A modified Thompson sampling-based learning algorithm for unknown linear systems

Mukul Gagrani[a], Sagar Sudhakara[b], Aditya Mahajan[c], Ashutosh Nayyar[b], Ouyang Yi[d]

[a]Qualcomm, [b]USC, [c]McGill, [d]Preferred Networks

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Significant interest in RL for control

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Robotics

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Self driving cars

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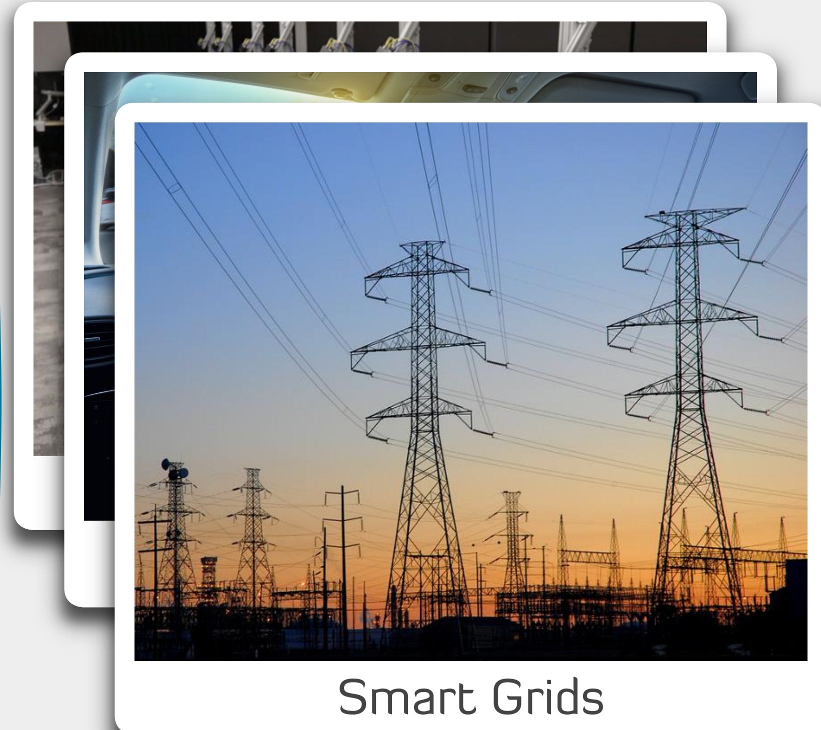

Smart Grids

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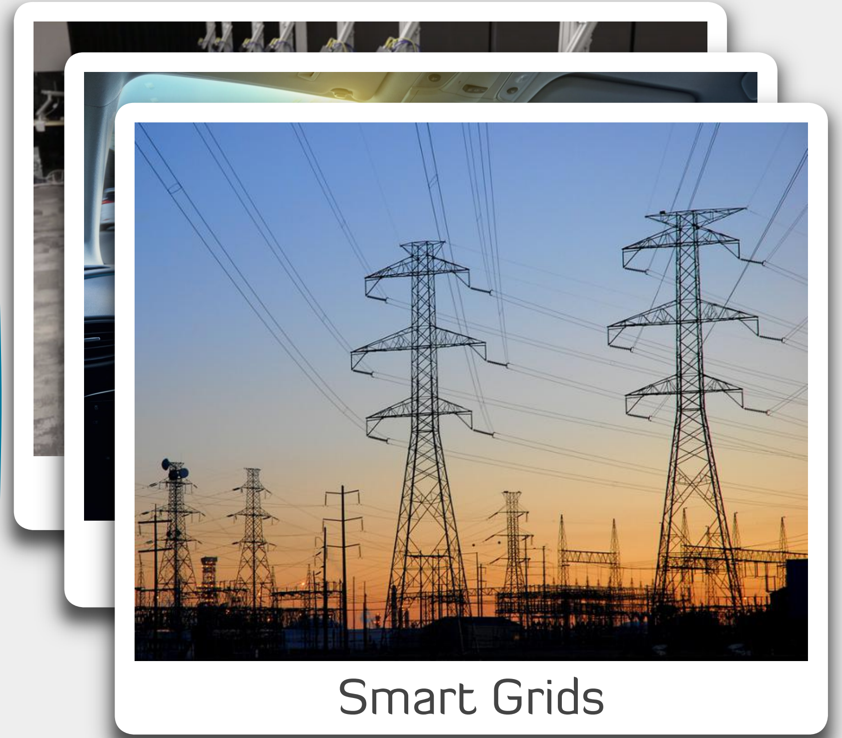
Smart Grids

Simplest setting: Linear quadratic regulation

- Different classes of RL algorithms
- Provide different performance guarantees under different assumptions on the uncertainty

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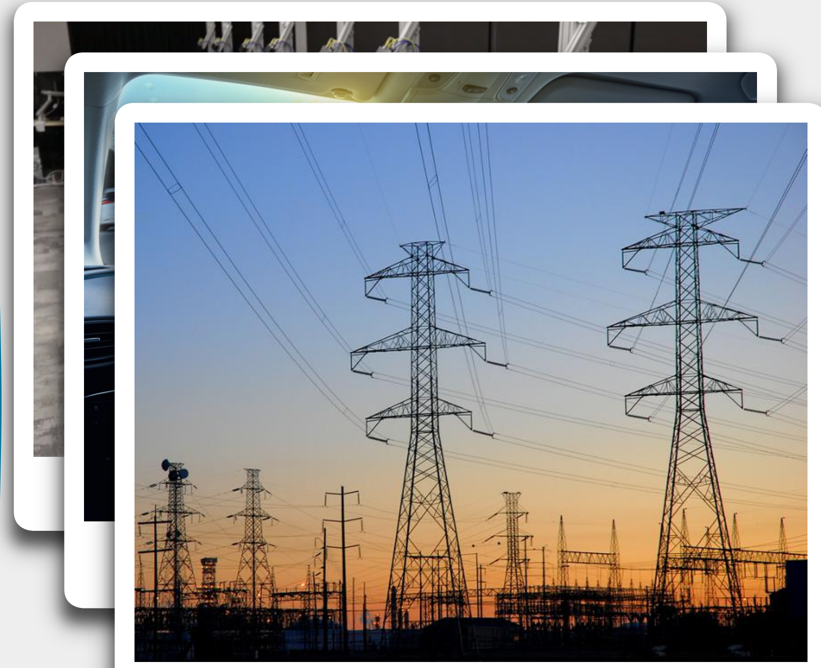

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- Different classes of RL algorithms
- Provide different performance guarantees under different assumptions on the uncertainty

> Relax the assumptions on uncertainty for a specific class of RL algorithms

Thompson sampling for LQ—(Gagrani et. al.)

Learning in unknown linear systems

Linear Quadratic Regulation

$$x_{t+1} = A_\theta x_t + B_\theta u_t + w_t, \quad w_t \sim N(0, \sigma_w^2 I)$$
$$c(x_t, u_t) = x_t^\top Q x_t + u_t^\top R u_t.$$

Given $\theta^\top = [A_\theta, B_\theta]$, choose a policy π to minimize

$$J(\pi; \theta) = \limsup_{T \to \infty} \frac{1}{T} \mathbb{E}\left[\sum_{t=1}^{T} c(x_t, w_t) \right].$$

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Optimal solution

When θ is known and (A_θ, B_θ) is stabilizable, optimal policy $\pi^\star$ is given by

$$u_t = G(\theta) x_t$$

where

- $G(\theta) = -(R + B_\theta^\top S_\theta B_\theta)^{-1} B_\theta^\top S_\theta A_\theta$
- S_θ is the solution of the algebraic Riccati eqn

Moreover: $J(\pi_\theta^\star; \theta) = \sigma_w^2 \mathrm{Tr}(S_\theta)$.

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- True parameter $\theta_\star$ is unknown
- Regret of any learning-based policy π:

$$R(T; \pi) = \mathbb{E}^\pi\left[\sum_{t=1}^{T} c(x_t, u_t) - TJ(\pi^\star_{\theta_\star}, \theta_\star)\right].$$

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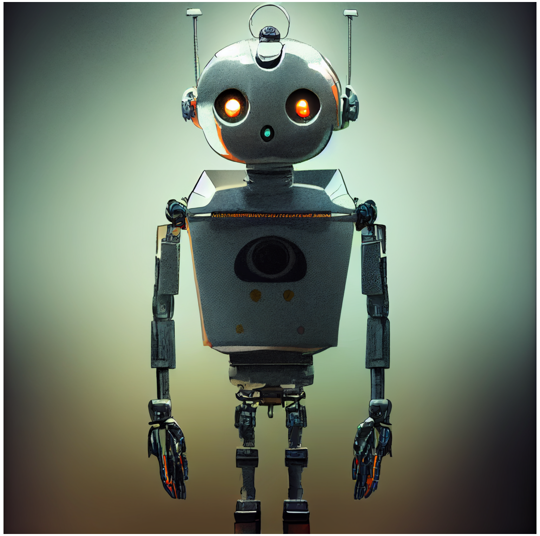
Key research question

▷ How does regret scale with horizon T?

Different learning frameworks

Explore vs Exploit



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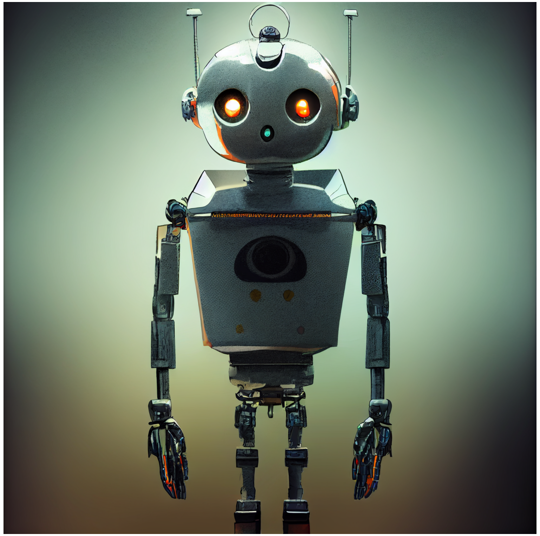

Certainty equivalence

- Generate estimate $\hat{\theta}_t$ based on past observations
- Use controller: $u_t = G(\hat{\theta}_t)\, x_t + \varepsilon_t$ (exploration noise)

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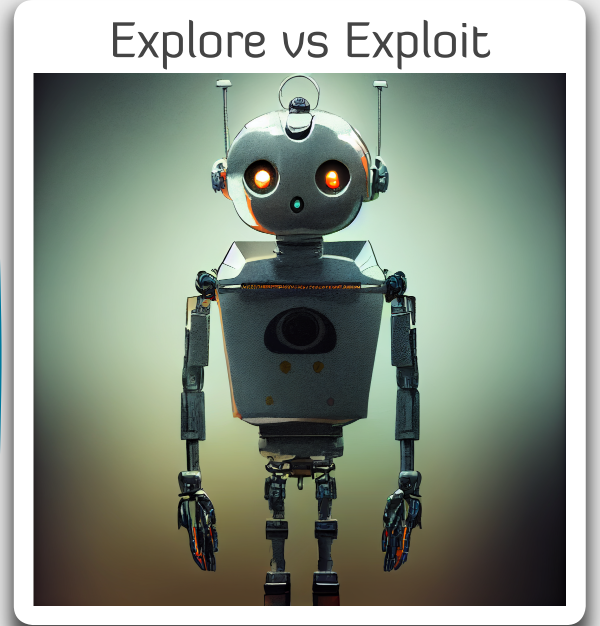

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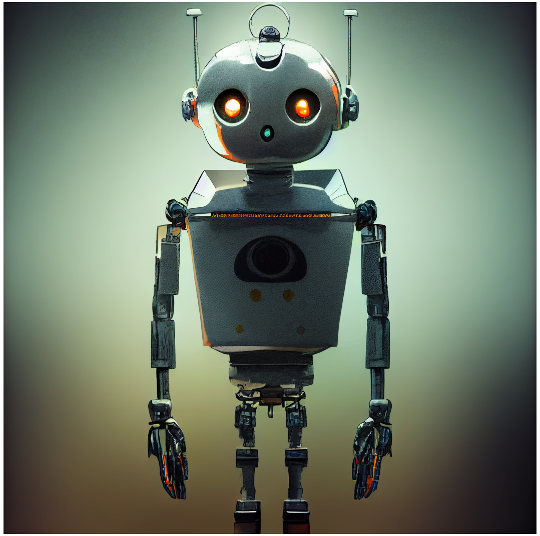

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Posterior/Thompson sampling

- Maintain posterior μ_t on $\theta_\star$
- Sample $\tilde{\theta}_t \sim \mu_t$
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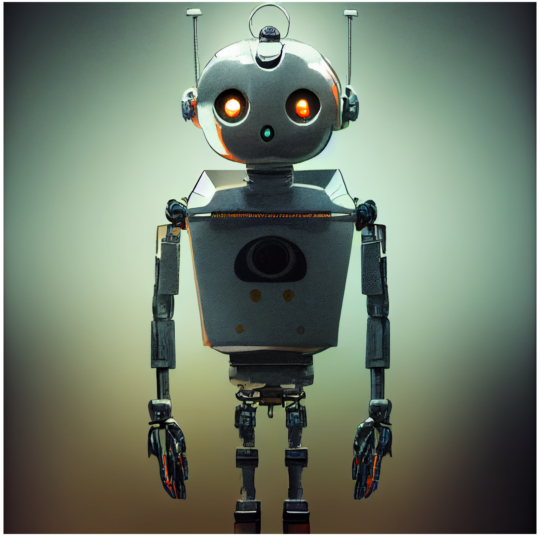

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Thompson sampling with dynamic episodes (TSDE)

[Ouyang, Gagrani, Jain 2020]

- Bayesian RL algorithm
- Generalization on Thompson sampling (or posterior sampling) for bandits
- Very simple algorithm which requires no hyper-parameter tuning and works well in practice

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Assumptions on the true parameter

- $\theta_\star$ lies in a compact set.

$$\theta_\star^\top = \left[\quad A_\star \quad \middle| \quad B_\star \quad \right] \in \underbrace{\Omega}_{\text{Compact set}}$$

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Assumptions on the true parameter

- $\theta_\star$ lies in a compact set.
- Independent **truncated Gaussian prior** on each row of $\theta_\star^\top$:

$$\bar{\mu}_1(\theta) = \left[\prod_{i=1}^{n} N(\widehat{\theta}_1(i), \Sigma_1) \right] \Bigg|_{\Omega}$$

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Properties of the posterior

- Posterior μ_t is also truncated Gaussian with $\mu_t(\theta) = \left[\prod_{i=1}^{n} N(\hat{\theta}_t(i), \Sigma_t)\right]\Big|_{\Omega}$ where

$$\hat{\theta}_{t+1}(i) = \hat{\theta}_t(i) + \frac{\Sigma_t z_t (x_{t+1}(i) - \hat{\theta}_t(i)^\top z_t)}{\sigma_w^2 + z_t^\top \Sigma_t z_t}$$

$$\Sigma_{t+1}^{-1} = \Sigma_t^{-1} + \frac{1}{\sigma_w^2} z_t z_t^\top.$$

where $z_t = \text{vec}(x_t, u_t)$.

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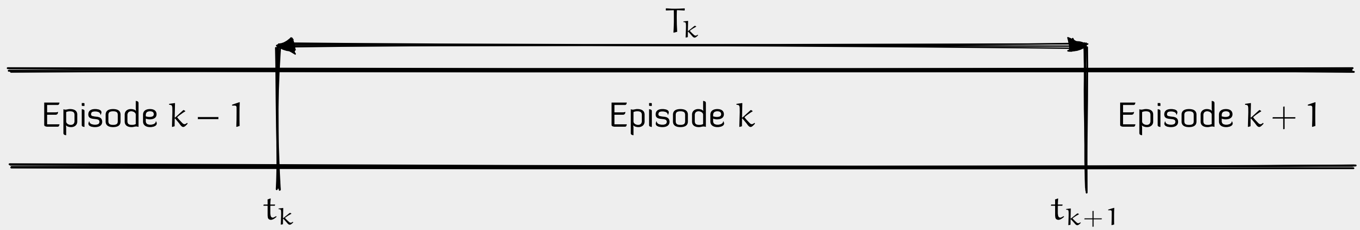

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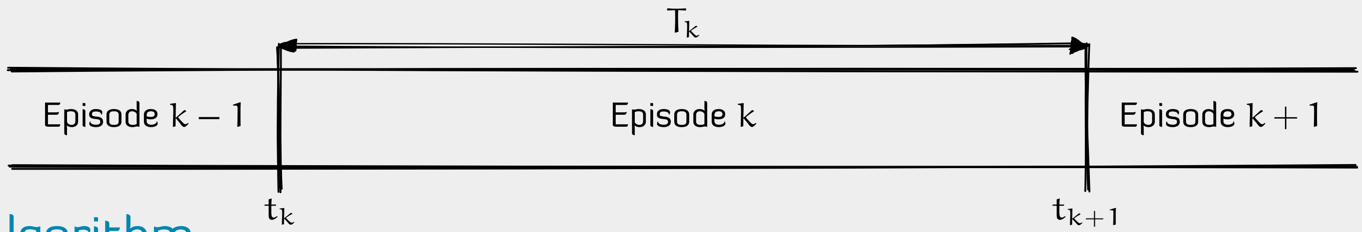

TSDE Algorithm

- At start of episode: Sample $\tilde{\theta}_k \sim \mu_{t_k}$
- During the episode: Use $u_t = G(\tilde{\theta}_k)\, x_t$
- Terminate episode if: $(t - t_k > T_{k-1})$ or $(\det \Sigma_t < \frac{1}{2} \det \Sigma_{t_k})$

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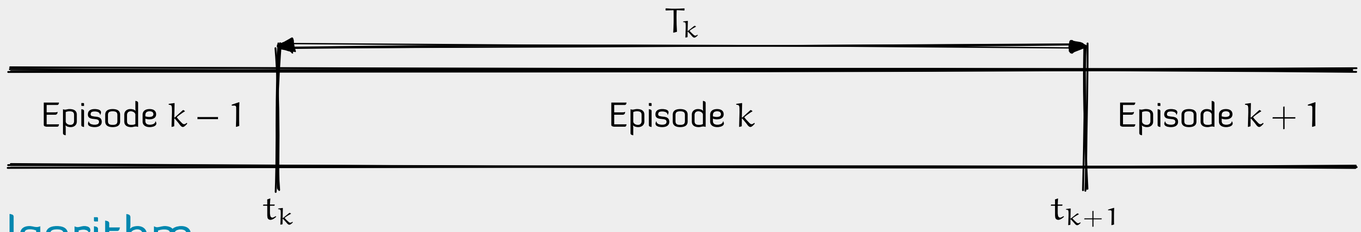

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Intuition: $\det \Sigma_t < \frac{1}{2} \det \Sigma_{t_k}$ implies that current posterior is much better than the posterior at the start of the episode. **Resample to exploit this knowledge**

Thompson sampling with dynamic episodes (TSDE)

[Ouyang, Gagrani, Jain 2020]

Assumption A1 There exists an $\delta \in (0, 1)$ such that for any $\theta, \phi \in \Omega$, $\|A_\theta + B_\theta G(\phi)\| \leq \delta$.

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Discussion on assumptions

- A1 is a **strong assumption**.
- Requires that close loop system dynamics under any mismatched controller should have **spectral norm** less than one.

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Theorem

Under A1, $R(T; \text{TSDE}) \le C\sqrt{T}\,(\log T)^q$

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- The regret is **Bayesian regret**, i.e., includes an expectation over the prior.
- Different from frequentist regret, which provides a high-probability bound on regret for the true parameter.

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Assumption ... $\le \delta$.

Why bother with TSDE

- Works very well in practice. Requires no parameter tuning.
- Continues to work well when A1 is violated.

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The strong assumption appears to be a limitation of the proof technique (and not the algorithm).

Can we relax it?

How should the stability assumption be relaxed?

Ideally, should only require the true $\theta_\star$ to be stabilizable

- Bayesian equivalent:

$$\mathbb{P}(\theta \in \Omega : \theta \text{ is stabilizable}) = 1$$

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First step in weakening the stability assumption

- Assumption A1 is defined in terms of **spectral norm**
- A natural relaxation is to replace spectral norm by **spectral radius**.
- . . . which is what we do in this paper

This paper: Natural relaxation of Assumption A1

Assumption A2	There exists an $\delta \in (0, 1)$ such that for any $\theta, \phi \in \Omega$, $\rho(A_\theta + B_\theta G(\phi)) \leq \delta$.

- Controller for system ϕ stabilizes system θ
- Still a strong assumption, but weaker (and more natural) than A1.

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Proof of regret bound of TSDE breaks down

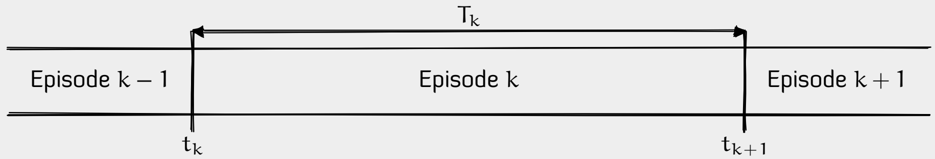
- Proof relies on showing that there is some constant α_0 such that

$$(\star) \qquad \mathbb{E}\Big[\max_{1 \leq t \leq T} \|x_t\|\Big] \leq \sigma_w + \alpha_0 \mathbb{E}\Big[\max_{1 \leq t \leq T} \|w_t\|\Big]$$

- Under (A1), $\mathbb{E}[\|x_{t+1}\|] \leq \delta \mathbb{E}[\|x_t\|] + \mathbb{E}[\|w_t\|]$, which implies $\alpha_0 = 1/(1-\delta)$.
- Such a bound does not work under (A2).

Need to modify the algorithm

Modified TSDE



Intuition

- Under (A2), in each episode the system is asymptotically stable.
- Asymptotic stability implies exponential stability.
- So, if the episode is sufficiently large, we can show that

$$\mathbb{E}[\|x_{t_{k+1}}\|] \leq \beta \mathbb{E}[\|x_{t_k}\|] + \bar{\alpha}\mathbb{E}\Big[\max_{t_k \leq t \leq t_{k+1}} \|w_t\|\Big]$$

which implies $(\star)$.

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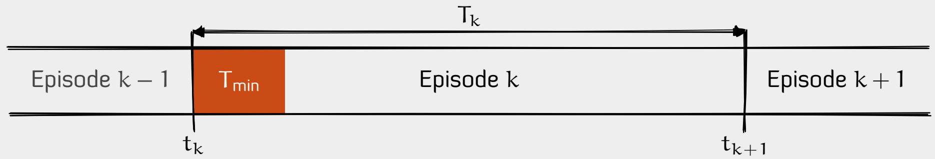

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- See paper for choice of T_{min}.

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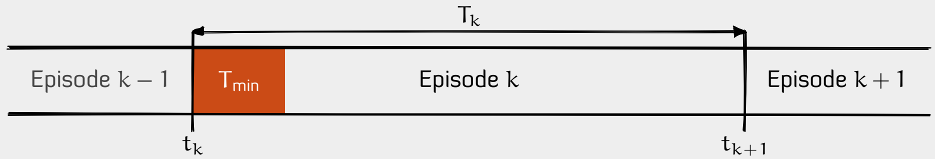

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Implication

- The second stopping condition is not triggered for the T_{min} steps of each episode.
- Requires other changes in the proof argument. See paper for details.

Main results

Assumption A2

There exists an $\delta \in (0, 1)$ such that for any $\theta, \phi \in \Omega$, $\rho(A_\theta + B_\theta G(\phi)) \leq \delta$.

Theorem

Under A2, $R(T; \text{m-TSDE}) \leq C\sqrt{T}\,(\log T)^q$

Main results

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Theorem Under A2, $R(T; \text{m-TSDE}) \leq C\sqrt{T}\,(\log T)^q$

Conclusion

- Relaxed a technical assumption for TSDE.
- Although A2 is weaker than A1, it still a **strong assumption**.
- Numerical experiments suggest that regret scales $\tilde{O}(\sqrt{T})$ even when A2 is not satisfied.
- Open question: How to further relax the stability assumption?

Thank you