Molecular Communication Using Timing & Payload

Christopher Rose[1]
I. Saira Mian[2]

[1]Rutgers University, WINLAB
[2] University College London

WINLAB IAB
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Biology-Inspired Molecular Communication

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Intriguing Science & Engineering

LOTS of recent work in the area

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It's a Snake!

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Is there a

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Unifying Elephant?

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Framework
+
Fundamental Limits
+
Applications

A (stab at a) Unified Framework

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Energy Use Is Fundamental

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Mean first passage time is key

Today's Talk

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Timing Channel Abstraction

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Information-Theoretic Modeling

(for Roy, Narayan, Predrag, Waheed and Anand)

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Energy

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Bounds

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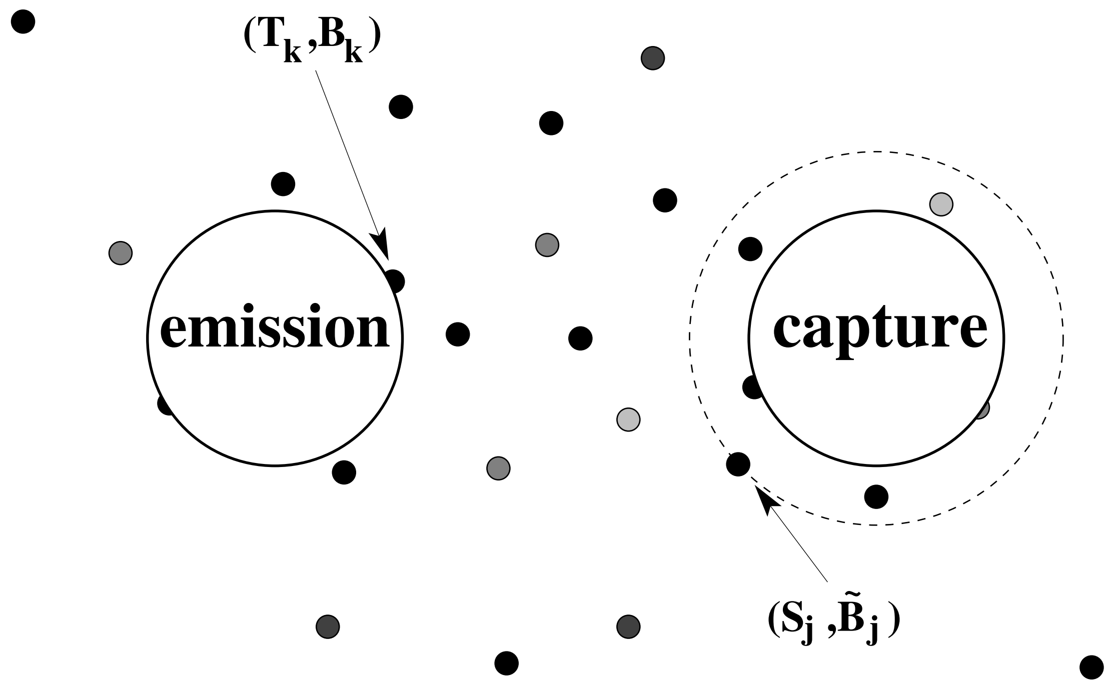
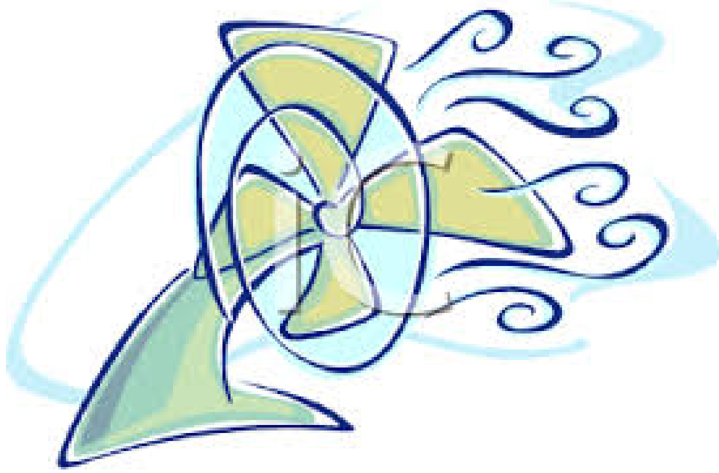
Ball Park Calculations

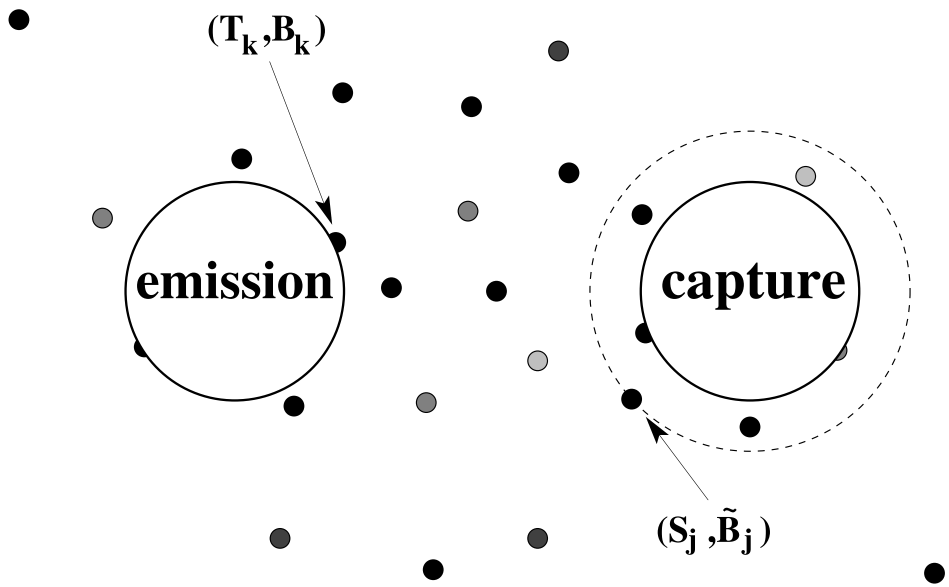
Diffusion Cartoon



Coding $\rightarrow$ **Emission** $\rightarrow$ **Transport** $\rightarrow$ **Capture** $\rightarrow$ **Decoding**

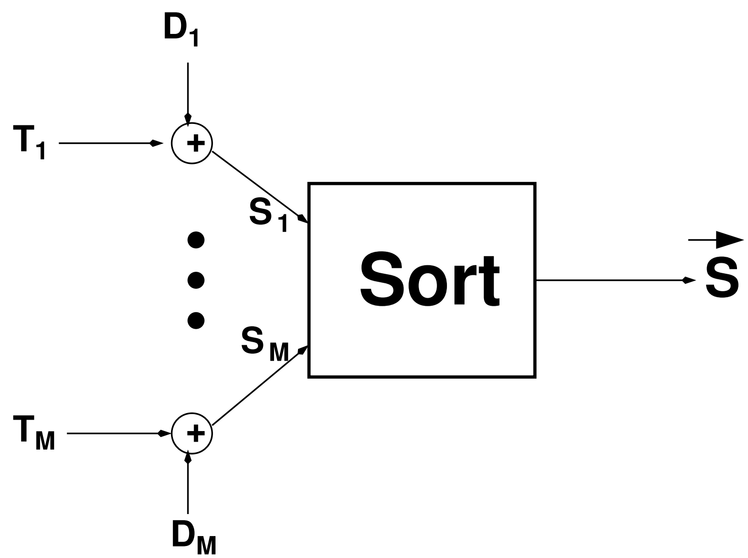
Diffusion with Drift Cartoon





Coding → Emission → Transport → Capture → Decoding

Mathematical Abstraction



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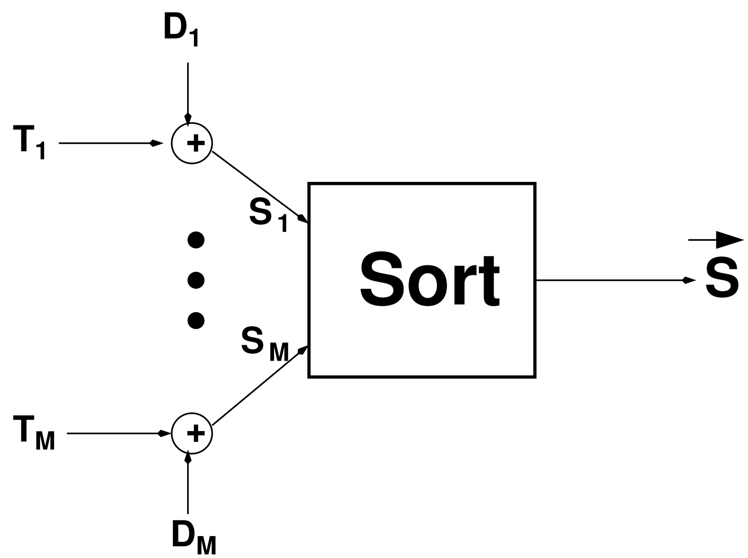

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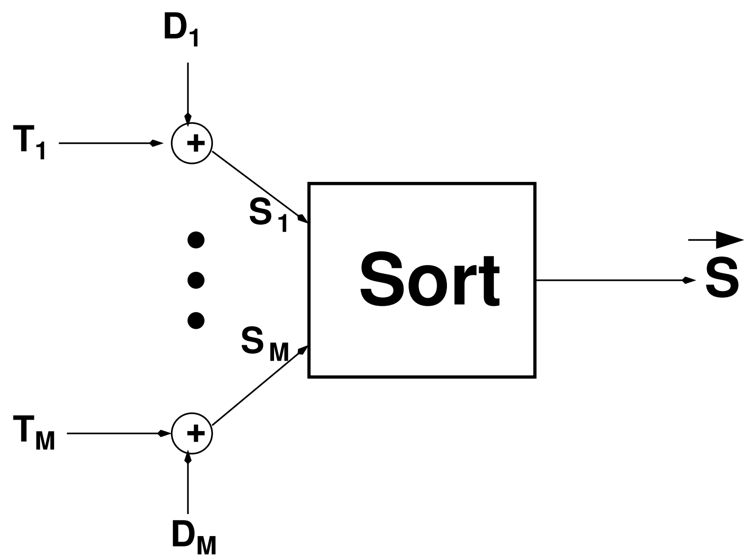

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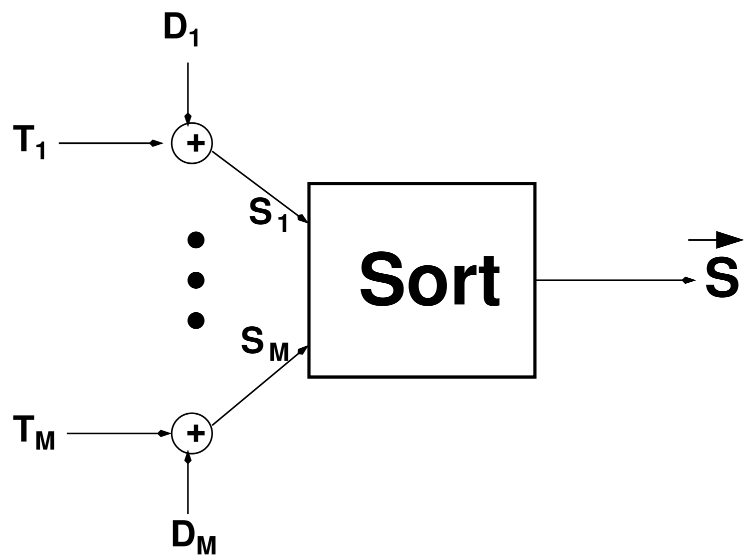

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First passage time: $E[D] = 1/\mu$

Mutual Information

M tokens on an interval $\tau(M)$

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$$\begin{aligned} I(\mathbf{S};\mathbf{T}) &= h(\mathbf{S}) - h(\mathbf{S}|\mathbf{T}) \\ &= h(\mathbf{S}) - h(\mathbf{D}) \\ &\leq M\left(h(S) - h(D)\right), \qquad \text{(i.i.d. } \mathbf{D}\text{)} \end{aligned}$$

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Consider Only Hypersymmetric $\mathbb{T}$

$$\max_{f_\mathbf{T}} I(\vec{\mathbf{S}}, \mathbf{T})$$

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$f_{\mathbf{T}}()$ hypersymmetry $\rightarrow$ $f_{\mathbf{S}}()$ hypersymmetry

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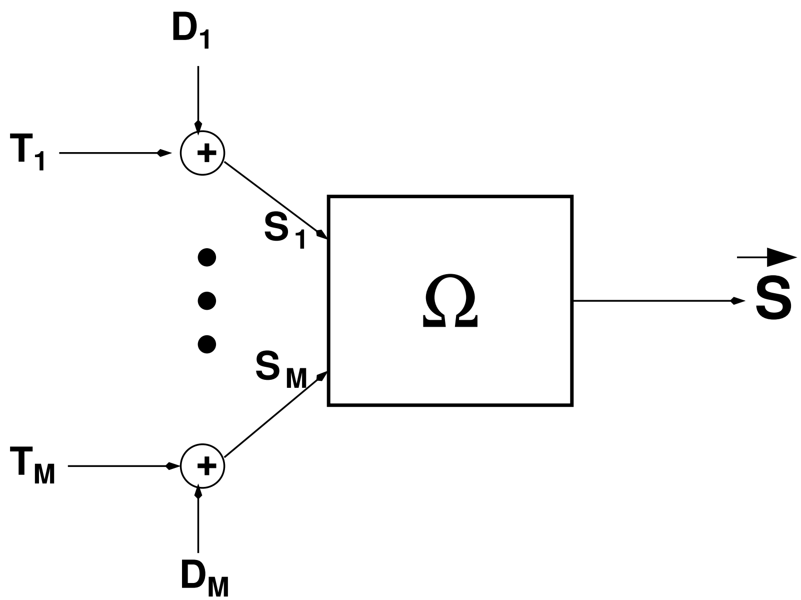
$$\boldsymbol{h(\vec{\mathbf{S}}) = h(\mathbf{S}) - \log M!}$$

Channel Redux



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$$\boldsymbol{I(\vec{\mathbf{S}}; \mathbf{T}) = \underbrace{h(\mathbf{S}) + H(\Omega|\vec{\mathbf{S}}, \mathbf{T})}_{\text{The Money!}} - \underbrace{(\log M! + h(\mathbf{D}))}_{\text{constant}}}$$

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$H(\Omega|\vec{\mathbf{S}}, \mathbf{T})$ maximized by correlated $\mathbf{T}$

$$H(\Omega|\vec{\mathbf{S}}, \mathbf{T}) = \log M!$$

identical launch times $T_1 = T_2 = \cdots = T_M$

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Channel Use Formalities Handwaving


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PUNCHLINE

$$\rho \equiv \frac{M}{\text{launch epoch}}$$

all ok if mean first passage time $E[D] < \infty$

Capacity Per Token

Define:

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(it's kinda the timing channel's "Gaussian")

Timing-Only Bits/Joule

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Theorem 1.

$$\mathcal{C}_T \geq \frac{1}{c_0}\left(\log \chi + \underbrace{e^{-\frac{1}{\chi}}\sum_{k=2}^{\infty}\left(\frac{1}{\chi}\right)^k (k\chi - 1)\frac{\log k!}{k!}}_{\text{per token order uncertainty}}\right)$$

Payload-Only Bits/Joule

Theorem 2.

$$\mathcal{C}_P = \frac{B}{c_1 + \Delta c_1 \left(B + \min_{\mathbf{t}} \frac{1}{M} H(\Omega | \vec{\mathbf{S}}, \mathbf{t}) \right)}$$

Lemma 3.

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Payload + Timing Bits/Joule Lower Bound

Theorem 4.

$$\mathcal{R}_{P+T} \approx \frac{\log\left(1+\frac{\chi M}{e}\right)+B}{c_1+\Delta c_1\left(B+\underbrace{e^{-\frac{1}{\chi}}\sum_{k=2}^{\infty}\left(\frac{1}{\chi}\right)^k(k\chi-1)\frac{\log k!}{k!}}_{\textit{per token order uncertainty}}\right)}$$

where $\mathcal{R}_{P+T} \leq \mathcal{C}_{P+T}$.

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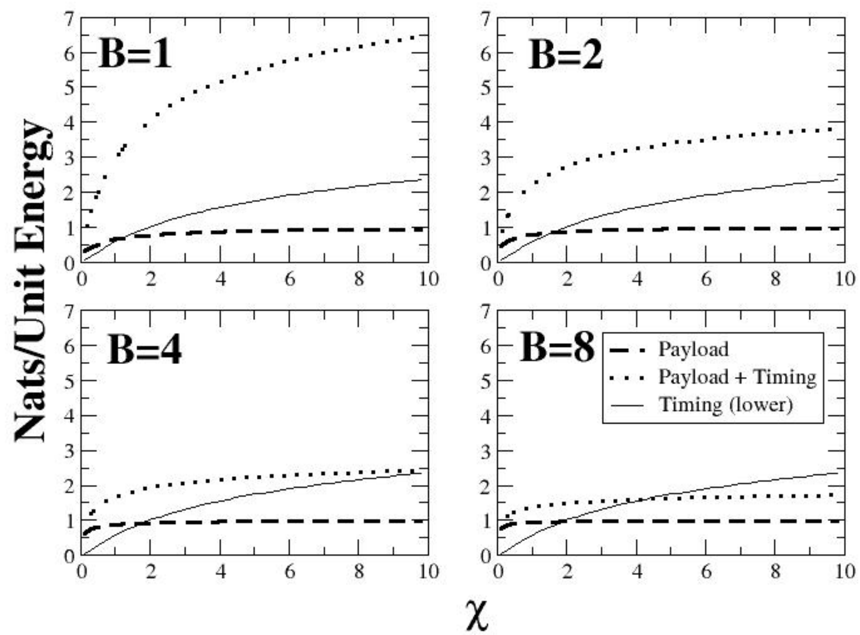
ASIDE: dumb header ($\frac{1}{M}\log M!$): $\mathcal{C}_{P+T} \to 0$ in M

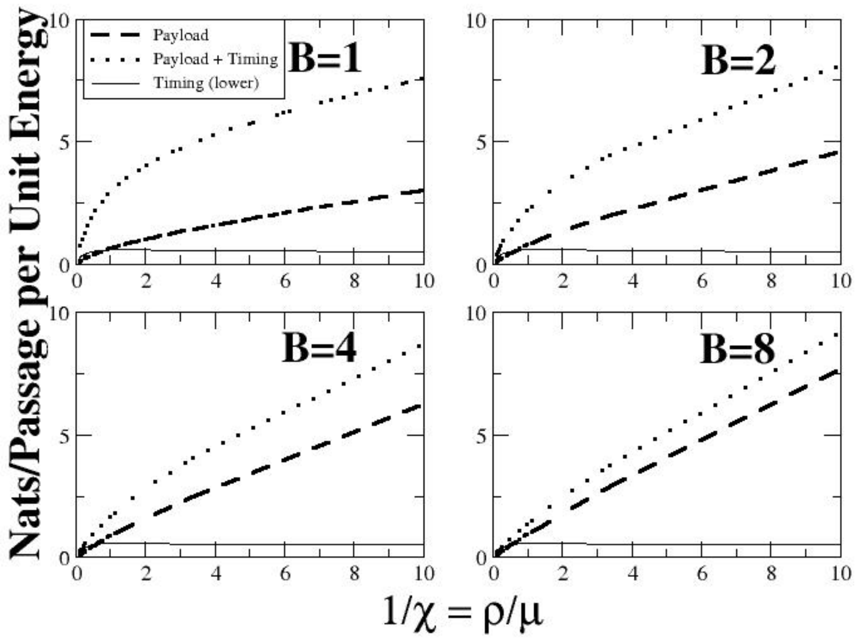
Info per Unit Energy



$\chi \leftrightarrow$ **passage rate per launch rate**

$c_0 = 1$**,** $c_1 = 0$**,** $\Delta c_1 = 1$

Info per Passage per Unit Energy



$\frac{1}{\chi} \leftrightarrow$ **launch rate per passage rate**

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Play Time Setup

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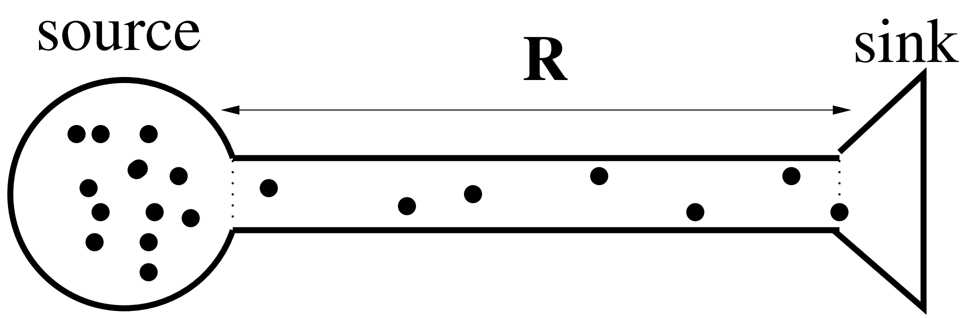

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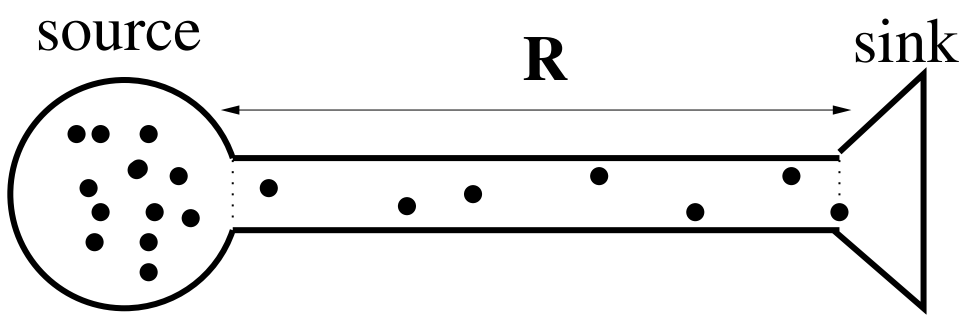

Protein Token Construction $4B$**ATP** $= 3.2B \times 10^{-19} J$

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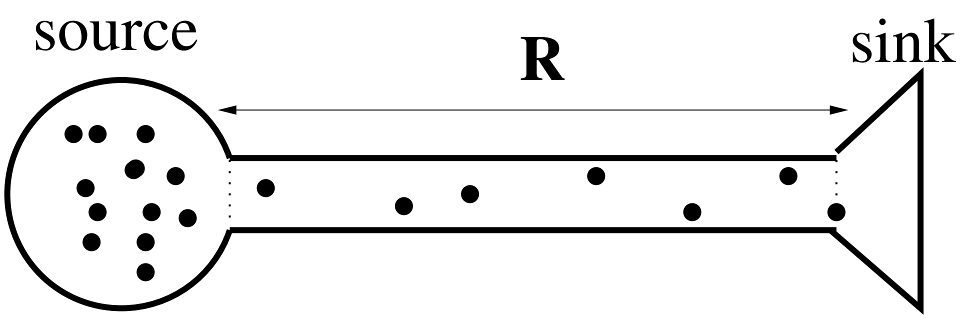

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$\approx 10^{-5} m^2/s$ in air

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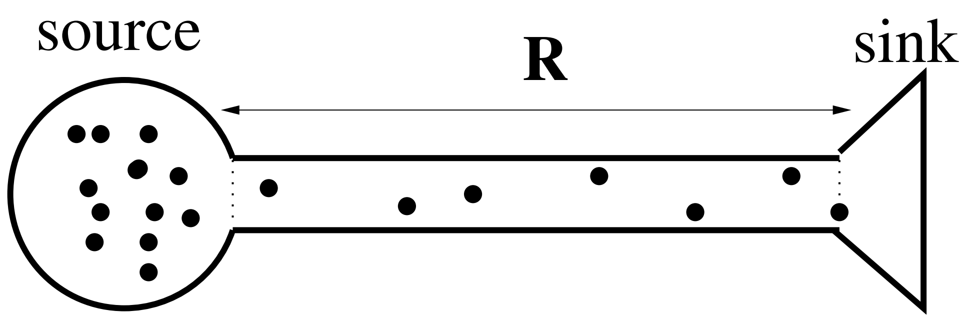

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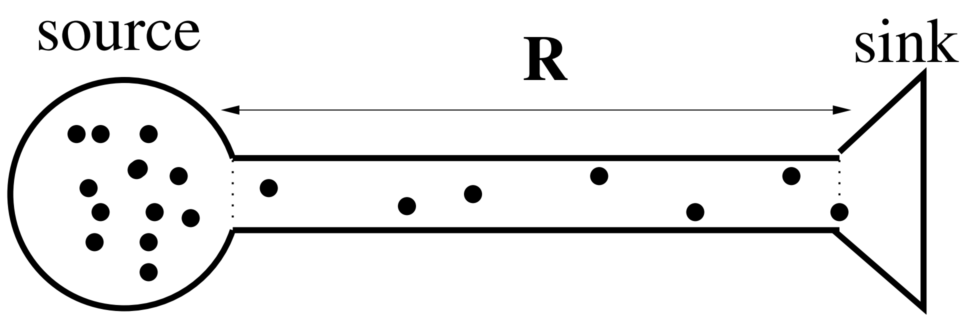

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Across a table ($1m$**):** $E[D] \approx 14hrs$ (need fan)

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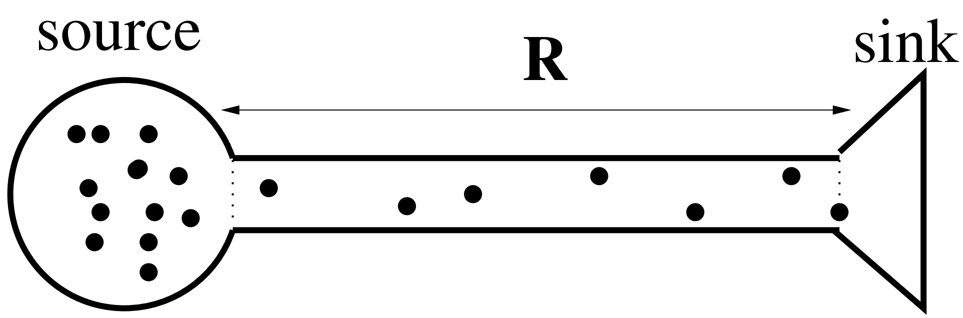

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Across a synapse ($20nm$**):** $E[D] = 0.2 \mu s$

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Tantalizing

Suppose token construction energy cost $\ll$ fan energy cost

$1mg$ RNA per second $\Rightarrow 3.6 \times 10^{18}$ bits/sec

Appropriately Awed Response

Molecular Communication

Molecular Communication

Timing + Payload Framework

Molecular Communication

Timing + Payload Framework

Lower Bounds

Molecular Communication

Timing + Payload Framework

Lower Bounds

Need Bit Efficiency?

Molecular Communication

Timing + Payload Framework

Lower Bounds

Need Bit Efficiency?

Slow release with timing &/or small payload

Molecular Communication

Timing + Payload Framework

Lower Bounds

Need Bit Efficiency?

Slow release with timing &/or small payload

Need Rate Efficiency?

Molecular Communication

Timing + Payload Framework

Lower Bounds

Need Bit Efficiency?

Slow release with timing &/or small payload

Need Rate Efficiency?

Fast release with payload + timing or large payload

Molecular Communication

Timing + Payload Framework

Lower Bounds

Need Bit Efficiency?

Slow release with timing &/or small payload

Need Rate Efficiency?

Fast release with payload + timing or large payload

Scary Efficiencies and Rates

Molecular Communication

Timing + Payload Framework

Lower Bounds

Need Bit Efficiency?

Slow release with timing &/or small payload

Need Rate Efficiency?

Fast release with payload + timing or large payload

Scary Efficiencies and Rates

(beware transport latency)