Designing Intelligent Nano/Microbots: Synthetic Active Matter

1. Introduction to Synthetic Active Matter
2. Powering Active Particle and Fluid Motion
3. Collective Behavior of Autonomous Nano/Microbots

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Grand challenge in science: Mastering energy and information at the nano/microscale

Create technologies that rival those of living things:

Requires designing intelligent systems

Use free energy of chemical fuels to fabricate organized systems driven far from equilibrium
Intelligence requires:
- Information
- Ability to process (act on) information – information processor

Information: Gradient – Chemical, Light

Information processor: Self-powered object

Result of Information + Information Processing: Collective/Emergent behavior
E.g., Spatial and/or Temporal Assemblies

*Both* information and information processor require continuous input of energy

*Required design elements:*
- Autonomous movement through catalytic energy harvesting
- Control of directionality through chemical/light gradients
- Inter-bot communication via chemical signals
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APPLICATIONS OF AUTONOMOUS NANO/MICROBOTS

- Motors for nanomachines and biological cells
- Roving sensors
- Active delivery vehicles (versus passive diffusion)
- Patterns and arrays by directed deposition of materials
- Pumps and valves for nanofluidic and bio-chip devices
- Channel-less fluid flow

CATALYSIS IS THE ENGINE OF NANOTECHNOLOGY
Gradient-based Motion

External Fields

- Many types of fields: (magnetic, chemical, thermal, electric)
- Energy applied from external source
- Ensemble behavior of all particles


Self-generated Fields

- Catalytically generated fields: (chemical, thermal, electric)
- Energy harvested locally
- Particles move independently
- **Catalysis** and asymmetry

Powering Motion by Chemical Reactions

Consider the archetypal catalytic reaction: the hydrogenation of ethene to ethane.

\[
\text{H}_2\text{C}≡\text{CH}_2 + \text{H}_2 \xrightarrow{\text{catalyst}} \text{H}_3\text{C}—\text{CH}_3 \quad \Delta H = 135 \text{ kJ/mole}
\]

The enthalpy change corresponds to \(2.2 \times 10^{-19}\) Joules per turnover.

To move a spherical catalyst particle of radius 10 nm a distance of 100 nm in 1 second (i.e., a speed of 100 nm/sec)

Energy required = force \(\times\) distance

Force = \(6\pi\mu RV\) (Stokes Law)
where R is the radius of the sphere, V is the speed and \(\mu\) is the dynamic viscosity

In a viscous medium like water (dynamic viscosity \(\sim 10^{-3}\) Pa.sec), the energy required for the given movement is \(1.9 \times 10^{-24}\) Joules.

*This is 5 orders of magnitude smaller than the energy obtained in just 1 turnover in an archetypal catalytic alkene hydrogenation!* Turnover rate is also important. **Catalytic reactions are effective mechanisms for powering the autonomous movement of nano and micron-sized objects and even single molecules.**
Life at Low Reynolds Number

\[ \mathcal{R} = \frac{\text{Inertial Force}}{\text{Viscous Force}} \]

Forces at \( \mathcal{R} \ll 1 \)
- Viscosity (drag)
- Surface (interfacial tension)
- Diffusion (Brownian)
- Electrostatic (double-layer)
- \( F = ma \) is irrelevant

Scallop theorem: Propulsion by purely time-reversible reciprocal motion not possible

Designing Functional Nano/Microbots

Required Design Elements

• Movement Through Catalysis
• Cargo Loading, Transport, and Unloading
• Directional Movement Through Chemical Gradient (Chemotaxis)
• Emergent Collective Behavior Through Inter-Bot Communication via Chemical Signals

*Scientific American, May, 2009*
Platinum Blondes & Hot Rods

\[ 2\text{H}_2\text{O}_2(aq) \xrightarrow{\text{Pt/Au}} 2\text{H}_2\text{O}(l) + \text{O}_2(g) \]
Nanorod Synthesis

- Ag evaporation
- plating
- Aluminum oxide membrane
- Ag-filled Al$_2$O$_3$ membrane
- Free rods after etching

Mallouk et al.

- Electroplate Au and Pt
- HNO$_3$
- NaOH
Fabrication of Janus particles

Formation of monolayer

Hexane
Water
Glass slide

Ethanolic suspension of particles

Monolayer

Metal deposition

Monolayer
Cr evaporation
Au evaporation

PS
Au
Au/PS Janus particles
FESEM images of $1.5 \, \mu m$ polystyrene/gold Janus particles

Allows selective loading and delivery of cargo from each face
Rod Movement Experiments

- cover slip
- reaction mixture
- silicone spacer
- glass slide
- water drop

Observed from top by optical microscopy
Electrokinetic Propulsion

H₂O₂ \rightarrow fluid flow \rightarrow 2H^+ + 2e^- + H₂O₂

2H^+ + 2e^- + O₂ \rightarrow Pt \rightarrow e^- \rightarrow Au \rightarrow H^+ \rightarrow 2H₂O
Autonomous Moving Nanorods
(Real-Time)

2-μm Au/Pt rods in H₂O
… in 2.5% H₂O₂

real-time video at http://research.chem.psu.edu/axsgroup/

*First* demonstration of nano/micromotors powered by catalysis
*outside biological systems*
## RELATIVE SPEEDS

<table>
<thead>
<tr>
<th></th>
<th>Speed (km/h)</th>
<th>Body lengths per second</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cheetah</td>
<td>111</td>
<td>25</td>
</tr>
<tr>
<td>Human</td>
<td>37.5</td>
<td>5.4</td>
</tr>
<tr>
<td>Bacteria (flagellar)</td>
<td>1.5x10^-4</td>
<td>10</td>
</tr>
<tr>
<td>Au/Pt</td>
<td>5.8x10^-5</td>
<td>10</td>
</tr>
<tr>
<td>Brownian motion</td>
<td>6.6x10^-7</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Absolute speed limited by body size
Directionality Factor \( = \cos \theta \)

Net Forward \( (v_z) \) \( = \cos \theta \times d \)
Speed vs. Directionality

For 2.0 μm rods in 3.3% H₂O₂
## H₂O₂ Concentration Effects

<table>
<thead>
<tr>
<th>% H₂O₂</th>
<th>Average Speed (μm/s)</th>
<th>Directionality Factor</th>
<th>Net Forward (μm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.9</td>
<td>7.7 ± 0.9</td>
<td>0.78</td>
<td>6.60</td>
</tr>
<tr>
<td>3.3</td>
<td>7.9 ± 0.7</td>
<td>0.75</td>
<td>6.59</td>
</tr>
<tr>
<td>1.6</td>
<td>5.5 ± 0.6</td>
<td>0.65</td>
<td>3.84</td>
</tr>
<tr>
<td>0.33</td>
<td>5.0 ± 0.4</td>
<td>0.60</td>
<td>3.43</td>
</tr>
<tr>
<td>0.031</td>
<td>3.9 ± 0.5</td>
<td>0.19</td>
<td>0.92</td>
</tr>
<tr>
<td>pure H₂O</td>
<td>3.3 ± 0.5</td>
<td>0.01</td>
<td>0.04</td>
</tr>
</tbody>
</table>
WHAT DETERMINES O₂ PRODUCTION RATE?

1. Rate of diffusion of H₂O₂ to the catalyst surface

2. Rate of H₂O₂ decomposition -

   Depends on catalyst turnover rate and surface area

Faster Pt/Au motors incorporate carbon nanotubes (Wang)
Higher velocity due to higher rate of peroxide decomposition at the CNT-Pt segment
TEMPERATURE-MODULATED MOVEMENT

Thermally modulating and activating the motion

On-demand acceleration and slowing down

Pt-Au Nanomotors at room (A) and elevated (B)

High temperature Electrochemical Propulsion

Faster kinetics of the fuel redox processes and lower solution viscosity associated with the heat pulse.

Wang, Small 2009
DIRECTION OF MOTION

Moves Pt end forward: Excludes Bubble propulsion (momentum recoil)

Bubble Propulsion Catalytic Motors: Whitesides, Sanchez, Wang, Feringa
Electrokinetic Mechanism

At Pt: \[ H_2O_2 \rightarrow O_2 + 2H^+ + 2e^- \]

At Au: \[ H_2O_2 + 2H^+ + 2e^- \rightarrow H_2O \]

\[ i_{e^-} = i_{H^+} \]

\[ E = \frac{J_{H^+}}{\sigma} \]

\[ v = \frac{\zeta \varepsilon E}{\mu} \]

\( J \) = current density
\( \sigma \) = conductivity
\( E \) = electric field

*J. Am. Chem. Soc., 2006*
Measuring Current in Small Systems

- Pt/Au motor
- Interdigitated Array
  - baseline: <0.00001 A/m²
  - water: ~0.00001 A/m²
  - 0.6% H₂O₂: 0.27 A/m²
  - 3% H₂O₂: 0.53 A/m²

- Predicted Electric Field \( E = \frac{J}{\sigma} \)
  - \( J = 0.53 \text{ A/m}² \)
  - \( \sigma = 4.1 \text{ } \mu\text{S/cm} \)
  - \( E = 13.1 \text{ V/cm} \)

Allows Prediction of Speed and Direction of Motion For Different Bimetallic Pairs (Langmuir, 2006)
## Tracking Data for Bimetallic Nanorods in 5 wt % Aqueous H₂O₂ Solution

<table>
<thead>
<tr>
<th>Bimetallic Nanorod</th>
<th>Speed (μm/s)</th>
<th>Directionality</th>
<th>Leading end (observed)</th>
<th>Leading end (predicted)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rh-Au</td>
<td>23.8 ± 2.9</td>
<td>0.73 ± 0.15</td>
<td>Rh</td>
<td>Rh</td>
</tr>
<tr>
<td>Pt-Au</td>
<td>20.0 ± 3.8</td>
<td>0.84 ± 0.04</td>
<td>Pt</td>
<td>Pt</td>
</tr>
<tr>
<td>Pd-Au</td>
<td>15.3 ± 2.0</td>
<td>0.92 ± 0.05</td>
<td>Pd</td>
<td>Pd</td>
</tr>
<tr>
<td>Pt-Ru</td>
<td>30.2 ± 4.0</td>
<td>0.65 ± 0.11</td>
<td>Pt</td>
<td>Pt</td>
</tr>
<tr>
<td>Au-Ru</td>
<td>24.0 ± 2.0</td>
<td>0.90 ± 0.05</td>
<td>Au</td>
<td>Au</td>
</tr>
<tr>
<td>Rh-Pt</td>
<td>17.0 ± 3.0</td>
<td>0.79 ± 0.13</td>
<td>Rh</td>
<td>Rh</td>
</tr>
<tr>
<td>Rh-Pd</td>
<td>16.2 ± 1.8</td>
<td>0.84 ± 0.14</td>
<td>Rh</td>
<td>Rh</td>
</tr>
<tr>
<td>Pt-Pd</td>
<td>13.6 ± 2.3</td>
<td>0.63 ± 0.10</td>
<td>Pt</td>
<td>Pt</td>
</tr>
<tr>
<td>Ni-Au</td>
<td>4.75 ± 1.1</td>
<td>0.33 ± 0.12</td>
<td>Ni</td>
<td>Ni</td>
</tr>
</tbody>
</table>

*Langmuir, 2006*
Effect of Ethanol on the Catalytically Generated Current Between a Platinum and a Gold Electrode

<table>
<thead>
<tr>
<th>% Ethanol (v/v)</th>
<th>Current density&lt;sup&gt;a&lt;/sup&gt; ($\times10^2$ A/m²)</th>
<th>Axial velocity ($\mu$m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2.61(3)</td>
<td>19</td>
</tr>
<tr>
<td>10</td>
<td>1.67(1)</td>
<td>8.8</td>
</tr>
<tr>
<td>20</td>
<td>1.21(2)</td>
<td>7.2</td>
</tr>
<tr>
<td>33</td>
<td>0.90(1)</td>
<td>5.6</td>
</tr>
<tr>
<td>90</td>
<td>0.278(3)</td>
<td>2.4</td>
</tr>
<tr>
<td>H₂O&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.0043(8)</td>
<td>-</td>
</tr>
</tbody>
</table>

<sup>a</sup>Current density calculated from measured current divided by the area of exposed platinum (2.62x10⁻⁴ m²).

<sup>b</sup>H₂O is the baseline current density in pure deionized water without added H₂O₂ or ethanol.
Plot of axial velocities of Pt/Au rods vs. current density in ethanol/H$_2$O$_2$ solutions
Figure 10. Electroviscous velocity normalized by zeta potential (units of $\mu$m s$^{-1}$ mV$^{-1}$) as a function of total proton flux out of anode surface $J_{\text{anode}}$ (defined in the text) for data of Moran et al. (2010) ($\triangle$) and current data ($\square$). These plots support the prediction of (3.61) that the ratio of velocity to zeta potential should scale linearly with the proton flux. Also note that the slope of the old and new data is essentially the same; this is expected because the constants in the scaling relationship ($\lambda_D, h, D_+$, etc) are unchanged from the old to the new simulations.

Rod Speed vs. Conductivity

As conductivity increases, velocity should decrease!

$v = \frac{\zeta \varepsilon E}{\mu f}$

$v = \frac{\zeta \varepsilon J}{\mu \sigma f}$

slowing due to decreased conductivity
Simulation-generated plots of normalized proton concentration $c^*$ (colors) and electrical potential $\phi^*$ (contour lines)

Charge density $\rho_e/\rho_{e0}$ (color) and electric field (streamlines)

Reaction induced charge auto-electrophoresis (RICA) velocity magnitude (colors) and streamlines (black lines) for the case $\zeta = -10$ mV and dimensionless flux $j/j_d = 0.8$.

The reactions lead to an asymmetry in the proton concentration such that an excess of protons builds up at the anode and protons are depleted at the cathode. The excess of protons results in positive charge density at the anode and the generation of electric field pointing from the anode to the cathode.

\[ A_{\text{red}} \]

\[ H^+ + A_{\text{ox}} + e^- \]

\[ \text{fluid flow} \]

\[ e^- \rightarrow \]

\[ H^+ \rightarrow \]

\[ B_{\text{red}} \]

\[ H^+ + B_{\text{ox}} + e^- \]
(A) A self-propelled bioelectrochemical motor consisting of a carbon fiber functionalized with glucose oxidase (GOx) and redox polymer I on one end and bilirubin oxidase (BOD) and redox polymer II on the opposite end. When the fiber is placed on a pH 7 buffer solution containing 10 mM glucose, electrons flow along the path glucose → GOx → I → carbon fiber → II → BOD → O₂, and the fiber is propelled at the solution-O₂ interface by the ion flow accompanying the flow of electrons. (B) When an insulator is introduced between the two electrocatalytic fiber ends, the fiber does not move.

Relevance to Biological Systems

• Examples of motility mechanisms:
  – flagellar systems (ATP motors) (*e. coli*)
  – polymerization systems (*listeria*)
  – unknown systems (*synechococcus*)

• Our system may help understand how *synechococcus* bacteria swim

---

Design of Magnetic Motors

~1.5μm striped rods after release. Concavity permits designation of metal order

Following Whitesides (2003)

Angew. Chem., 2005
Autonomous Magnetized Moving Rods Response to Magnet

Rod orientation

B field

Rod orientation

B field

~1.5 μm striped rods moving in dilute solution of H₂O₂

Angew. Chem., 2005

Rod size and magnetic moments similar to magnetotactic bacteria
## Effects of the Field

<table>
<thead>
<tr>
<th></th>
<th>Not magnetized 0% H₂O₂</th>
<th>No field 5% H₂O₂</th>
<th>In field 5% H₂O₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Directionality (0.1 sec)</td>
<td>0.0</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Net forward (μm/sec)</td>
<td>0.0</td>
<td>2.9</td>
<td>2.4</td>
</tr>
<tr>
<td>Directionality (2 sec)</td>
<td>-</td>
<td>0.6</td>
<td>0.8</td>
</tr>
<tr>
<td>Rotational diffusion coefficient (deg²/sec)</td>
<td>200</td>
<td>2000</td>
<td>60</td>
</tr>
</tbody>
</table>
Demonstrating Micron Control

Spelling “PSU” by hand, rotating a stack of NdFeB magnets to steer the magnetized rods while in a dilute solution of hydrogen peroxide

Other Magnetically Guided Catalytic Motors: Wang, Sanchez
real-time video at http://research.chem.psu.edu/axsgroup/
Designing Functional Nano/Microbots

Required Design Elements

• Movement Through Catalysis
• Cargo Loading, Transport, and Unloading
• Directional Movement Through Chemical Gradient (Chemotaxis)
• Emergent Collective Behavior Through Inter-Bot Communication via Chemical Signals
Transporting Cargo: The Vision

Wang, ACS Nano (2009)
Attaching Payload to Nano/Micromotors

(a) Catalytic motor

(b) SAM of biotin terminated disulfide

Cargo attachment by:
(a) electrostatic interaction between the negative polypyrrole (PPy) end of a platinum/gold/polypyrrole motor and a positively charged polystyrene (PS) amidine micro-sphere
(b) biotin-streptavidin binding between the gold tips of platinum/gold rods functionalized with a biotin-terminated disulfide and streptavidin-coated cargo

Nano Lett., 2008

Other Cargo-carrying Catalytic Motors: Wang, Sanchez
Pt-Au-PPy with Amidine Microspheres

Rod: 3 μm; Cargo: 2 μm

1000 x Dark Field Reflection Microscopy
Experimentally observed doublet speeds versus theoretical expectations based on calculations.

The equivalent sphere radius $R_{\text{eq}}$ of a rod (Pt-Au-PPy) or a rod-sphere doublet is the radius of a sphere which has the same drag coefficient.

<table>
<thead>
<tr>
<th>$R_{\text{cargo}}$ (μm)</th>
<th>$R_{\text{eq}}$ doublet calculated by CDL-BIEM (μm)</th>
<th>Velocity ratio predicted by $R_{\text{eq}}$</th>
<th>Experimentally observed velocity ratio $(\frac{U_{\text{doublet}}}{U_{\text{rod}}})$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>I</td>
</tr>
<tr>
<td>0</td>
<td>0.46 - 0.53</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>0.38</td>
<td>0.59 - 0.65</td>
<td>0.78 - 0.81</td>
<td>0.80 ± 0.03</td>
</tr>
<tr>
<td>0.60</td>
<td>0.76 - 0.81</td>
<td>0.61 - 0.66</td>
<td>0.67 ± 0.01</td>
</tr>
<tr>
<td>1.05</td>
<td>1.14 - 1.18</td>
<td>0.40 - 0.45</td>
<td>0.53 ± 0.01</td>
</tr>
</tbody>
</table>
Optical microscopy images of a Pt-Ni-Au-Ni-Au-PPy motor pulling 1.05 µm radius cargo showing the trajectory over 4 sec.

Nano Lett., 2008
From Motors to Micropumps

- Suspended motor moves itself.
- Immobilized motor moves surrounding fluid
- Channel-free directed fluid flow
Catalytically Induced Fluidic Pumping-Marangoni Convection
Microfluidics By Catalysis:

Real-time convective-motion of 2 μm gold rods on Ag patterned gold surface at 500x*

Real-time pattern formation of 1 μm polystyrene spheres on Ag patterned gold surface at 500x*

*0.5% w/w aqueous solution of hydrogen peroxide
Microfluidics By Catalysis

Convection and pattern formation not unique to gold and polystyrene!

Real-time movie of silica spheres 2.3 μm in diameter exhibiting pattern formation on Ag patterned gold surface at 500x
Colloid Behavior as a Function of the Surface Charge

Real-time convective-motion of amidine terminated polystyrene (2 μm) spheres on Ag patterned gold surface at 500x

Real-time pattern formation of 1 μm polystyrene spheres on Ag patterned gold surface at 500x

Why are polystyrene spheres of the same density behaving differently when only the colloid surface properties differ?
Evidence In Support of Electrokinetics

Real-time movie of silica spheres 2.3 \( \mu m \) in diameter pattern formation is now quenched on Ag patterned gold surface at 500x

Real-time movie of gold rods 2 \( \mu m \) in length convection is now quenched on Ag patterned gold surface at 500x

It is possible to turn off the convection/pattern formation by electrically isolating the silver from the gold!
Possible Model

Here silver carries out the reduction of hydrogen peroxide (cathode) and gold the oxidation of hydrogen peroxide (anode). The proton gradient establishes an electric current.

*J. Am. Chem. Soc.*, 2005
BUBBLE POWERED SELF-PROPELLED MICROBOTS

\[ \text{H}_2\text{O}_2 \rightarrow \text{H}_2\text{O} + \frac{1}{2} \text{O}_2 \]
AUTONOMOUS TRAJECTORIES FROM TUBULAR MICROJETS

Solovev et al., Small, 5, 1688 (2009)
DEPENDENCE ON FUEL CONCENTRATION

Bubble recoil mechanism

OPTIMUM FUEL CONDITIONS

CONTROLLED MOTION OF TUBULAR MICROJETS

Stepping motor (with NdFeB magnet)

Computer

Stepping motor (with NdFeB magnet)

Computer
1. EASY loading, transport of different micro-objects.

2. POWERFUL MICROENGINE

3. Delivery in specific targets.

SCALABILITY OF JET ENGINES

Biggest Man made Jet Engine

Smallest Man made Jet Engine

CERTIFICATE

The smallest man-made jet engine measures just 600nm across and weighs 1 picogram (1 x 10^-15 kg). It was produced by Alex A. Solovev, Samuel Sanchez, Yongfeng Mei and Oliver G. Schmidt at the Leibniz Institute for Solid State and Materials Research (IFW Dresden) and demonstrated in Dresden, Germany, in September 2010.
The micromachine-based target isolation concept offers numerous potential bioanalytical applications

Wang, Nano Lett. 2011
Selection and Isolation of Cancer Cells in Biological Fluids

**Immuno-micromachine for isolating CTCs**

Capture and transport of a CEA + pancreatic cancer cell by an anti-CEA mAb modified rocket
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Quorum-Sensing Autonomous Nano/Microbots

- Bots Secrete Ions
- Electric Field Results from Different Diffusion Rates of the Cations vs. Anions
- Bots Move in Response to the Electric Field
- Bots Move Cooperatively in Response to Neighbors’ Ion Gradients

Angew. Chem., 2009
DIFFUSIOPHORETIC MOTION OF PARTICLES BASED ON A GRADIENT OF ELECTROLYTE CONCENTRATION:
ELECTROPHORESIS TENDS TO DOMINATE OVER CHEMOPHORESIS

\[ U = \left( \frac{d\ln(C)}{dx} \right) \left( \frac{D_C - D_A}{D_C + D_A} \right) \left( \frac{k_B T}{e} \right) \frac{\epsilon (\zeta_p - \zeta_w)}{\eta} + \left( \frac{d\ln(C)}{dx} \right) \left( \frac{2 \epsilon k_B T^2}{\eta e^2} \right) \left\{ \ln \left[ 1 - \tanh^2 \left( \frac{e \zeta_w}{4 k_B T} \right) \right] - \ln \left[ 1 - \tanh^2 \left( \frac{e \zeta_p}{4 k_B T} \right) \right] \right\} \]

\( U \) is the particle speed, \( \frac{d\ln(C)}{dx} \) is the electrolyte gradient
\( D_C \) and \( D_A \) are the diffusion constants of the cation and anion components
\( k_B \) is the Boltzmann constant, \( T \) is the temperature, \( e \) is the elementary charge
\( \epsilon \) is the solution permittivity, \( \eta \) is the dynamic viscosity of the solution,
\( \zeta_p \) is the zeta potential of the particle,
\( \zeta_w \) is the zeta potential of the wall (\( \zeta_w = 0 \) away from the wall)

Speed proportional to ion gradient and charge on the particle
Under low Reynolds number conditions (\( R \sim 10^{-5} \)),
the mass and radius of the particle are not important

Quorum-Sensing Autonomous Nano/Microbots

- Bots Secrete Ions
- Electric Field Results from Different Diffusion Rates of the Cations vs. Anions
- Bots Move in Response to the Electric Field
- Bots Move Cooperatively in Response to Neighbors’ Ion Gradients

Angew. Chem., 2009
Photochemistry of Silver Chloride

\[ 4 \text{AgCl} + 2 \text{H}_2\text{O} \xrightarrow{\text{hv, } \text{Ag}^+} 4 \text{Ag} + 4 \text{H}^+ + 4\text{Cl}^- + \text{O}_2 \]
Silver chloride particles in deionized water undergo Brownian motion in visible wavelength light. After 2 sec, the UV light is switched on. Large schools of colloids form at longer times. Video plays in real time.
Emergent Collective Behavior Through Communication via Chemical Signals

(a-c) AgCl particles in deionized water (a) before UV illumination, (b) after 30 s of UV exposure, and (c) after 90 s.
(d-f) Simulation of AgCl particles in deionized water after (d) 0 timesteps, (e) 250 timesteps, and (f) 750 timesteps.
Change in concentration at a given lattice site with time

\[
C_{x,y}(t + \Delta t) = (1 - b)\left\{ C_{x,y}(t) + a n_{x,y} + D\left[ C_{x+1,y}(t) + C_{x-1,y}(t) + C_{x,y+1}(t) + C_{x,y-1}(t) - 4C_{x,y}(t) \right] \right\}
\]

Chemical gradient across a lattice site in \(x\) and \(y\) directions

\[
\psi_x = C_{x+1,y}(t) - C_{x-1,y}(t)
\]

\[
\psi_y = C_{x,y+1}(t) - C_{x,y-1}(t)
\]

Probability of hopping in a given direction, \textit{in addition} to user-defined Brownian hop probability, \(\lambda_B\)

\[
\lambda_x(t) = \alpha|\psi_x|
\]

\[
\lambda_y(t) = \alpha|\psi_y|
\]

The modified NetLogo program was run for 1000 time steps with schooling defined as 4+ particles occupying a single lattice site
A Typical Simulation Of Particle Collective Behavior

(a) Initially randomly distributed particles.
(b) Particles after 2000 times-steps.
(c) A plot of the chemical values of every lattice site at 2000 time-steps.

Brighter shades of green approaching white indicate higher chemical concentrations.

Schooling Propensity vs Particle Sensitivity to Gradient

Proportion of Particles in Schools at T=1000

Particle Sensitivity to Gradient, $\alpha$

Constant Parameters
- Population ($N$): 250
- Chemical Diffusion Constant ($D$): 0.05
- Chemical Secretion Rate ($\alpha$): 0.25
- Extinction Rate of Chemical ($\beta$): 0.025
- Brownian Hop Probability ($\lambda_{bh}$): 0.025

Faraday Discuss., 2009
Schooling Propensity vs Brownian Hop Probability

**Constant Parameters**
- Population (N): 250
- Chemical Diffusion Constant (D): 0.05
- Chemical Secretion Rate (a): 0.25
- Extinction Rate of Chemical (b): 0.025
- Sensitivity to Gradient (α): 0.025

Proportion of Particles in Schools at T = 1000

Faraday Discuss., 2009
Faraday Discuss., 2009

**Schooling Propensity vs Chemical Secretion Rate**

- **Proportion of Particles in Schools at T = 1000**

- **Chemical Secretion Rate, \( a \)**

- **Constant Parameters**
  - Population (\( N \)): 250
  - Chemical Diffusion Constant (\( D \)): 0.05
  - Brownian Hop Probability (\( \lambda_b \)): 0.025
  - Extinction Rate of Chemical (\( b \)): 0.025
  - Sensitivity to Gradient (\( \alpha \)): 0.025

---

*Faraday Discuss., 2009*
Schooling Propensity vs Extinction Rate of Chemical

**Constant Parameters**
- Population \((N)\): 250
- Chemical Diffusion Constant \((D)\): 0.05
- Brownian Hop Probability \((\lambda_b)\): 0.025
- Chemical Secretion Rate \((a)\): 0.25
- Sensitivity to Gradient \((\alpha)\): 0.025

Proportion of Particles in Schools at \(T = 1000\)

Extinction Rate of Chemical
Schooling Propensity vs Population

**Constant Parameters**
- Extinction Rate of Chemical \( b \): 0.025
- Chemical Diffusion Constant \( D \): 0.05
- Brownian Hop Probability \( \lambda_a \): 0.025
- Chemical Secretion Rate \( \alpha \): 0.25
- Sensitivity to Gradient \( \alpha \): 0.025
Silver chloride particles (dark objects) with silica particles. When the UV light is switched on at 3 seconds, silver chloride particles begin to move and also attract silica particles. Video plays in real time.
Collective Particle Behavior

New Design Principles

• Two or more different particle types can move autonomously to organize themselves spatially

• Allows coordinated movement of dissimilar particles that are not attached to each other making it easier to transport and deliver cargo at designated areas

Angew. Chem., 2009
Microfireworks with Silver Chloride Particles

Real time video
The UV light is alternately turned on and off

Angew. Chem., 2009
Oscillatory Behavior and Emergent Synchronization of Particles Under Redox Conditions

\[ 4 \text{AgCl} + 2 \text{H}_2\text{O} \rightarrow 4 \text{Ag} + 4 \text{H}^+ + 4 \text{Cl}^- + \text{O}_2 \]

2 \text{Ag} + \text{H}_2\text{O}_2 + 2 \text{H}^+ + 2 \text{Cl}^- \rightarrow 2 \text{AgCl} + 2\text{H}_2\text{O}
A solution containing AgCl particles (darker objects), silica tracer spheres (lighter objects), and 1% (v/V) H$_2$O$_2$ in water. The particles are illumined with UV light over a microscope slide. The AgCl particles are seen to move through solution, and alternately bind and release the silica tracer particles. The video is 194 µm in width. Movie plays in real-time.
A UV-illuminated aqueous solution containing 2.3 μm silica tracer particles, 0.33 mM HCl, and 0.17% (v/V) H₂O₂ is imaged above an array of 9 μm diameter silver disks with 11 μm spacings. As a traveling wave of tracer particle motion passes the array, the disks appear to flash on and off as their color alternates between reflective silver and darkened AgCl.
Current from a 90 µm silver disk patterned on a SiO₂ wafer in the presence of 0.17% (v/V) H₂O₂, 0.17 mM HCl and silica tracer spheres, under UV illumination. After a few seconds of illumination, current oscillations are recorded which match the oscillations of tracer particles. Negative currents are oxidative with respect to the silver surface. **Inset**, the 90 µm diameter silver disk connected to an insulated silver wire that monitored the reaction current on the disk surface.
Real Time Video:
Solution containing AgCl particles and 1% H₂O₂ in water under UV illumination
Designing Functional Nano/Microbots

Required Design Elements

• Movement Through Catalysis
• Cargo Loading, Transport, and Unloading
• Directional Movement Through Chemical Gradient (Chemotaxis)
• Emergent Collective Behavior Through Inter-Bot Communication via Chemical Signals

Scientific American, May, 2009
DIFFUSIOPHORETIC MOTION OF PARTICLES BASED ON A GRADIENT OF ELECTROLYTE CONCENTRATION:
ELECTROPHORESIS TENDS TO DOMINATE OVER CHEMOPHORESIS

\[
U = \left( \frac{d\ln(C)}{dx} \right) \left( \frac{D_C - D_A}{D_C + D_A} \right) \left( \frac{k_B T}{e} \right) \alpha \left( \zeta_p - \zeta_w \right) + \left( \frac{d\ln(C)}{dx} \right) \left( \frac{2\varepsilon k_B T^2}{\eta e^2} \right) \left[ \ln \left[ 1 - \tanh^2 \left( \frac{e\zeta_w}{4k_B T} \right) \right] - \ln \left[ 1 - \tanh^2 \left( \frac{e\zeta_p}{4k_B T} \right) \right] \right]
\]

\( U \) is the particle speed, \( \frac{d\ln(C)}{dx} \) is the electrolyte gradient
\( D_C \) and \( D_A \) are the diffusion constants of the cation and anion components
\( k_B \) is the Boltzmann constant, \( T \) is the temperature, \( e \) is the elementary charge
\( \varepsilon \) is the solution permittivity, \( \eta \) is the dynamic viscosity of the solution,
\( \zeta_p \) is the zeta potential of the particle,
\( \zeta_w \) is the zeta potential of the wall (\( \zeta_w = 0 \) away from the wall)

Speed proportional to ion gradient and charge on the particle
Under low Reynolds number conditions (\( R \sim 10^{-5} \)),
the mass and radius of the particle are not important

**Movement Due to External Salt Gradient:**
*Oil Reservoir Salinity: 50,000 – 150,000 ppm*
Directions of Particle and Fluid Flow Components in Diffusiophoresis

Assumption: Particle and underlying substrate are negatively charged, and $D_- > D_+$ (e.g. NaCl)
Migration of silica microspheres (d = 2.3 μm) towards a gel containing 1 mM NaCl
Migration of silica microspheres (d = 2.3 μm) in competing concentration gradients of NaCl solution
Silica microspheres ($d = 2.3 \, \mu m$) navigating past glass fiber barriers in response to an agarose gel containing 1 mM NaCl (located to the right of the field of vision in both images)
Silica tracer particles (d = 2.34 \mu m) preferentially migrate towards NaCl-leaching gel. Gels contain 10 mM D-glucose (left) and 1 mM NaCl (right).
### Silica Particles in The Presence of an Agarose Gel Soaked in 1 mM NaCl

<table>
<thead>
<tr>
<th>Particles</th>
<th>Average Velocity (x)</th>
<th>SD</th>
<th>Average Velocity (y)</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.34μm ~200 μm from gel</td>
<td>1 mM NaCl</td>
<td>1.32</td>
<td>0.27</td>
<td>-0.056</td>
</tr>
<tr>
<td></td>
<td>1 mM KCl</td>
<td>0.97</td>
<td>0.16</td>
<td>-0.024</td>
</tr>
<tr>
<td>0.90μm ~200 μm from gel</td>
<td>1 mM NaCl</td>
<td>1.32</td>
<td>0.32</td>
<td>-0.020</td>
</tr>
<tr>
<td></td>
<td>1 mM KCl</td>
<td>0.93</td>
<td>0.29</td>
<td>-0.049</td>
</tr>
</tbody>
</table>

**Speed:** μm/sec
Experimental Setup for Particle Movement in an Electric Field

U is the particle speed
ε is the solution permittivity
E is the applied electric field
η is the dynamic viscosity of the solution,
ζ_p is the zeta potential of the particle,
ζ_W is the zeta potential of the wall (ζ_W = 0 away from the wall)

\[ U = \frac{\varepsilon (\zeta_P - \zeta_W)}{\eta} E \]

- Suspension of microspheres
- Gold contact (100 nm thick)
- Gasket
- Glass slide
Comparison of Movement in an Applied Electric Field to Diffusiophoretic Migration

Velocity Versus Electric Field Strength for 2.34 µm Silica Particles in “Deionized” Water

Observed Diffusiophoretic Velocity Towards a 1 mM NaCl Gel

\[ y = 1.9147x \]

\[ R^2 = 0.9188 \]
Microfluidic Setup

Channel width: 240 μm
Channel height: 100 μm
Flow rate: 350 μm/s
Particle: Fluorescent Carboxylated polystyrene; 100 nm radius

Region used for data collection
Direction of flow

Particle inlet
NaCl inlet
Chemotaxis of Carboxylated Polystyrene Nanospheres

200 nm PS-COOH Microspheres

- Blue line: Water
- Red line: 100 mM NaCl

Normalized Fluorescence Intensity (a.u.)

Distance (µm)

Lateral shift: 18µm (~12.6 µm/s)
Comparison of Movement in an Applied Electric Field to Diffusiophoretic Migration

Velocity Versus Electric Field Strength

\[ y = 1.9147x \]
\[ R^2 = 0.9188 \]

Diffusiophoretic velocity of 200 nm PS-COOH nanoparticles observed in microfluidic system
Theoretical Determination of Electric Field Strength Required to Match Observed Diffusiophoretic Velocity

Smoluchowski Equation:

$$E = \frac{U \eta}{\varepsilon \zeta}$$

U: velocity
η: viscosity
ε: permittivity
ζ: zeta potential of particles

Result: Assuming $\zeta = -60$ mV,

**diffusiophoretic velocity of 12.6 µm/s requires an electric field of 4.12 V/cm**

*Under low Reynolds number conditions, diffusiophoretic velocity independent of radius of the particle*
• Simple channel, purely unidirectional laminar flow assumed

• Wall effects ignored (floor effects not ignored)

• Chemicals and particles diffuse in across the channel (y-direction) according to Fick’s laws (1D-diffusion)

• Chemical and particles flow down the channel (x-direction) at a given constant rate

• Particles react to their chemical environments and move accordingly across the channel (y-direction, 1D)
Modeling Diffusiophoresis

User Defined Parameters

- Incoming particle number density
- Incoming chemical concentration (Molar)
- Flow rate
- Particle diffusion constants: \[ D = \frac{k_B T}{6\pi \eta a} \]
  - Temperature (T)
  - Viscosity (\(\eta\))
  - Particle Size (\(a_{\text{active}}, a_{\text{inactive}}\))
- Monovalent ion diffusion constants
  - Salt as a whole diffuses with a diffusion constant equal to the harmonic average of these.
- Zeta potentials of particles and underlying substrate (z-direction)
  - Potentials of walls at max and min y direction are ignored.
Modeling Salt Gradients in a Microfluidic Flow

Average Particle Count at Specified Location

- Ion sensitive colloidal particles
- Non-ion sensitive particles

Distance from Channel Center (microns)
Migration as a Function of Diffusion Constants
Good Agreement Between Modeling and Experimental Microfluidics Data

Channel width: 200 µm
Flow rate = 350 µm/s
Imaged at 500 µm
Experiment time: ~1.42 s
$D_A = 2.07 \times 10^{-5} \text{ cm}^2/\text{s (Cl}^-\text{)}$
$D_C = 1.33 \times 10^{-5} \text{ cm}^2/\text{s (Na}^+\text{)}$
Particle sizes: 0.2 µm
Viscosity: 0.001 Pa
Temperature: 25 °C
Effect of Particle Zeta Potential on Particle Movement in Microfluidic Channel

Varying Particle Zeta Potential

[Graph showing displacement across channel (microns) vs. distance from channel inlet (microns) for different zeta potentials.]
Calculating Theoretical Diffusion Profile

Fick's Second Law

The rate of change in the concentration at any point depends on the difference between the fluxes entering and exiting that point.

\[
\frac{\partial \phi}{\partial t} = D \frac{\partial^2 \phi}{\partial x^2}
\]

Assuming a perfect source of electrolyte with a concentration of \(C_S\) diffusing into an infinite water bath. Assume the water bath starts out without any electrolyte

\[
C(x, t) = C_S \left[ 1 - \frac{2}{\sqrt{\pi}} \int_{x}^{\infty} e^{-n^2} \, dn \right]
\]

Diffusiophoresis Equation

Using the electrolyte profile calculated above, we can calculate the speed if we know the temperature, diffusion constants, and zeta potentials
Theoretical Diffusion Profile

Concentration vs Time at 3 Distances from Source

Assuming Average $D = 1 \times 10^{-9} \text{ m}^2/\text{s}$

Source Concentration = 1 M
Theoretical Diffusion Profile

Concentration vs. Distance from Source at 3 Different Times

Assuming Average $D = 1 \times 10^{-9}$ m$^2$/s
Source Concentration = 1 M
Possible Relevance to Oil Recovery

Flush the well with fresh water

Some pockets of salt water remain in crevices

Those pockets of high salt will diffuse out, creating an electric field that acts on all charged surfaces, including exposed oil-water interfaces.
LoSal Enhanced Oil Recovery (BP)
Movement Through Polymerization


Enzyme polymerizes actin monomer which aids in cell motion

Polymerization-Powered Micromotors

These Motors Utilize Asymmetrically Bound Grubbs-type Catalyst On Au/Silica Janus Microspheres To Convert Monomer Into Polymer
Particle Comparison

Before Polymerization

After Polymerization
Note: Polymer Formed Dissolves in Solvent, Does Not Precipitate Out
The motor consumes monomers at the silica face creating an area of low monomer concentration. Fluid in the low concentration region flows \textit{towards} the higher concentration region at the gold face. Consequently, the motor moves in the \textit{opposite} direction.
Does Enhanced Diffusion with Increasing Substrate Concentration Translate into Directed Motion: *Chemotaxis*?
Chemotaxis of Polymerization-Powered Motors

Normalized particle population at the gel edge as a function of time:
- The motor particles in a norbornene gradient (red)
- Unfunctionalized Au-Silica Janus spheres in norbornene gradient (blue)
- Motor particles in a norbornane gradient (green)

Angew. Chem., 2011
Substrate Catalysis Enhances Single Enzyme Diffusion

**Single Enzyme Urease Diffusion**

<table>
<thead>
<tr>
<th>Diffusion Coefficient ($10^{-7}$ cm²/s)</th>
<th>0 M</th>
<th>0.001 M</th>
<th>0.1 M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Urease</td>
<td>3.0</td>
<td>3.5</td>
<td>4.0</td>
</tr>
<tr>
<td>Urease with Inhibitor (Pyrocatechol)</td>
<td>3.5</td>
<td>4.0</td>
<td>4.5</td>
</tr>
</tbody>
</table>

**Single Enzyme Catalase Diffusion**

<table>
<thead>
<tr>
<th>Diffusion Coefficient ($10^{-7}$ cm²/s)</th>
<th>0 M</th>
<th>0.01 M</th>
<th>0.1 M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Catalase</td>
<td>6.0</td>
<td>6.5</td>
<td>7.0</td>
</tr>
<tr>
<td>Catalase with Inhibitor (NaCN)</td>
<td>6.0</td>
<td>6.5</td>
<td>7.0</td>
</tr>
<tr>
<td>Inhibited Catalase + Active Catalase (untagged)</td>
<td>5.0</td>
<td>5.5</td>
<td>6.0</td>
</tr>
</tbody>
</table>

*J. Am. Chem. Soc., 2010*
Mean square displacement (MSD) of urease obtained from Brownian dynamics simulations, assuming 10 nanosecond impulse time per reaction:
No reaction (*black*)
Maximum reaction rate assuming a force of 12 pN/turnover (*red*)
Solid lines are linear fits at longer time scales.

*J. Am. Chem. Soc.*, 2010
Relative diffusion coefficient of catalase obtained from Brownian dynamics simulations, assuming 10 nanosecond impulse time per reaction:

Maximum reaction rate assuming a force of 9 pN/turnover (red)
Catalase Trajectory

- $F_R = 9 \text{ pN}$
- $F_R = 0 \text{ pN}$

Axes:
- $X$-axis (µm)
- $Y$-axis (µm)
- $Z$-axis (µm)
Single Enzyme Chemotaxis

Y-shaped microfluidic channel used for single-molecule enzyme chemotaxis studies
Shift for catalase towards 100 mM glucose and glucose oxidase
Behavior of Free Dye Molecules towards Different Substrate Concentration Gradients

![Graph showing normalized fluorescence intensity (a.u.) vs. distance (µm) for NHS-Rhodamine in water, 10 mM hydrogen peroxide, and 100 mM glucose.](image-url)
Applicability of the Scallop Theorem

At low Reynolds’ number propulsion by time-reversible reciprocal motion not possible?? (Scallop Theorem)

At low Reynolds’ number propulsion by non-reciprocal motion can be achieved

Non-reciprocal conformational changes in a model enzyme

A) The reciprocal swim cycle of an unperturbed scallop opening and closing its shell.

B) The motion path of a similar swimmer which undergoes a single rotation after it has traveled a distance \((d)\) into its cycle.

The forward paths are shown in red, the return paths are shown in blue. Also, Lauga, PRL, 2011
Designing Intelligent Nano/Microbots: Synthetic Active Matter

1. Introduction to Synthetic Active Matter
2. Powering Active Particle and Fluid Motion
3. Collective Behavior of Autonomous Nano/Microbots

AYUSMAN SEN

Department of Chemistry, Penn State University
E-mail: asen@psu.edu
Intelligent Catalytic Motors

Intelligence requires (a) information and (b) ability to process (act on) information – information processor

Information: Gradient – Chemical, Light

Information processor: Self-powered object

Result of Information + Information Processing: Collective/Emergent behavior
e.g., Spatial and/or Temporal Assemblies

*Both* information and information processor require continuous input of energy

Information Processor can *change* the Information
e.g., Assume an initial fuel gradient:
Higher the motor density → Faster fuel consumption →
Steeper fuel gradient → More directional (& faster) chemotaxis
Artists drawing of a nanoscale submarine moving through a human capillary.

- taken from Audi Magazine, 10/03