Ringmaster ASGD: The First Asynchronous SGD with Optimal Time Complexity

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Problem setup

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Optimization objective

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Different ways of parallelizing SGD

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Different ways of parallelizing SGD

- Synchronized approaches

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- Problems of ASGD

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The core optimization problem in Machine Learning (and beyond)

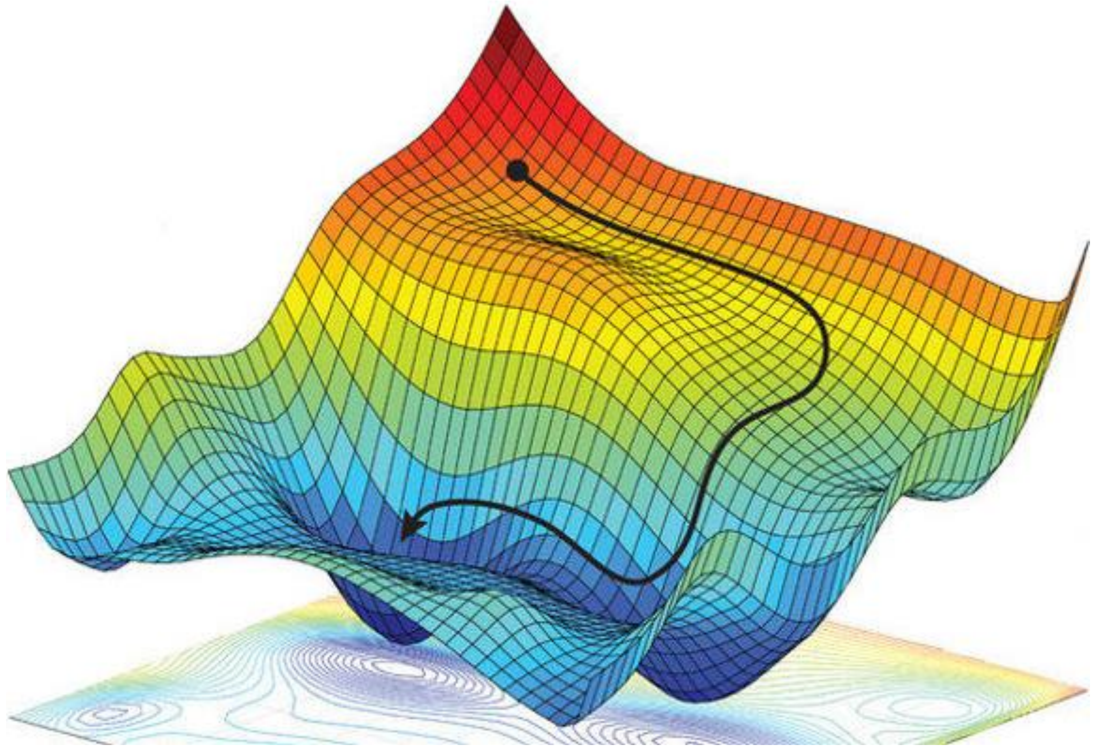
$$\min_{x \in \mathbb{R}^d} \left\{ f(x) := \mathbb{E}_{\xi \sim \mathcal{D}} \left[f(x; \xi) \right] \right\}$$

Loss of a data sample ξ

The distribution of the training dataset

$$\mathcal{D} = \mathrm{Uniform}([m]) \qquad \frac{1}{m} \sum_{i=1}^{m} f(x; \xi_i)$$

A common method in ML is Stochastic Gradient Descent (SGD)



Stepsize / Learning rate

$$x^{k+1} = x^k - \gamma g(x^k)$$

Unbiased gradient estimator, e.g.,

$$\nabla f(x^k; \xi^k)$$

$$\frac{1}{B} \sum_{i=1}^{B} \nabla f(x^k; \xi_i^k)$$

How to parallelize SGD in heterogeneous systems?

$\nabla f(x;\xi)$

Compute time = τ_1

τ_1

$\nabla f(x;\xi)$

Compute time = τ_2

τ_2

$\nabla f(x;\xi)$

Compute time = τ_3

τ_3

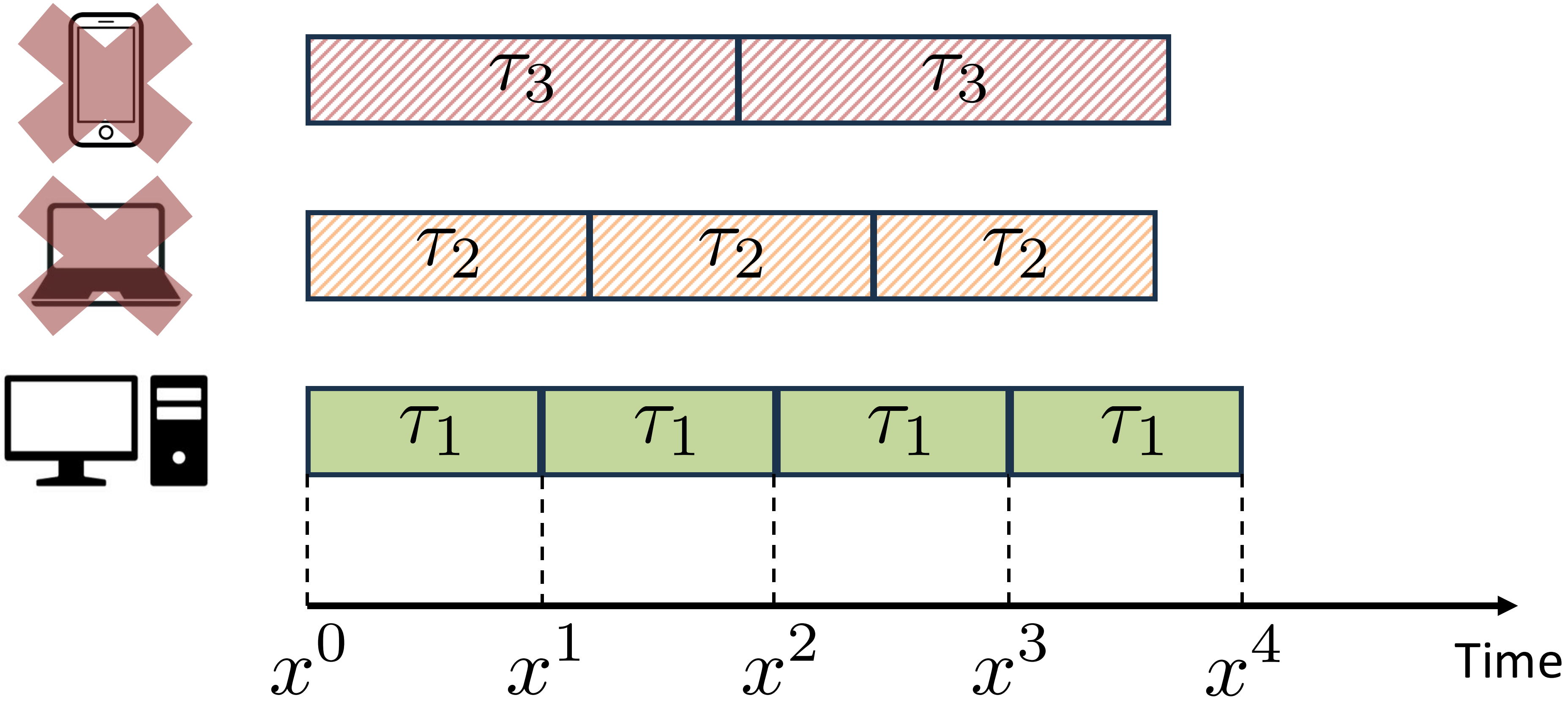
$\mathbb{E}[g(x^k)] = \nabla f(x^k)$

Server

$$x^{k+1} = x^k - \gamma g(x^k)$$

How to construct?

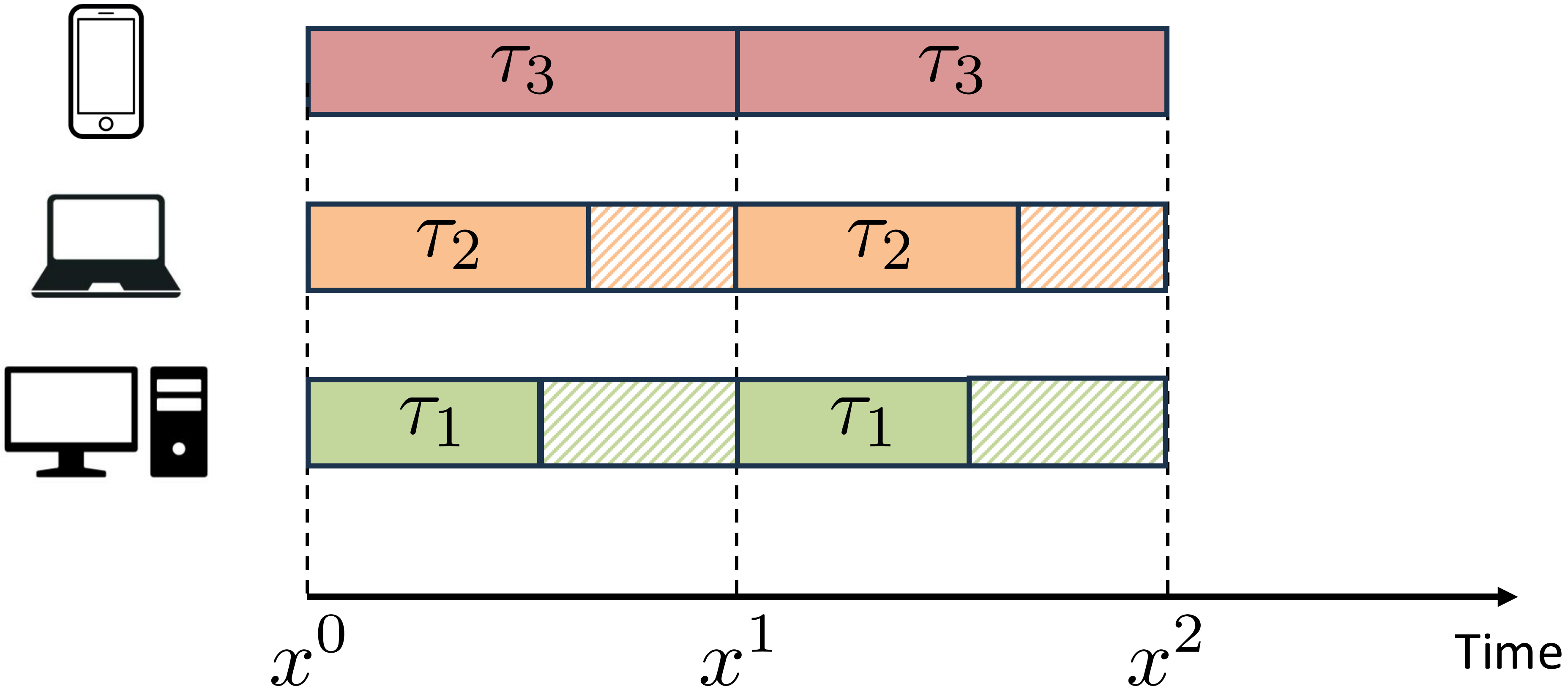
Hero SGD:
The fastest worker does it all



$$x^{k+1} = x^k - \gamma \boxed{\nabla f(x^k; \xi^k)}$$

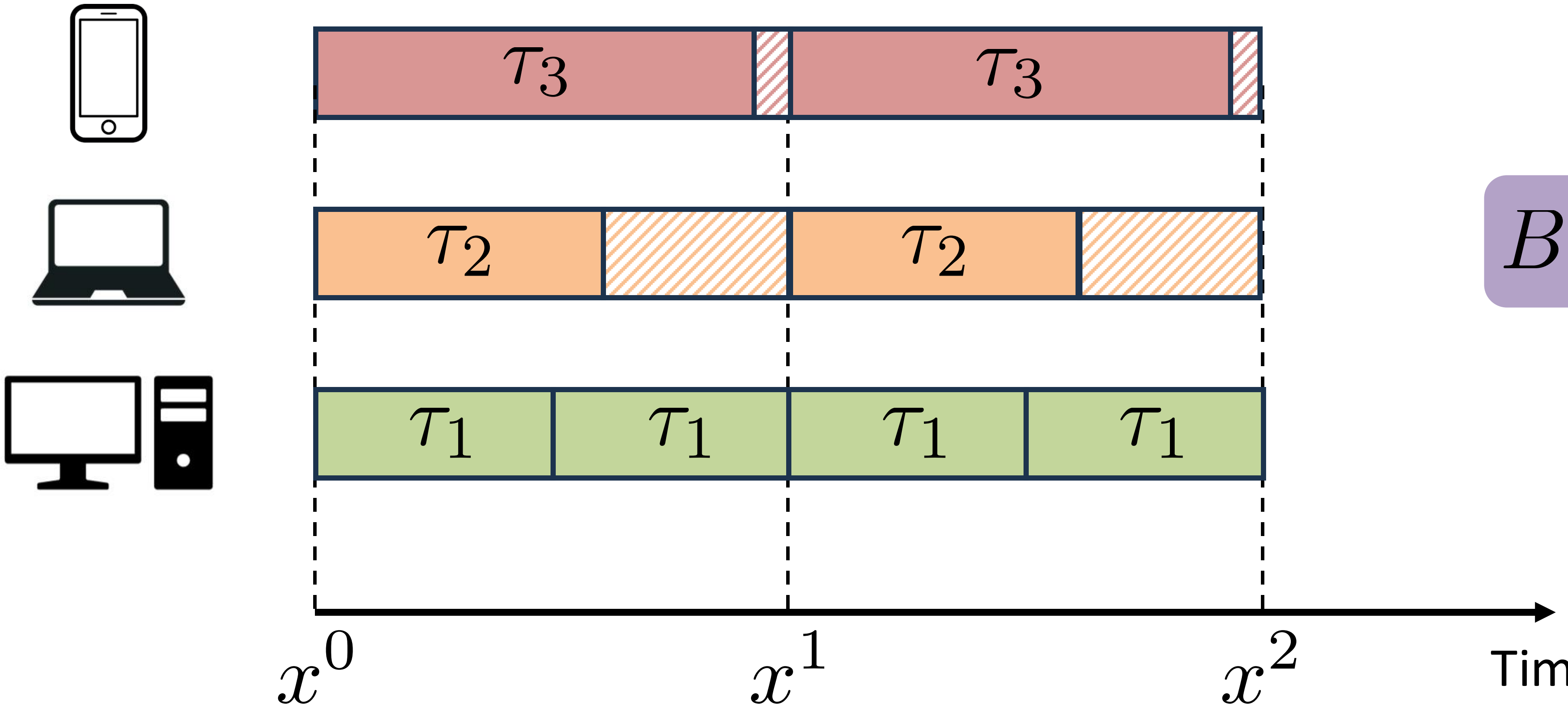
Minibatch SGD:
Each worker does one job only

$n = 3$



$$x^{k+1} = x^k - \gamma \frac{1}{n} \sum_{i=1}^{n} \nabla f(x^k; \xi_i^k)$$

Rennala SGD: Asynchronous batch collection

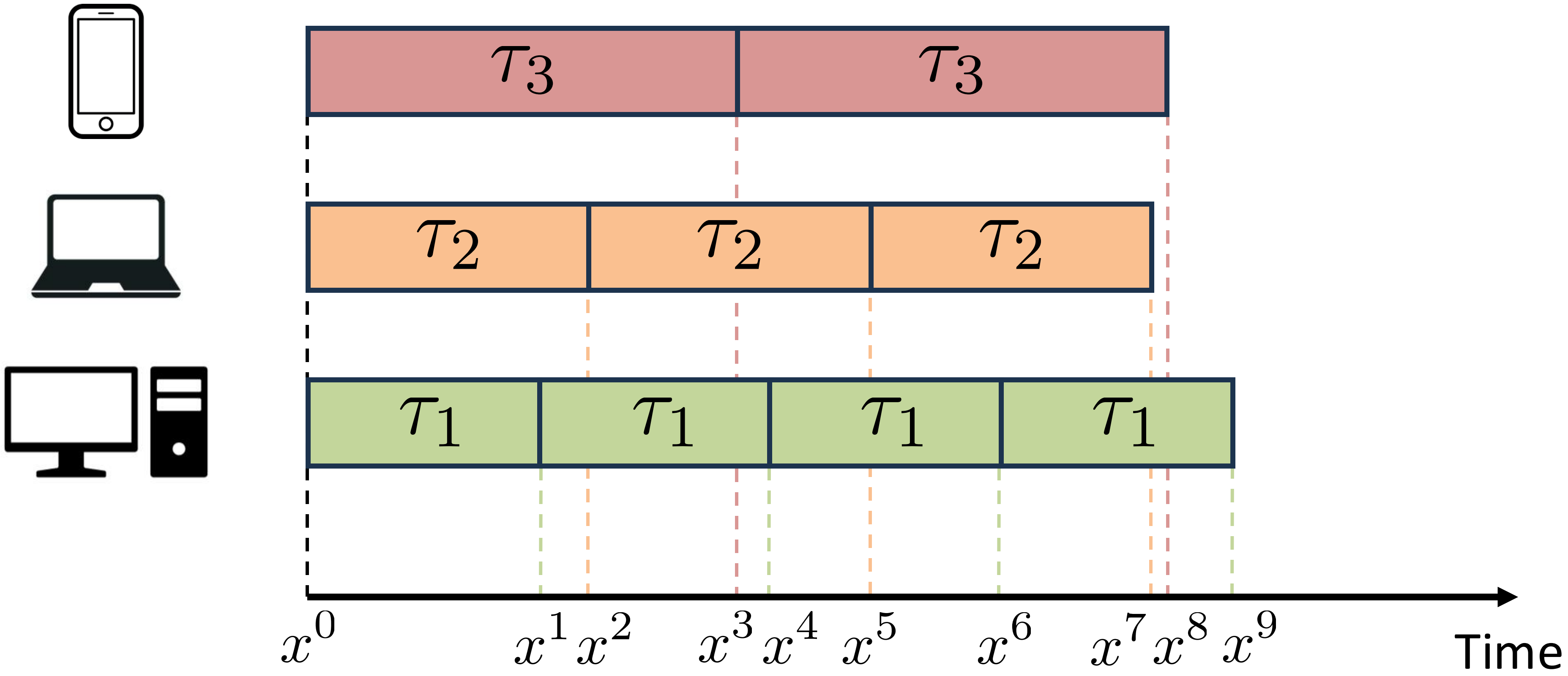


$B = 4$

$$x^{k+1} = x^k - \gamma \frac{1}{B} \sum_{j=1}^{B} \nabla f(x^k; \xi_j^k)$$

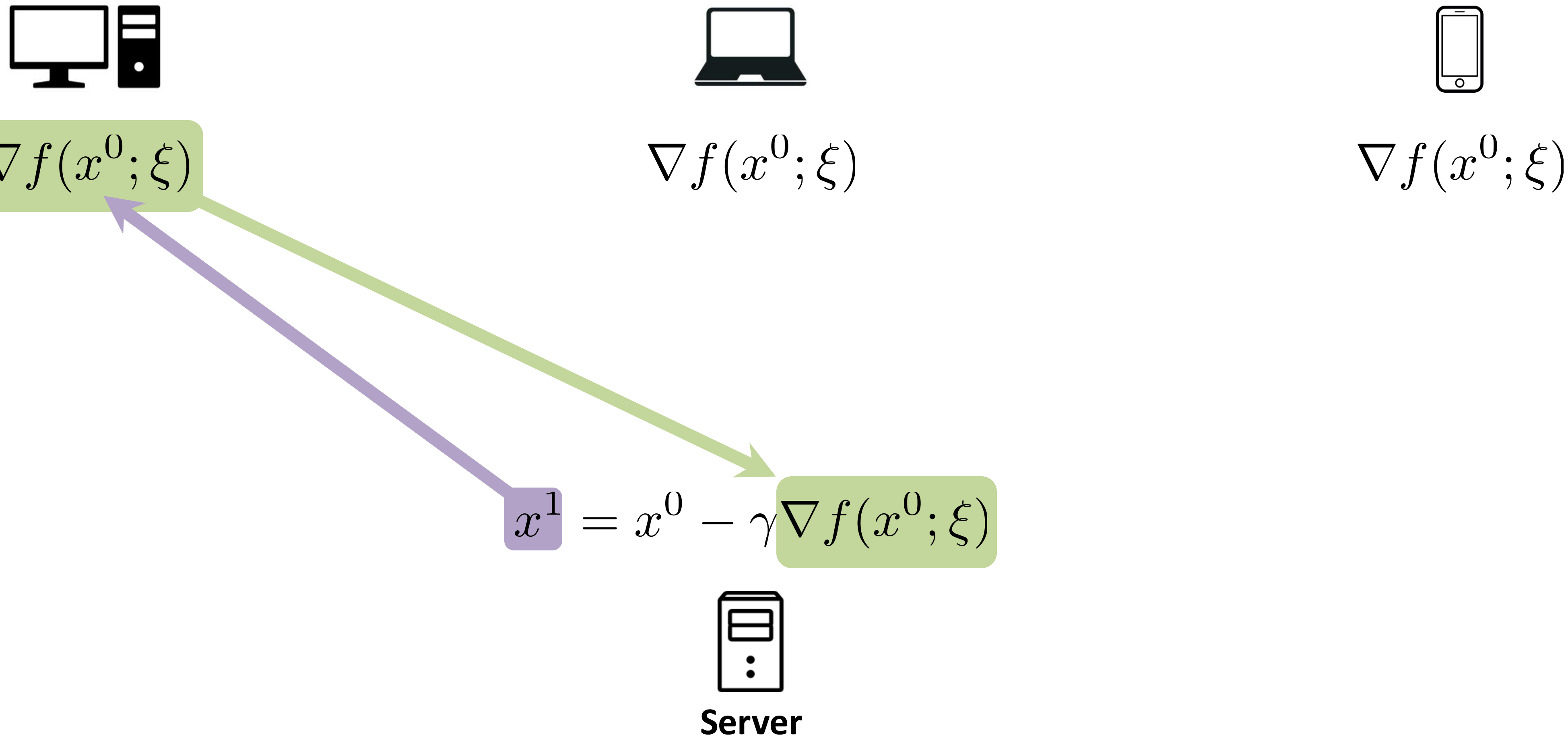
Tyurin and Richtárik (2024)

Asynchronous SGD
Remove the synchronization

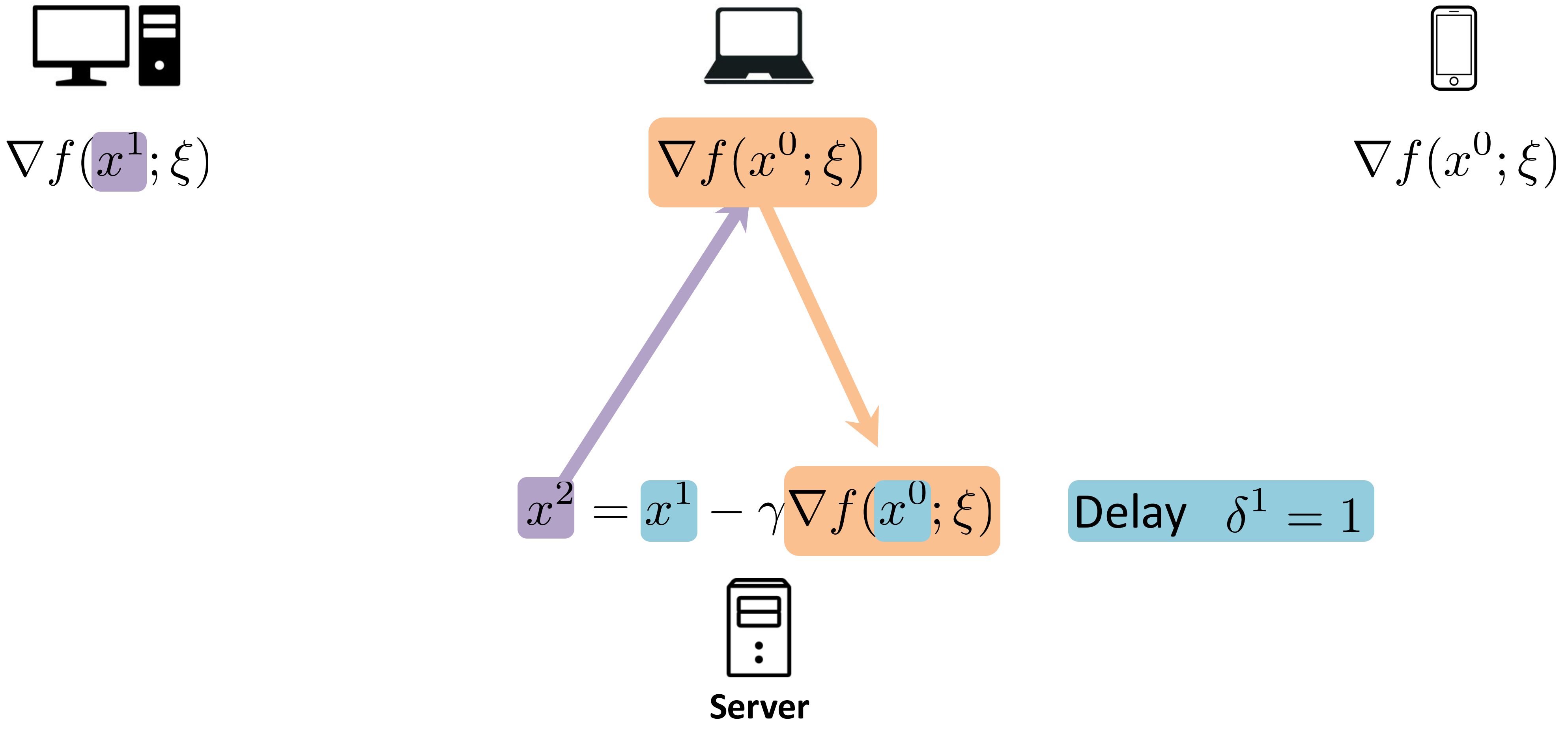


$$x^{k+1} = x^k - \gamma \cancel{g(x^k)}$$

Updates of Asynchronous SGD has delayed stochastic gradients



Updates of Asynchronous SGD has delayed stochastic gradients



Updates of Asynchronous SGD has delayed stochastic gradients

$\nabla f(x^1;\xi)$

$\nabla f(x^2;\xi)$

$\nabla f(x^0;\xi)$

$$x^3 = x^2 - \gamma \nabla f(x^0;\xi)$$

Delay $\delta^2 = 2$

Server

Updates of Asynchronous SGD has delayed stochastic gradients

$$x^{k+1} = x^k - \gamma \nabla f(x^{k-\delta^k}; \xi)$$

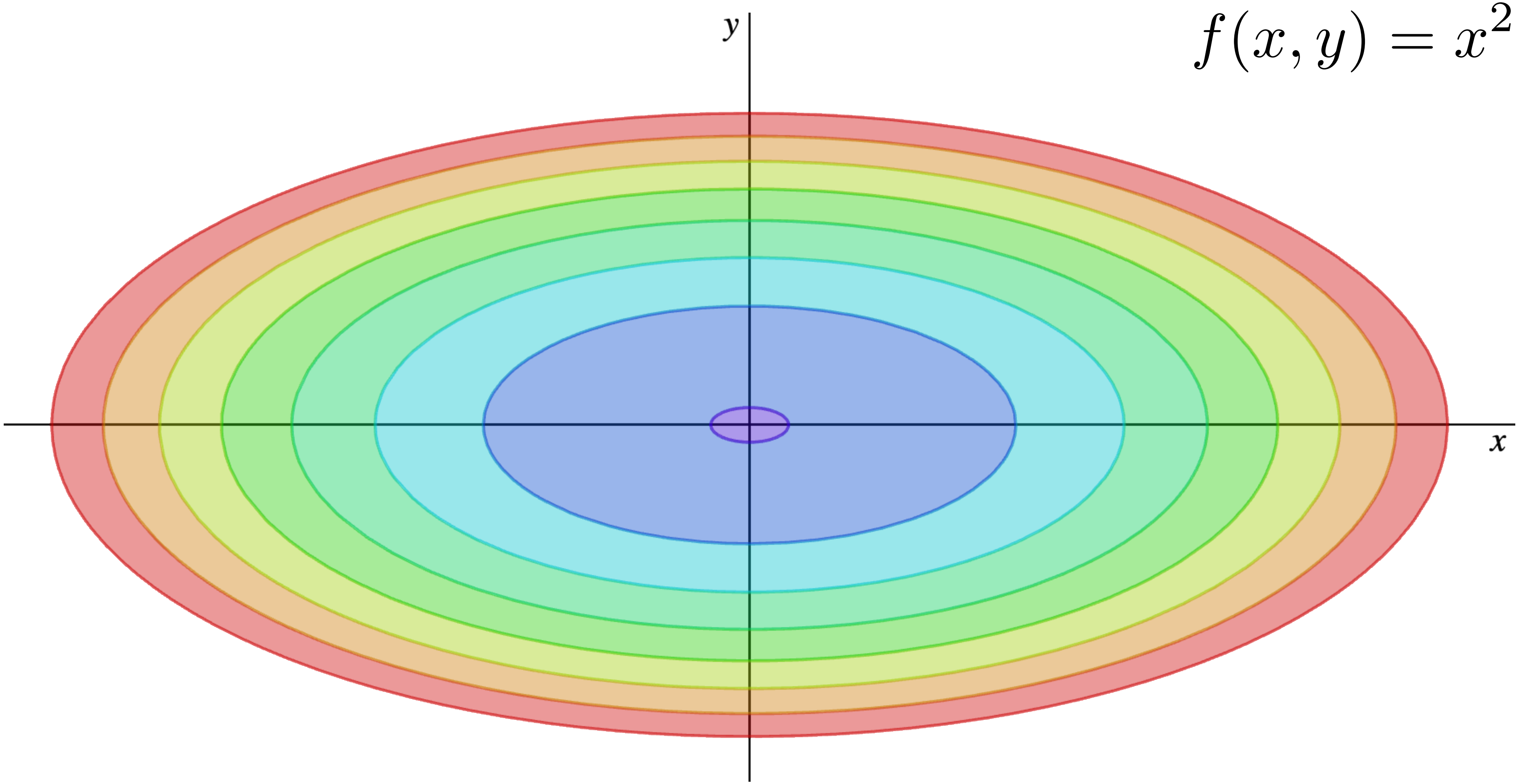
Delay δ^k

Server

Niu, et al. (2011).
HOGWILD!: A lock-free approach to parallelizing stochastic gradient descent.

Asynchronous SGD can get wild: delays can degrade performance

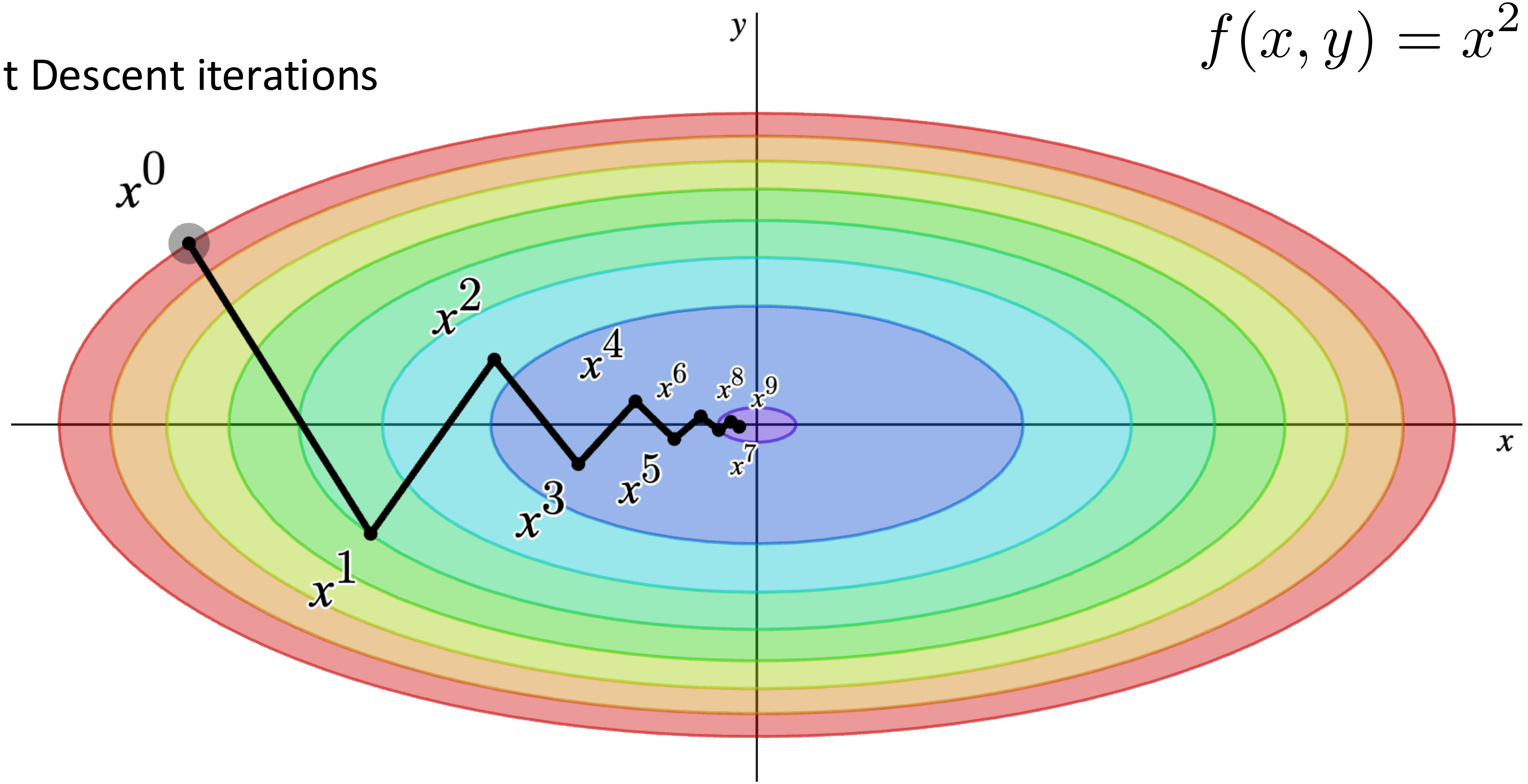
$$f(x, y) = x^2 + 5y^2$$



Asynchronous SGD can get wild: delays can degrade performance

Gradient Descent iterations

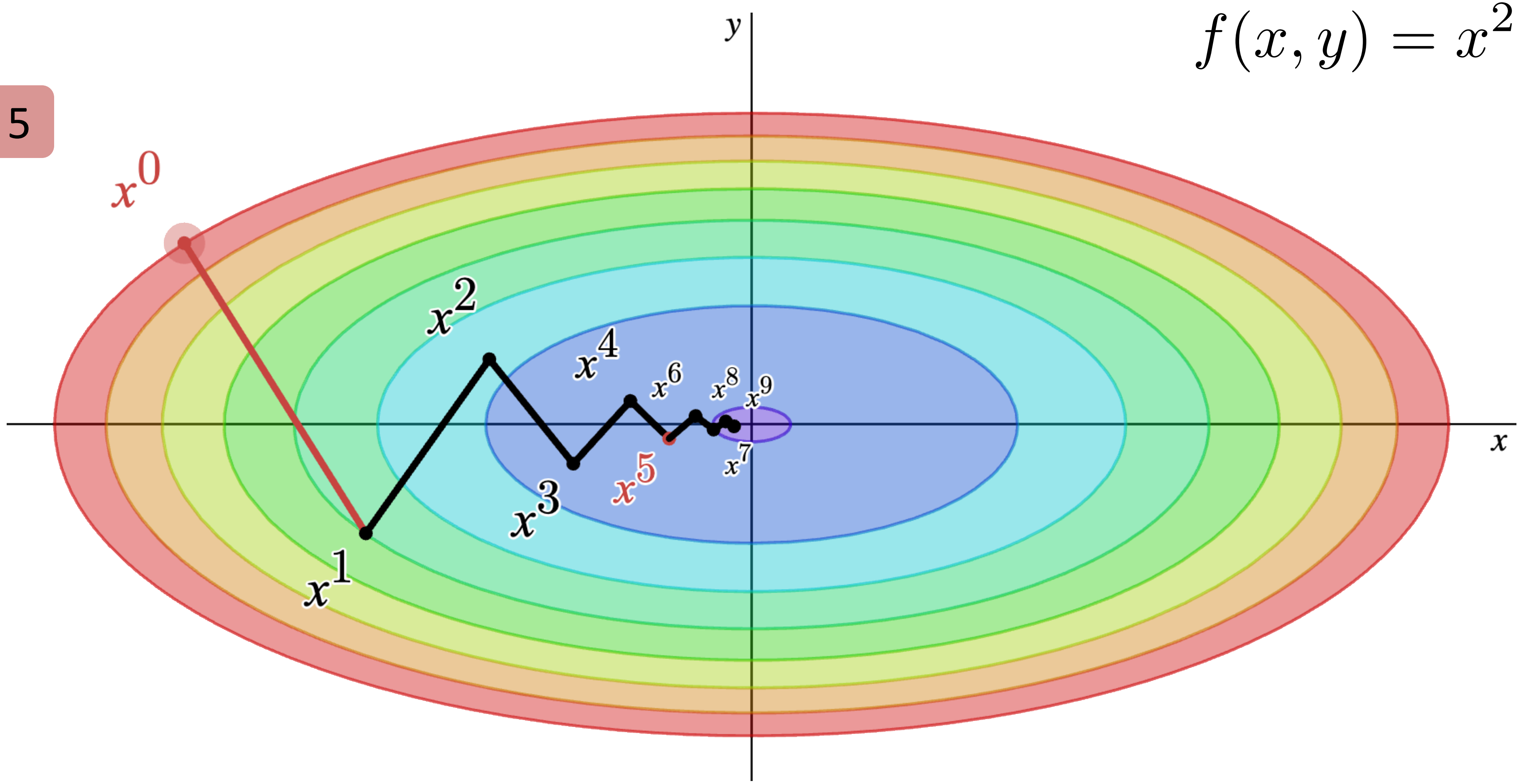
$$f(x, y) = x^2 + 5y^2$$



Asynchronous SGD can get wild: delays can degrade performance

$$f(x, y) = x^2 + 5y^2$$

Delay = 5



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$$f(x, y) = x^2 + 5y^2$$

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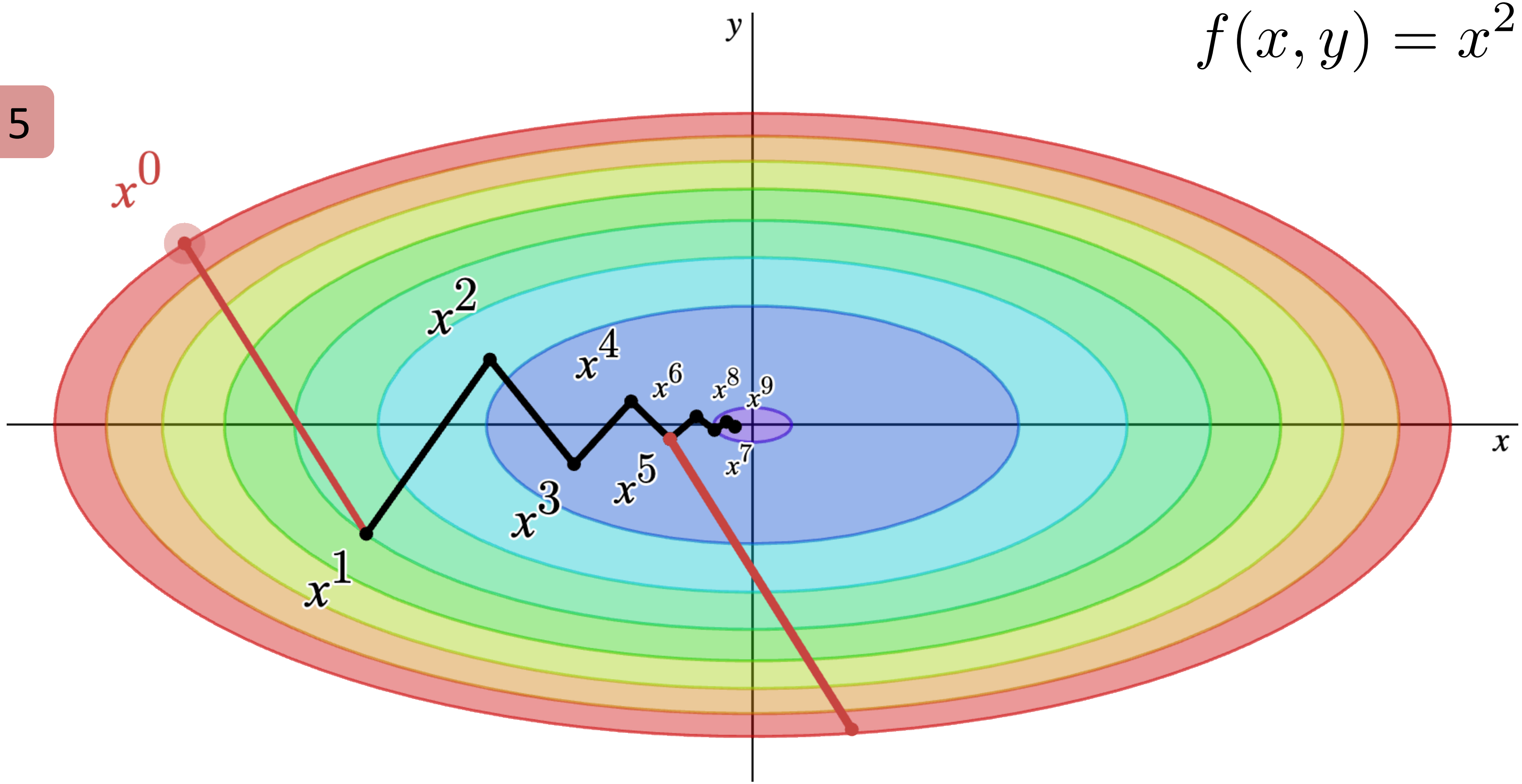
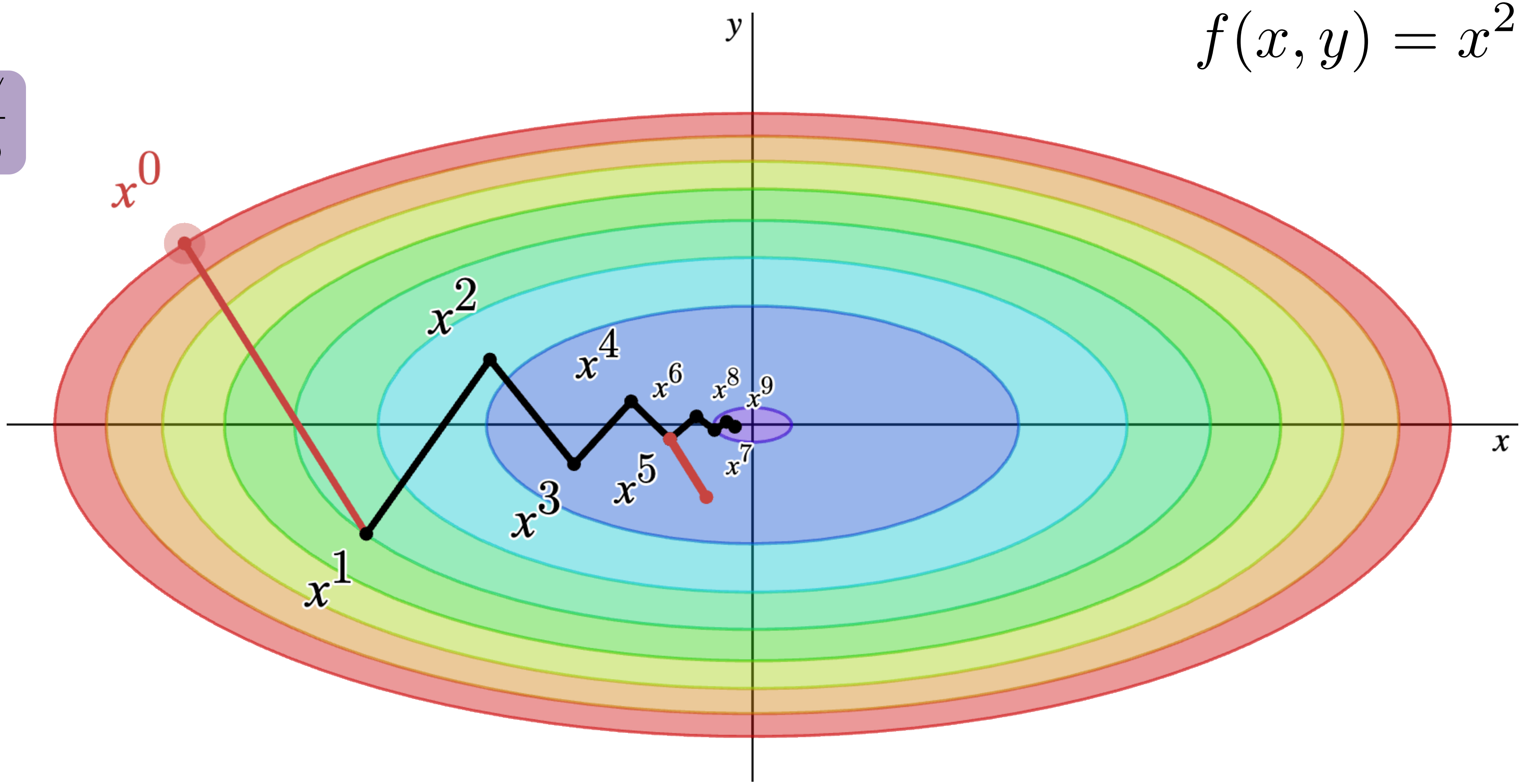


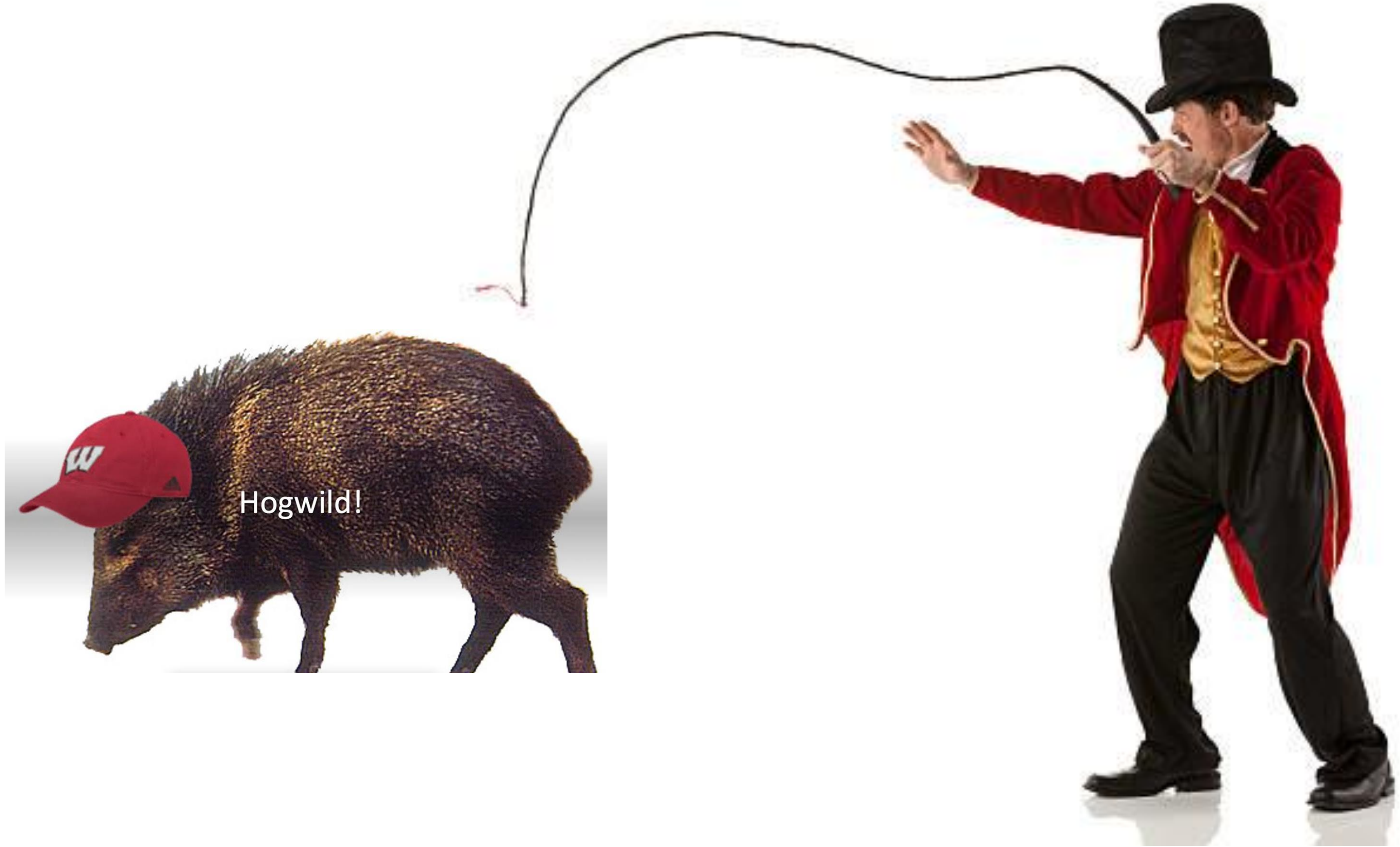
How to fix this?
Make the stepsize smaller

$$\gamma = \frac{\gamma}{5}$$

$$f(x, y) = x^2 + 5y^2$$



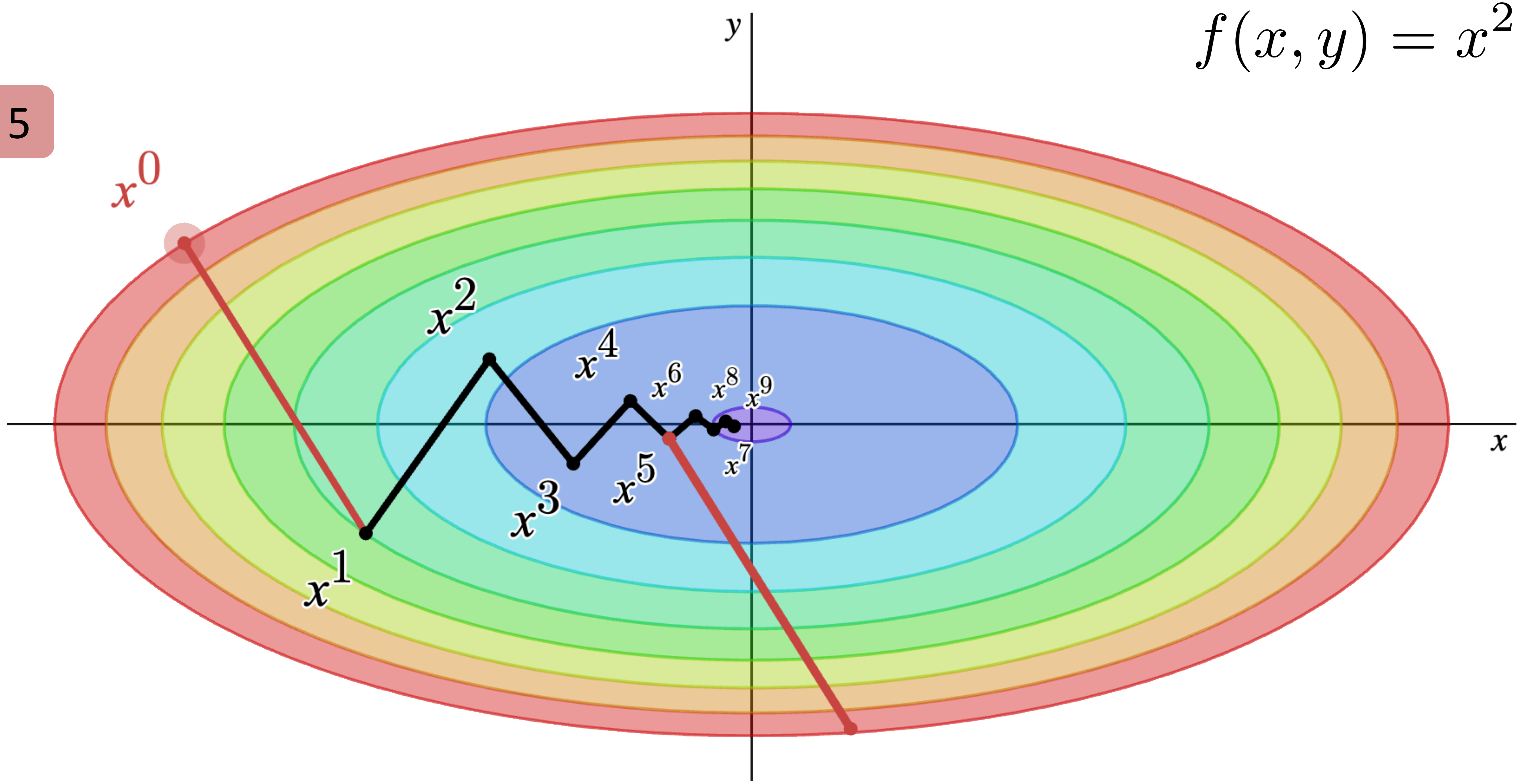
Asynchronous SGD is too wild: Ringmaster ASGD ***tames*** it



The smaller the delay, the better the gradient

Delay = 5

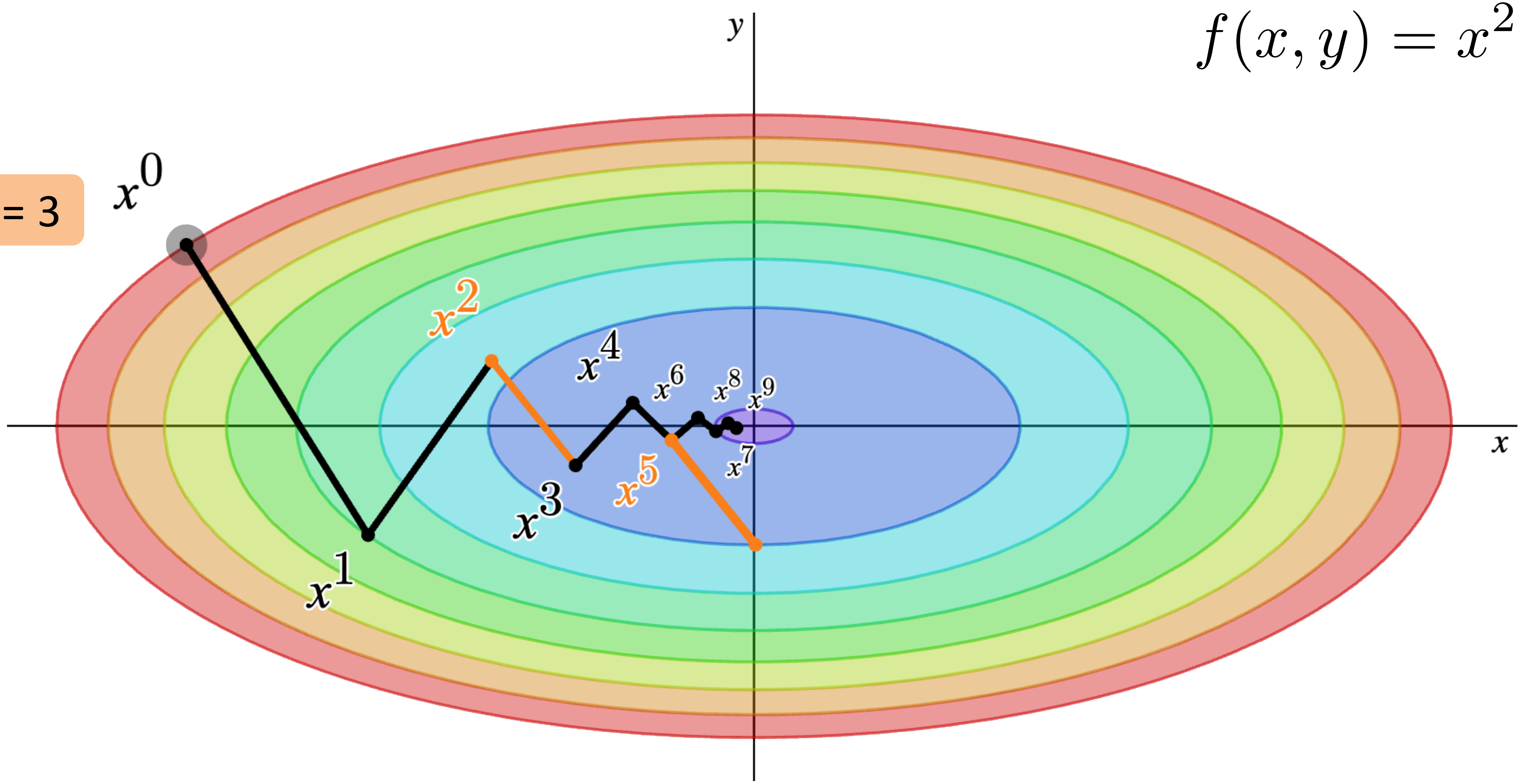
$$f(x, y) = x^2 + 5y^2$$



The smaller the delay, the better the gradient

$$f(x, y) = x^2 + 5y^2$$

Delay = 3



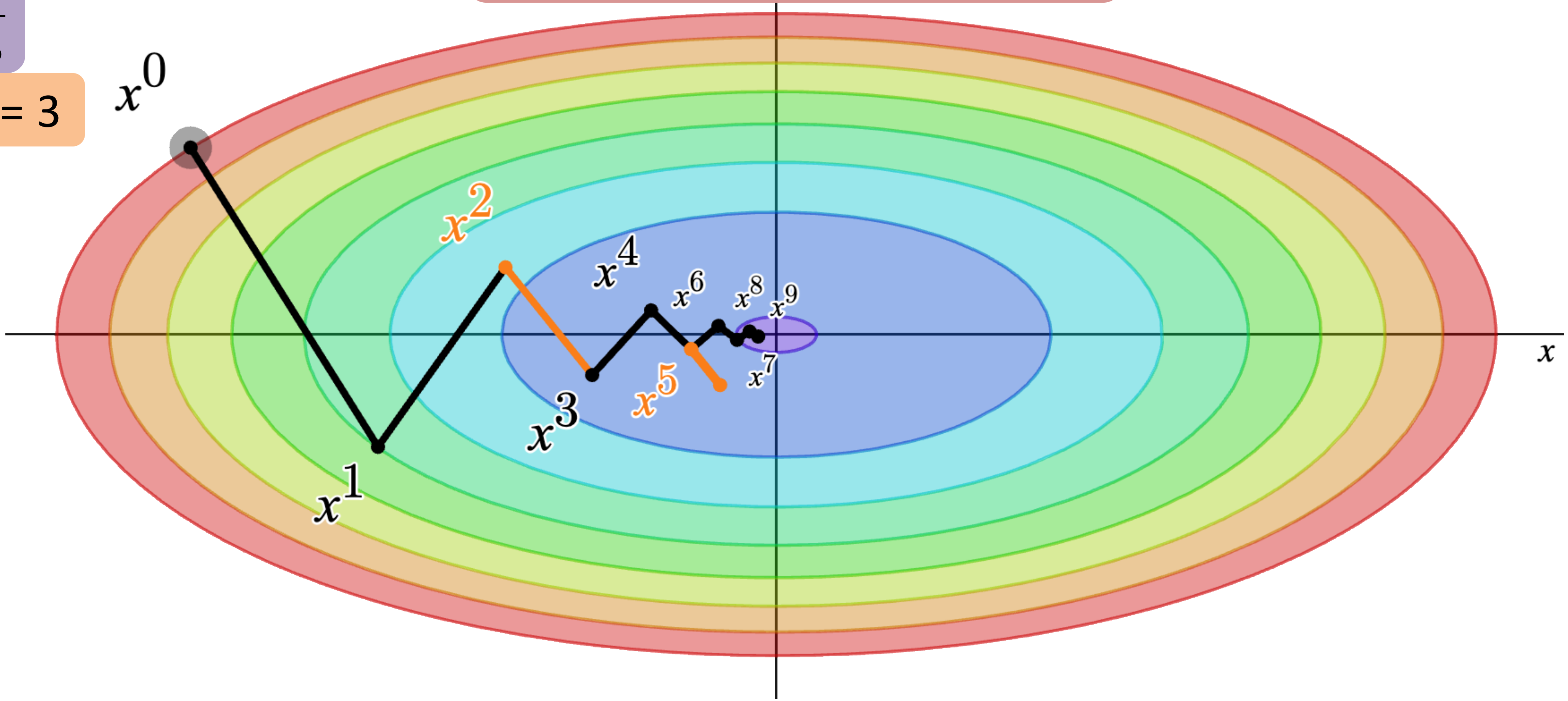
The smaller the delay, the better the gradient

$f(x, y) = x^2 + 5y^2$

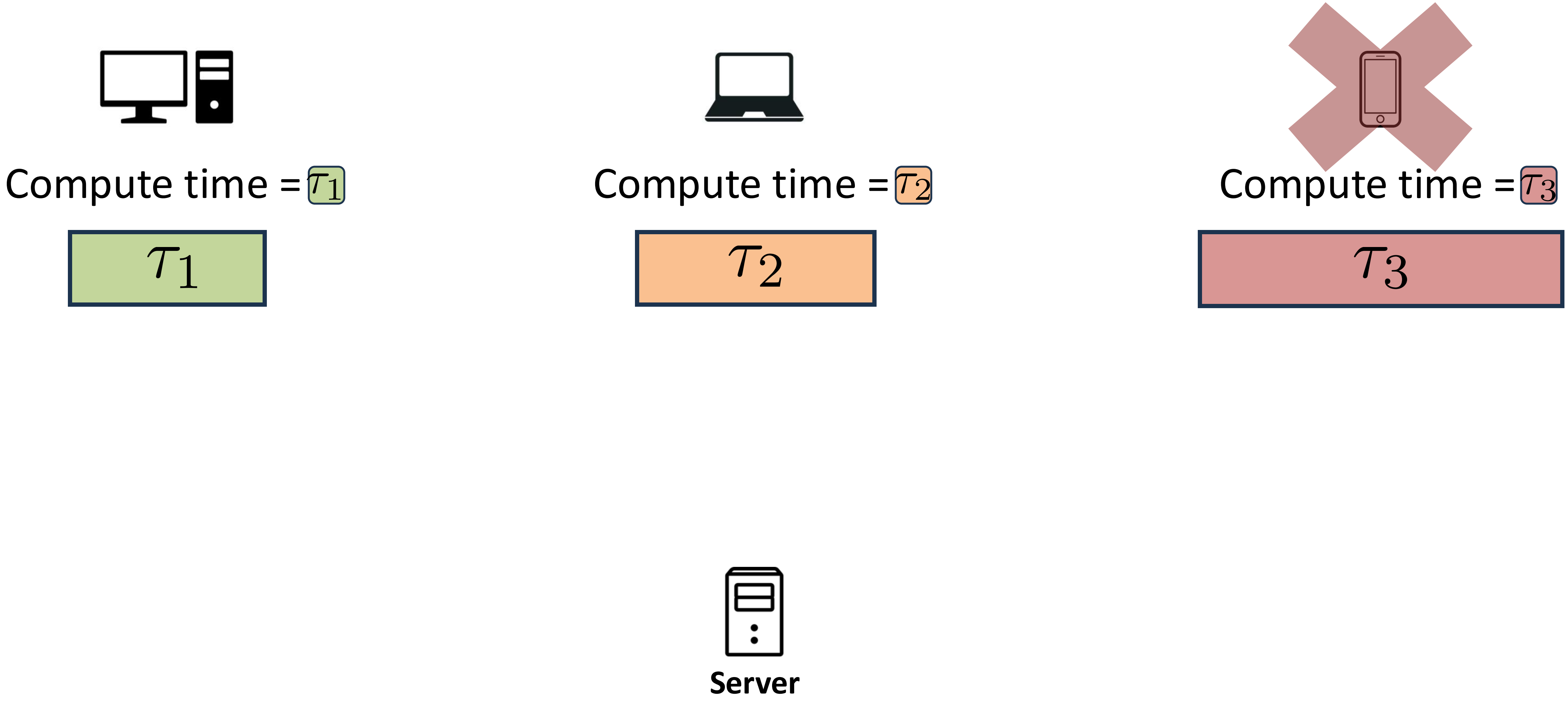
$\gamma = \frac{\gamma}{3}$

Delay = 3

How can we reduce the delay?



Naive approach:
Remove slow workers



Naive approach: Remove slow workers

$$\mathbb{E}\left[\|\nabla f(x;\xi) - \nabla f(x)\|^2\right] \leq \sigma^2$$

Use only the first $m_\star = \arg\min_{m \in [n]} \left\{ \left(\frac{1}{m} \sum_{i=1}^{m} \frac{1}{\tau_i} \right)^{-1} \left(1 + \frac{\sigma^2}{m\varepsilon} \right) \right\}$ fastest workers

$$\mathbb{E}\left[\|\nabla f(x)\|^2\right] \leq \varepsilon$$

Problem: τ_i-s may be unknown and dynamic

Ringmaster ASGD:
Have a threshold on delays

$\nabla f \left(x^{k-\delta^k}; \xi_i^{k-\delta^k} \right)$

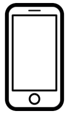
If: $\delta^k < R$

$$x^{k+1} = x^k - \gamma \nabla f \left(x^{k-\delta^k}; \xi_i^{k-\delta^k} \right)$$

Else: Ignore the gradient and send the current point x^k to the worker

Server

Ringmaster ASGD:
Have a threshold on delays



$\nabla f\left(x^k; \xi_i^k\right)$

How to choose the delay threshold R

If: $\delta^k < R$

$$x^{k+1} = x^k - \gamma \nabla f\left(x^{k-\delta^k}; \xi_i^{k-\delta^k}\right)$$

Else: Ignore the gradient and send the current point x^k to the worker

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Certain threshold choices in Ringmaster ASGD recover previous methods

$$R = \max\left\{1, \left\lceil \frac{\sigma^2}{\varepsilon} \right\rceil\right\}$$

$R = 1$
Hero SGD

Sweet spot

$R = \infty$
HOGWILD!

Theoretical results validate our intuition

$$\mathcal{O}\left(\boxed{R}\over\varepsilon + \frac{\sigma^2}{\varepsilon^2}\right)$$

Number of iterations

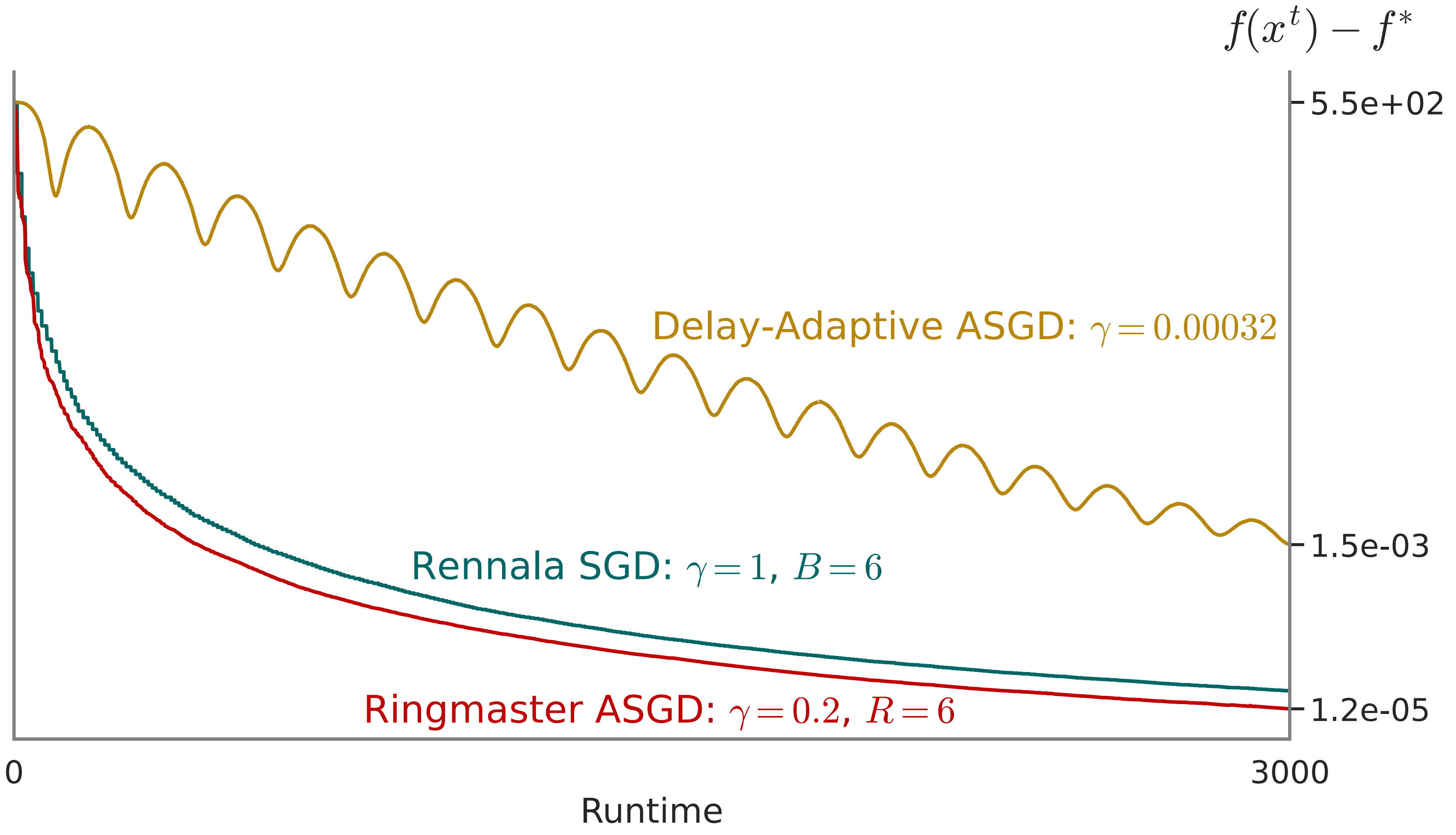
$$\mathcal{O}\left(\min_{m\in[n]}\left[\boxed{\left(\frac{1}{m}\sum_{i=1}^{m}\frac{1}{\tau_i}\right)^{-1}}\left(\frac{1}{\varepsilon}+\boxed{\frac{\sigma^2}{m\varepsilon^2}}\right)\right]\right)$$

Time complexity

non-decreasing

decreasing

Ringmaster ASGD outperforms existing baselines



Recap of what we have covered

$$\min_{x \in \mathbb{R}^d} \left\{ f(x) := \mathbb{E}_{\xi \sim \mathcal{D}} \left[f(x; \xi) \right] \right\}$$

Problem setup

Optimization objective

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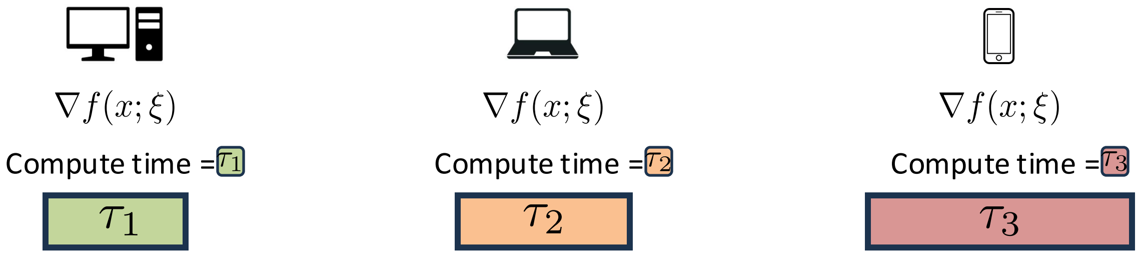

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$$\min_{x \in \mathbb{R}^d} \{ f(x) := \mathbb{E}_{\xi \sim \mathcal{D}} [f(x;\xi)] \}$$

$\nabla f(x;\xi)$

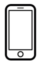
Compute time = τ_1

$\boxed{\tau_1}$

$\nabla f(x;\xi)$

Compute time = τ_2

$\boxed{\tau_2}$



$\nabla f(x;\xi)$

Compute time = τ_3

$\boxed{\tau_3}$

$$x^{k+1} = x^k - \gamma g(x^k)$$

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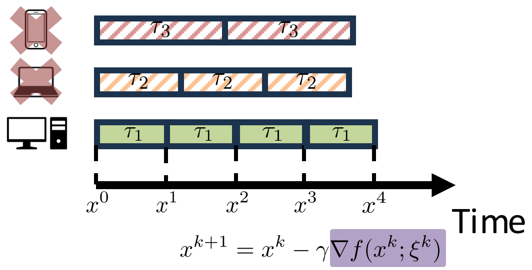

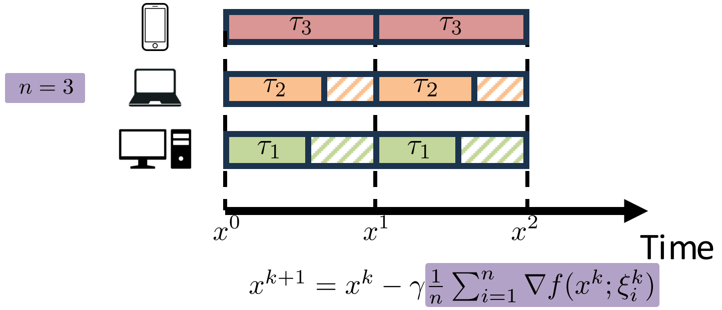

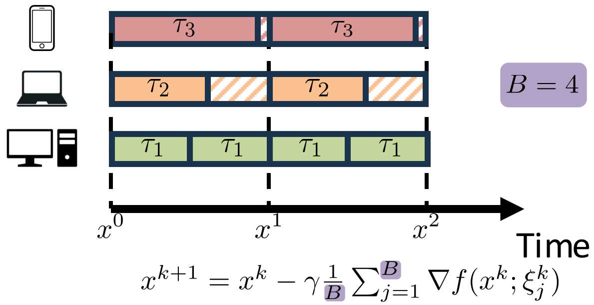

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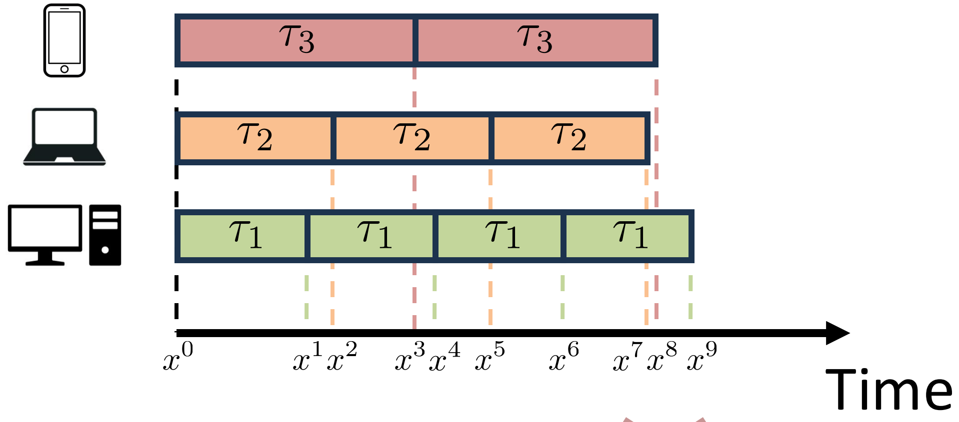

$$x^{k+1} = x^k - \gamma \cancel{g(x^k)}$$

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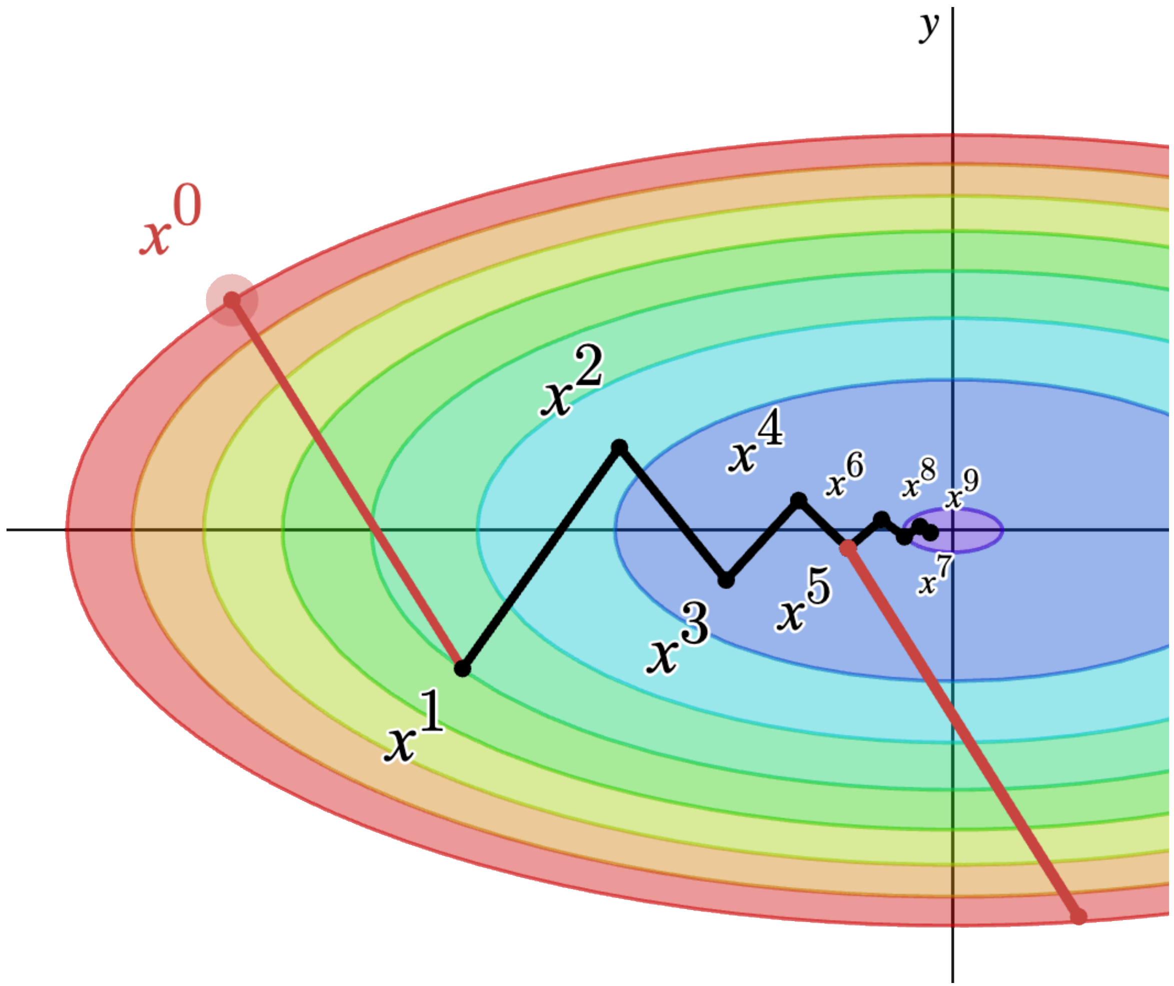

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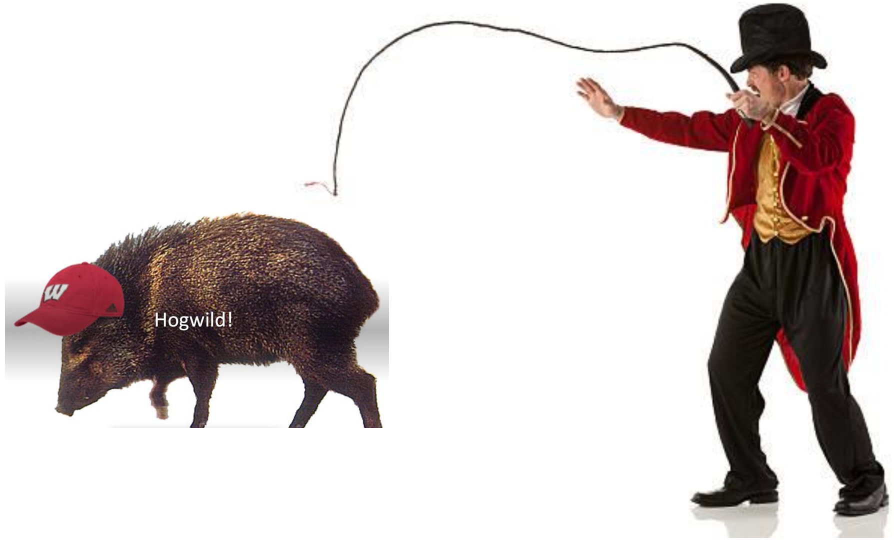

$\nabla f\left(x^k; \xi_i^k\right)$

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Ringmaster ASGD

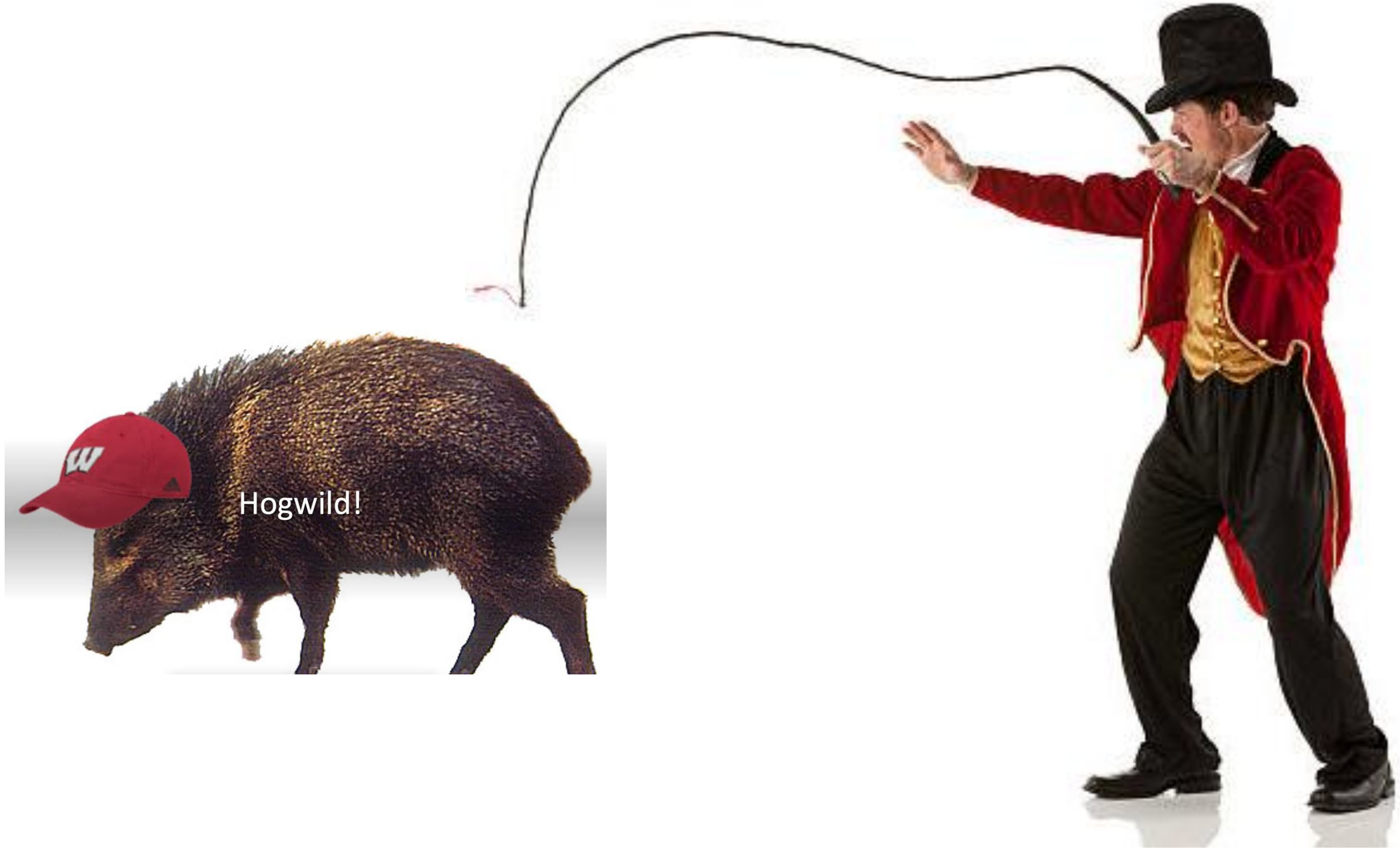
Alexander Tyurin
Skoltech

Peter Richtárik
KAUST

Closely related papers

Artavazd Maranjyan, Omar Shaikh Omar, Peter Richtárik (2024)
MindFlayer: Efficient asynchronous parallel SGD in the presence of heterogeneous and random worker compute times

Artavazd Maranjyan, El Mehdi Saad, Peter Richtarik, and Francesco Orabona (2025)
ATA: Adaptive Task Allocation for Efficient Resource Management in Distributed Machine Learning


Hogwild!