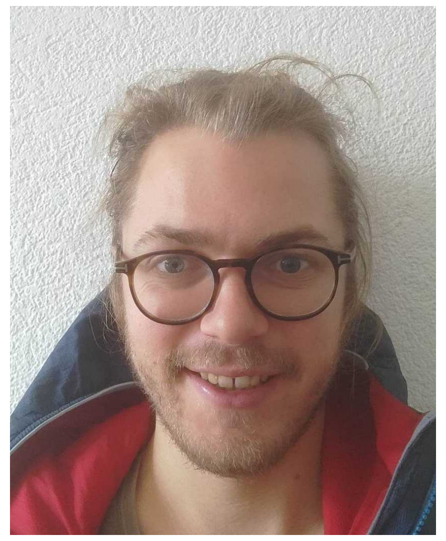
Adversarially Robust Distributed Optimization

A Unified Breakdown Analysis of Byzantine Robust Gossip

Renaud Gaucher

Redeem retreat
September 2025



Aymeric Dieuleveut

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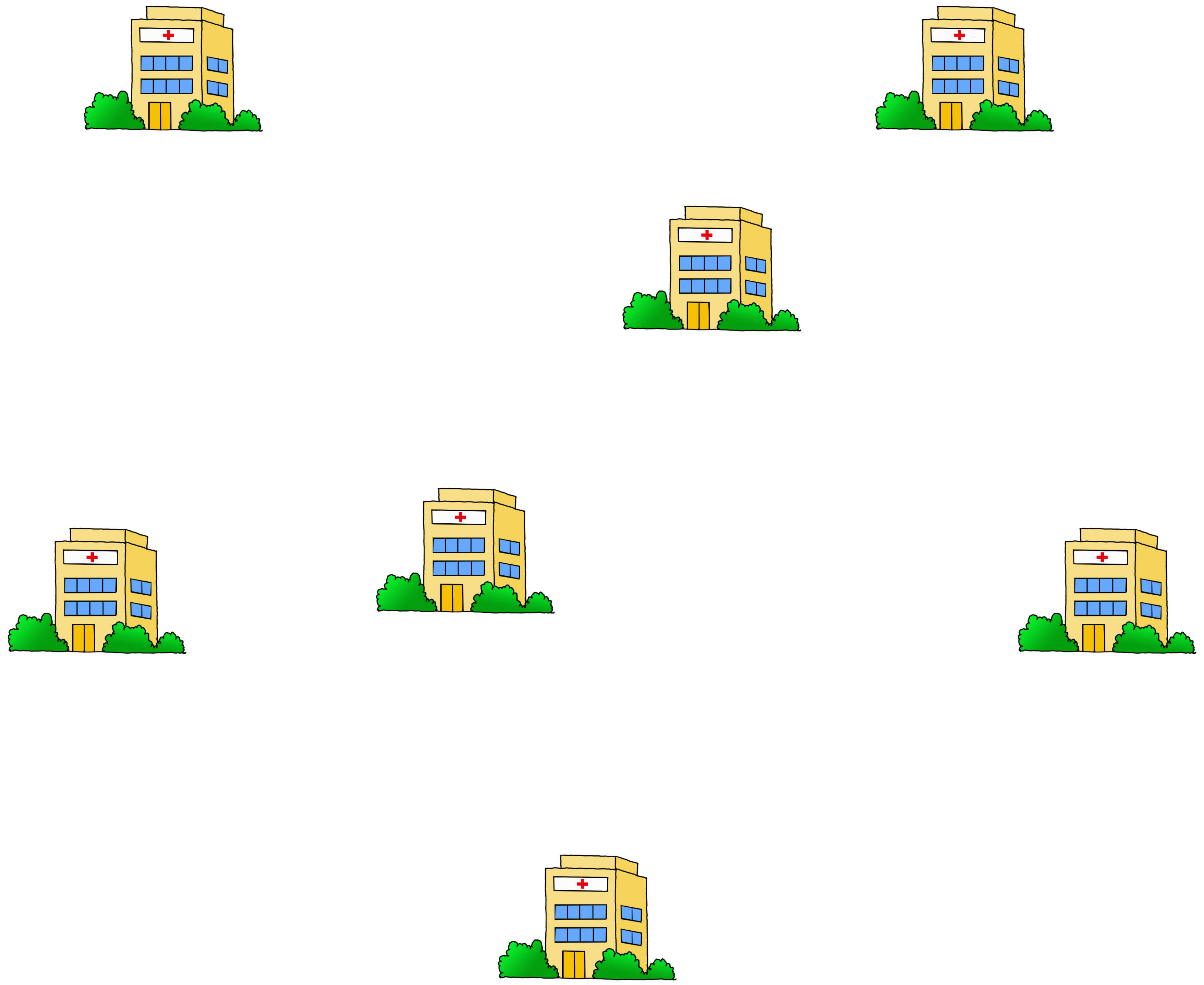
Hadrien Hendrikx

Inria Grenoble

Distributed Optimization in Machine Learning



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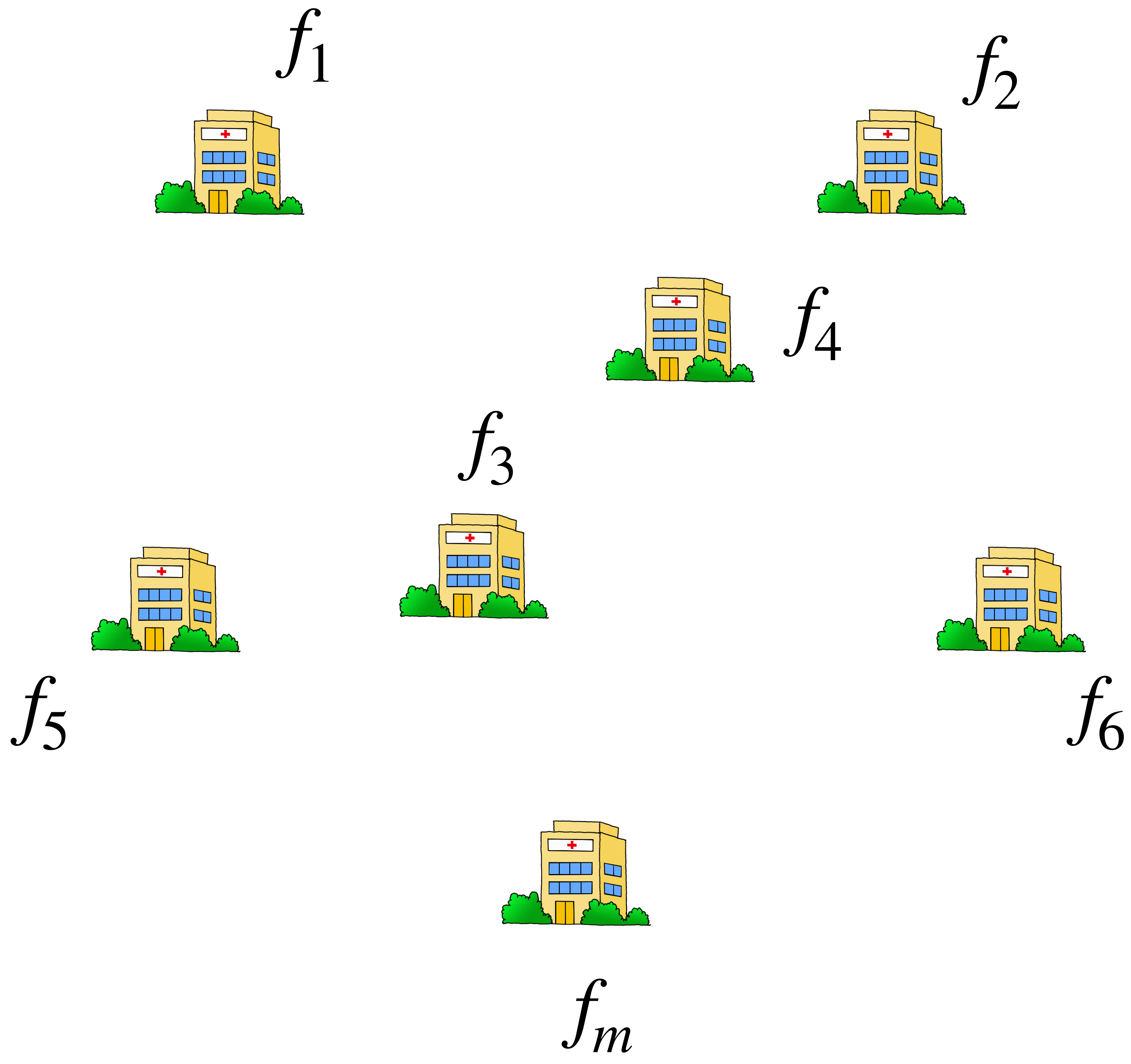
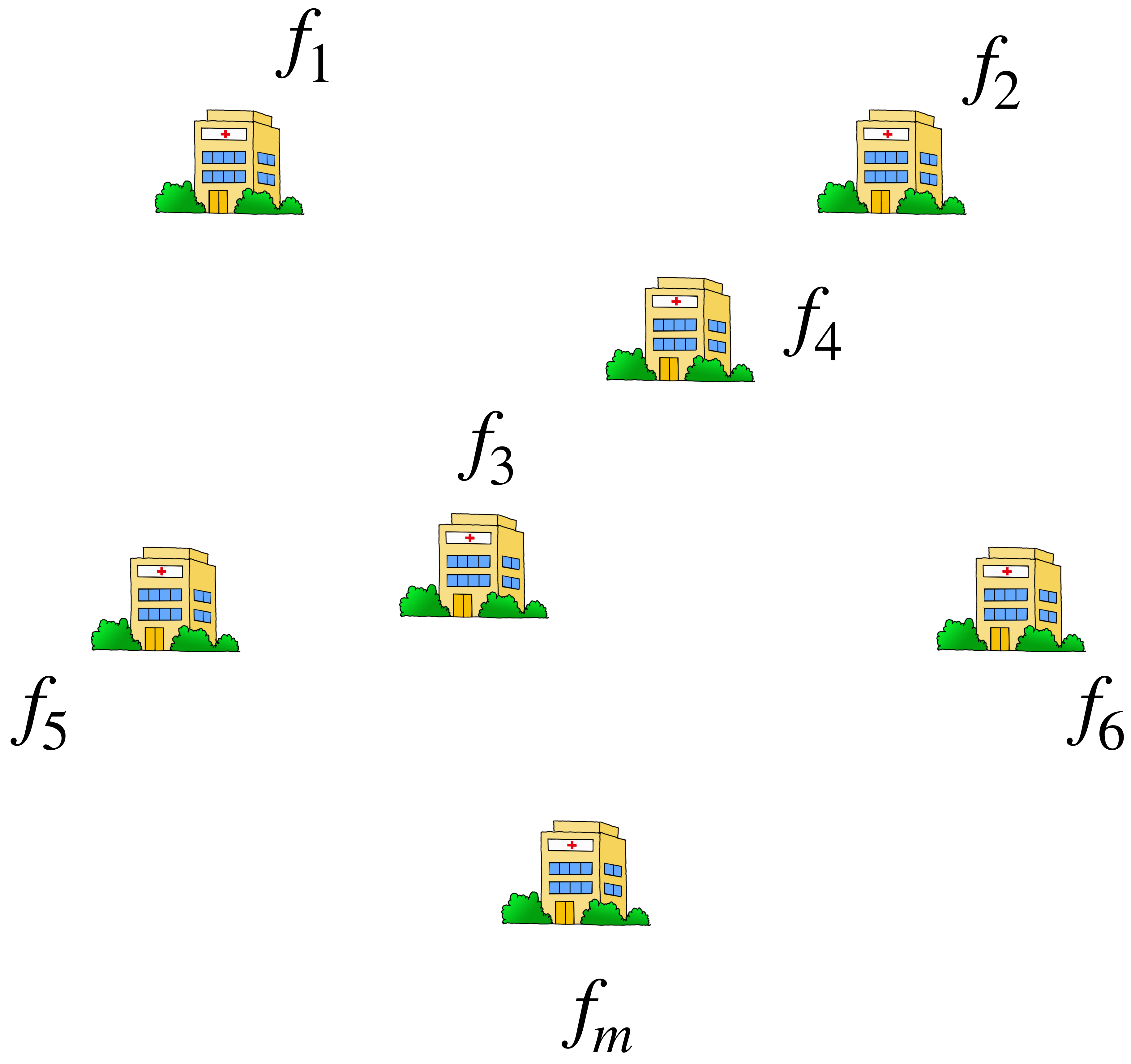


Distributed Optimization in Machine Learning

Number of nodes in the network

local loss of node i

$$\min_{x \in \mathbb{R}^d} f(x) = \frac{1}{m} \sum_{i=1}^{m} f_i(x)$$



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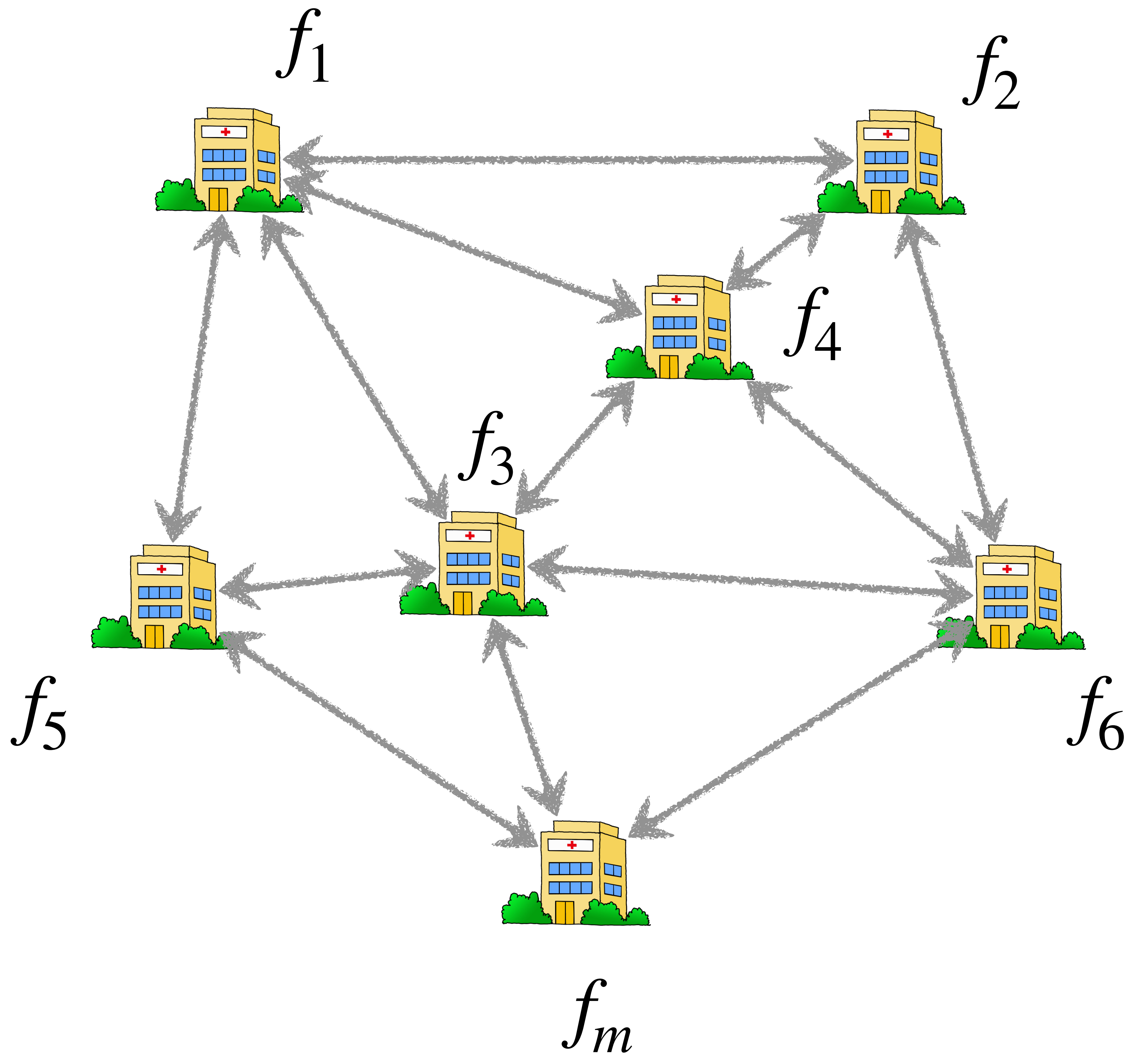
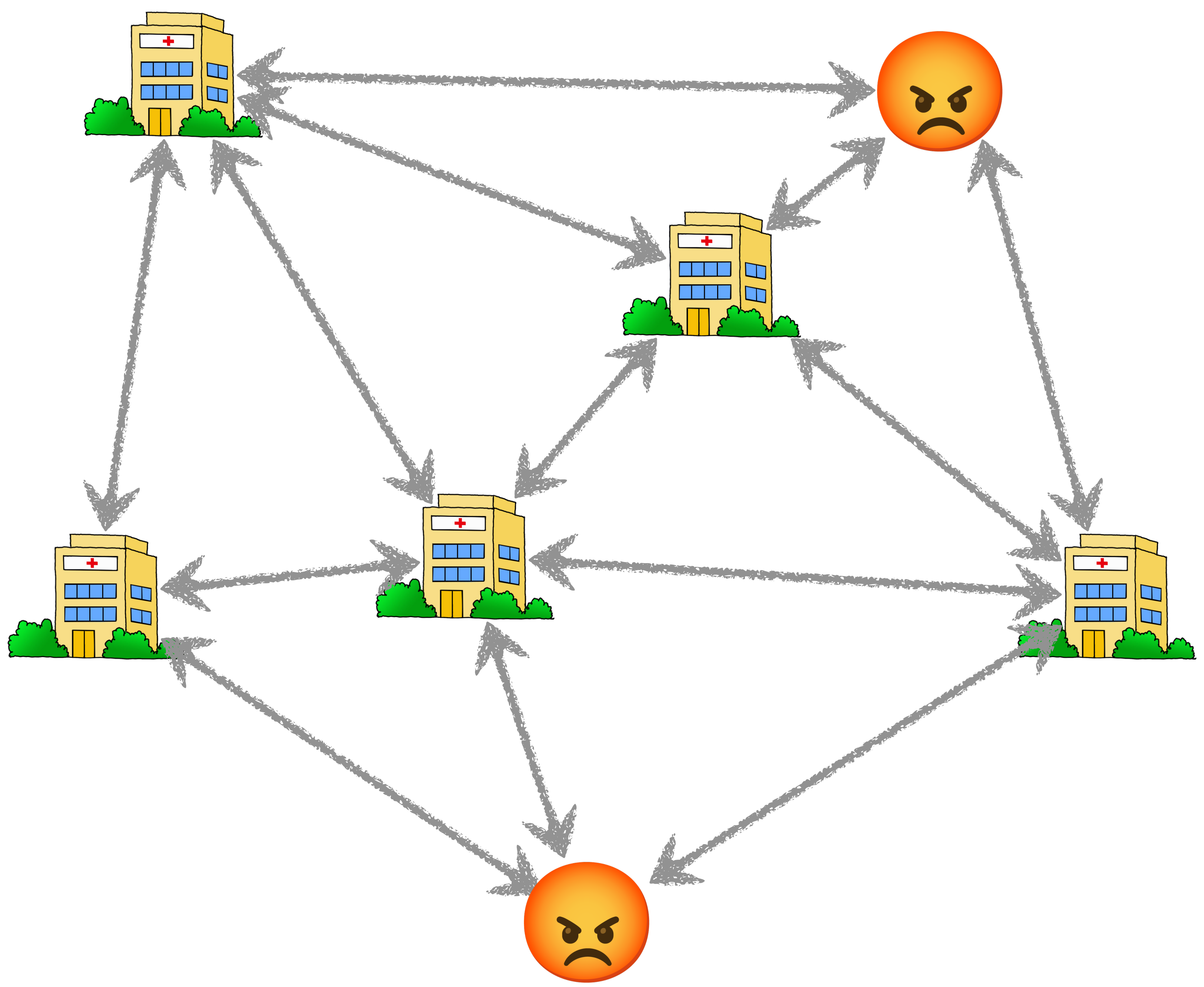


- Nodes can access their local loss function only
- Nodes collaborate to minimize the sum
- Synchronous communications

Distributed Optimization with Adversaries (Byzantines)

Goal: $$\min_{x \in \mathbb{R}^d} \frac{1}{|\text{honest}|} \sum_{i \in \text{honest}} f_i(x)$$



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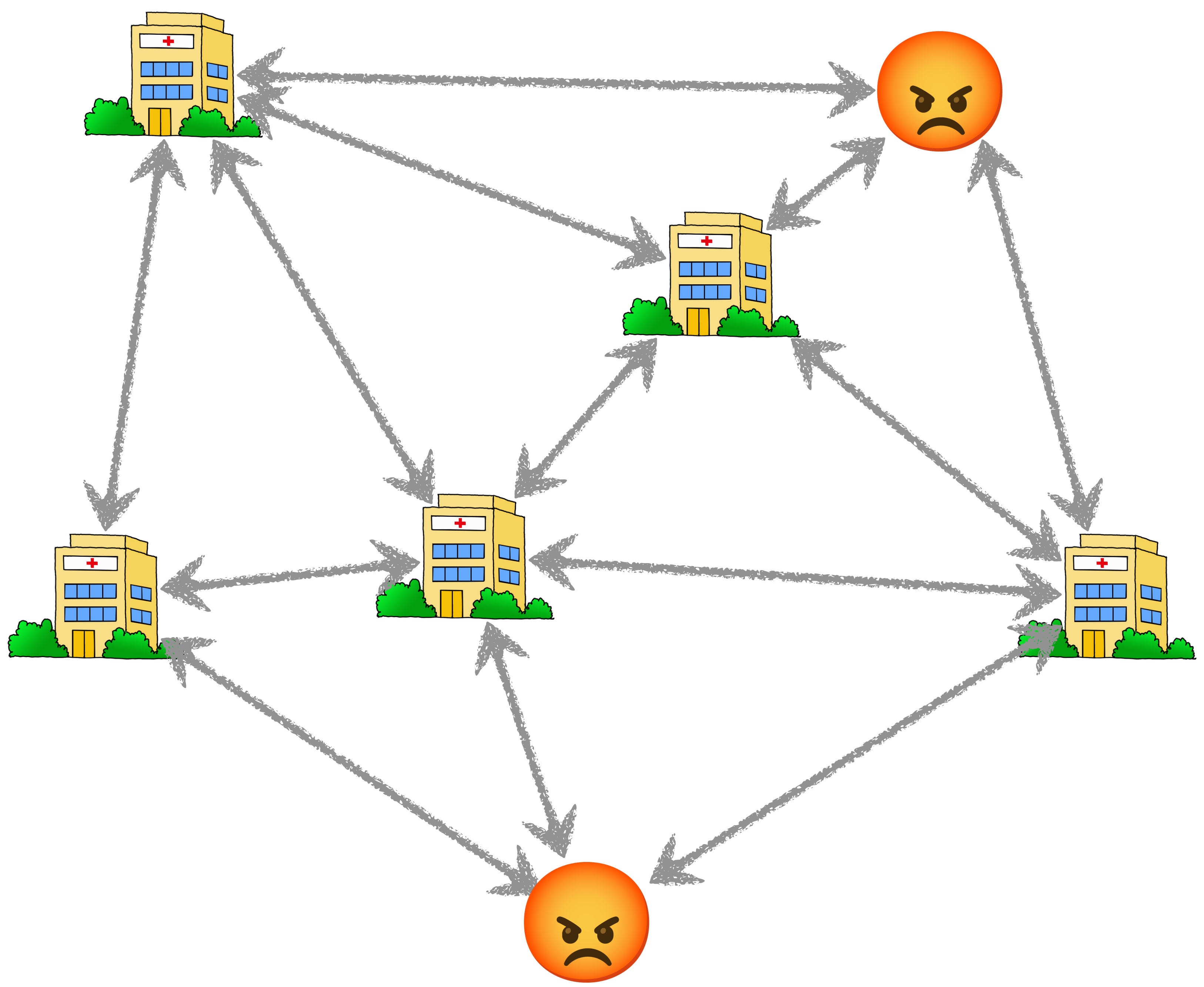

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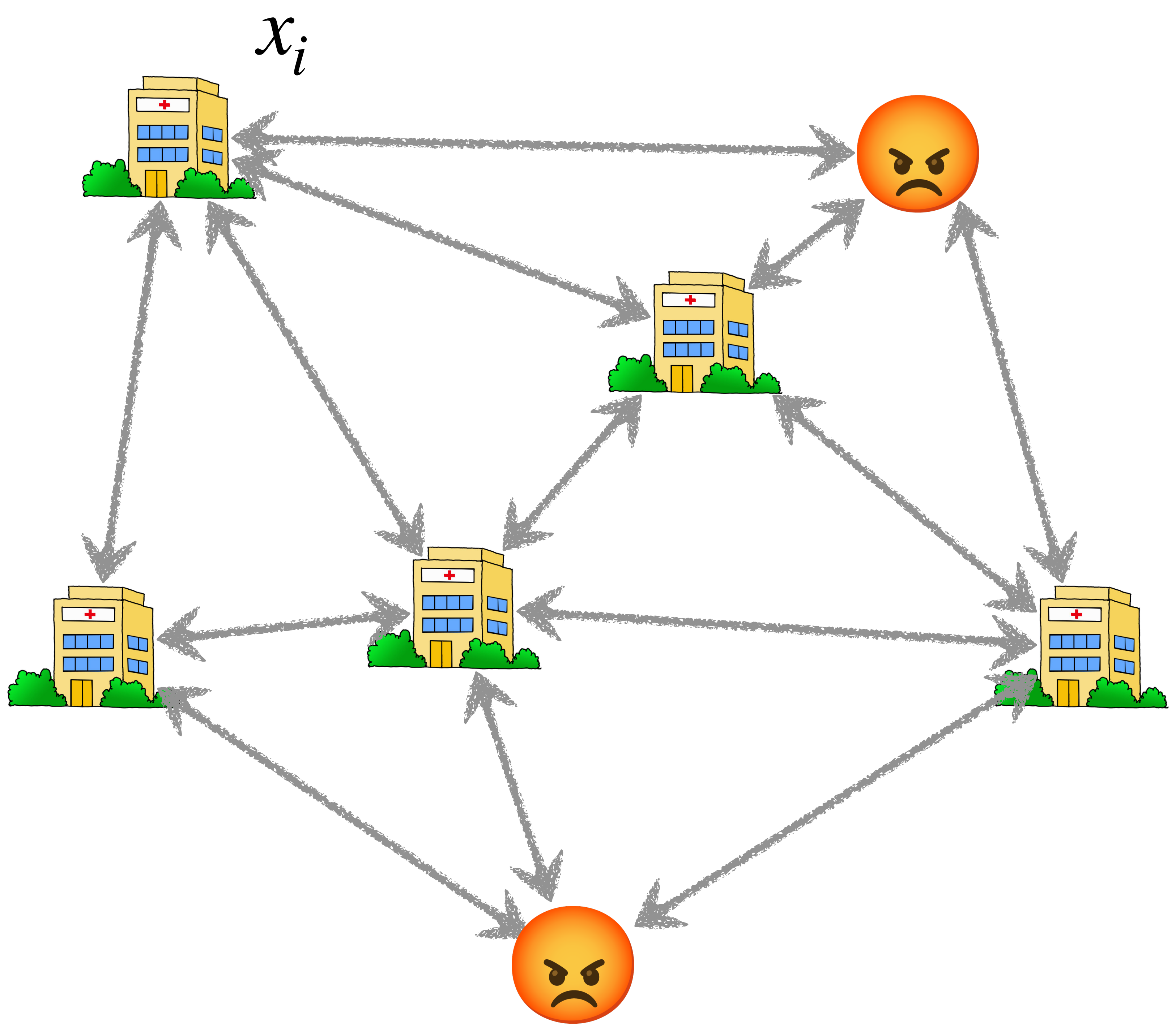

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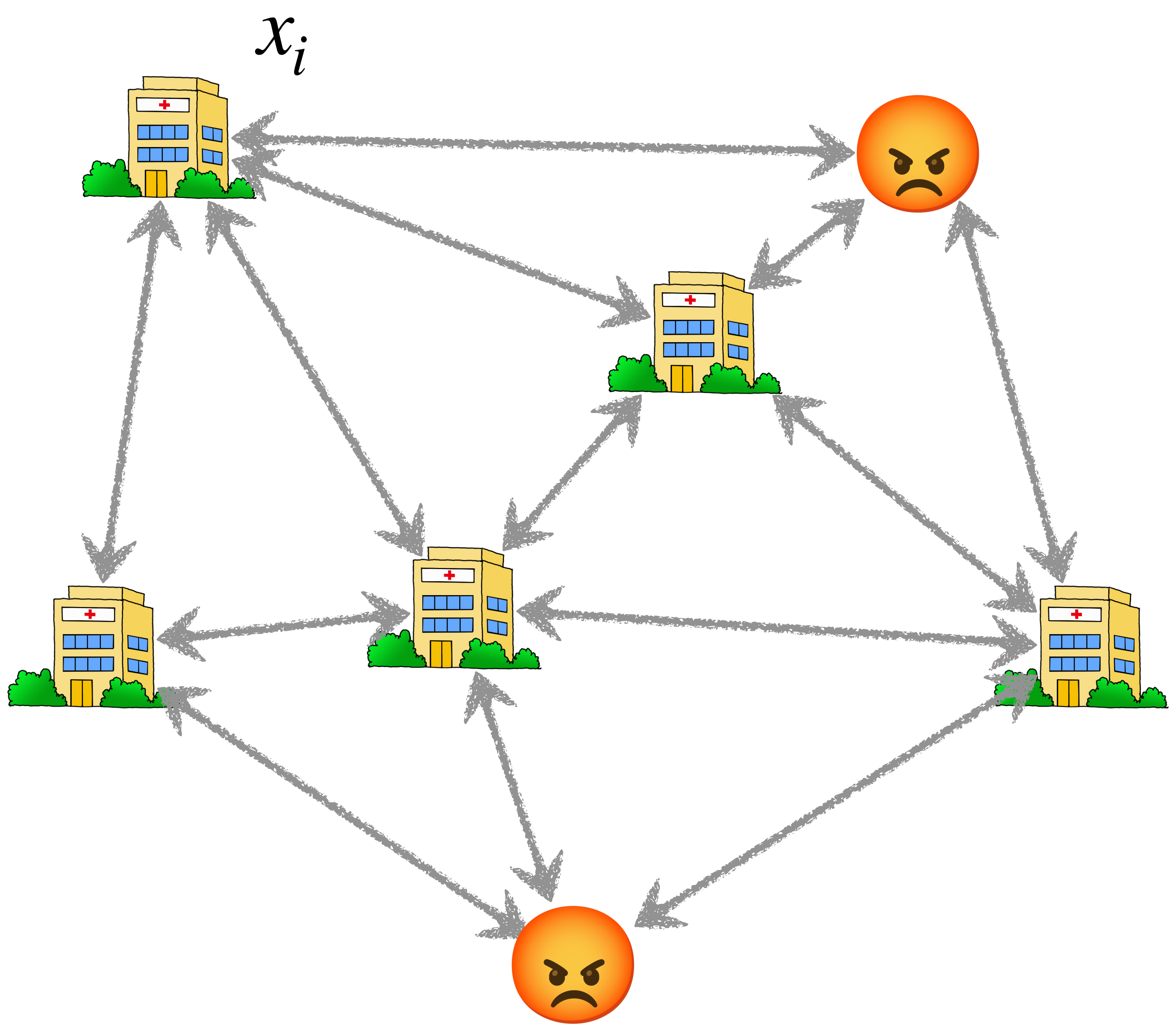
Each honest node has at most b Byzantine neighbors



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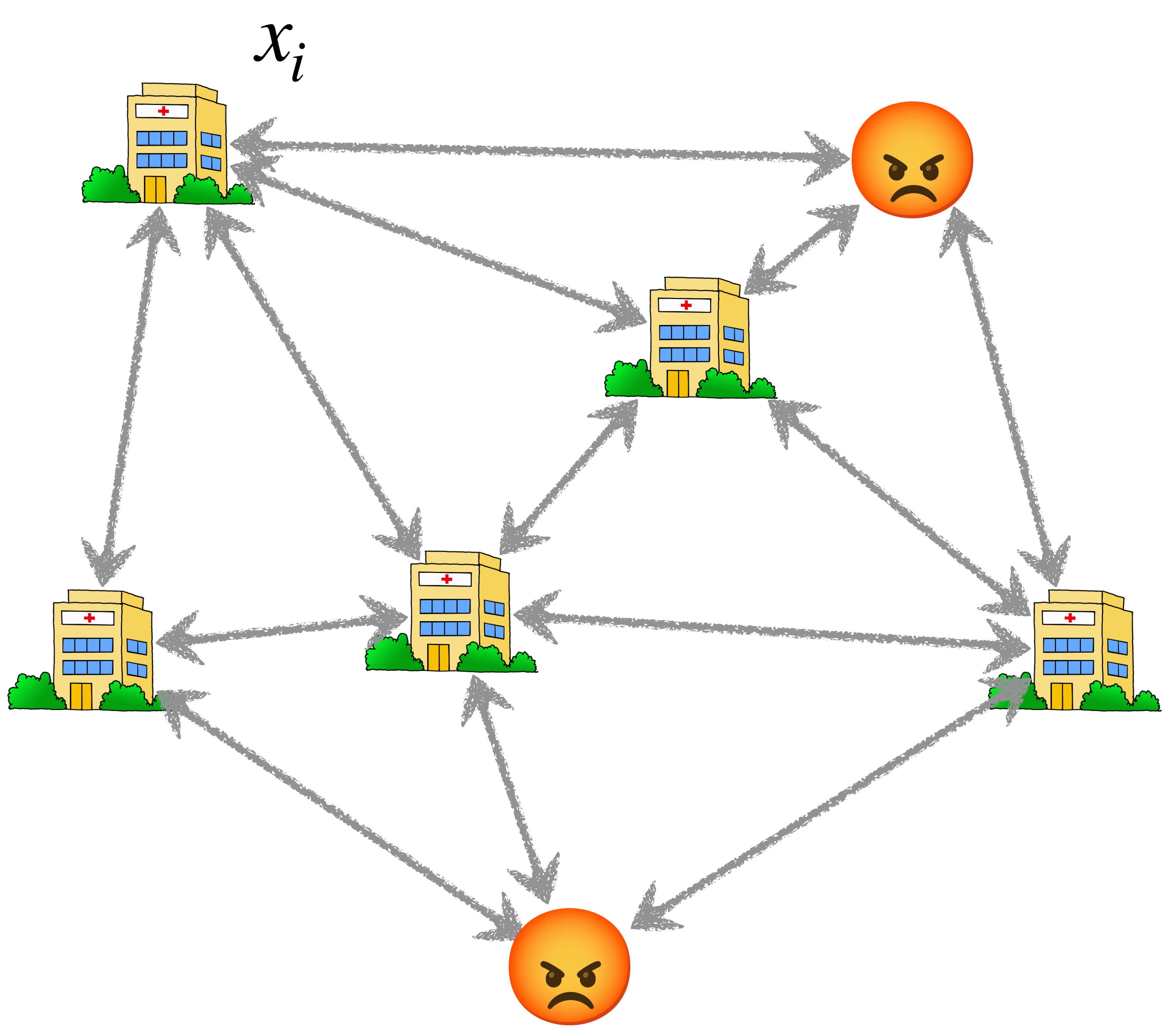
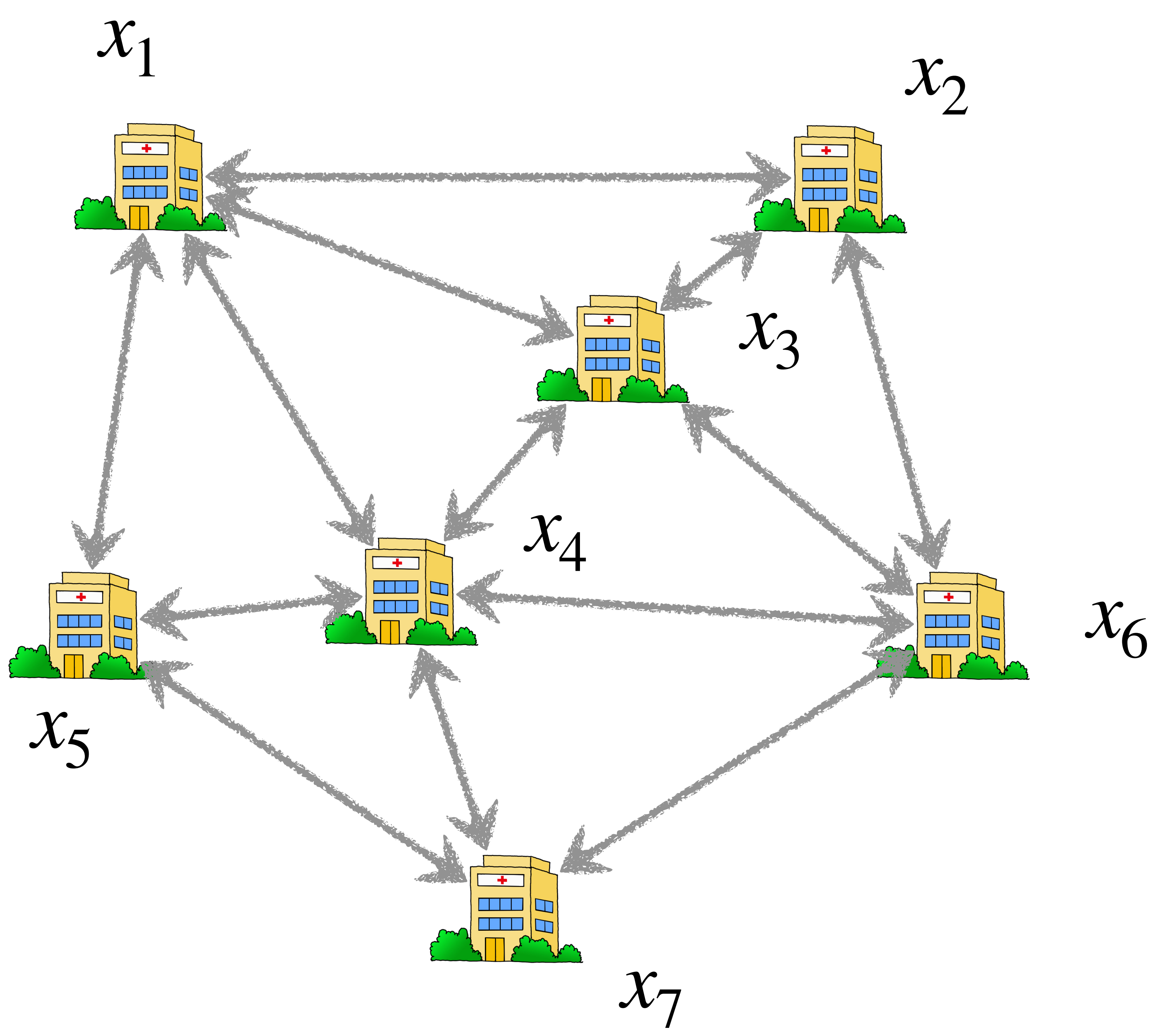


Definition: r - robustness

$$\frac{1}{|\text{honest}|} \sum_{i \in \text{honest}} \left\| x_i^t - \bar{x}_h^0 \right\|^2 \leq r \frac{1}{|\text{honest}|} \sum_{i \in \text{honest}} \left\| x_i^0 - \bar{x}_h^0 \right\|^2$$

with $r < 1$

Gossip communication



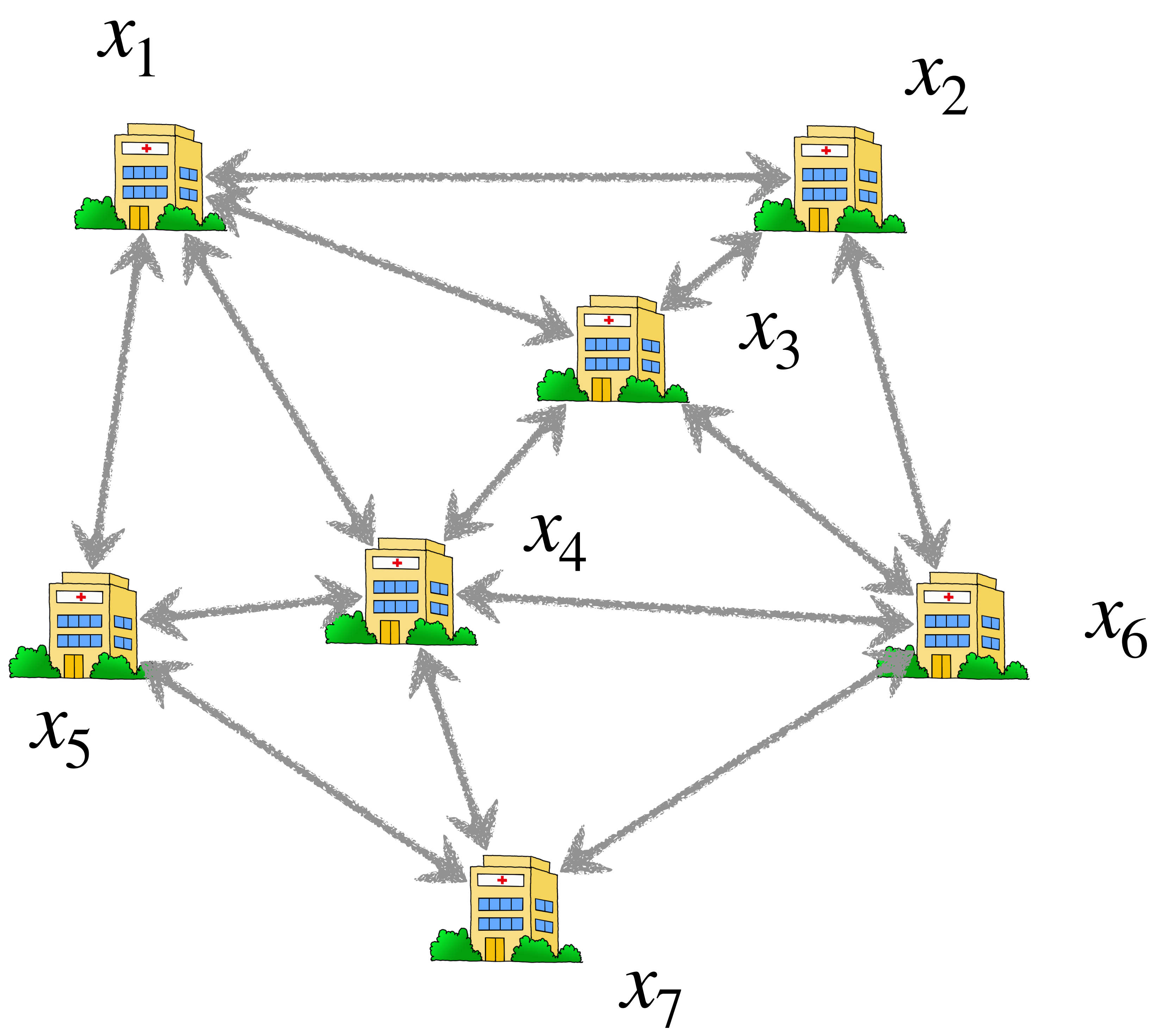
Goal

$$\bar{x} = \frac{1}{m} \sum_{i=1}^{m} x_i$$

Gossip communication

Update of node i

$$x_i^{t+1} = x_i^t - \eta \sum_{j \in \text{neighbors(i)}} \left(x_i^t - x_j^t \right)$$



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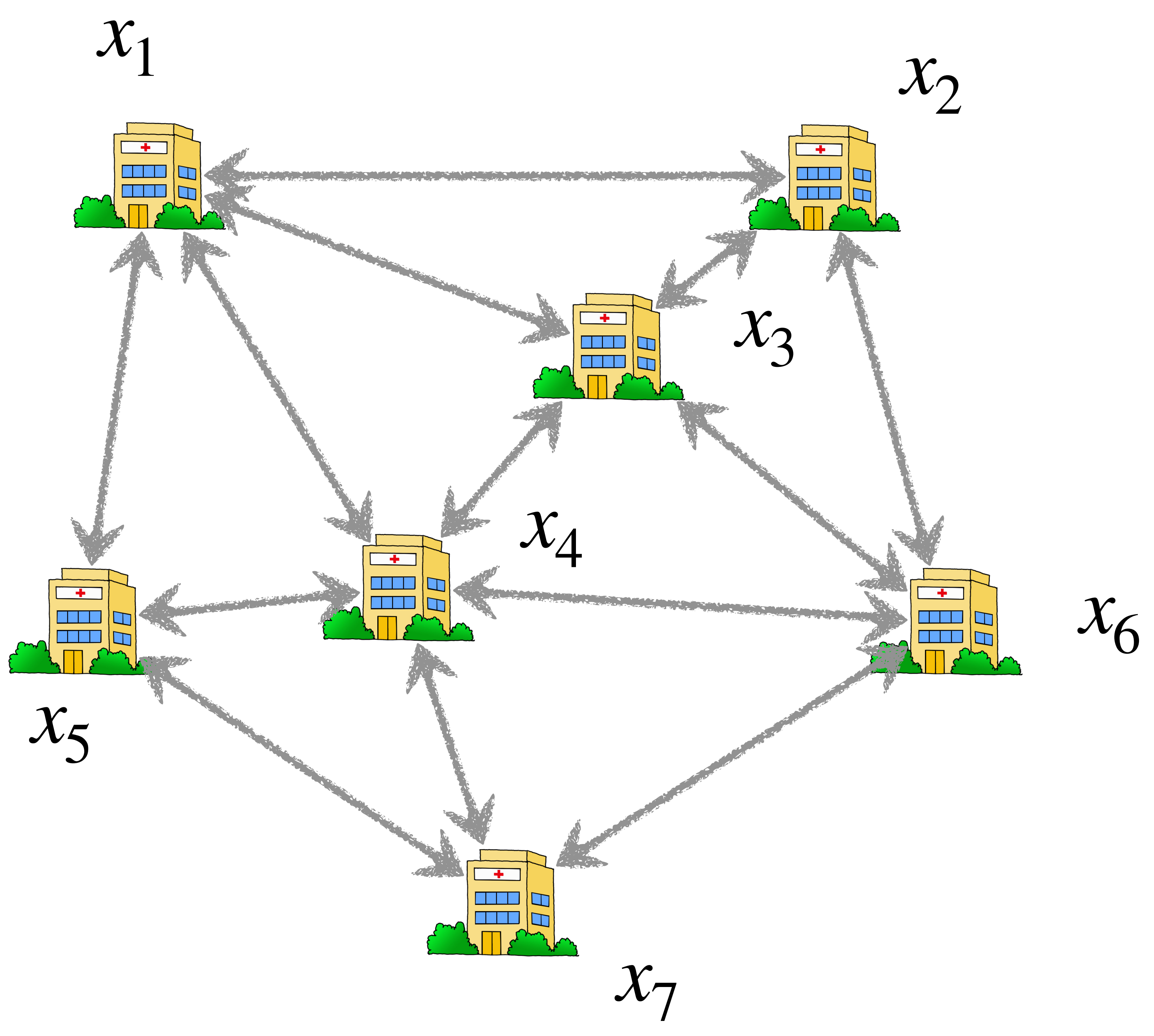
Using $L = \text{Diag(degrees)} - \text{Adjacency}$ and $X^t = \begin{pmatrix} x_1^t \\ \vdots \\ x_h^t \end{pmatrix}$

$$X^{t+1} = (I - \eta L) X^t$$



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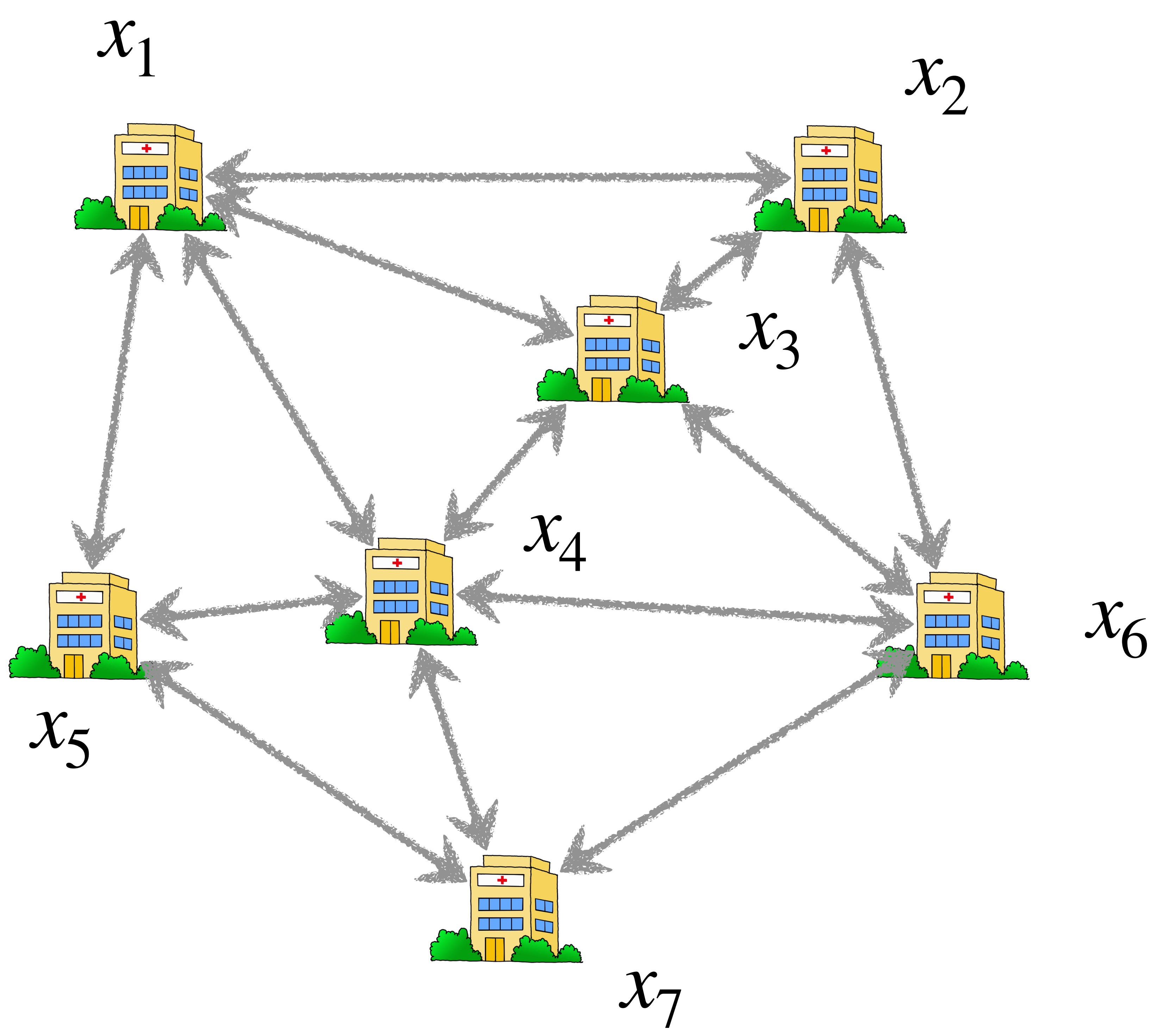
Theorem (folklore)

Spectral gap

$$\| X^t - \overline{X}^0 \| \leq \left(1 - \frac{\mu_2(L)}{\mu_{max}(L)} \right)^t \| X^0 - \overline{X}^0 \|$$



Goal

$$\bar{x} = \frac{1}{m} \sum_{i=1}^{m} x_i$$

The Robust Gossip framework

Non-robust update of node i

$$x_i^{t+1} = x_i^t - \eta \sum_{j \in \text{neighbors}(i)} \left(x_i^t - x_j^t \right)$$

The Robust Gossip framework

Robust gossip update of node i

$$x_i^{t+1} = x_i^t - \eta F\Big(\big(x_i^t - x_j^t\big)_{j \in \text{neighbors(i)}} \Big)$$

The Robust Gossip framework

Robust gossip update of node i

$$x_i^{t+1} = x_i^t - \eta\, F\Big(\big(x_i^t - x_j^t\big)_{j \in \text{neighbors(i)}}\Big)$$

Definition: Robust aggregation function

$$\Big\| F(z_1, \ldots, z_n) - \sum_{i \in \text{honest}} z_i \Big\|^2 \leq \rho\, b \sum_{i \in \text{honest}} \| z_i \|^2$$

quality / robustness of F

number of *byzantine* vectors in $z_1, \ldots, z_n$

Instances of robust aggregations

1. Sort $||z_1|| \leq \ldots \leq ||z_n||$

2.a) Remove vectors larger than $||z_{n-b}||$

$$F(z_1, \ldots, z_n) = \sum_{i=1}^{n-b} z_i$$

$\rho = 4$

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$\rho = 4$

2.b) Clip vectors larger at $\|z_{n-2b}\|$

$$F(z_1, \ldots, z_n) = \sum_{i=1}^{n} \frac{z_i}{\|z_i\|} \min \left(\|z_i\|, \|z_{n-2b}\| \right)$$

$\rho = 2$

F-Robust Gossip is r-robust

Theorem

$$\frac{1}{|\text{honest}|} \sum_{i \in \text{honest}} \left\| x_i^1 - \bar{x}_h^0 \right\|^2 \leq r \frac{1}{|\text{honest}|} \sum_{i \in \text{honest}} \left\| x_i^0 - \bar{x}_h^0 \right\|^2$$

with $r = 1 - \dfrac{\mu_2(L) - 2\rho b}{\mu_{max}(L)}$

Algebraic connectivity

In fully connected graphs $\mu_2(L) = |\text{honest}|$

↪ r-robust until a proportion of $1/(2\rho+1)$ aversaries

Tightness of the breakdown point

Theorem

There are arbitrarily sparse graphs and initial values $\{x_i^0\}$ on which, if $2b \geq \mu_2(L)$, no decentralized algorithm is r-robust with r <1

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↪ $\rho = 1$ is the best we can have !

↪ *At most* $1/3$ adversaries in fully-connected graphs

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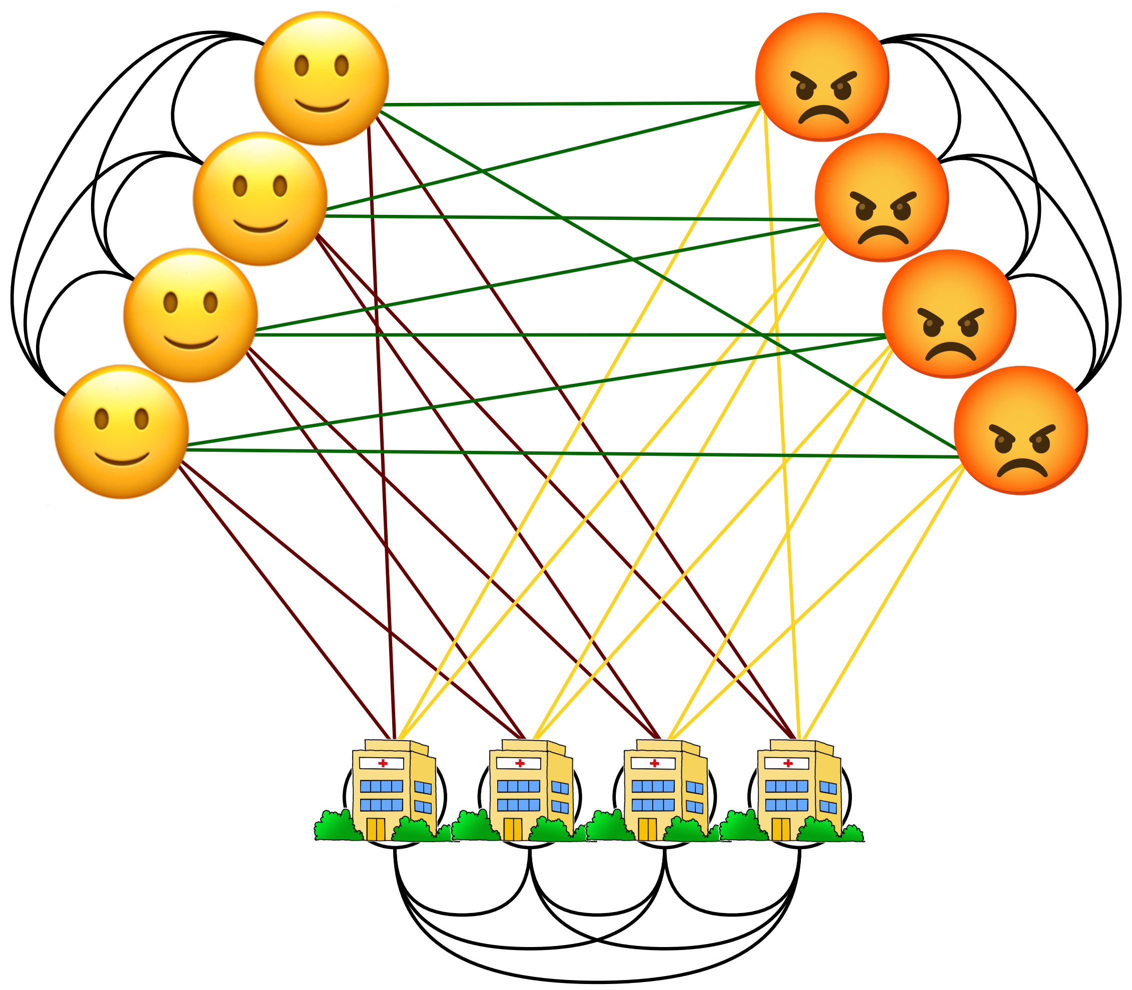

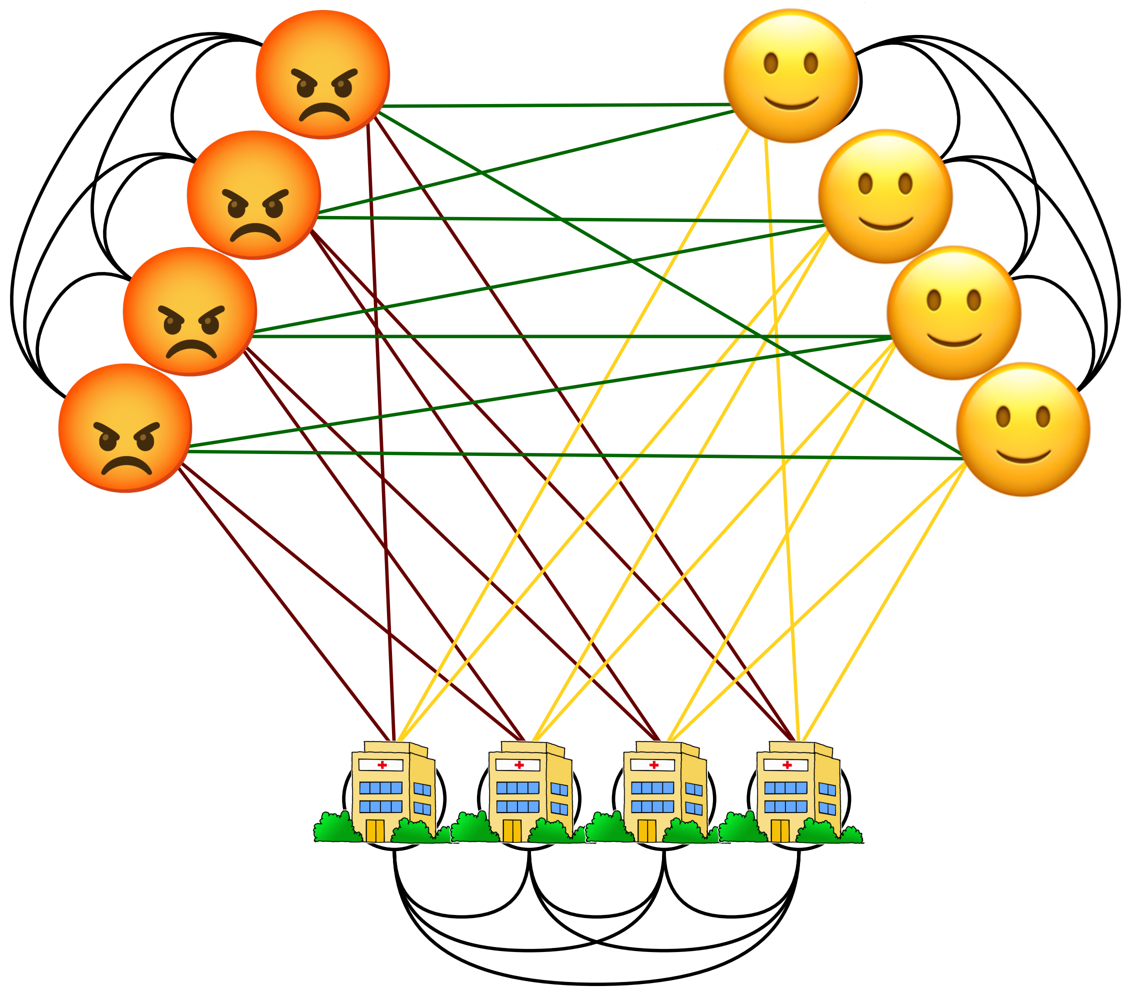

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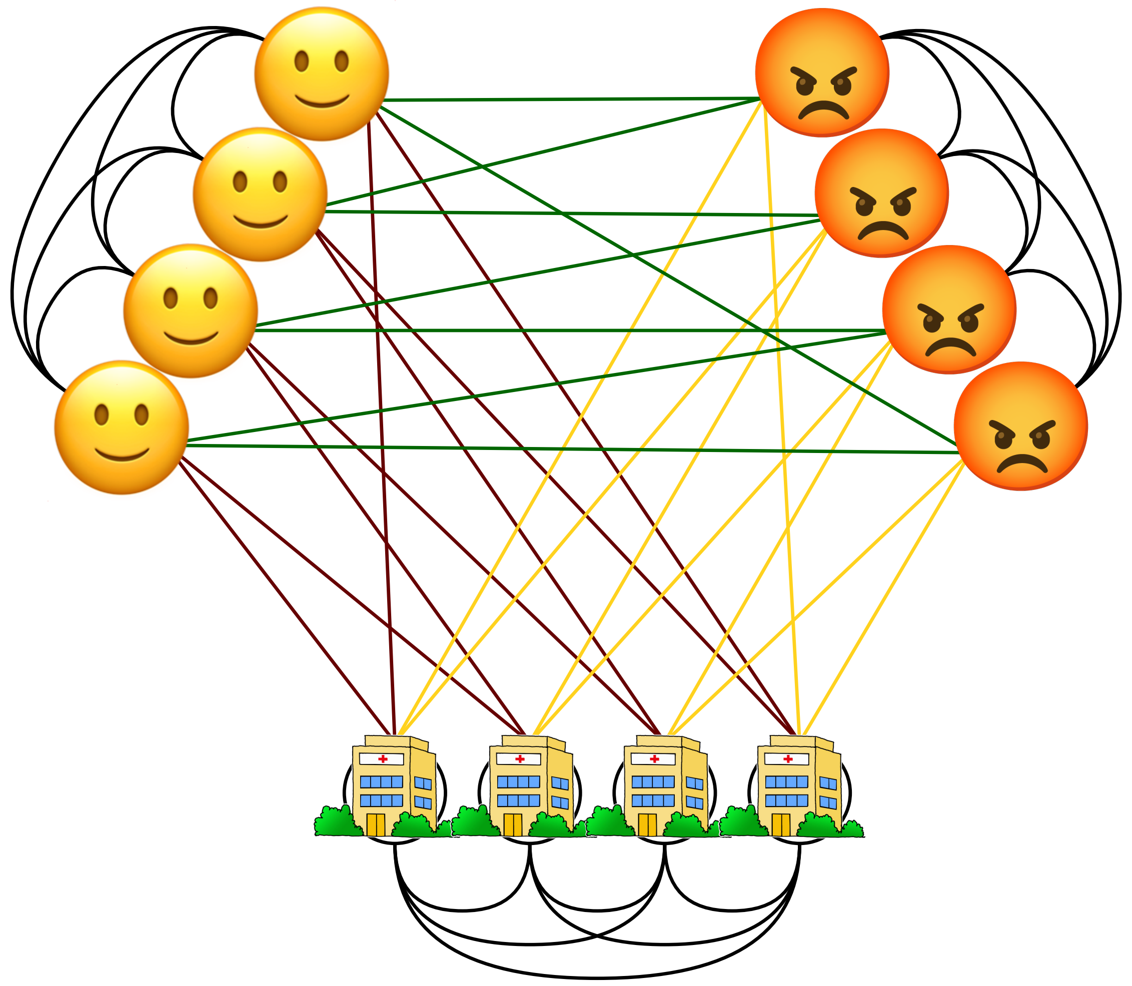

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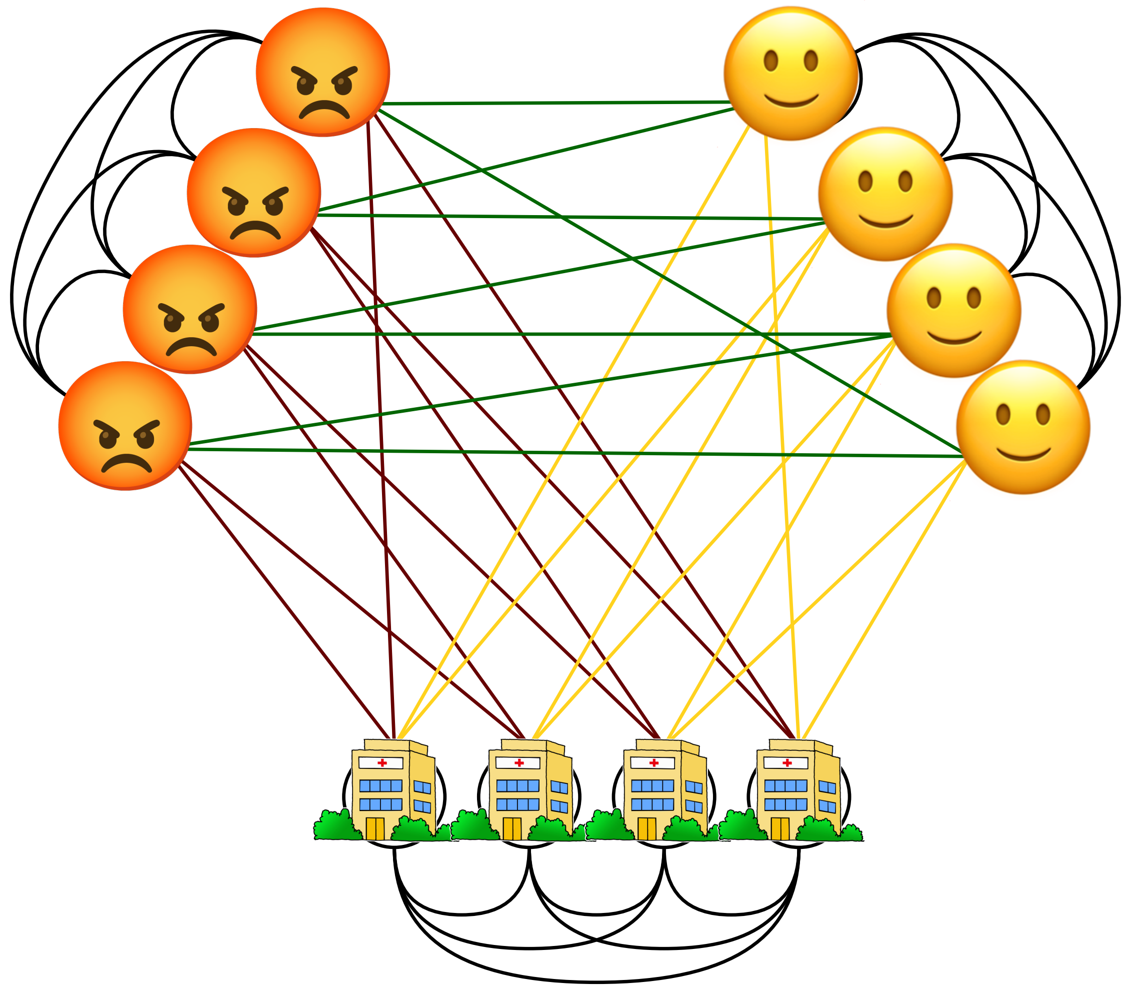

Asymptotic consensus

« Breakdown ratio » $\delta = 2\rho b/\mu_2(L)$

Spectral gap of the graph $\gamma = \mu_2(L)/\mu_{max}(L)$

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Corrollary: After T iterations of F-RG

$$\frac{1}{|\text{honest}|} \sum_{i \in \text{honest}} \left\| x_i^T - \bar{x}_h^T \right\|^2 \leq \big(1-\gamma(1-\delta)\big)^T \frac{1}{|\text{honest}|} \sum_{i \in \text{honest}} \left\| x_i^0 - \bar{x}_h^0 \right\|^2$$

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$$\left\| \bar{x}_h^T - \bar{x}_h^0 \right\|^2 \leq \frac{4\delta}{\gamma(1-\delta)^2} \frac{1}{|\text{honest}|} \sum_{i \in \text{honest}} \left\| x_i^0 - \bar{x}_h^0 \right\|^2$$

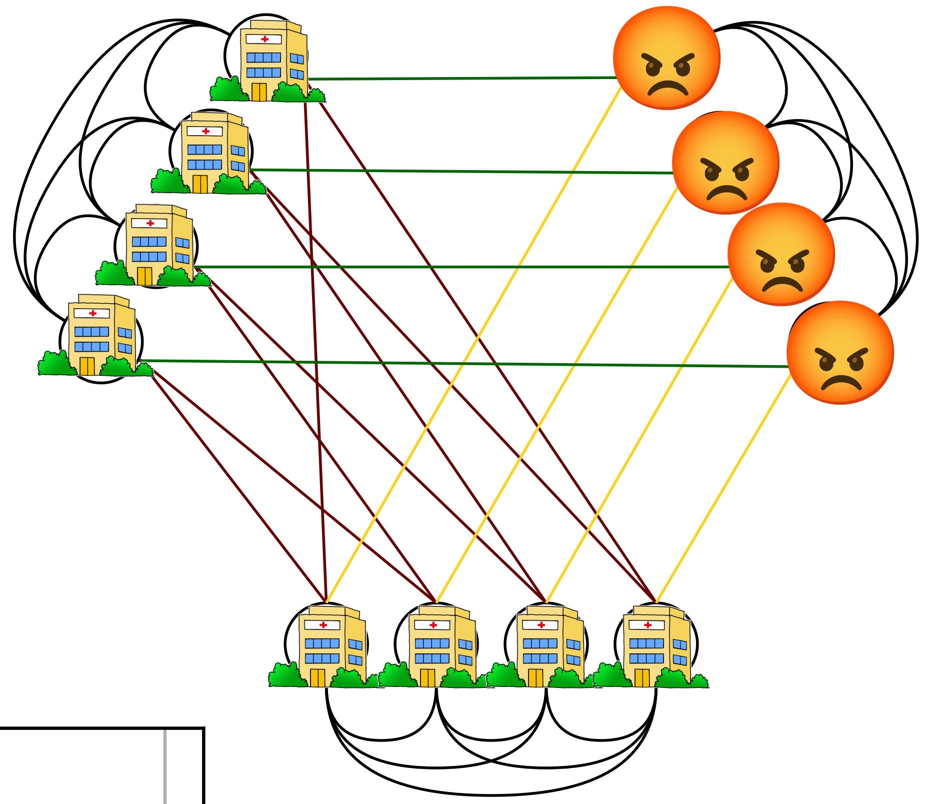
F-RG recovers existing algorithms

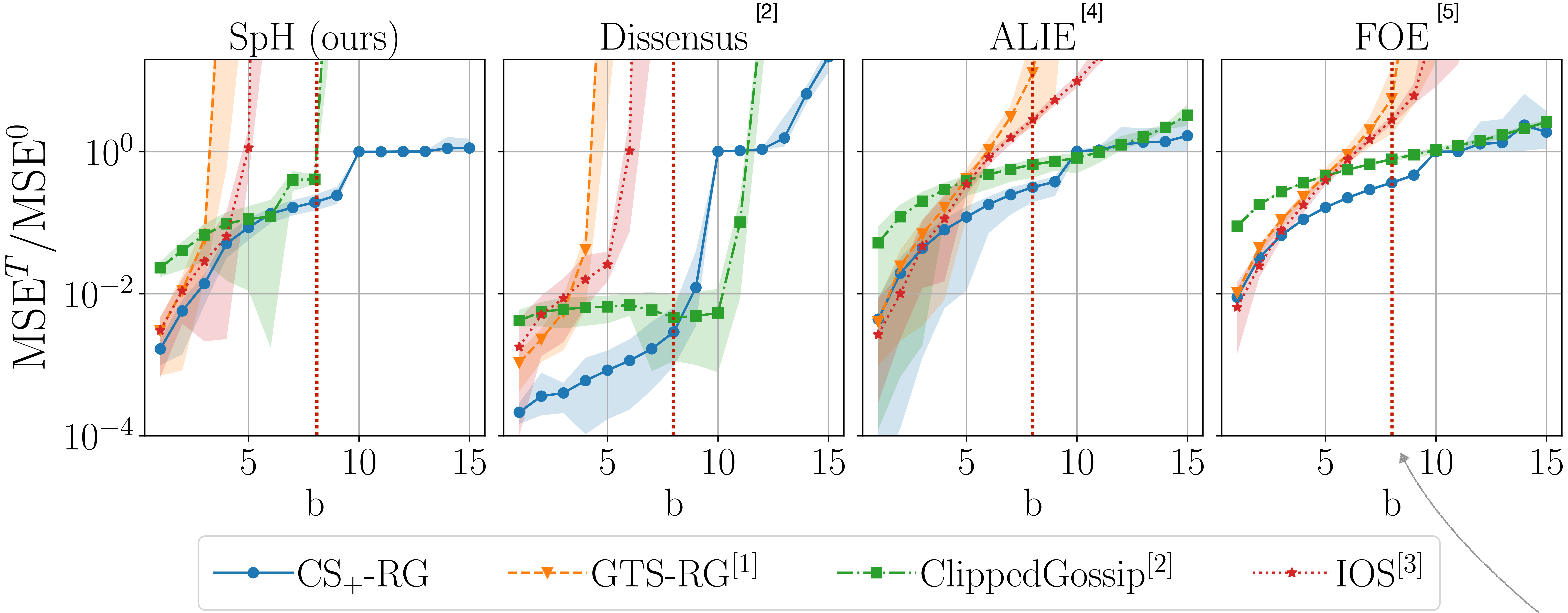
- Trimming + F-RG corresponds, in fully connected graphs, to *Nearest Neighbor Averaging* [1]
- Clipping + F-RG with another *oracle* clipping threshold recovers *ClippedGossip* [2] (w. $\rho = 4$)

[1] Robust collaborative learning with linear gradient overhead, Farhadkhani et al., ICML 2023

[2] Byzantine-Robust Decentralized Learning via ClippedGossip, He et. al. arxiv 2022

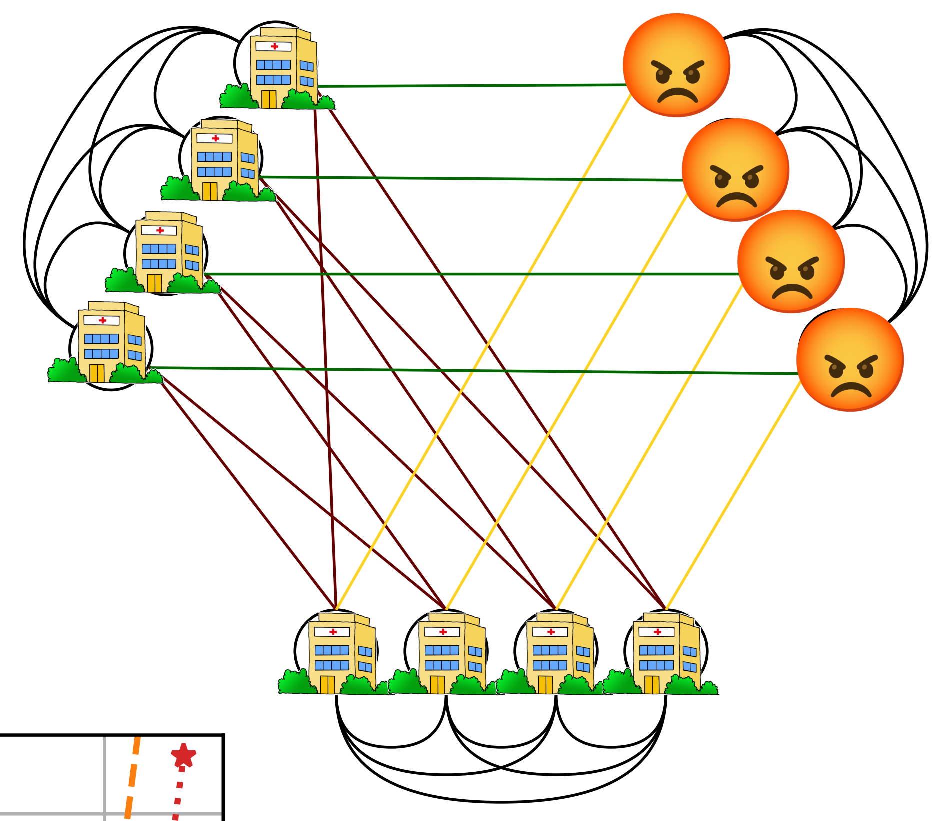
Experiments - communication only

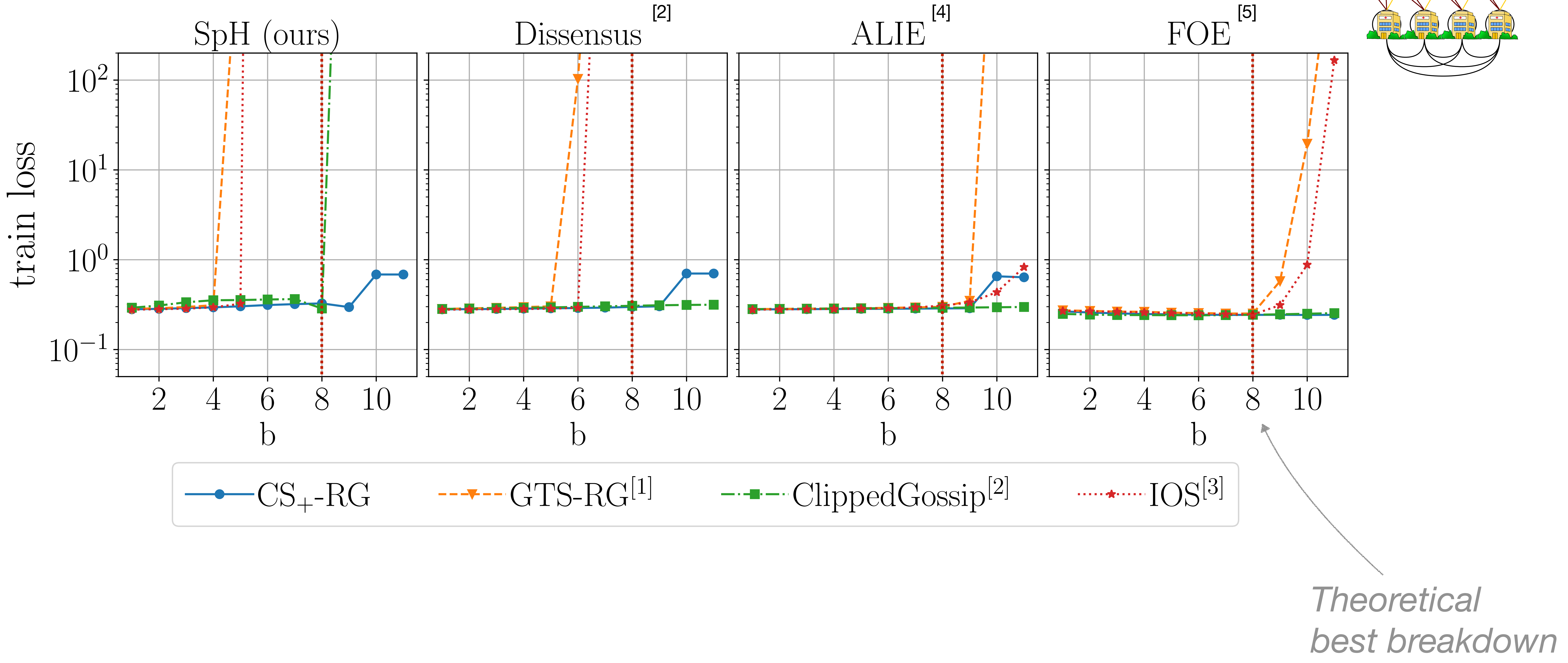




Theoretical best breakdown

Experiments - CNN on MNIST





More in the paper

- ☑ Convergence for local SGD steps + communication with F-RG
- ☑ A new attack that builds on the spectral properties of the graph
- ☑ Experiments

[1] Robust collaborative learning with linear gradient overhead, Farhadkhani et al., ICML 2023

[2] Byzantine-Robust Decentralized Learning via ClippedGossip, He et. al. arxiv 2022

[3] Byzantine-resilient decentralized stochastic optimization with robust aggregation rules, Wu et. al. IEEE tsp 2023

[4] A little is enough: Circumventing defenses for distributed learning, Baruch et. al. NeurIPS 2019

[5] Fall of empires: Breaking byzantine tolerant SGD by inner product manipulation, Xie et. al., UAI, 2020

Experiments - communication w. Erdos Renyi