Cyber-Physical Systems

Laura Nenzi

Università degli Studi di Trieste II Semestre 2023

Lecture 16: Spatio-Temporal Reach and Escape Logic

Availability: I can always find a station with at least one bike in a radius of 500 meters

Spread: after 10 time units, there exists a location l' at a certain distance from location l where the number of infected individuals is more than 50

Reliability: we can always find a path of sensors such that all sensors have a battery level greater than 0.5

Spots: regions with low density of protein A are always surrounded by regions with high level of protein B

How to specify such spatio-temporal behaviours in a formal and human-understandable language ?

How to monitor their onset efficiently?

Part 1 :

- Space Model and traces
- Spatio- Temporal Reach and Escape Logic (STREL)

Part 2:

- Monitoring
- Applicability to different scenarios

INPUTS

OUTPUTS

Running Example: Wireless Sensor Network

Space Model, Signal and Traces

Spatial Configuration

We consider a discrete space described as a weighted (direct) graph

Reasons:

- many applications, like bike sharing systems, smart grid and sensor networks are naturally framed in a discrete spatial structure
- in many circumstances continuous space is abstracted as a grid or as a mesh, e.g. numerical integration of PDEs

$$
Space Model S = \langle L, W \rangle
$$

- L is a set of nodes that we call locations;
- $W \subseteq L \times \mathbb{R} \times L$ is a proximity function associating a label $w \in \mathbb{R}$ to distinct pair $\ell_1, \ell_2 \in L$. If $(\ell_1, w, \ell_2) \in W$, it means that there is an edge from ℓ_1 to ℓ_2 with weight $w \in \mathbb{R}$

Example

$$
\text{Route} \quad \tau = \ell_0 \ell_1 \ell_2 \dots
$$

It is a infinite sequence s.t. $\forall i \geq 0 \exists w s.t. (\ell_i, w, \ell_{i+1}) \in W$

 $\ell_0 \ell_1 \ell_2 \ell_1 \dots$ is a route

 $\ell_0 \ell_1 \ell_2 \ell_3$... is a not route

 $\tau[i]$ to denote the $i-th$ node τ $\tau(\ell)$ to denote the first occurrence of $\ell \in \tau$

$$
|\text{Route Distance } d^f_{\tau}[i]|
$$

The distance d_{τ}^{J} \int The distance $d_{\tau}^{J}[i]$ up to index *i* is:

$$
d^f_\tau[i] = \begin{cases} 0 & i = 0\\ f\left(d^f_{\tau[1..]}[i-1], w\right) & (i > 0) \text{ and } \tau[0] \stackrel{w}{\mapsto} \tau[1] \end{cases}
$$

$$
d_{\tau}^{f}(\ell) = d_{\tau}^{f} [\tau(\ell)]
$$

$$
\begin{vmatrix}\n\text{Route Distance} & d_{\tau}^{f}[i]\n\end{vmatrix}
$$

 $weight(x, y) = x + y$

 $hops(x, y) = x + 1$

$$
d_{\ell_0\ell_1\ell_2}^{weight}[2] = \text{weight}(d_{\ell_1\ell_2}^{weight}[1], 4) = d_{\ell_1\ell_2}^{weight}[1] + 4 = ...
$$

= weight($d_{\ell_2}^{weight}[0], 2$) + 4 = 6

Location Distance
$$
d_S^f[e_i, e_j]
$$

$$
d_S^f[e_i, e_j] = \min\{d_\tau[e_j] | \tau \in Routers(S, e_i)\}\
$$

$$
d_S^{hops}[\ell_0, \ell_2] = \textbf{2}
$$

Location Distance

$$
d_S^f[e_i, e_j] = \min\{d_\tau[e_j] | \tau \in Routers(S, e_i)\}\
$$

$$
d_S^{hops}[\ell_0, \ell_2] = \mathbf{1}
$$

Signal and Trace

Spatio-Temporal Signals $\sigma: L \to \mathbb{T} \to D$

Spatio-Temporal Trace $\vec{x}: L \to \mathbb{T} \to D^n$

$$
x(\ell) = (\nu_B, \nu_T)
$$

$$
x(\ell, t) = (\nu_B(t), \nu_T(t))
$$

Dynamic Spatial Model

$$
(t_i, S_i)
$$
 for $i = 1, ..., n$ and $S(t) = S_i \forall t \in [t_i, t_{i+1})$

Spatio-Temporal Reach and Escape Logic (STREL) | these are inequality of the form (*g*(ν1*,...,* ^ν*n*) [≥] ⁰), for *^g* [∶] ^R*ⁿ* [→] ^R. Considering the event of the battery showld be greater than 0, or $\frac{1}{2}$, or $\frac{1}{2}$, $\frac{1}{2}$,

It is an extension of the Signal Temporal Logic with a number of re is an extension of the sight it temperature should be less than 3000 minutes that the state of the Signal To

Definition 8 (STREL Syntax) φ := *true* $|\mu| \neg \varphi |\varphi_1 \wedge \varphi_2 | \varphi_1 U_I \varphi_2 |\varphi_1 S_I \varphi_2 | \varphi_1 \mathcal{R}_d^f \varphi_2 |\mathcal{E}_d^f \varphi_1$ STREL Syntax

In addition, we can derive: where *true* is the Boolean *true* constant, *µ* is an *atomic predicate* (*AP*), *negation*

- rm addition, we can derive:
• The disjunction operator: ∨
- the temporal operators: F_I , G_I , O_I , H_I
- the spatial operators: somewhere, everywhere and surround
 d) are the spatial operation of \mathcal{O} , and \mathcal{O} are the spatial operation of \mathcal{O}

$$
\text{Reach: } \varphi_1 \mathcal{R}_{\lfloor d_1, d_2 \rfloor}^f \varphi_2
$$

[3*,*5]*pink* and *hops*

[3*,*∞]*orange* while `¹⁰ does not. `¹ satisfies !*hops*

j<⌧(`′) The Bookhapic from ι and all its elements with index less than τ $(S$, \vec{x} , ℓ , $t)$ satisfies $\;\varphi_1 {\cal R}^J_{\lceil d_1, d_2\rceil} \varphi_2\;$ iff it satisfies φ_2 in a location ℓ' reachable from ℓ through a route τ, with a length $d_{\tau}^{f}(\ell') \in [d_1, d_2]$ and such that $\tau[0] = \ell$ and all its elements with index less than $\tau(\ell')$ satisfy φ_1 $(S$, \vec{x} , ℓ , t) satisfies $\varphi_1 \mathcal{R}_{[d_1,d_2]}^f \varphi_2$ iff it satisfie *j*<⌧(`′) $\frac{1}{2}$ ements with index let

[2*,*3]*yellow*. All green points

$$
\begin{array}{ccc}\n\text{Escape:} & \mathcal{E}^f_{[d_1, d_2]} \varphi\n\end{array}
$$

dhops

 $(S$, \vec{x} , ℓ , t) satisfies $\mathcal{E}^f_{[d_1,d_2]} \varphi$ if and only there exists a route τ and a (S, x, t, t) satisfies $\varepsilon^{\check{}}_{[d_1, d_2]}$ φ if and only there exists a route t and a
location t' ∈ τ such that $\tau[0] = \ell$, d_S^f $[\ell, \ell']$ ∈ $[d_1$, d_2] and all elements $\tau[0], \dots \tau[k]$ (with $\tau(l') = k$) satisfy φ π [k] (with $\tau(l') = k$) satisfy φ $P'P' = [d, d_2]$ and all $[K]$ (With $\tau(\iota) = K$) satisty φ

$$
\begin{array}{cc}\n\text{Example:} & \mathcal{E}_{[3,\infty]}^{hops} \text{orange} \\
\end{array}
$$

$$
\tau = \ell_9 \ell_{10} \ell_{11} \ell_{12}
$$

\n
$$
\frac{1}{\ell_9} \frac{1}{\ell_9} \frac{1}{\ell_{12}}
$$

\n
$$
\tau[0] = \ell_9, \tau[3] = \ell_{12}
$$

\n
$$
\frac{d_{S}^{hops}[\ell_9, \ell_{12}] = 3}{\ell_{12}}
$$

 $\mathcal{P}(\mathcal{P}(\mathcal{P}))$ describes the possibility of $\mathcal{P}(\mathcal{P})$

a route with a distance that belongs to the interval *d*.

] ∈ [*d*1*, d*2] and all elements τ [0]*, ...*τ [*k*] (with τ (!′

τ [0]
<u>- Ιουλίου - Ιουλί</u>
- Ιουλίου - Ιου

Somewhere: $\oint_{[0,1]}\phi(t)dt$ $|\textsf{Somewhere:} \quad \text{ } \textcircled{*}^f_{[d_1,d_2]} \varphi$ a route with a distance that belongs to the interval *d*. S solute where: $\oint [d_1, d_2]^\varphi$

satisfy the property because the distance *dhops* $(d_2)^\varphi$ *^S* [!9*,* !12] = 3 and all elements τ [0]*,* τ [1]*,* τ [2]*,* τ [3] the distance *dhops* Now we describe the other three derived operators.

escaping from a certain region passing from a certain region passing only through locations that satisfy ϕ

[3*,*∞]

 (S, \vec{x}, ℓ, t) satisfies $\oint_{[d_1, d_2]}^f \varphi$ iff there exists a
location ℓ' reachable from ℓ and a s t $d^f[\ell \ell'] =$ $\begin{bmatrix} 1 & 1 \\ 0 & 0 \end{bmatrix}$ and a s.t. $d_S^f[\ell, \ell'] \in [d,d]$, that satisfies \mathscr{B} $\left\{\begin{matrix} \mathbf{y} \\ \mathbf{y} \end{matrix}\right\}$ $\left\{\begin{matrix} d_1, d_2 \end{matrix}\right\}$, that satisfies φ |
| and a s.t $\left[d_1, d_2\right]$, that satisfies φ $\left\{\begin{array}{ccc} \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet \end{array}\right\}$ (*S*, \vec{x} , ℓ , t) satisfies $\left\{\begin{array}{ccc} \bullet' & \bullet & \bullet & \bullet \\ (d_1, d_2)^{\varphi} & \bullet & \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \end{array}\right\}$ $\int f \Gamma$ ^{*d*} le from ℓ , and a s.t. $d'_{S}[\ell, \ell'] \in$ $\cos \varphi$ $\begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}$ location ℓ' reachable from ℓ , and a s.t. $d_S^f[\ell, \ell'] \in$ *^S* [!10*,* !12] = 2. $\oint_{\mathcal{I}}$ $\oint_{\mathcal{I}}$ $\oint_{\mathcal{I}}$ $\oint_{\mathcal{I}}$ $\oint_{\mathcal{I}}$ $f(t)$ satisfies $\oint_{[d_1, d_2]}^{\mathcal{I}}$ iff there exists a $[d_1, d_2]$, that satisfies φ ϕ holds for (S*,x,* !*, t*) iff there exists a $[d_1, d_2]$, that satisfies φ *i* a $\delta \varphi$ and δ Γ , Γ

 $\overline{}$

 τ ⁵ satisfies the pink property. Everywhere. *^f*

 $\tau[0] = \ell_1, \tau[k] = \ell_{35}$ $\tau = \ell_1 \ldots \ell_{35}$ $\ldots \ell_{35}$ $\begin{cases} \n\hbox{hops}_{15}[B,5] \n\end{cases}$ because there is a path $\tau = \ell_1$, $\tau = \ell_2$ $\begin{array}{rcl} \hline & -1 & -1 \\ & -1 & -1 \\ \hline \end{array}$ [3*,*5]*pink* because there is a path ^τ ⁼ !¹ *...* !³⁵ with a length *^dhops* $\tau[0] = \ell_1, \, \tau[k] = \ell_{35}$ $\tau = \ell_1 ... \ell_{35}$ $\frac{1}{\sqrt{2}}$, $\frac{1}{\sqrt{2}}$, $\frac{1}{\sqrt{2}}$, $\frac{1}{\sqrt{2}}$, $\frac{1}{\sqrt{2}}$, $\frac{1}{\sqrt{2}}$, $\frac{1}{\sqrt{2}}$ \overline{y} and $\tau = \ell_1 \dots \ell$ \mathscr{L}_{35}

' holds for (S*, x,*

satisfy the property because the distance *dhops*

 \boldsymbol{r}

Now we describe the other three derived operators.

property. Note that the route to satisfy the route to satisfy the route to satisfy the property because to satisfy the proper

satisfy the orange property. Note that the route !10!11!¹² is not a good route to

 $d_{\tau}^{hops}(k) \in [3, 5]$ Everywhere. !*^f* \mathbf{r} \rightarrow \mathbf{r} a_{τ}^{100} β) ϵ $\lbrack \nu \nu \rbrack$ $\lbrack \nu, \nu \rbrack$ $_{\tau}^{hops}(k) \in [3,5]$ u_{τ} $(n) \in [0, 0]$

^τ [0] = !9, ^τ [3] = !12, *^dhops*

$$
\begin{array}{ll}\n\text{Surround:} & \varphi_1 \otimes_{[d_1, d_2]}^f \varphi_2 \\
\hline\n\end{array}
$$

S , \vec{x} , ℓ , t) iff there exists a φ_1 -region that contains ℓ , all locations in that region satisfies φ_1 and are reachable from ℓ via a path with length less than d_2 .

All the locations that do not belong to the φ_1 -region but are directly connected to a location of that region must satisfy φ_2 and be reached from ℓ via a path with length in the interval $[d_1, d_2]$.

Surround: ϕ² and, in any case, one has to reach a ϕ2-node at a distance between *d*¹ and $\begin{array}{ccc} \text{Surround:} & \text{green} \circ^{hops}_{[0,100]} \text{blue} \end{array}$

Offline Monitoring Algorithm *xA*(*t,* `)*, x^B* (*t,* `)

Spatial Boolean Signal $s_{\varphi}: L \to [0, T] \to \{0, 1\}$ such that $s_{\varphi}(\ell, t) = 1 \Leftrightarrow (\mathcal{S}, \vec{x}, \ell, t) \vDash \varphi$ Spatial Quantitative Signal Quantitative Signal Quantitative Signal Quantitative Signal Quantitative Signal Qu
Spatial Quantitative Signal Quantitative Signal Quantitative Signal Quantitative Signal Quantitative Signal Qu $\frac{1}{2}$ $\frac{1}{2}$

xA(*t,* `)*, x^B* (*t,* `)

xA(*t,* `)*, x^B* (*t,* `)

s' ∶ *L* → [0*,T*] → {0*,* 1} such that *s*'(`*,t*) = 1 ⇔ (S*, x*⃗*,* `*,t*) ⊧ '

Offline Monitoring Algorithm \overline{S} $\overline{$ *s*' ∶ *L* → [0*,T*] → {0*,* 1} such that *s*'(`*,t*) = 1 ⇔ (S*, x*⃗*,* `*,t*) ⊧ ' *xA*(*t,* `)*, x^B* (*t,* `) 5 VII LII III

Spatial Quantitative Signal

 $\rho_{\varphi}: L \to [0, T] \to \mathbb{R} \cup \pm \infty$ such that Spatial Quantitative Signal $\rho_{\varphi}(\ell, t) = \rho(\mathcal{S}, \vec{x}, \ell, t)$

s' ∶ *L* → [0*,T*] → {0*,* 1} such that *s*'(`*,t*) = 1 ⇔ (S*, x*⃗*,* `*,t*) ⊧ '

INPUTS

OUTPUTS

Offline Monitoring Algorithm

Spatial Boolean satisfaction Spatial Quant. satisfaction

Spatial Boolean signals Spatial Quant. signals

Secondary signals

Primary signals

Computational consideration

- Temporal operators: like in STL monitoring [1] is **linear** in the length of the signal times the number of locations in the spatial model.
- Spatial properties are more expensive, they are based on a variations of the classical Floyd-Warshall algorithm. The number of operations to perform is quadratic for the reach operator and cubic for the escape

Static Space and Regular Grid

The formation of Patterns Introduction SSTL Case Study Monitoring SSTL Algorithms Results Conclusions

Space model: a K×K grid treated as a graph, cell $(i, j) \in L = \{1, ..., K\} \times \{1, ..., K\}$

Spatio-Temporal Trajectory: $x: L \to \mathbb{T} \to \mathbb{R}^2$ s.t. $x(\ell) = (x_A, x_B)$

Spot formation property *spotform* ∶= F[*Tpattern,Tpattern*+]G[0*,Tend*]((*x^A* ≤ *h*)S[*w*1*,w*2](*x^A* > *h*))

Spot formation property

$$
\phi_{spot_{form}} = F_{[19,20]} G((A \le 0.5) \circ^{hops}_{[1,w_2]} (A > 0.5))
$$

(c)

 $x_A(50,\ell)$ Boolean sat. Quantitative sat.

$$
\phi_{pattern} := \text{m}^{hops} \otimes_{\text{In 151}}^{hops} \phi_{spot_{form}}
$$

 $\overline{}$

Static Space and Stochastic Systems

Application to Stochastic Systems

STREL can be applied on stochastic systems considering methodologies as Statistical Model Checking (SMC) Statistical Model Checking (SMC)

Stochastic process \mathcal{M} = $(\mathcal{T}, \mathcal{A}, \mu)$ where \mathcal{T} is a trajectory space and μ is a probability measure on a o-algebra of τ ' is satisfied by M is the *satisfaction probability S*('*, t*), i.e. the probability that a $\mathop{\mathsf{ord}}\nolimits\mathcal T$, and $\mathop{\mathsf{ord}}\nolimits\mathcal T$ ' is satisfied by M is the *satisfaction probability S*('*, t*), i.e. the probability that a

We approximate the satisfaction probability $S(\varphi,t)$, i.e. the probability that a trajectory generated by the stochastic process M satisfies the formula ϕ . trajectory generated by the stochastic process M satisfies the formula ' at the time *t*: pproximate the satisfaction probability $S(\varphi, t)$, i.e. the probability th α , γ δεπειατεά by the stochastic process*ive* satisfies the formala ψ. trajectory generated by the stochastic process M satisfies the formula terms of the formula σ S atisfaction probability $S(\varphi,t)$, i.e. the probability that a the stochastic process *M* satisfies the formula d α *γ* the stochastic process, α satisfies the formal ψ. α is satisfaction probability Γ (*i* t), i.e. the probability that and interest at a set of the probability that proximate the satisfaction probability $S(\varphi, t)$, i.e. the probability that ory generated by the stochastic process ${\cal M}$ satisfies the formula $\varphi.$ The quantitative counterpart of the satisfaction probability is the *expected robustness*, $M_{\rm{max}}$ Spatio-Temporal Properties (Invited Tutorial) 111 μ The average robustness *E*(*R*') is the mean of the distribution, P (X 2 *{*~*x* 2 *D |* ⇢(*,* ~*x,* 0) 2 [*a, b*]*}*) = P (*R*'(X) 2 [*a, b*])

robustness distribution in do something similar with the the the trajectories of \mathbb{N} We can do something similar with the

Bike Sharing Systems (BSS)

London Santander Cycles Hire network

- 733 bike stations (each with 20-40 slots) - a total population of 57,713 agents (users) picking up and returning bikes

We model it as a Population Continuous Time Markov Chain (PCTMC) with timedependent rates, using historic journey and bike availability data.

Prediction for 40 minutes.

Bike Sharing Systems (BSS)

Spatio-Temporal Trajectory: $x: L \to \mathbb{T} \to \mathbb{Z}^2$ s.t. $x(i, t) = (B_i(t), S_i(t))$

Space model

- Locations: $L = \{bike \ stations\},\$
- Edges: $(\ell_i, w, \ell_j) \in W$ iff $w = || \ell_i \ell_j || < 1$ kilometer

std in [0, 0.0158] , mean std = 0.0053. std in [0, 0.0158] , mean std = 0.0039.

Availability of Bikes $\phi_1 = G\{\otimes_{[0,d]}^{weight}(B > 0) \land \otimes_{[0,d]}^{weight}(S > 0)\}$

 $d = 300 \text{ m}$

$\phi_1 = G\{\otimes_{[0,d]}^{weight}(B > 0) \wedge \otimes_{[0,d]}^{weight}(S > 0)\}$ Availability of Bikes

Satisfaction probability of some BBS stations vs distance d=[0,1.0]

| Bike Sharing Systems (BSS) Time $\overline{}$ Timed Availability The property we are not consider that a user $\overline{}$

$$
\psi_1 = G\left\{ \otimes_{[0,d]}^{weight} (F_{[t_w, t_w]} B > 0) \land \otimes_{[0,d]}^{weight} (F_{[t_w, t_w]} S > 0) \right\}
$$

Average walking speed of 6.0 km/h, e.g. d = 0.5 km -> t_w = 6 minutes

aspect into consideration by consideration by consideration by consideration by considering a new property: th
The consideration by consideration by consideration by consideration by consideration by consideration by cons

equal to *d*, that, eventually in a time equal to *t^w* has at least one free slot. The results similar to the results of previous property **considering the format is more than i**f α The results similar to the results of previous property

Dynamic Space

Mobile Ad-hoc sensor NETwork (MANET)

Mobile Ad-hoc sensor NETwork (MANET)

Space model $S(t)$

- Locations: $L = \{devices\},\$
- Edges: $(\ell_i, w, \ell_j) \in W$ iff $w = || \ell_i \ell_j || < min(r_i, r_j)$

Spatio-Temporal Trajectory: $x: L \longrightarrow \mathbb{T} \to \mathbb{Z} \times \mathbb{R}^2$ s.t. $x(i, t) = (nodeType, battery, temperature)$ $nodeType = 1, 2, 3$ for coordinator, rooter, and end device

Connectivity in a MANET

"an end device is either connected to the coordinator or can reach it via a chain of routers"

"broken connection is restored within h time units"

Connectivity in a MANET

"an end device is either connected to the coordinator or can reach it via a chain of routers"

$$
\phi_{connect} = device \mathcal{R}_{[0,1]}^{hop}(router \mathcal{R}^{hop} coord)
$$

"broken connection is restored within h time units"

$$
\phi_{connect_restore} = G(\neg \phi_{connect} \rightarrow F_{[0,h]}\phi_{connect})
$$

Boolean Satisfaction at each time step

$$
\phi_{connect} = device \mathcal{R}_{[0,1]}^{hop}(router \mathcal{R}^{hop} coord)
$$

Delivery in a MANET ² ⁼ *device* ^R*hops* [0*,*1] (*router*R*hops*

"from a given location, we can find a path of (hops) length at least 5 such
that all pades along the path house bettery lovel greater than 0.5" the estate of the estate o
Estate of the estate of the that all nodes along the path have a battery level greater than 0.5"

[0*,*5]*coord*)

$$
\psi_3 = \mathcal{E}_{[5,\infty]}^{hops}(battery > 0.5)
$$

Reliability in a MANET

"reliability in terms of battery levels, e.g. battery level above 0.5

$$
\phi_{reliable_router} = ((battery > 0.5) \land router) \mathcal{R}^{hop} coord
$$

$$
\phi_{reliable_connect} = device \mathcal{R}_{[0,1]}^{hop}(\phi_{reliable_outer})
$$

Moonlight: https://github.com/MoonLightSuite/MoonLight/wiki

First, you need to download JAVA (version 8) and set the environmental variable

JAVA_HOME= path to JAVA home directory

Then you need to get or generate the executable for Python or MATLAB.

First, you need to clone our repository

\$ git clone https://github.com/MoonLightSuite/MoonLight.git

or download it (link).

Then you need to compile it by executing the following Gradle tasks in the console

```
(atomicExpression)
              ! Formula
\overline{2}Formula & Formula
3
              Formula | Formula
4
             Formula -> Formula<br>Formula until [a b] Formula
5
6
            | Formula since [a b] Formula
7
              eventually [a b] Formula
8
              globally [a b] Formula
9
              once [a b] Formula
10historically [a b] Formula
11escape (distance Expression) [a b] Formula
12
              Formula reach (distanceExpression) [a b] Formula
13
              somewhere (distance Expression) [a b] Formula
14
              everywhere (distanceExpression) [a b] Formula
15
              {Formula}16
```
Bibliography

Mining Requirements:

- Ezio Bartocci, Luca Bortolussi, Laura Nenzi, Guido Sanguinetti, System design of stochastic models using robustness of temporal properties. Theor. Comput. Sci. 587: 3-25 (2015)
- **Deshmukh et al. Mining Requirements from Closed-loop Control Models (HSCC '13, IEEE Trans. On Computer Aided Design '15)**
- ▶ Bartocci, E., Bortolussi, L., Sanguinetti, G.: Data-driven statistical learning of temporal logic properties, FORMATS, 2014
- ▶ Bufo, S., Bartocci, E., Sanguinetti, G., Borelli, M., Lucangelo, U., Bortolussi, L.i,Temporal logic based monitoring of assisted ventilation in intensive care patients, ISoLA, 2014.
- u Nenzi L., Silvetti S., Bartocci E., Bortolussi L. (2018) *A Robust Genetic Algorithm for Learning Temporal Specifications from Data.* QEST 2018. LNCS, vol 11024. Springer, Cham.