Structural Characteristics of Wireless Sensor Networks

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Presentation Outline

- **Introduction and Motivation**
- Related work
- Work on data gathering sensor networks
  - A heterogeneous sensor network
  - Single hopping or multi-hopping in heterogeneous sensor networks?
  - A hybrid mode of communication
  - Single hopping or multi-hopping in homogeneous sensor networks?
- Future directions
- Conclusions

Introduction and Motivation

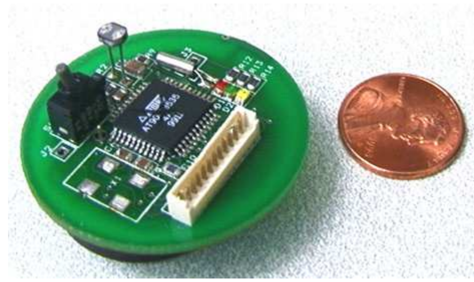

Figure 1: A Berkeley Mote

- Military interest and Smart Dust Project
- Tiny, low-cost wireless nodes for monitoring a phenomenon of interest
- A single central base station (many-to-one data flow)
- Military: surveillance, target detection, monitoring forces, etc.
- Civilian: forest fire detection, habitat monitoring, etc.
- Commercial: precision agriculture, intrusion detection, inventory control, etc.

Motivation

Two main classes of sensor networks

- Data gathering sensor networks
  - E.g. Temperature monitoring in buildings, ecological monitoring in forests, etc.
  - Notion of a data gathering cycle
  - Possibility of in-network data aggregation and clustering, e.g. acoustic sensing in forests
- Event detection sensor networks
  - E.g. Intrusion detection, Forest fire detection etc.
  - Events of interest are rare
  - Latency and idle listening are important issues

Motivation (contd.)

Our focus:

- Data gathering sensor networks
- Heterogeneous sensor networks
  - Better scalability
  - Suitable for clustering and data aggregation
  - Account for: Many-to-one communication paradigm and non-uniform energy drainage
  - Guarantee: Connectivity and coverage, System lifetime
  - Determine: Node densities, battery energy and mode of communication

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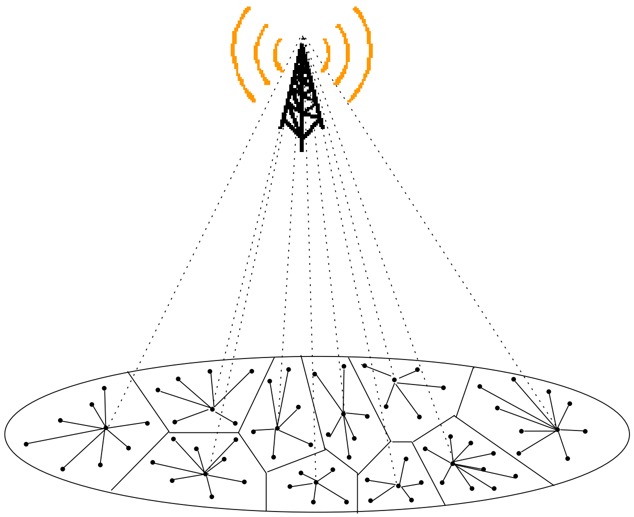
Related Work

Data gathering networks (homogeneous nodes)

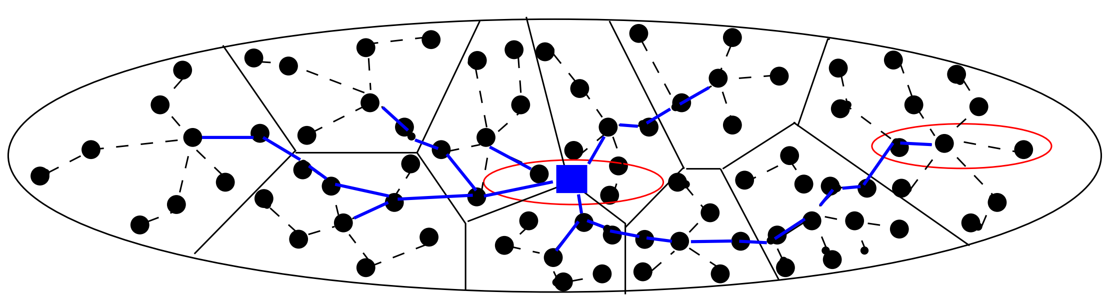
- **LEACH**, Heinzelman et al.
  - Clustering, data aggregation at the cluster heads
  - Remote base station
  - Single hopping in cluster and to the base station
  - Periodic cluster head rotation for load balancing
  - What is the optimum number of cluster heads?
  - All nodes require complex hardware $\Longrightarrow$ scalability issues



Related Work (contd.)

Data gathering networks (homogeneous nodes)

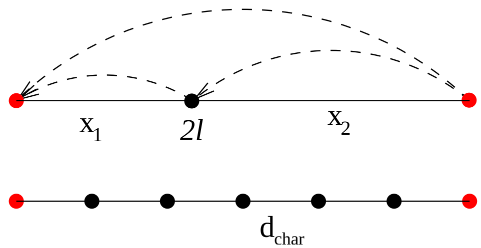
- Bandyopadhyay and Coyle, Purdue ECE
  - Clustering, data aggregation at the cluster heads
  - Base station at the center
  - Multi-hopping in cluster, and to the base station
  - Minimize the total network-wide energy expenditure
  - What is the optimum number of cluster heads?
  - Hot Spots around the base station and the cluster heads



Related Work (contd.)

Realistic model for energy consumption

- Model for energy consumption in a sensor node, Shih et al.
  - Transmission $l + \mu x^k$, reception l, idle mode energy l
- Consequences of the above energy model, Bhardwaj et al.
  - Routing implications due to l
    - Trade-off: Routing overheads ($2l$) versus multi-hop gain ($\mu(x_1 + x_2)^k > \mu {x_1}^k + \mu {x_2}^k$)



    - Optimum inter-hop distance, d_{char},

$$d_{char} = \left(\frac{2l}{\mu(k-1)} \right)^{1/k}$$

    - Only for linear topology
  - MAC implications due to l, need for synchronization

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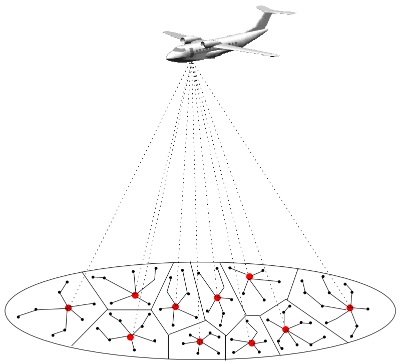
A Heterogeneous Sensor Network[a][b]



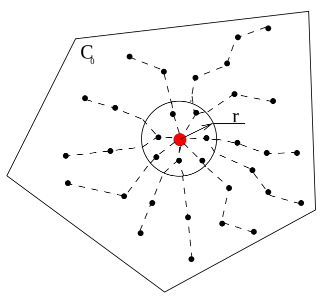
- Two types of nodes, type 0 (sensors) with intensity λ_0, and type 1 (cluster heads) with intensity λ_1
- Nodes differ in hardware cost α_i, and battery energy E_i
- Multi-hopping in cluster (r), single hopping to the remote base station (H), $H >> r$
- Require network connectivity and sensing coverage of the region
- Objective: Minimize system cost, ensure lifetime of T cycles

[a] V. Mhatre, C. P. Rosenberg, D. Kofman, R. R. Mazumdar, and N. B. Shroff. A minimum cost surveillance sensor network with a lifetime constraint. To appear in *IEEE Transactions on Mobile Computing* 2004.

[b] V. Mhatre, C. Rosenberg, D. Kofman, R. Mazumdar, and N. Shroff. Design of surveillance sensor grids with a lifetime constraint. In proc. of *1st European Workshop on Wireless Sensor Networks (EWSN), Berlin, Germany*, Jan 2004.

A Heterogeneous Sensor Network (contd.)

- Voronoi cell formation
- Hot spots around cluster heads due to multi-hopping load
- Lifetime: Critical nodes and cluster heads expire simultaneously

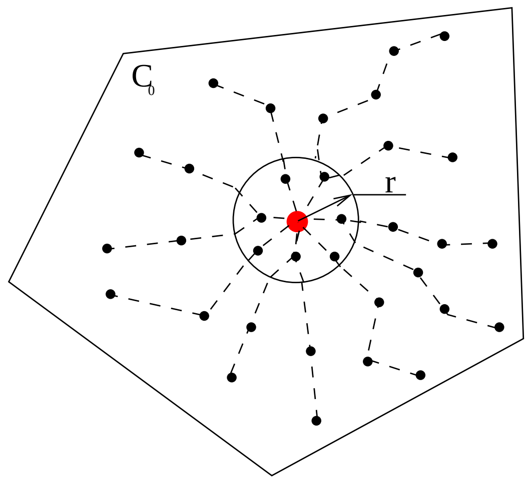


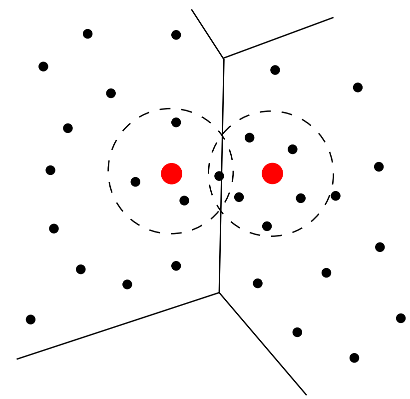
$$
\begin{aligned}
\text{minimize} \quad & \lambda_0(\alpha_0 + \beta E_0) + \lambda_1(\alpha_1 + \beta E_1) \\
\text{subject to} \quad & \lambda_0 + \lambda_1 \geq a \\
& \frac{E_1}{P_1} = \frac{E_0}{P_0} \geq T
\end{aligned}
$$

- To compute P_0 and P_1, i.e., energy spent per cycle

A Heterogeneous Sensor Network (contd.)

$$P_0 = E_0^t + P_0^r, \quad P_1 = \mathbf{E}[N_v](E_0^r + E_f) + E_1^t$$





$$\mathbf{E}[N_v] = \frac{\lambda_0}{\lambda_1}, \quad \mathbf{E}[N_v(r)] = \frac{\lambda_0}{\lambda_1}(1 - e^{-\lambda_1 \pi r^2})$$

$$\begin{aligned} P_0^r &= (E_0^r + E_0^t)\left(\frac{\mathbf{E}[N_v] - \mathbf{E}[N_v(r)]}{\mathbf{E}[N_v(r)]}\right) \\ &= (E_0^r + E_0^t)\left(\frac{e^{-\lambda_1 \pi r^2}}{1 - e^{-\lambda_1 \pi r^2}}\right) \end{aligned}$$

A Heterogeneous Sensor Network (contd.)

- Approximation: $\lambda_0 >> \lambda_1$, since $H >> r$ and $\alpha_1 >> \alpha_0$

$$\lambda_1 = \left(\frac{1}{\pi r^2}\right) \log\left(1 + \frac{\lambda_0 \pi r^2}{c} + \sqrt{\left(1 + \frac{\lambda_0 \pi r^2}{c}\right)^2 - 1}\right), \text{ and } \lambda_0 = a$$

- λ_1 from cost minimization, λ_0 from connectivity-coverage

- Use λ_0 and λ_1 to obtain E_0 and E_1

- For $k = 2$ (line of sight) and $\mu r^k >> l$

$$\lambda_1 = \frac{\sqrt{\lambda_0}}{\sqrt{\frac{\pi}{4}\left(H^2 + \frac{(\alpha_1 - \alpha_0)}{\beta T \mu}\right)}}$$

- Accounted for hot spots, node heterogeneity, lifetime constraint, radio model, etc.

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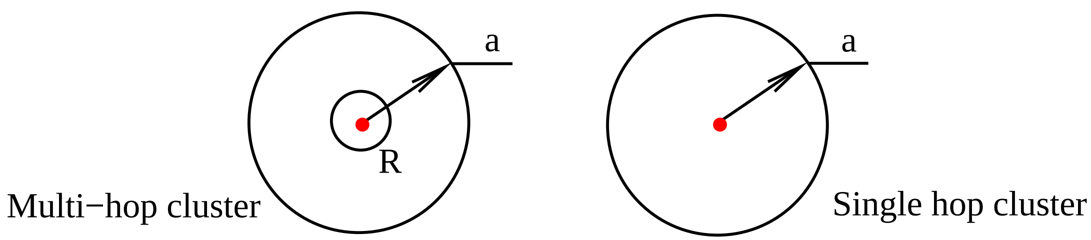
Single hopping or multi-hopping in heterogeneous sensor networks?[a]

- Single hopping or multi-hopping? If multi-hopping, with what communication radius?
- Sensing radius and communication radius are different
- Number of sensors, n_0, given (sensing requirements)
- Optimize over no. of cluster heads n_1, and communication radius R



$$A^2 = n_1 a^2$$

$$E_0^m = T\left(\frac{A^2(2l + \mu R^k)}{n_1 R^2} - l\right), \quad E_0^s = T\left(l + \frac{\mu A^k}{{n_1}^{\frac{k}{2}}}\right)$$

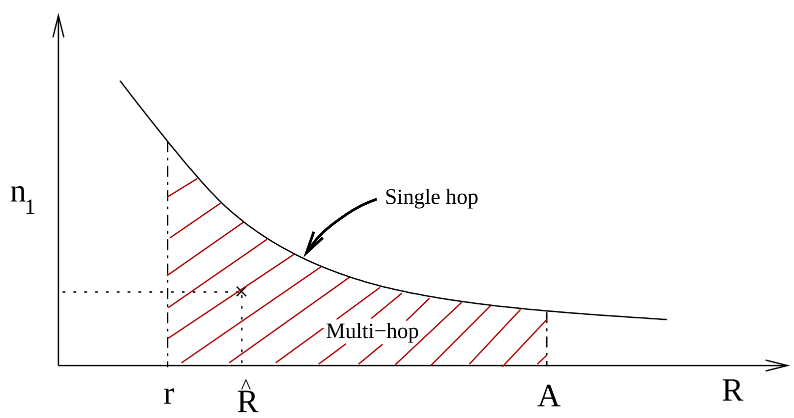
[a] V. Mhatre and C. Rosenberg. Design guidelines for wireless sensor networks: Communication, clustering and aggregation. In *Ad Hoc Networks Journal, Elsevier Science*, 2003.

Single hopping or multi-hopping in heterogeneous sensor networks? (contd.)

$$\begin{aligned} \text{minimize} \quad & f_m(\bar{y}) = n_0(\alpha_0 + \beta E_0) + n_1(\alpha_1 + \beta E_1) \\ \text{subject to} \quad & g_1(\bar{y}) = n_1 R^2 - A^2 \leq 0 \\ & g_2(\bar{y}) = r - R \leq 0 \\ & g_3(\bar{y}) = R - A \leq 0 \end{aligned}$$

$$r = A\sqrt{\frac{1}{n_0}\log\left(\frac{n_0}{\epsilon}\right)}$$

Single hopping is a special case of multi-hopping when $g_1(\bar{y}) = 0$



Single hopping or multi-hopping in heterogeneous sensor networks? (contd.)

Solution:

- Unconstrained minimization, check for feasibility

$$\hat{R} = \left(\frac{4l}{\mu(k-2)}\right)^{1/k}, \qquad N_m(\hat{R}) = \left(\frac{n_0\beta T A^2(2l+\mu\hat{R}^k)}{\hat{R}^2(\alpha_1+\beta T(l'+\mu' H^{k'}))}\right)^{\frac{1}{2}}$$

- Else, choose the one with lower cost among
  - Multi-hopping with $R = r$, and $N_m(r)$, check for feasibility
  - Single hopping

$$N_s = \left(\frac{n_0 k\beta T\mu A^k}{2(\alpha_1+\beta T(l'+\mu' H^{k'}))}\right)^{\frac{2}{k+2}}$$

NOTE: $\hat{R}$ versus d_{char}, 2-D hotspot versus 1-D hotspot

$$d_{char} = \left(\frac{2l}{\mu(k-1)}\right)^{1/k}$$

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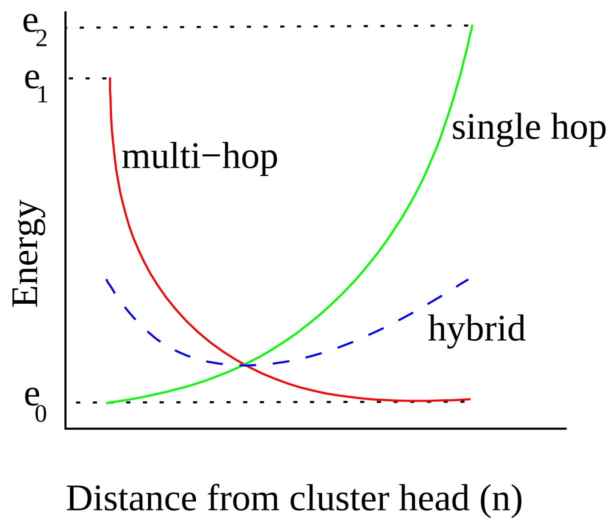
A hybrid mode of communication



- Worst case load determines lifetime
- Single hop mode: load on farthest nodes
- Multi-hop mode: load on nearest nodes
- Hybrid mode: role rotation, uniform energy drainage pattern
- Require power control capabilities at all the nodes

A hybrid mode of communication (contd.)

Working of the scheme

- Nodes use single hopping for ϕT cycles and multi-hopping for $(1-\phi)T$ cycles, $0 \leq \phi \leq 1$
- Energy load for both cases is convex in shape $\Longrightarrow$ weighted load is also convex
- Choose ϕ so that the endpoints of the hybrid curve are at the same height (min-max)
- With this ϕ, obtain expression for E_0 and proceed with the minimization problem
- Dependence on k, A

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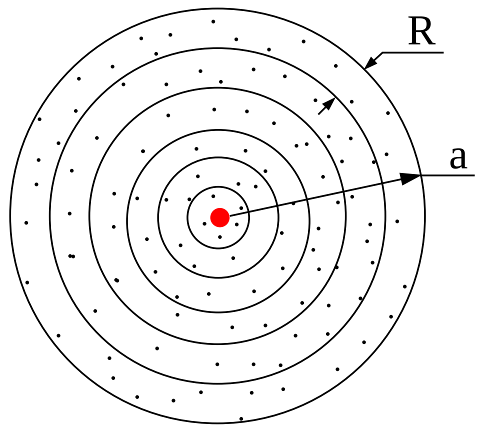
Single hopping or multi-hopping in homogeneous sensor networks?[a]

- Heterogeneous network $\Longrightarrow$ hot spots, but homogeneous networks role rotation possible
- Homogeneous single hop network: LEACH $\Longrightarrow$ Homogeneous multi-hop network: Multi-hop LEACH (M-LEACH)
- Fixed communication radius R
- Cluster head rotation like LEACH ensures
  - Cluster heads are relieved
  - Critical nodes are relieved
  - Uniform energy drainage pattern
- For connectivity in multi-hopping, $R \geq r$

$$r = A\sqrt{\frac{1}{n_0}\log\left(\frac{n_0}{\epsilon}\right)}$$

[a] V. Mhatre and C. Rosenberg. Homogeneous vs heterogeneous sensor networks: A comparative study. To appear in *International Conference on Communications (ICC 2004)*, Paris, France.

Single hopping or multi-hopping in homogeneous sensor networks? (contd.)



$$P(n_1, R) = n_1(l' + \mu' H^{k'}) + n_0(l + \mu R^k) + n_1 \left(\frac{n_0}{n_1}\right)(l + E_f) +$$
$$n_1 \left\{ \sum_{n=1}^{a/R} (2l + \mu R^k) n_0 \frac{(a^2 - n^2 R^2)}{A^2} \right\}$$

Eliminating n_1,

$$P(a, R) = \frac{\theta A^2}{a^2} + n_0(2l + E_f + \mu R^k) + \frac{n_0(2l + \mu R^k)(4a + R)(a - R)}{6aR}$$

Minimize as a function of R and a with $r \leq R \leq a$

Numerical Results (contd.)

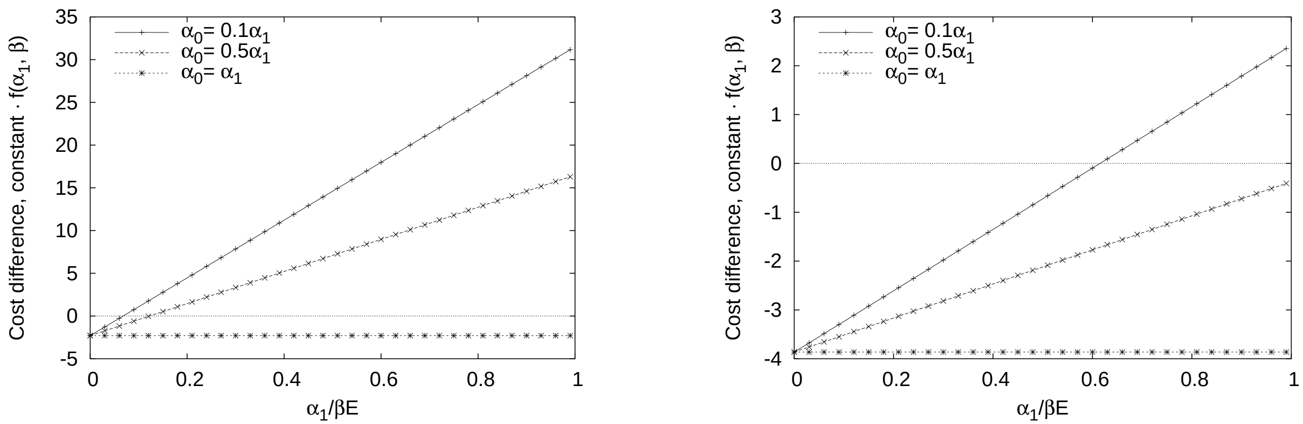
	Scenario I	Scenario II
No. of sensor nodes, n_0	100	10^5
Radius of the region, A	**56m**	**1000m**
Distance from the base station, H	**125m**	**2000m**
Length of each packet	525 bytes	525 bytes
μ (in-cluster)	$42\ nJ/m^2$	$5.46\ pJ/m^4$
μ' (to base station)	$5.46\ pJ/m^4$	$5.46\ pJ/m^4$
k (in-cluster)	**2**	**4**
k' (to base station)	4	4
$l = l'$	$0.21\ mJ$	$0.21\ mJ$
E_f (per packet)	$0.021 mJ$	$0.021 mJ$

Scenario I	n_1	P	a	R
LEACH	2	5×10^{-4}J	-	-
M-LEACH	3	6.78×10^{-4}J	**32.8**	**32.8**

Scenario II	n_1	P	a	R
LEACH	16	21.53×10^{-3}J	-	-
M-LEACH	2	5.73×10^{-3}J	**707m**	**70m**

A rule of thumb: a versus R, single hopping or multi-hopping

Homogeneous or heterogeneous?



(a) Scenario I (b) Scenario II

Figure 2: Cost difference between the optimum homogeneous and the optimum heterogeneous networks as a function of hardware cost

- Optimum cases for Scenario I: Homogeneous network is LEACH, heterogeneous network uses single hopping
- Optimum cases for Scenario II: Homogeneous network is M-LEACH ($R = 70m$), heterogeneous network uses multi-hopping ($\hat{R} = 93m$)

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Future Directions

Ideal MAC

- Assumption of ideal MAC gives benchmark results
- From ideal MAC to non-ideal MAC
  - Perfect synchronization during multi-hopping
  - No idle energy expenditure
  - No packet collisions
  - Objective: To design a near-ideal MAC
- Repeat the cost-minimization analysis for the non-ideal MAC

Directional antennas

- Energy gains due to directionality
- MAC and routing issues with directional antennas

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Conclusions

- Studied the design and dimensioning problem in heterogeneous sensor networks
- Obtained results for clustering, mode of communication and battery energy
- Proposed and studied a hybrid mode of communication for heterogeneous sensor networks
- Proposed and studied a multi-hop extension of LEACH called M-LEACH
- Future directions: non-ideal MAC, directional antennas on sensor nodes and more...

Questions, Comments, Suggestions..

Thank You!!

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