{G}_{[0,30]}(\omega \leq \bar{\omega}) \rightarrow \mathbf{G}_{[0,10]}(v \leq \bar{v})$ (if the engine speed is always less than $\bar{\omega}$ rpm, then the vehicle speed can not exceed $\bar{v}$ km/h in less than 10 sec)
- $\phi_3(\bar{v},\bar{\omega}) = \mathbf{F}_{[0,10]}(v \geq \bar{v}) \rightarrow \mathbf{G}_{[0,30]}(\omega \leq \bar{\omega})$ (the vehicle speed is above $\bar{v}$ km/h than from that point on the engine speed is always less than $\bar{\omega}$ rpm)



	Adaptive DEA		Adaptive GP-UCB		S-TaLiRo		
Req	nval	times	nval	times	nval	times	Alg
ϕ_1	$\mathbf{4.42 \pm 0.53}$	2.16 ± 0.61	$\mathbf{4.16 \pm 2.40}$	0.55 ± 0.30	5.16 ± 4.32	0.57 ± 0.48	UR
ϕ_1	$\mathbf{6.90 \pm 2.22}$	5.78 ± 3.88	8.7 ± 1.78	1.52 ± 0.40	39.64 ± 44.49	4.46 ± 4.99	SA
ϕ_2	$\mathbf{3.24 \pm 1.98}$	1.57 ± 1.91	7.94 ± 3.90	1.55 ± 1.23	12.78 ± 11.27	1.46 ± 1.28	CE
ϕ_2	$\mathbf{10.14 \pm 2.95}$	12.39 ± 6.96	23.9 ± 7.39	9.86 ± 4.54	59 ± 42	6.83 ± 4.93	SA
ϕ_2	$\mathbf{8.52 \pm 2.90}$	9.13 ± 5.90	13.6 ± 3.48	4.12 ± 1.67	43.1 ± 39.23	4.89 ± 4.43	SA
ϕ_3	$\mathbf{5.02 \pm 0.97}$	2.91 ± 1.20	5.44 ± 3.14	0.91 ± 0.67	10.04 ± 7.30	1.15 ± 0.84	CE
ϕ_3	$\mathbf{7.70 \pm 2.36}$	7.07 ± 3.87	10.52 ± 1.76	2.43 ± 0.92	11 ± 9.10	1.25 ± 1.03	UR



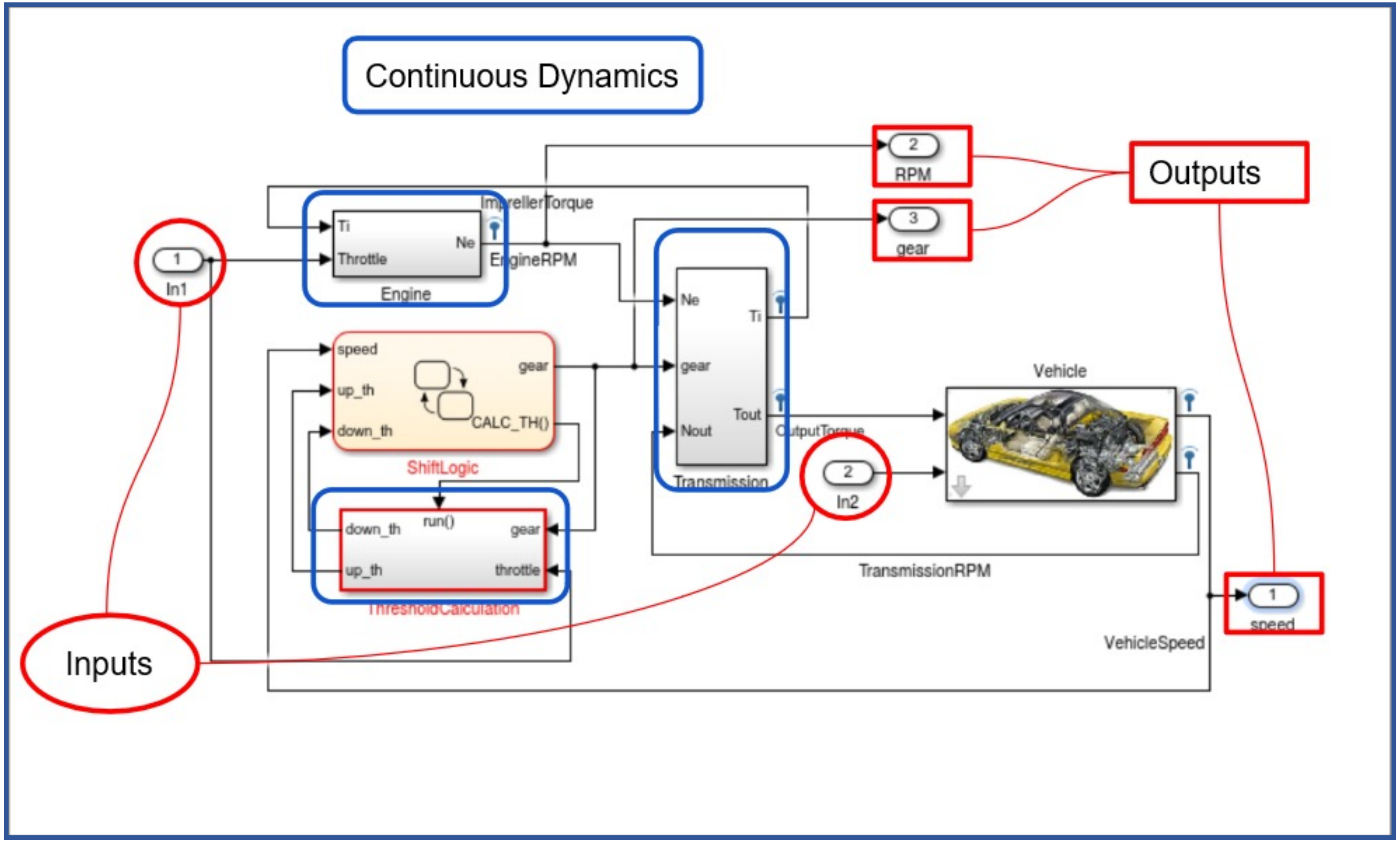
```
(atomicExpression)
| ! Formula
| Formula & Formula
| Formula | Formula
| Formula => Formula
| Formula until [a b] Formula
| Formula since [a b] Formula
| eventually [a b] Formula
| globally [a b] Formula
| once [a b] Formula
| historically [a b] Formula
| escape(distanceExpression)[a b] Formula
| Formula reach (distanceExpression)[a b] Formula
| somewhere(distanceExpression) [a b] Formula
| everywhere (distanceExpression) [a b] Formula
| {Formula}
```

Model

Inputs:

Throttle

Brake



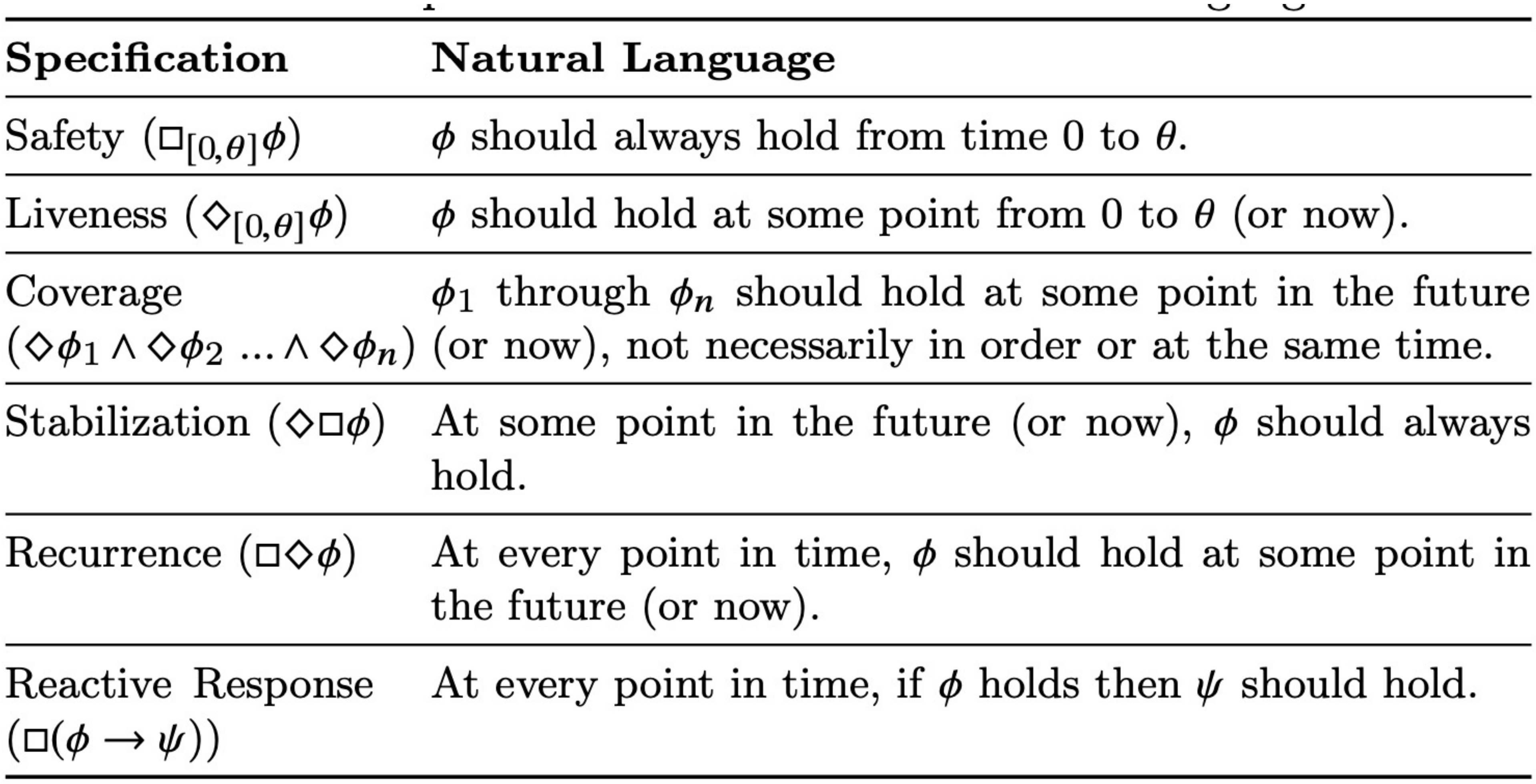
Outputs:

RPM

Gear

Speed

https://it.mathworks.com/help/simulink/slref/modeling-an-automatic-transmission-controller.html



Specification	**Natural Language**
Safety ($\Box_{[0,\theta]}\phi$)	ϕ should always hold from time 0 to θ.
Liveness ($\Diamond_{[0,\theta]}\phi$)	ϕ should hold at some point from 0 to θ (or now).
Coverage ($\Diamond\phi_1 \wedge \Diamond\phi_2 \ldots \wedge \Diamond\phi_n$)	ϕ_1 through ϕ_n should hold at some point in the future (or now), not necessarily in order or at the same time.
Stabilization ($\Diamond\Box\phi$)	At some point in the future (or now), ϕ should always hold.
Recurrence ($\Box\Diamond\phi$)	At every point in time, ϕ should hold at some point in the future (or now).
Reactive Response ($\Box(\phi \rightarrow \psi)$)	At every point in time, if ϕ holds then ψ should hold.

	Automatic Transmission	
	Natural Language	**MTL**
ϕ_1^{AT}	The engine speed never reaches $\bar{\omega}$.	$\Box(\omega < \bar{\omega})$
ϕ_2^{AT}	The engine and the vehicle speed never reach $\bar{\omega}$ and $\bar{v}$, resp.	$\Box((\omega < \bar{\omega}) \wedge (v < \bar{v}))$
ϕ_3^{AT}	There should be no transition from gear two to gear one and back to gear two in less than 2.5 sec.	$\Box((g_2 \wedge X g_1) \rightarrow \Box_{(0,2.5]} \neg g_2)$
ϕ_4^{AT}	After shifting into gear one, there should be no shift from gear one to any other gear within 2.5 sec.	$\Box((\neg g_1 \wedge X g_1) \rightarrow \Box_{(0,2.5]} g_1)$
ϕ_5^{AT}	When shifting into any gear, there should be no shift from that gear to any other gear within 2.5sec.	$\wedge_{i=1}^{4} \Box((\neg g_i \wedge X g_i) \rightarrow \Box_{(0,2.5]} g_i)$
ϕ_6^{AT}	If engine speed is always less than $\bar{\omega}$, then vehicle speed can not exceed $\bar{v}$ in less than T sec.	$\neg(\Diamond_{[0,T]}(v > \bar{v}) \wedge \Box(\omega < \bar{\omega}))$
ϕ_7^{AT}	Within T sec the vehicle speed is above $\bar{v}$ and from that point on the engine speed is always less than $\bar{\omega}$.	$\Diamond_{[0,T]}((v \geq \bar{v}) \wedge \Box(\omega < \bar{\omega}))$
ϕ_8^{AT}	A gear increase from first to fourth in under 10secs, ending in an RPM above $\bar{\omega}$ within 2 seconds of that, should result in a vehicle speed above $\bar{v}$.	$((g_1\ \mathcal{U}\ g_2\ \mathcal{U}\ g_3\ \mathcal{U}\ g_4) \wedge \Diamond_{[0,10]}(g_4 \wedge \Diamond_{[0,2]}(\omega \geq \bar{\omega}))) \rightarrow \Diamond_{[0,10]}(g_4 \rightarrow X(g_4\ \mathcal{U}_{[0,1]}\ (v \geq \bar{v})))$

Bibliography

Falsification:

- Silvetti S., Policriti A., Bortolussi L. (2017) *An Active Learning Approach to the Falsification of Black Box Cyber-Physical Systems.* IFM 2017. LNCS, vol 10510. Springer, Cham.
- Several excellent papers on the first development of falsification technology can be found on the web-site of S-TaLiRo : https://sites.google.com/a/asu.edu/s-taliro/references
- Jyotirmoy Deshmukh, Marko Horvat, Xiaoqing Jin, Rupak Majumdar, and Vinayak S. Prabhu. 2017. Testing Cyber-Physical Systems through Bayesian Optimization. *ACM Trans. Embed. Comput. Syst.* 16, 5s, Article 170 (September 2017)
- Deshmukh, Jyotirmoy, Xiaoqing Jin, James Kapinski, and Oded Maler. Stochastic Local Search for Falsification of Hybrid Systems. In *International Symposium on Automated Technology for Verification and Analysis*, pp. 500-517.