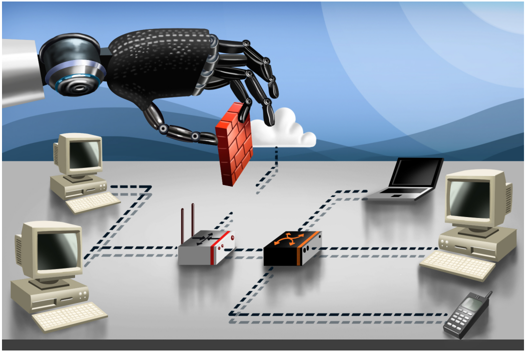
Self-Learning Systems for Cyber Defense

Kim Hammar, Rolf Stadler

CDIS Fall Retreat 2022
Oct 27-28

Self-Learning Security Systems: Current Landscape



Levels of security automation

No automation.
Manual detection.
Manual prevention.
No alerts.
No automatic responses.
Lack of tools.

1980s

Operator assistance.
Manual detection.
Manual prevention.
Audit logs.
Security tools.

1990s

Partial automation.
System has automated functions for detection/prevention but requires manual updating and configuration.
Intrusion detection systems.
Intrusion prevention systems.

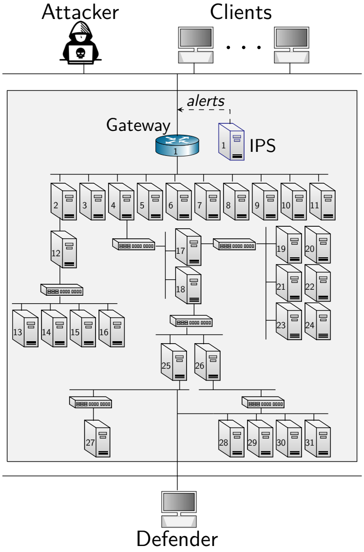
2000s-Now

High automation.
System automatically updates itself.
Automated attack detection.
Automated attack mitigation.

Research

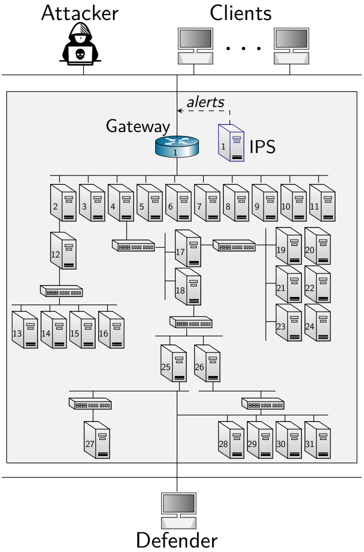
Challenges: Evolving and Automated Attacks

- **Challenges**
  - Evolving & automated attacks
  - Complex infrastructures



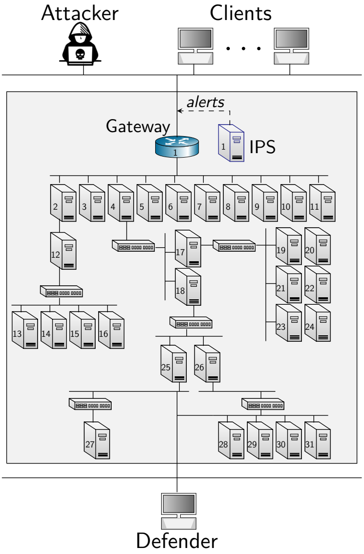
Goal: Automation and Learning

- **Challenges**
  - Evolving & automated attacks
  - Complex infrastructures
- **Our Goal**:
  - Automate security tasks
  - Adapt to changing attack methods

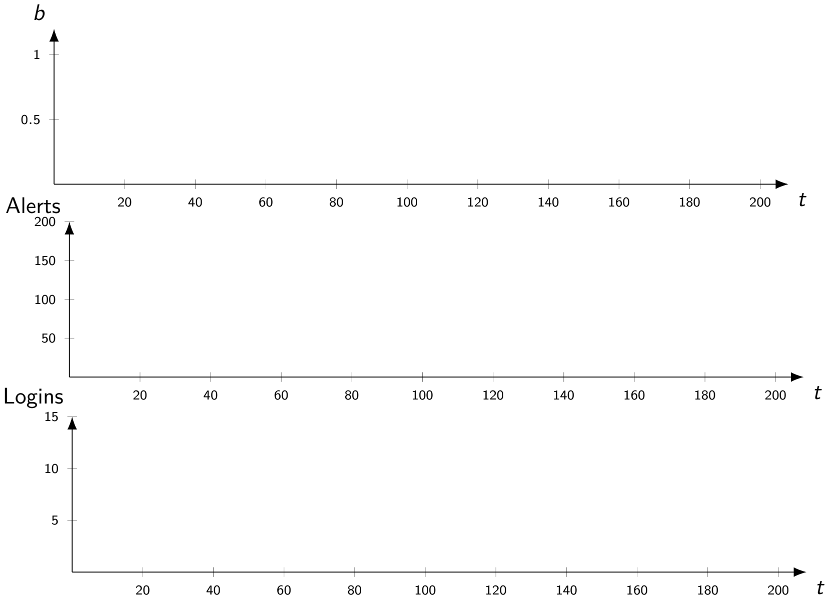


Approach: Self-Learning Security Systems

- **Challenges**
  - Evolving & automated attacks
  - Complex infrastructures
- **Our Goal**:
  - Automate security tasks
  - Adapt to changing attack methods
- **Our Approach: Self-Learning Systems**:
  - real-time telemetry
  - stream processing
  - theories from control/game/decision theory
  - computational methods (e.g. dynamic programming & reinforcement learning)
  - automated network management (SDN, NFV, etc.)



Example Use Case: Intrusion Prevention



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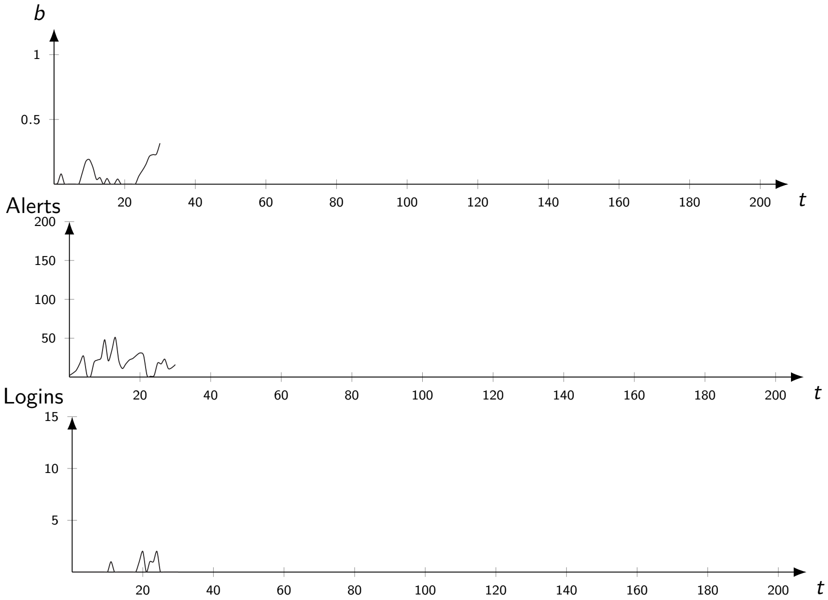

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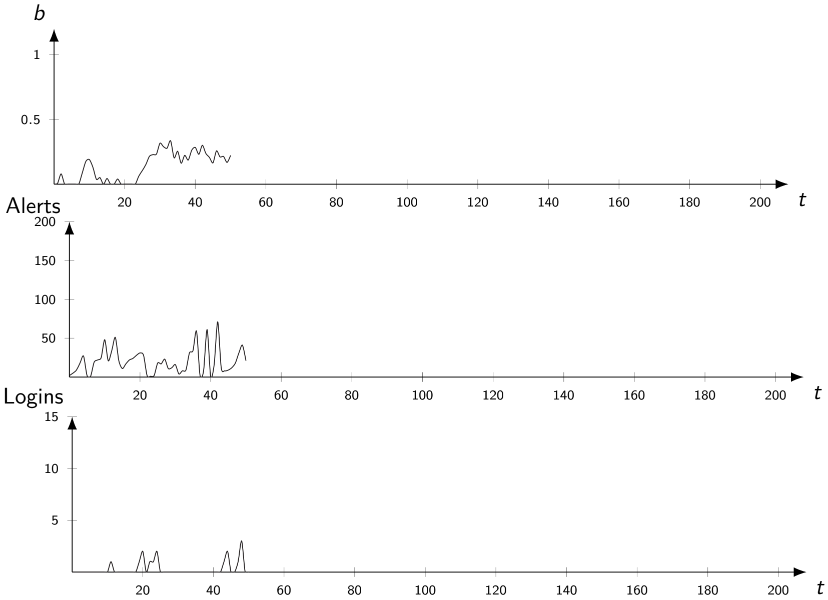

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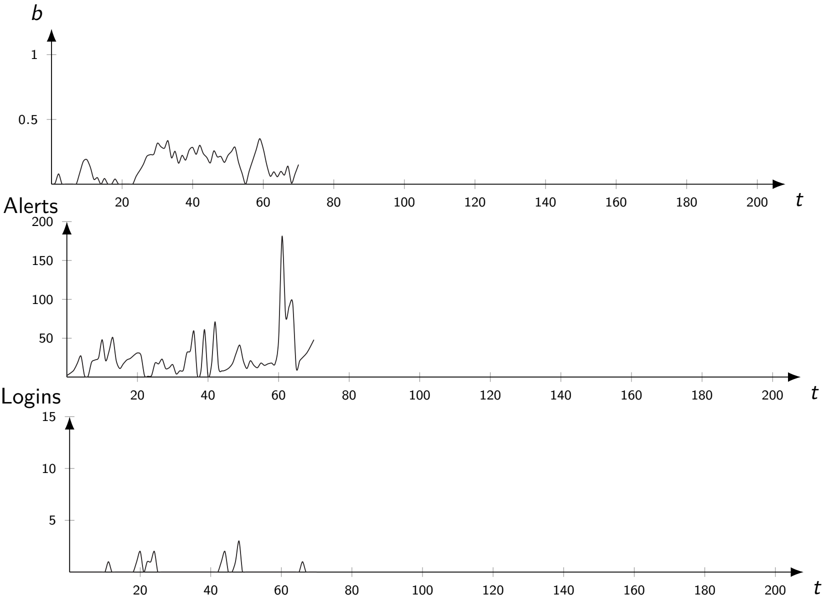

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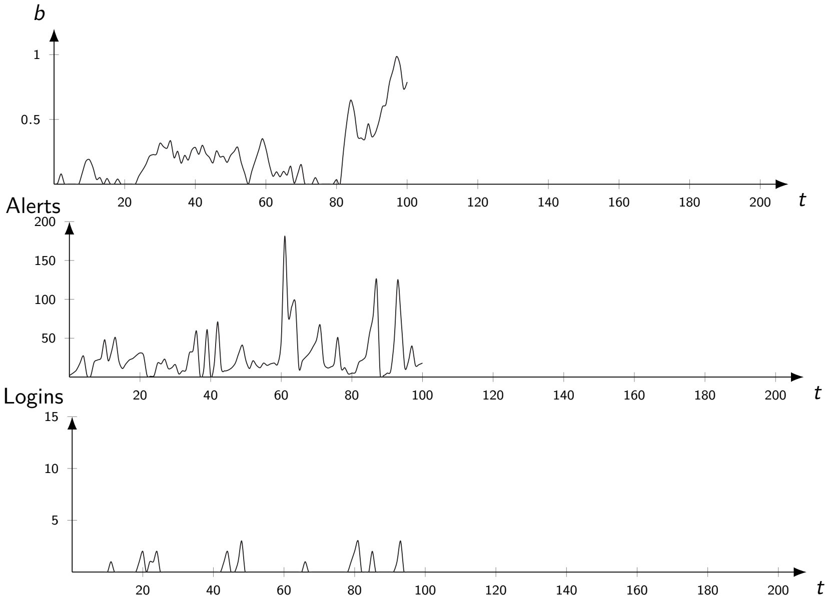

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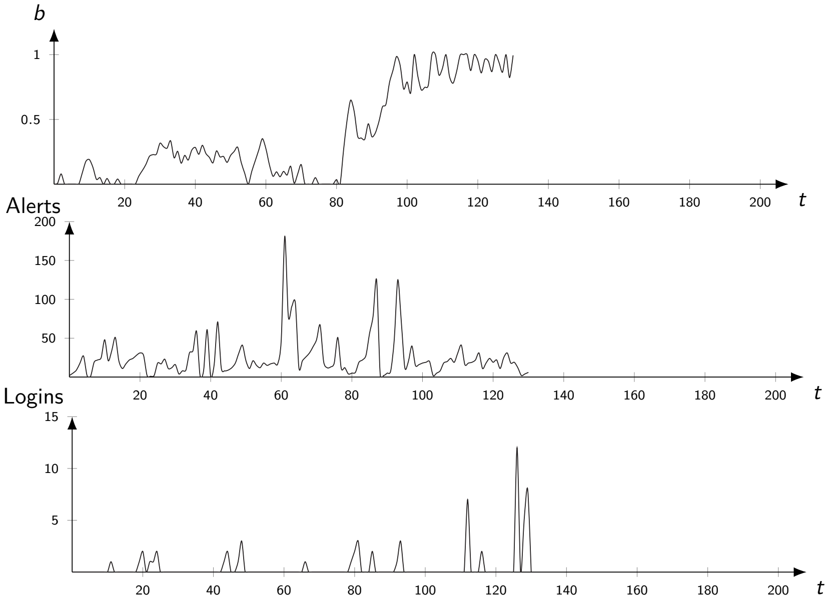

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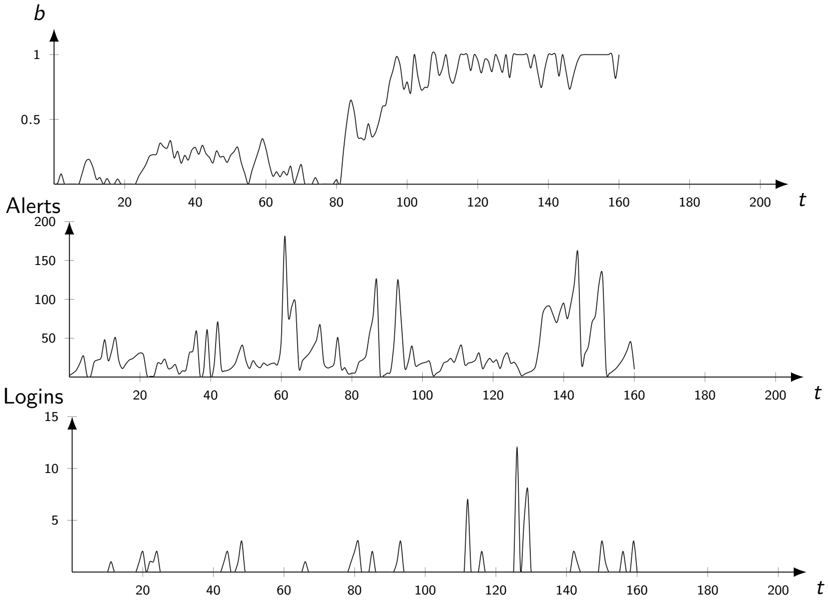
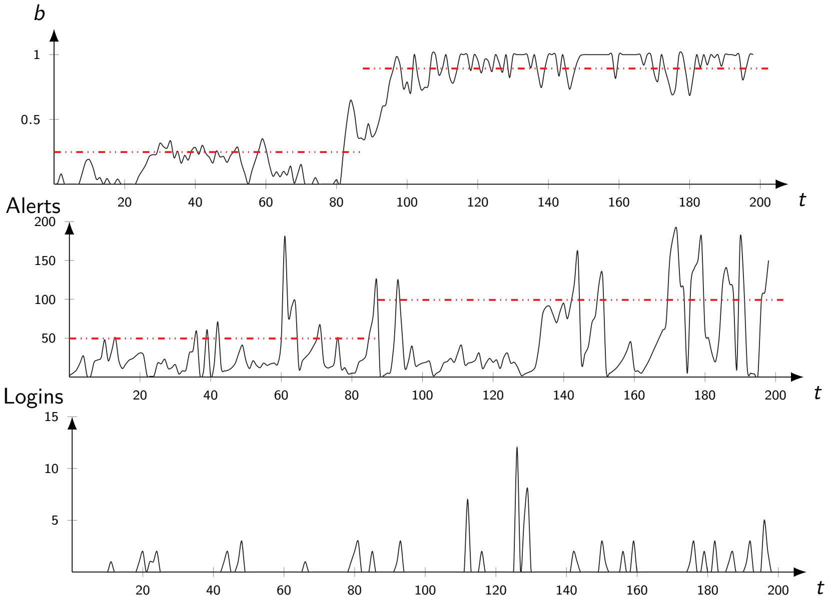


The Intrusion Prevention Problem



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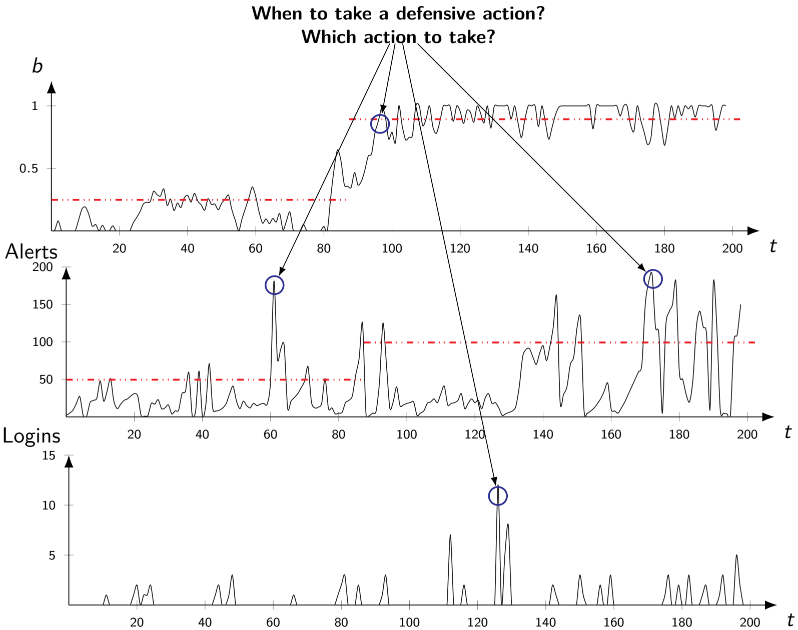

Outline

- **Use Case & Motivation:**
  - Use case: Intrusion prevention
  - Self-learning security systems: current landscape
- **Our Approach**
  - Network emulation and digital twin
  - Stochastic game simulation and reinforcement learning
- **Summary of results so far**
  - Comparison with related work
  - Intrusion prevention through optimal multiple stopping
  - Dynkin games and learning in dynamic environments
  - System for policy validation
- **Outlook on future work**
  - Extend use case
  - Rollout-based methods
- **Conclusions**
  - Takeaways

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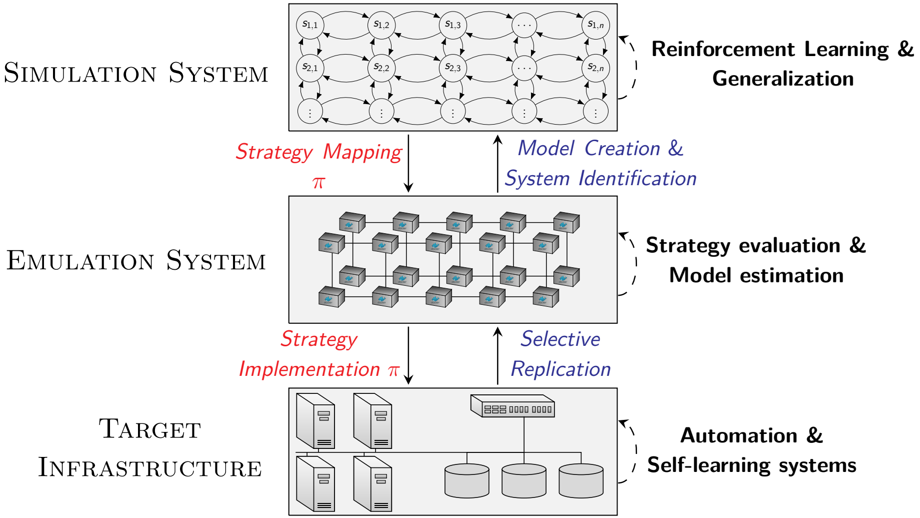

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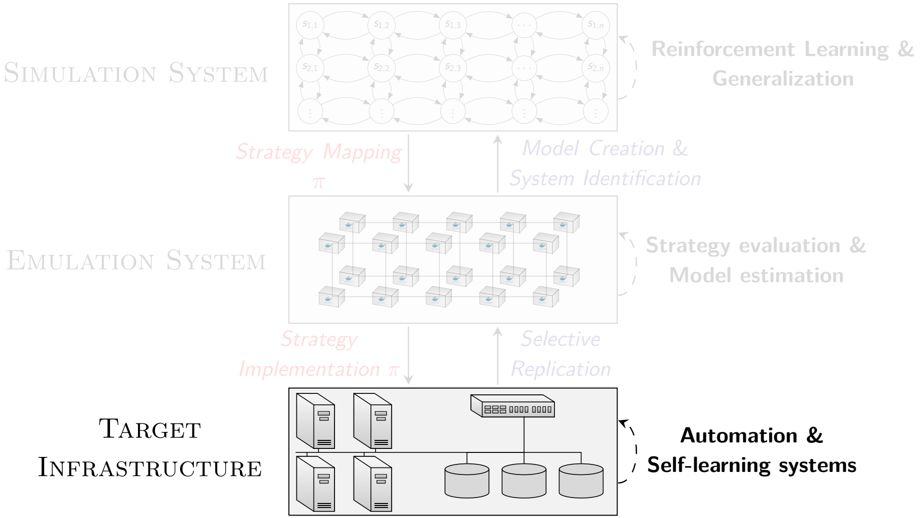

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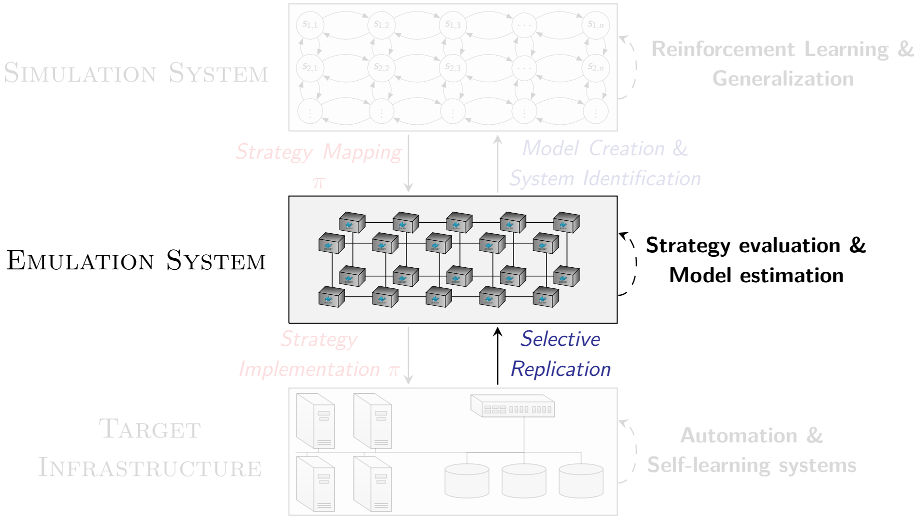

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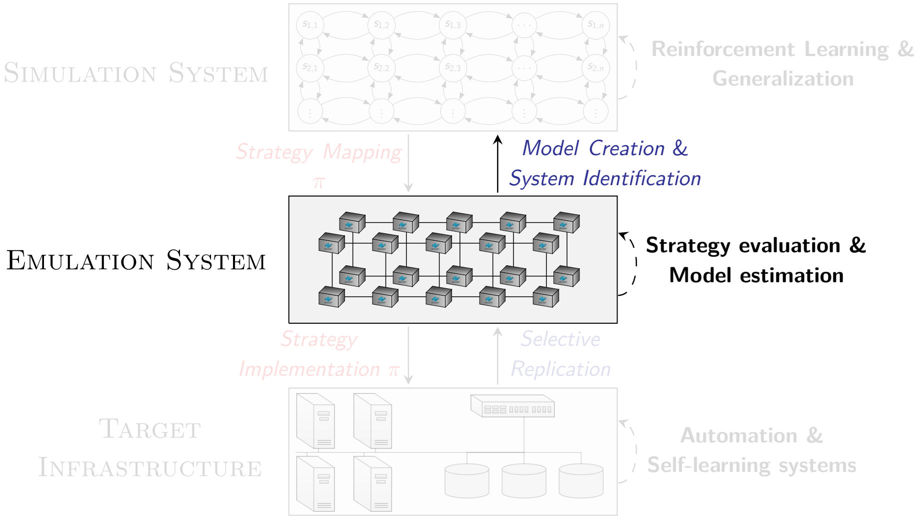

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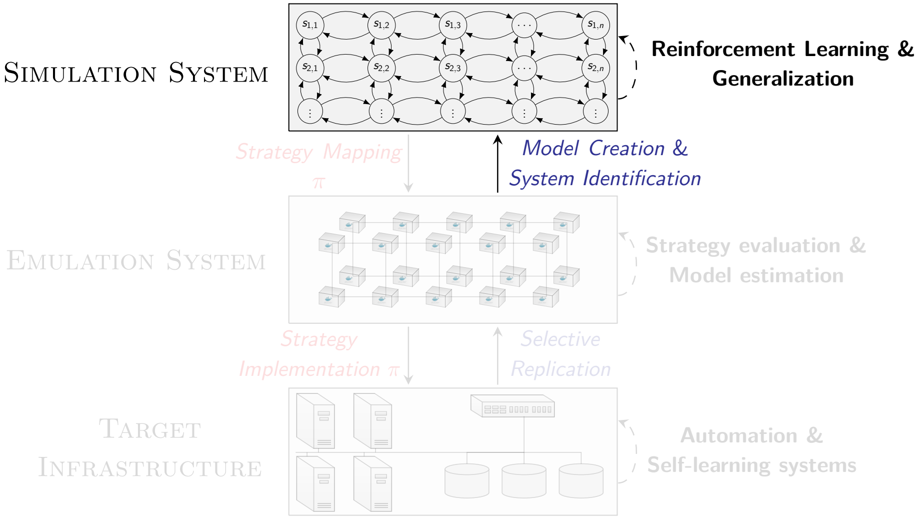

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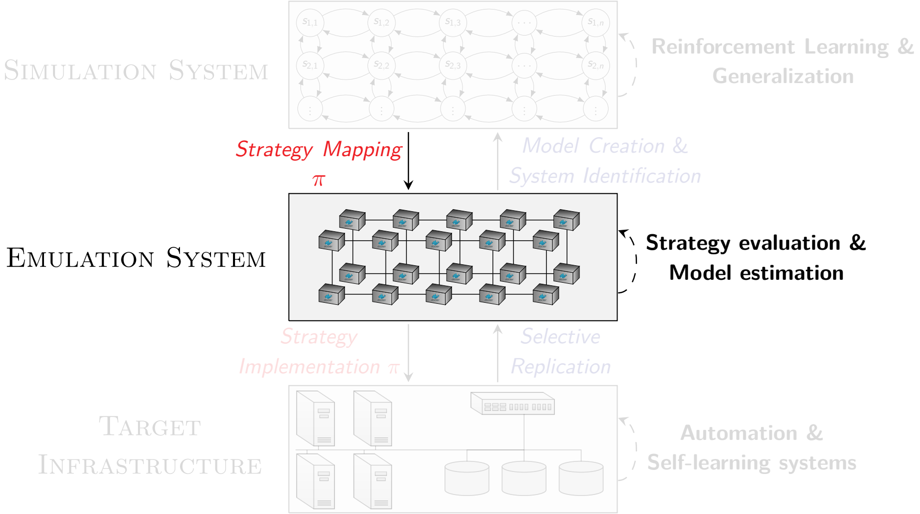

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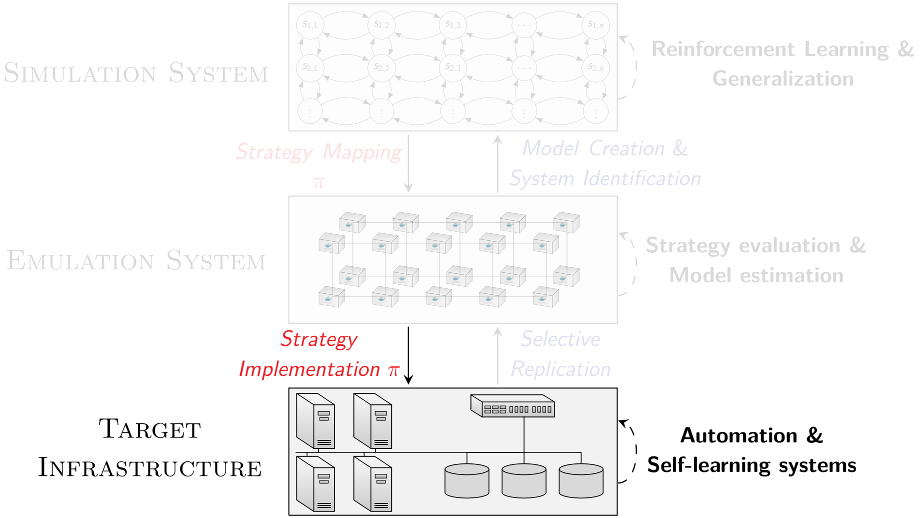

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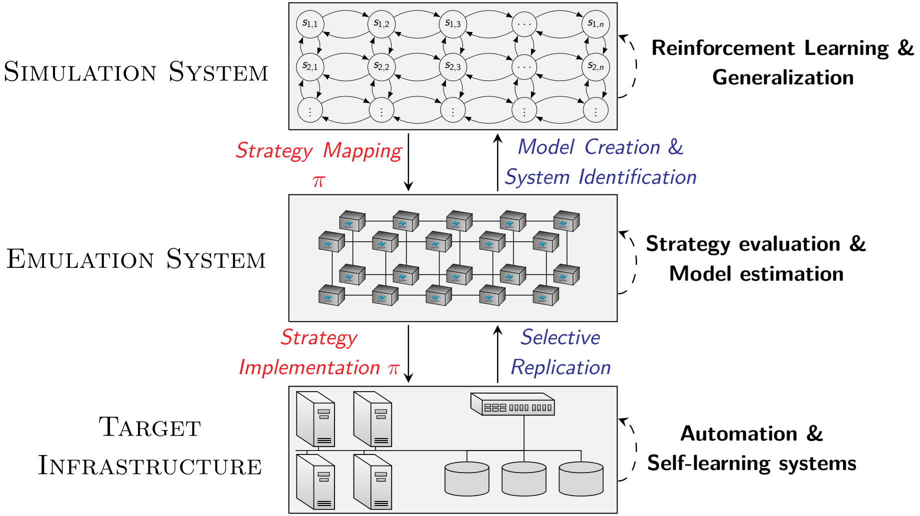
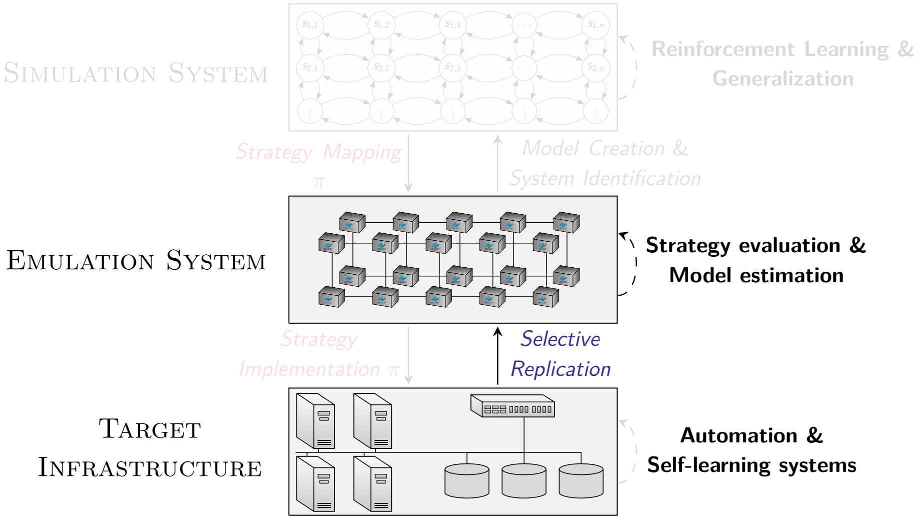
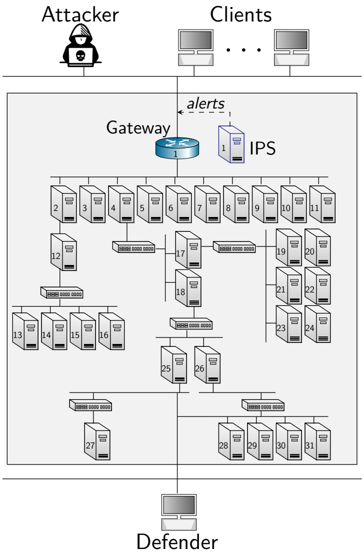


Creating a Digital Twin of the Target Infrastructure



Creating a Digital Twin of the Target Infrastructure

- Emulate **hosts** with docker containers
- Emulate **IPS and vulnerabilities** with software
- Network isolation and **traffic shaping** through NetEm in the Linux kernel
- Enforce **resource constraints** using cgroups.
- Emulate **client arrivals** with Poisson process
- **Internal connections** are full-duplex & loss-less with bit capacities of 1000 Mbit/s
- **External connections** are full-duplex with bit capacities of 100 Mbit/s & 0.1% packet loss in normal operation and random bursts of 1% packet loss



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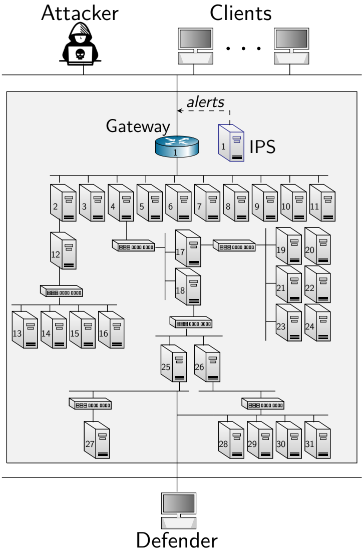

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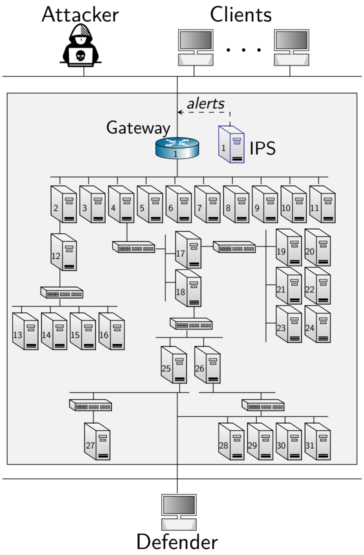

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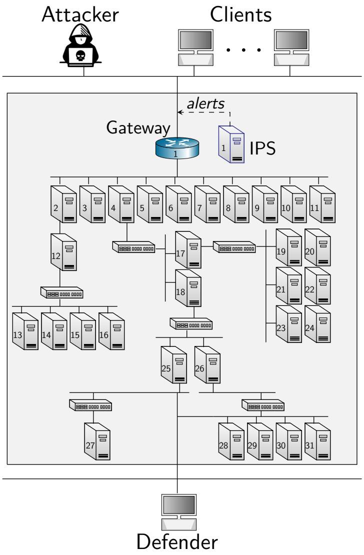

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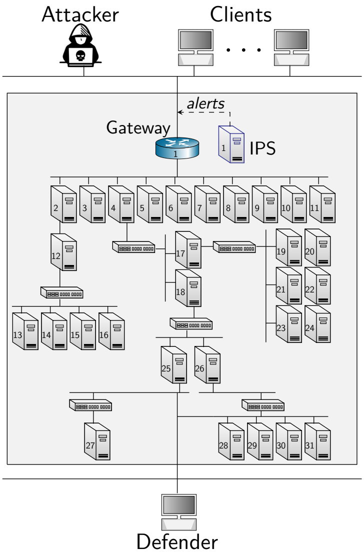

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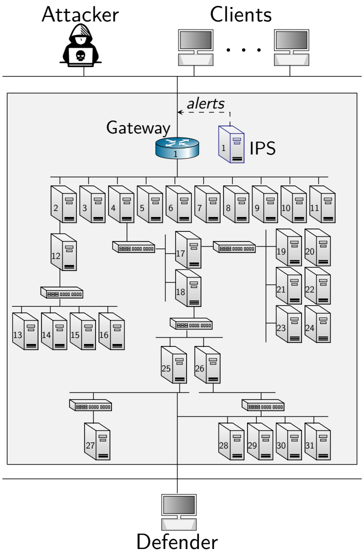
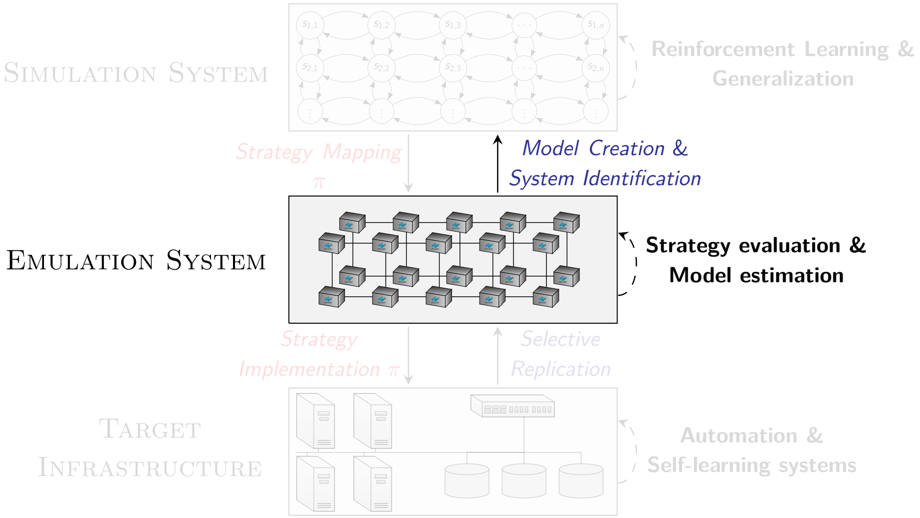
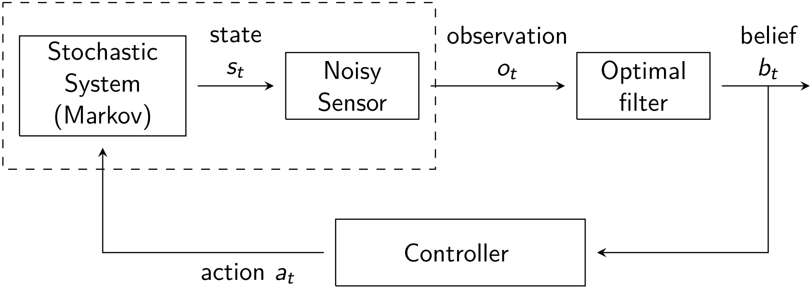


Our Approach for Automated Network Security



System Model

- We model the evolution of the system with a discrete-time dynamical system.
- We assume a Markovian system with stochastic dynamics and partial observability.



System Model

- We model the evolution of the system with a discrete-time dynamical system.
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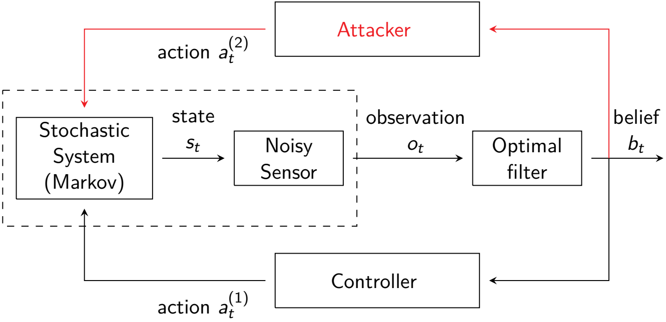
- A Partially Observed Markov Decision Process (POMDP)
  - If attacker is static.
- A Partially Observed Stochastic Game (POSG)
  - If attacker is dynamic.



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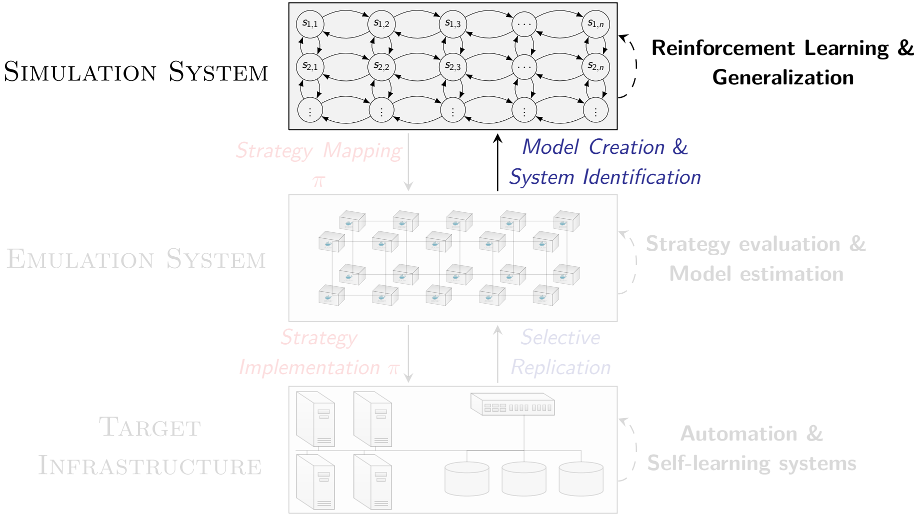
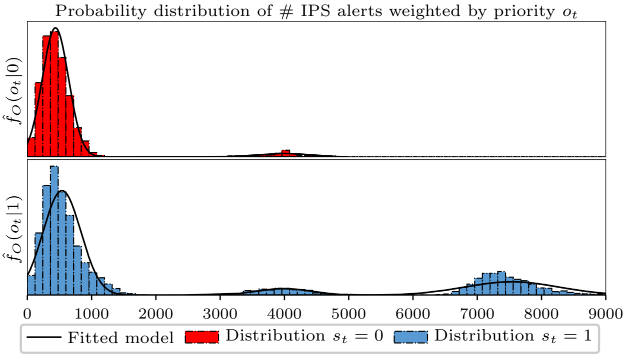


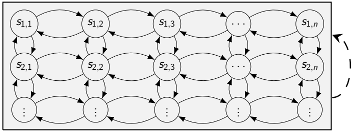
System Identification



- The distribution f_O of defender observations (system metrics) is unknown.
- We fit a Gaussian mixture distribution $\hat{f}_O$ as an estimate of f_O in the target infrastructure.
- For each state s, we obtain the conditional distribution $\hat{f}_{O|s}$ through expectation-maximization.

The Simulation System

Simulation System



Reinforcement Learning & Numerical methods

- **Simulations**:
  - Markov decision processes
  - Stochastic games
- **Learning/computing defender strategies**:
  - Reinforcement learning
  - Stochastic approximation
  - Computational game theory
  - Dynamic programming
  - Optimization

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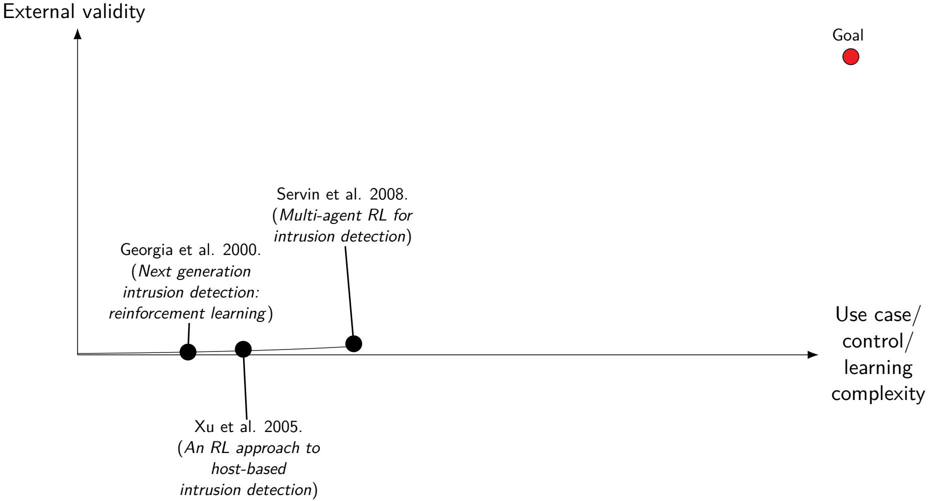

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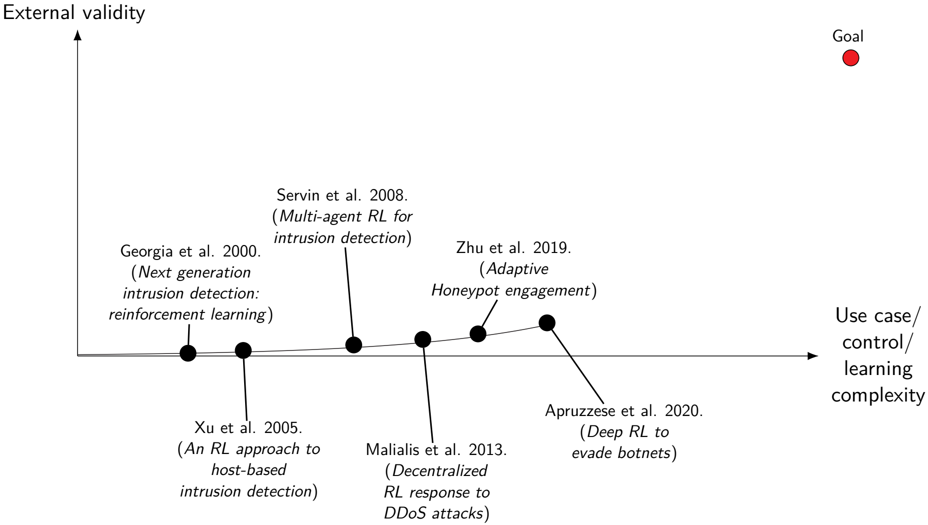

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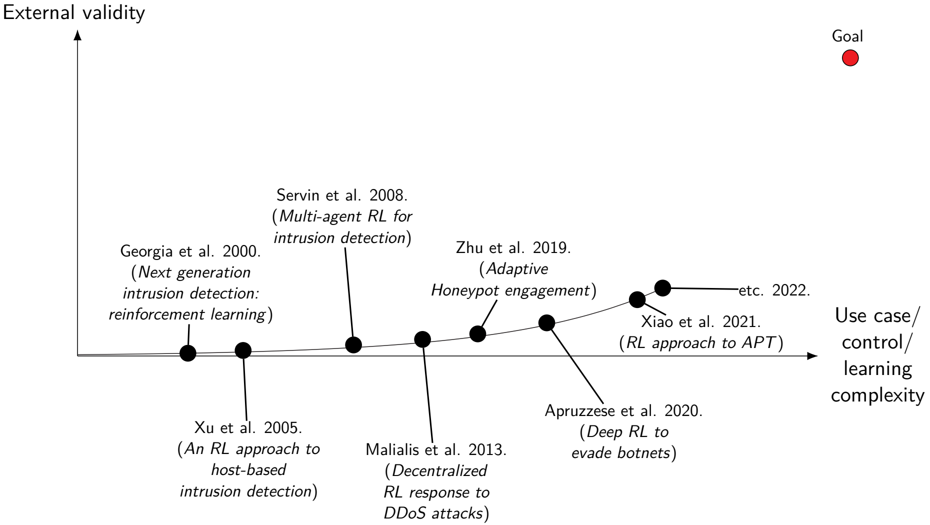

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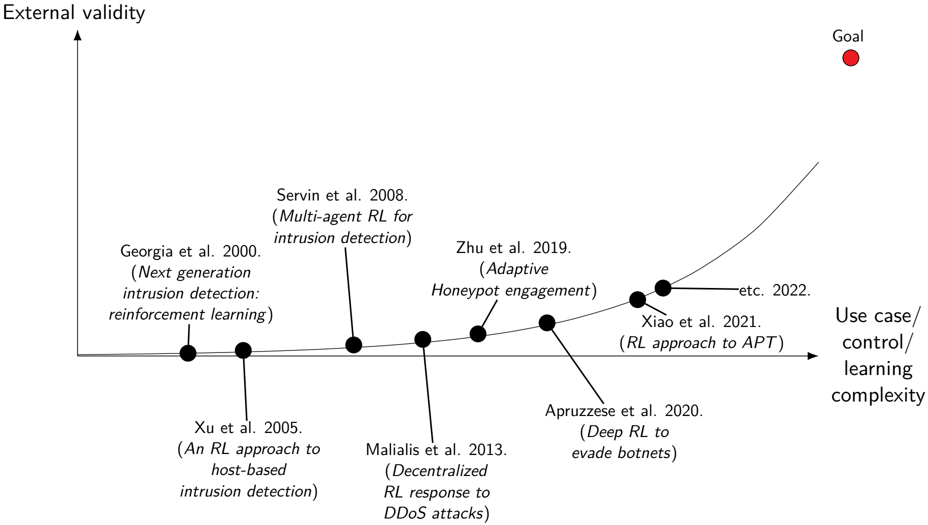

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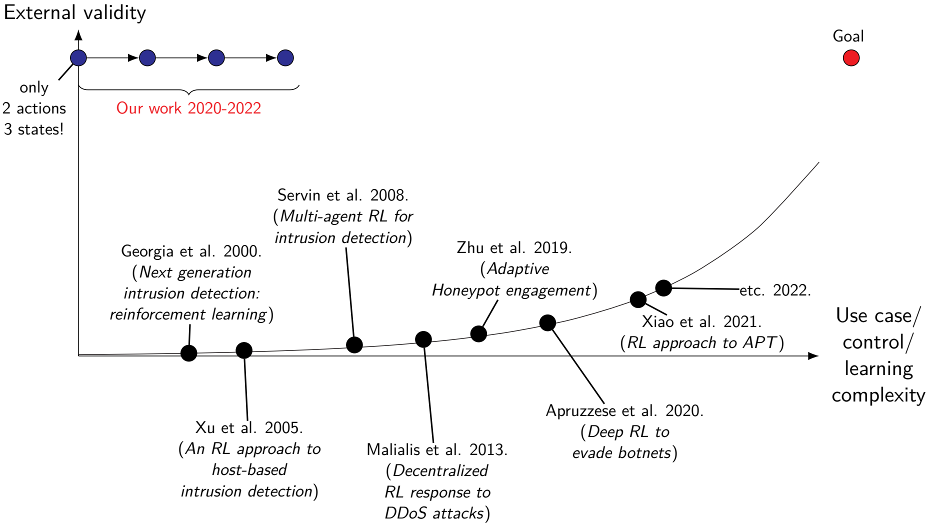

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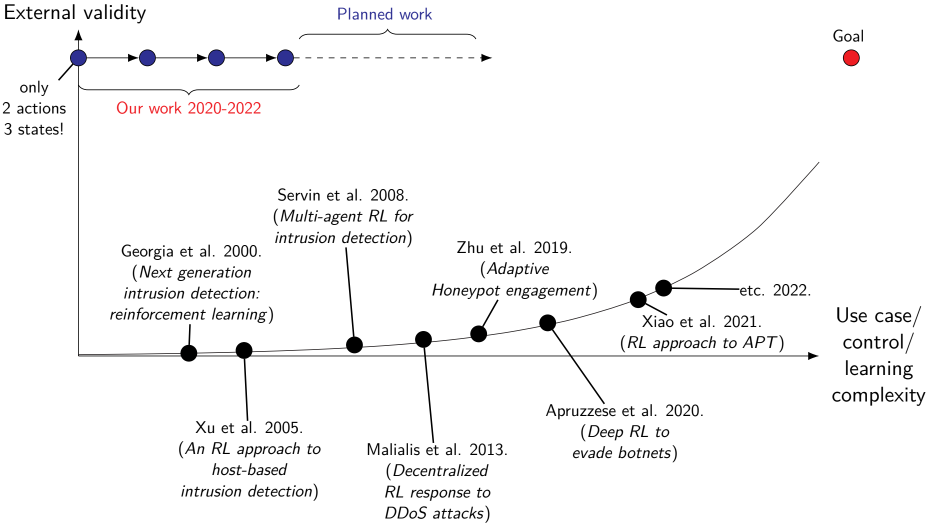


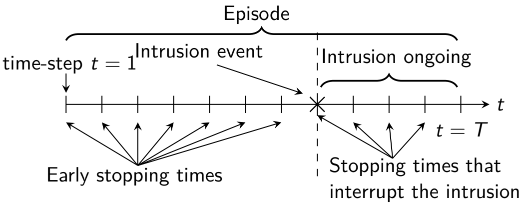
1: Intrusion Prevention through Optimal Stopping[1]

- **Intrusion Prevention as an Optimal Stopping Problem**:
  - A stochastic process $(s_t)_{t=1}^{T}$ is observed sequentially
  - Two options per t: (i) continue to observe; or (ii) stop
  - Find the *optimal stopping time* τ^*:

$$\tau^* = \arg\max_{\tau} \mathbb{E}_{\tau}\left[\sum_{t=1}^{\tau-1} \gamma^{t-1}\mathcal{R}^{C}_{s_t s_{t+1}} + \gamma^{\tau-1}\mathcal{R}^{S}_{s_\tau s_\tau}\right]$$

where $\mathcal{R}^{S}_{ss'}$ & $\mathcal{R}^{C}_{ss'}$ are the stop/continue rewards

- Stop action = Defensive action



[1] Kim Hammar and Rolf Stadler. "Learning Intrusion Prevention Policies through Optimal Stopping". In: *International Conference on Network and Service Management (CNSM 2021)*. http://dl.ifip.org/db/conf/cnsm/cnsm2021/1570732932.pdf. Izmir, Turkey, 2021.

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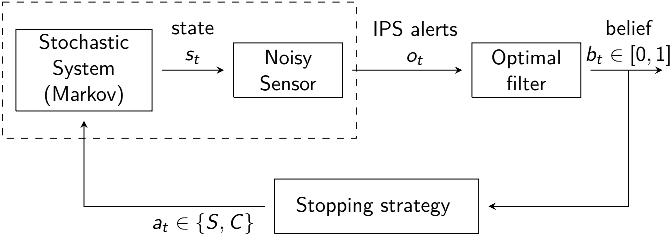

- **States:** Intrusion $s_t \in \{0, 1\}$, terminal $\emptyset$.
- **Observations:**
  - Number of IPS Alerts $o_t \in \mathcal{O}$
  - o_t is drawn from r.v. $O \sim f_O(\cdot|s_t)$.
  - Based on history h_t of observations, the defender can compute the belief $b_t(s_t) = \mathbb{P}[s_t|h_t]$.
- **Actions:** $\mathcal{A}_1 = \mathcal{A}_2 = \{S, C\}$
- **Rewards:** security and service.
- **Transition probabilities:** Follows from game dynamics.

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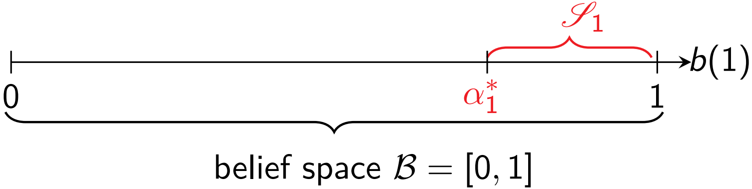
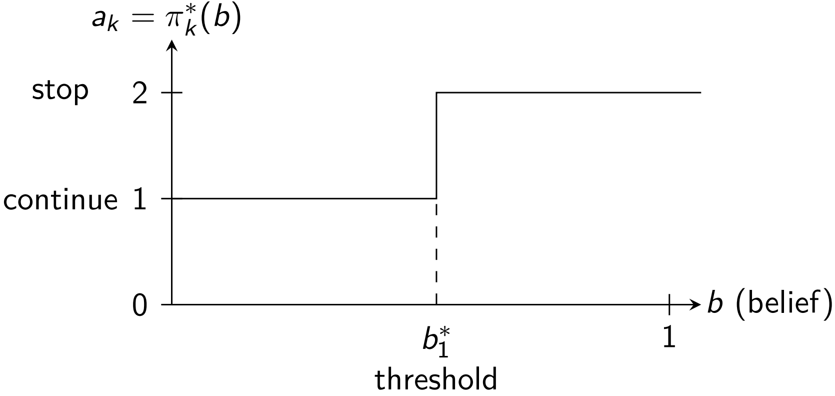
Convex Stopping set with Threshold $\alpha_1^* \in \mathcal{B}$

$$\underbrace{0 \longrightarrow 1}_{\text{belief space } \mathcal{B} = [0,1]} \quad b(1)$$

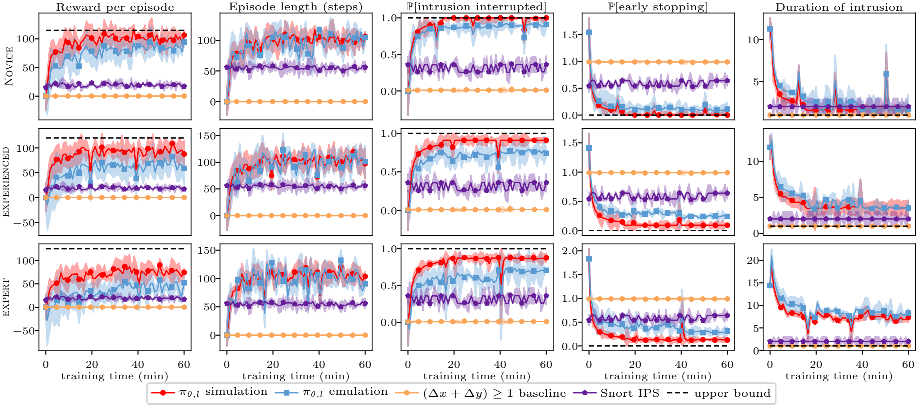
Convex Stopping set with Threshold $\alpha_1^* \in \mathcal{B}$



Bang-Bang Controller with Threshold $\alpha_1^* \in \mathcal{B}$



Learning Curves in Simulation and Emulation

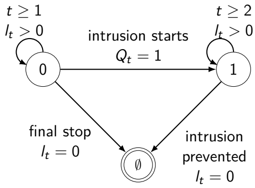


2: Intrusion Prevention through Optimal Multiple Stopping[3]

- **Intrusion Prevention through Multiple Optimal Stopping:**
  - Maximize reward of stopping times $\tau_L, \tau_{L-1}, \ldots, \tau_1$:

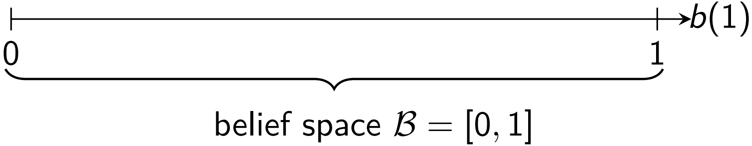
$$\pi_l^* \in \arg\max_{\pi_l} \mathbb{E}_{\pi_l}\Bigg[\sum_{t=1}^{\tau_L - 1} \gamma^{t-1}\mathcal{R}^C_{s_t,s_{t+1},L} + \gamma^{\tau_L - 1}\mathcal{R}^S_{s_{\tau_L},s_{\tau_L+1},L} + \ldots + \sum_{t=\tau_2+1}^{\tau_1 - 1}\gamma^{t-1}\mathcal{R}^C_{s_t,s_{t+1},1} + \gamma^{\tau_1 - 1}\mathcal{R}^S_{s_{\tau_1},s_{\tau_1+1},1}\Bigg]$$

- Each stopping time = one defensive action

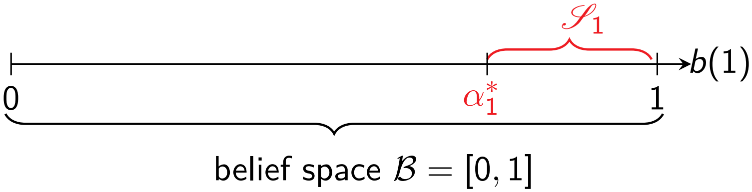


[3] Kim Hammar and Rolf Stadler. "Intrusion Prevention Through Optimal Stopping". In: *IEEE Transactions on Network and Service Management* 19.3 (2022), pp. 2333–2348. DOI: 10.1109/TNSM.2022.3176781.

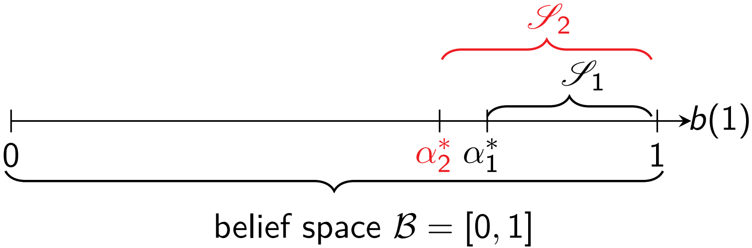
Structural Result: Optimal Multi-Threshold Policy & Nested Stopping Sets



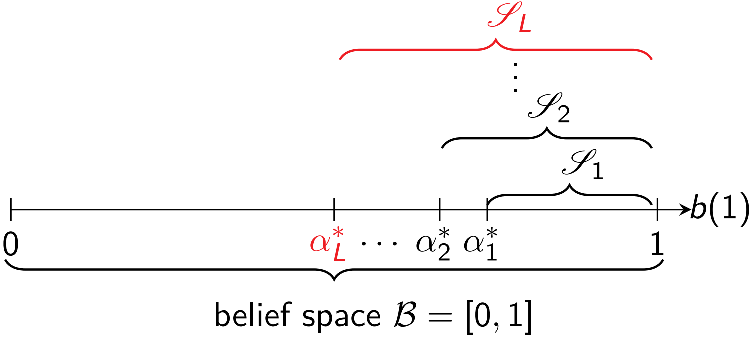
Structural Result: Optimal Multi-Threshold Policy & Nested Stopping Sets



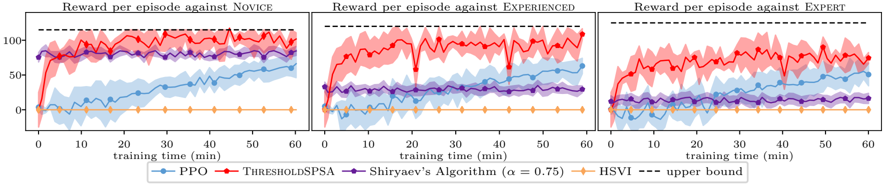
Structural Result: Optimal Multi-Threshold Policy & Nested Stopping Sets



Structural Result: Optimal Multi-Threshold Policy & Nested Stopping Sets

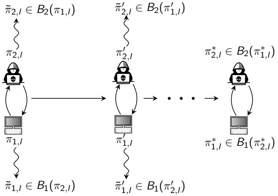


Comparison against State-of-the-art Algorithms



3: Intrusion Prevention through Optimal Multiple Stopping and Game-Play[4]

- **Optimal stopping (Dynkin) game**:
  - Dynamic attacker
  - Stop actions of the defender determine when to take defensive actions
  - Goal: find Nash Equilibrium (NE) strategies and game value



$$J_1(\pi_{1,l}, \pi_{2,l}) = \mathbb{E}_{(\pi_{1,l}, \pi_{2,l})}\left[\sum_{t=1}^{T} \gamma^{t-1} \mathcal{R}_{l_t}(s_t, \boldsymbol{a}_t)\right]$$

$$B_1(\pi_{2,l}) = \underset{\pi_{1,l} \in \Pi_1}{\arg\max}\, J_1(\pi_{1,l}, \pi_{2,l})$$

$$B_2(\pi_{1,l}) = \underset{\pi_{2,l} \in \Pi_2}{\arg\min}\, J_1(\pi_{1,l}, \pi_{2,l})$$

$$(\pi^*_{1,l}, \pi^*_{2,l}) \in B_1(\pi^*_{2,l}) \times B_2(\pi^*_{1,l}) \quad \text{NE}$$

[4] Kim Hammar and Rolf Stadler. "Learning Security Strategies through Game Play and Optimal Stopping". In: *Proceedings of the ML4Cyber workshop, ICML 2022, Baltimore, USA, July 17-23, 2022*. PMLR, 2022.

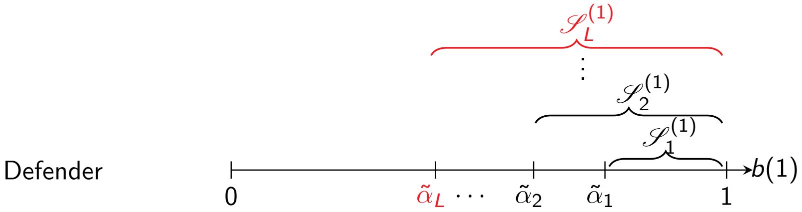
Structure of Best Response Strategies

Defender

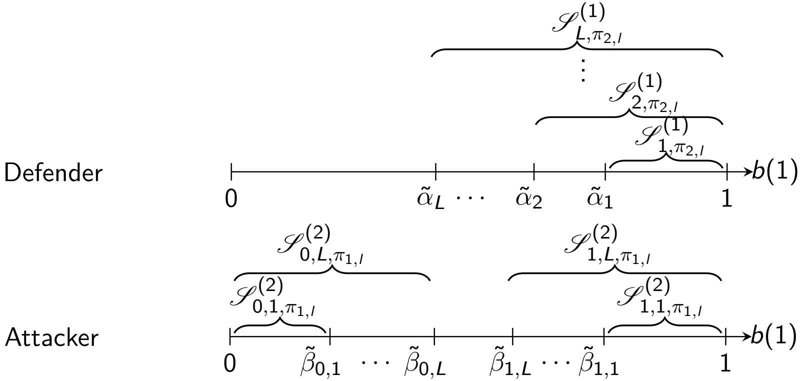
Structure of Best Response Strategies

Structure of Best Response Strategies

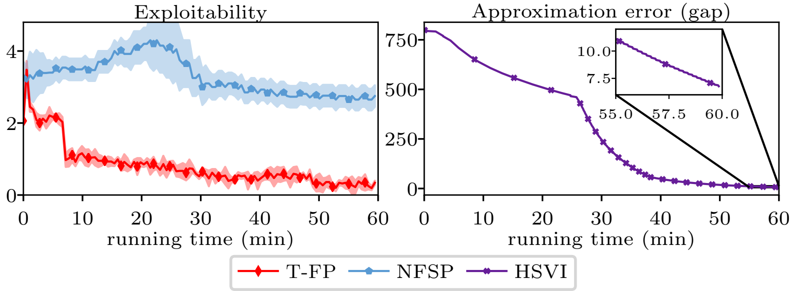
Structure of Best Response Strategies



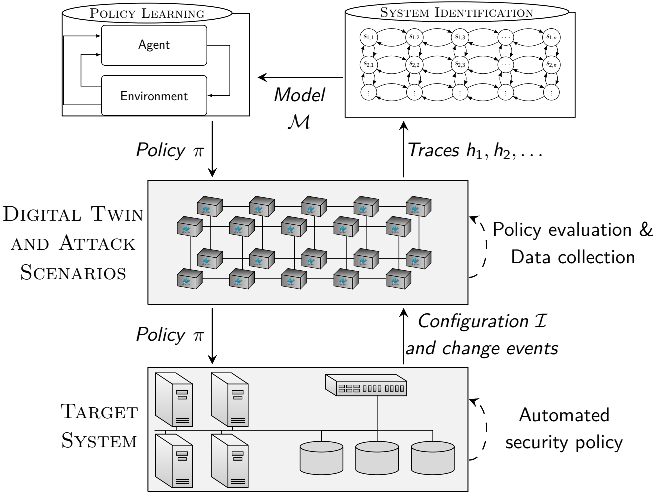
Structure of Best Response Strategies



Converge Rates and Comparison with State-of-the-art Algorithms



4: Learning in Dynamic IT Environments[5]



[5] Kim Hammar and Rolf Stadler. "An Online Framework for Adapting Security Policies in Dynamic IT Environments". In: *International Conference on Network and Service Management (CNSM 2022)*. Thessaloniki, Greece, 2022.

4: Learning in Dynamic IT Environments[6]

Algorithm 1: High-level execution of the framework

Input: *emulator*: method to create digital twin
φ: system identification algorithm
ϕ: policy learning algorithm

Algorithm $(\mathit{emulator}, \varphi, \phi)$
    do in parallel
        $\textsc{DigitalTwin}(\mathit{emulator})$
        $\textsc{SystemIdProcess}(\varphi)$
        $\textsc{LearningProcess}(\phi)$
    end

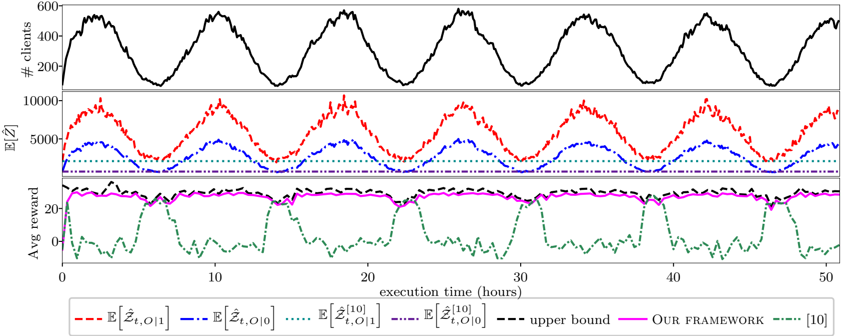
Procedure $\textsc{DigitalTwin}(\mathit{emulator})$
    Loop
        $\pi \leftarrow \textsc{ReceiveFromLearningProcess}()$
        $h_t \leftarrow \textsc{CollectTrace}(\pi)$
        $\textsc{SendToSystemIdProcess}(h_t)$
        $\textsc{UpdateDigitalTwin}(\mathit{emulator})$
    EndLoop

Procedure $\textsc{SystemIdProcess}(\varphi)$
    Loop
        $h_1, h_2, \ldots \leftarrow \textsc{ReceiveFromDigitalTwin}()$
        $\mathcal{M} \leftarrow \varphi(h_1, h_2, \ldots)$ `// estimate model`
        $\textsc{SendToLearningProcess}(\mathcal{M})$
    EndLoop

Procedure $\textsc{LearningProcess}(\phi)$
    Loop
        $\mathcal{M} \leftarrow \textsc{ReceiveFromSystemIdProcess}()$
        $\pi \leftarrow \phi(\mathcal{M})$ `// learn policy` π
        $\textsc{SendToDigitalTwin}(\pi)$
    EndLoop

[6] Kim Hammar and Rolf Stadler. "An Online Framework for Adapting Security Policies in Dynamic IT Environments". In: *International Conference on Network and Service Management (CNSM 2022)*. Thessaloniki, Greece, 2022.

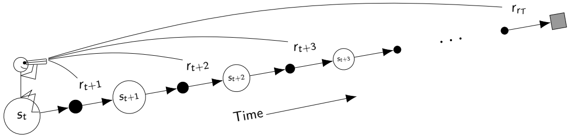
Learning in Dynamic IT Environments[7]



Results from running our framework for 50 hours in the digital twin/emulation.

[7] Kim Hammar and Rolf Stadler. "An Online Framework for Adapting Security Policies in Dynamic IT Environments". In: *International Conference on Network and Service Management (CNSM 2022)*. Thessaloniki, Greece, 2022.

Current and Future Work



1. **Closing the gap to reality**
   - Additional defender actions
   - Utilize SDN controller and NFV-based defenses
   - Increase observation space and attacker model
   - More heterogeneous client population

2. **Extend solution framework**
   - Model-predictive control
   - Rollout-based techniques
   - Extend system identification algorithm

3. **Extend theoretical results**
   - Exploit symmetries and causal structure
   - Utilize theory to improve sample efficiency
   - Decompose solution framework hierarchically

Conclusions

- We develop a *method* to automatically learn security strategies.
- We apply the method to an **intrusion prevention use case**.
- We show numerical results in a realistic emulation environment.
- We design a solution framework guided by the theory of optimal stopping.
- We present several theoretical results on the structure of the optimal solution.