

Microvascular Materials for Mass and Energy Transport

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2nd Annual Multifunctional Materials Meeting
PM: Dr. “Les” Lee

Award FA9550-12-1-0352



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Report Documentation Page

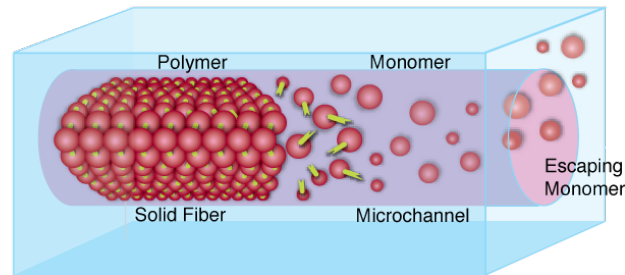
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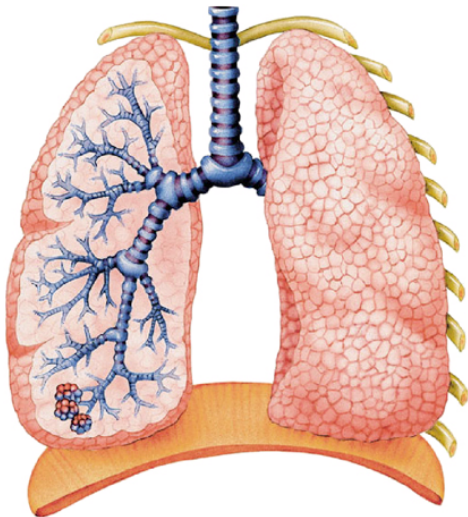
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Micro-Vascular Exchange Units : Bio-Inspired Energy & Mass Transfer

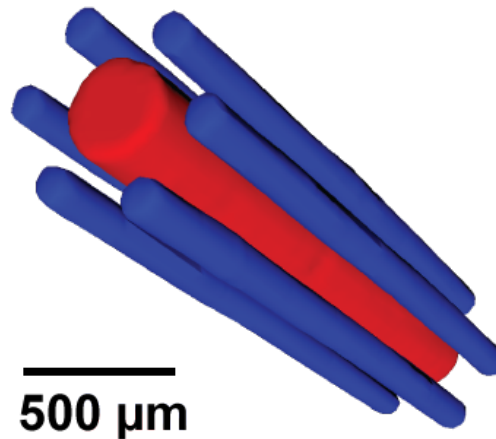
VaSC – Vaporization of a Sacrificial Component



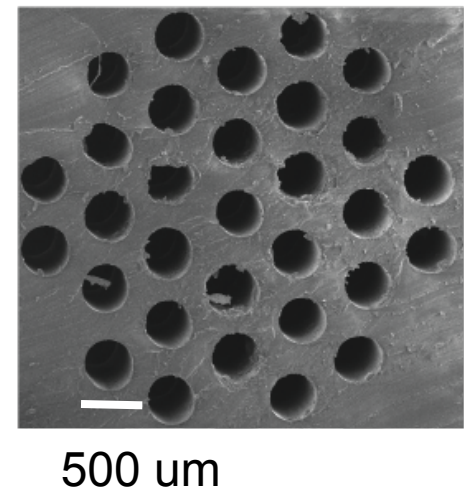
Our Motivation



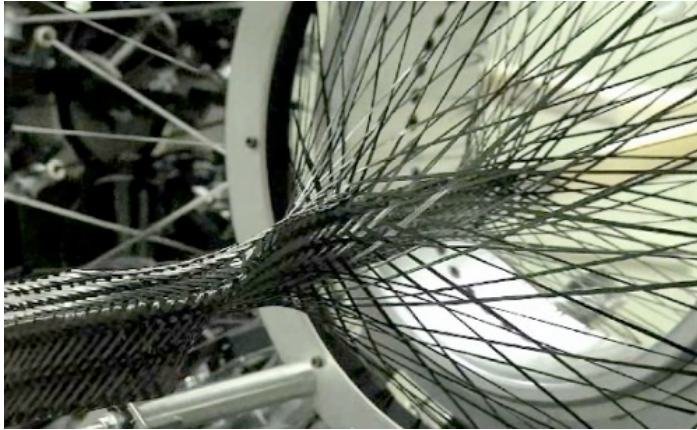
Exchange Unit



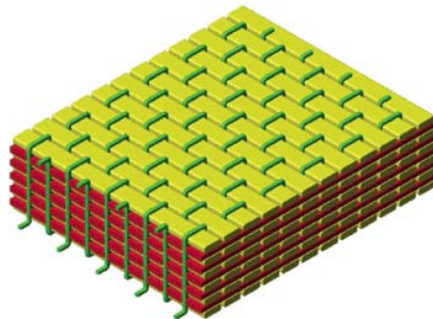
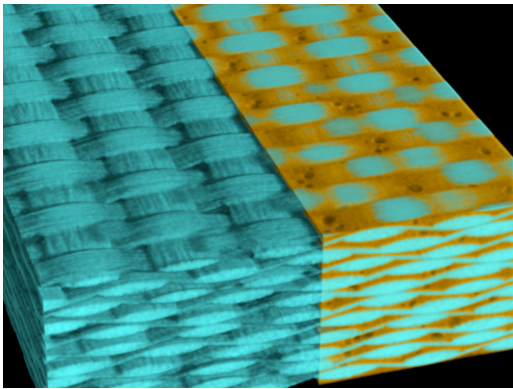
Optimization



Fiber Reinforced Composites



**Fiber Composite,
Stronger, Lighter**



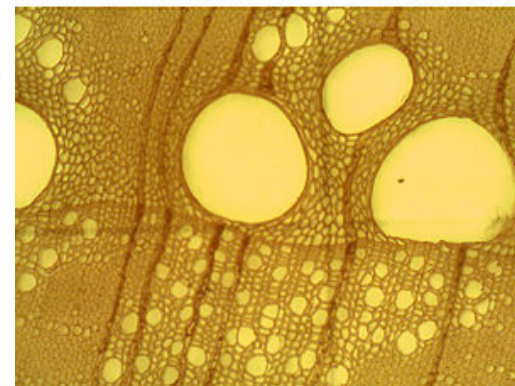
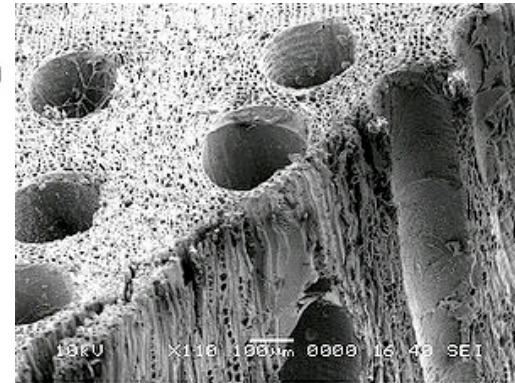
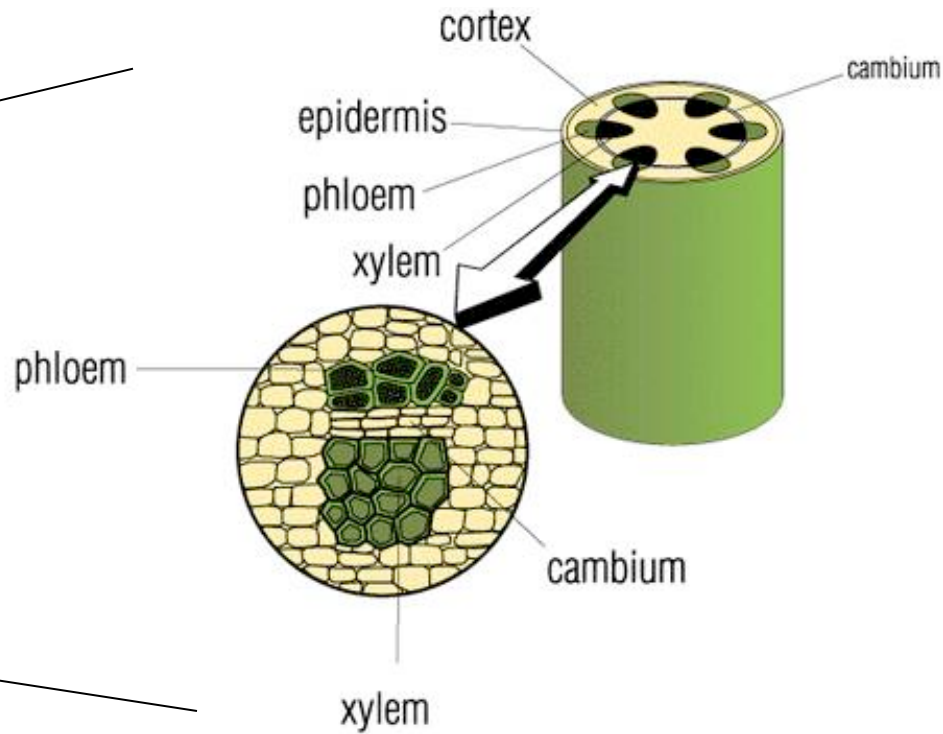
Interwoven fibers provide strength



50% Composite, 30% Lighter

Trees: Nature's Composites

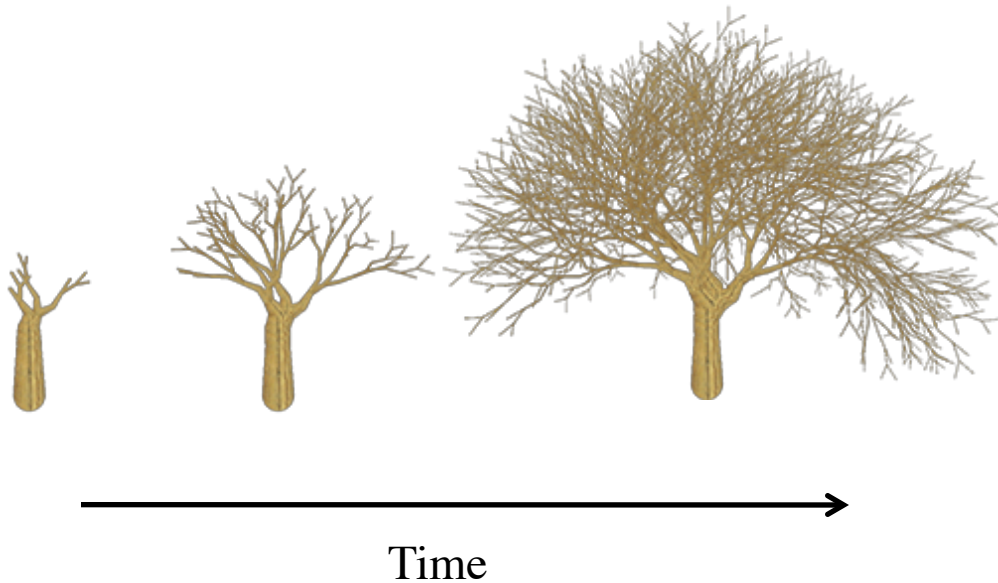
Pacific Yew Tree



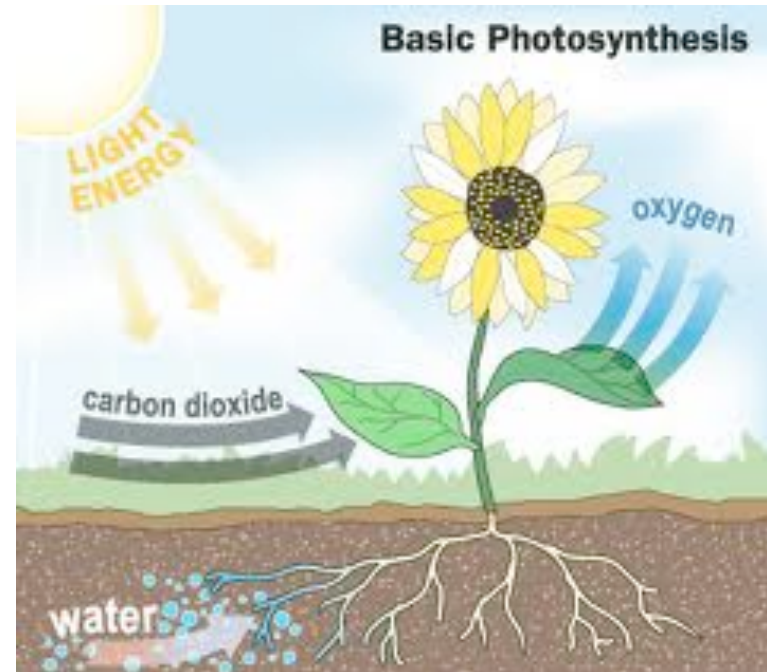
Vasculature Creates Living Materials

E/M Transport + Regional Chemistry = Growth, Homeostasis, Communication

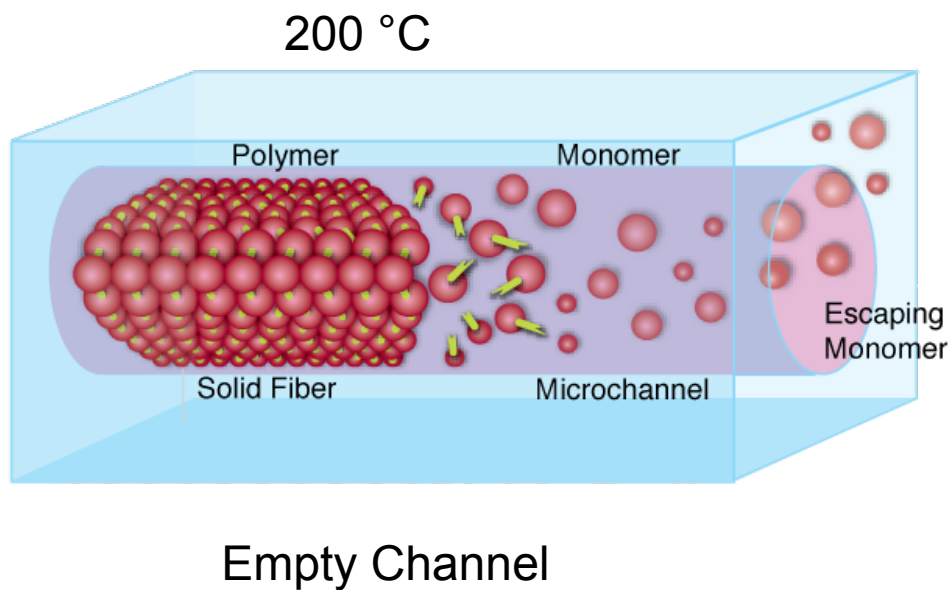
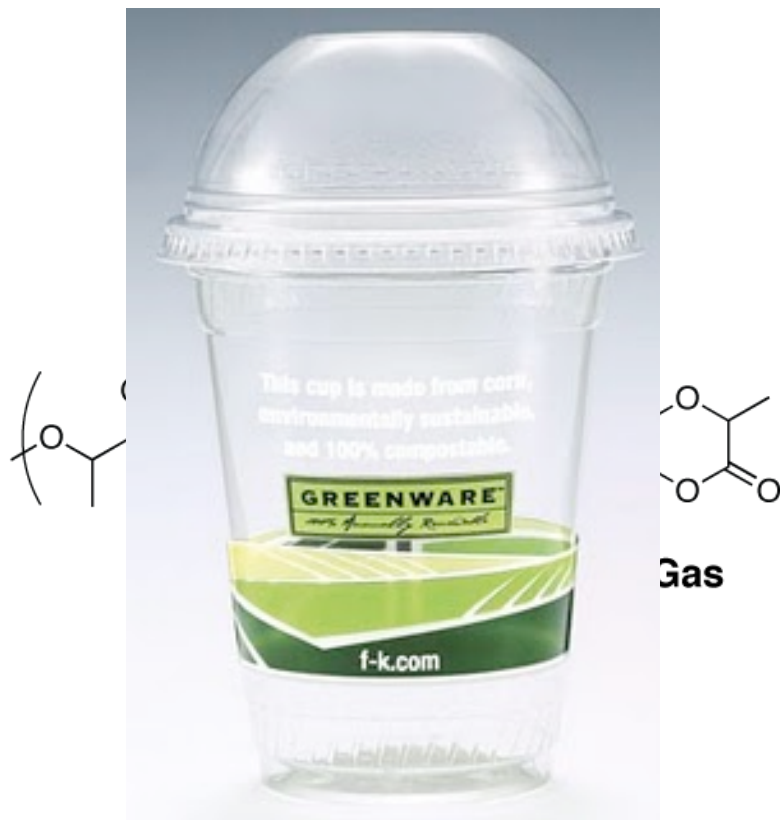
Growth



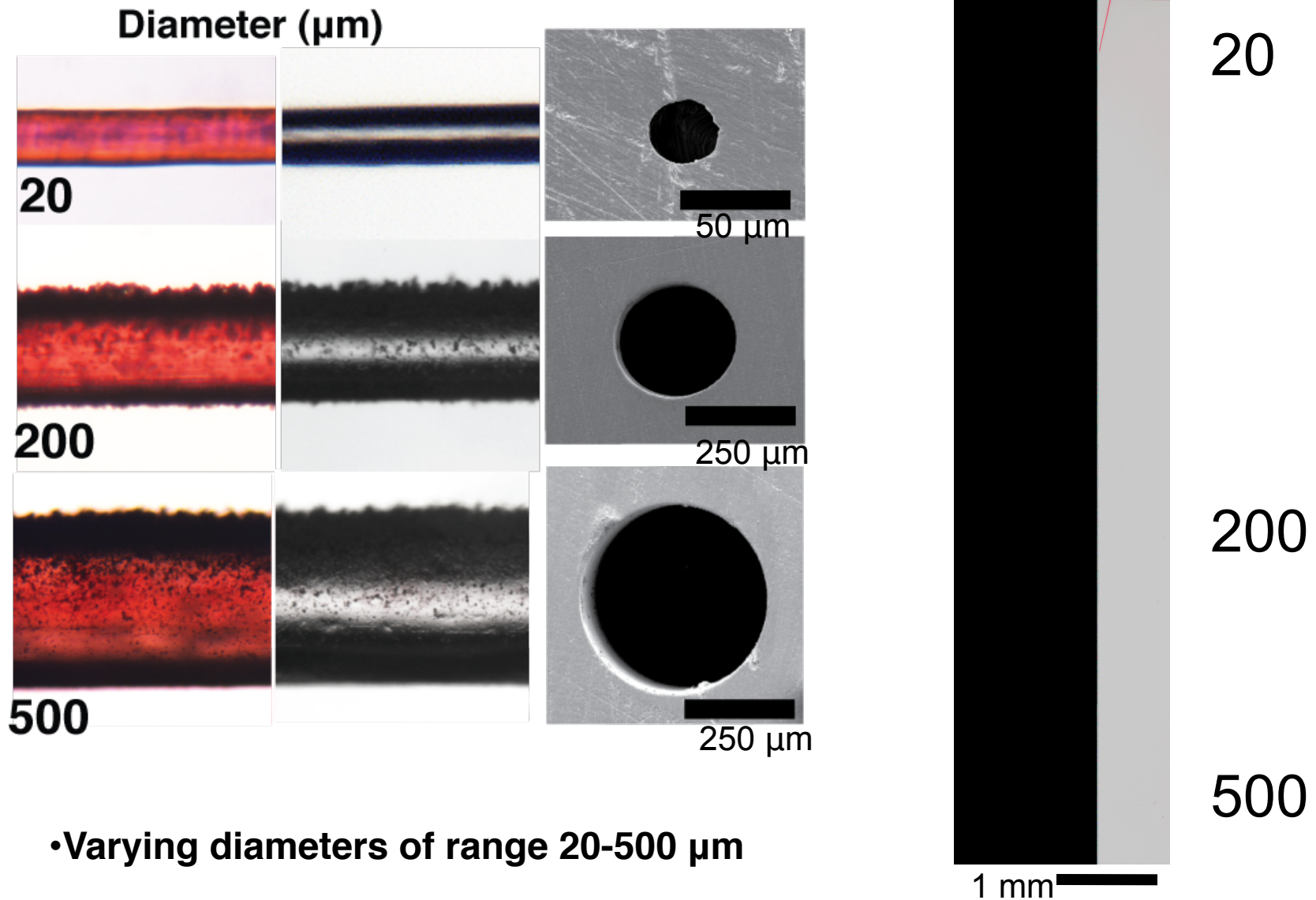
Reactivity



VaSC – Vaporization of a Sacrificial Component

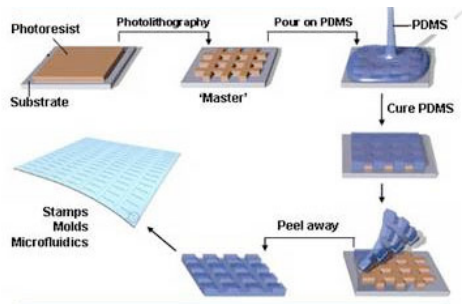
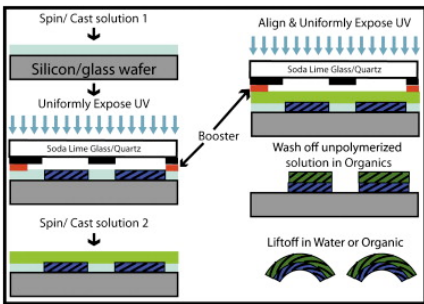


Size Range & Connection of Fibers

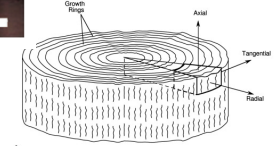
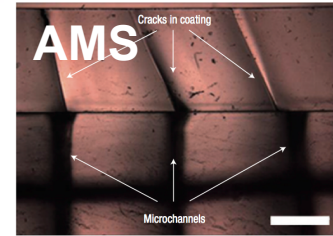
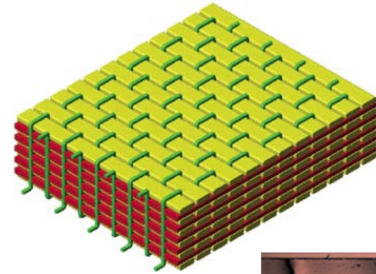


Different Micro-Fabrication Methods for Materials: Hamburger to Celery

Lithography



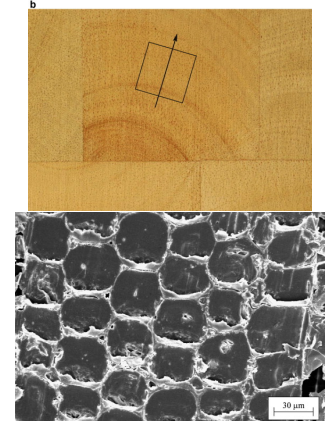
3D Techniques



Big Mac Assembly

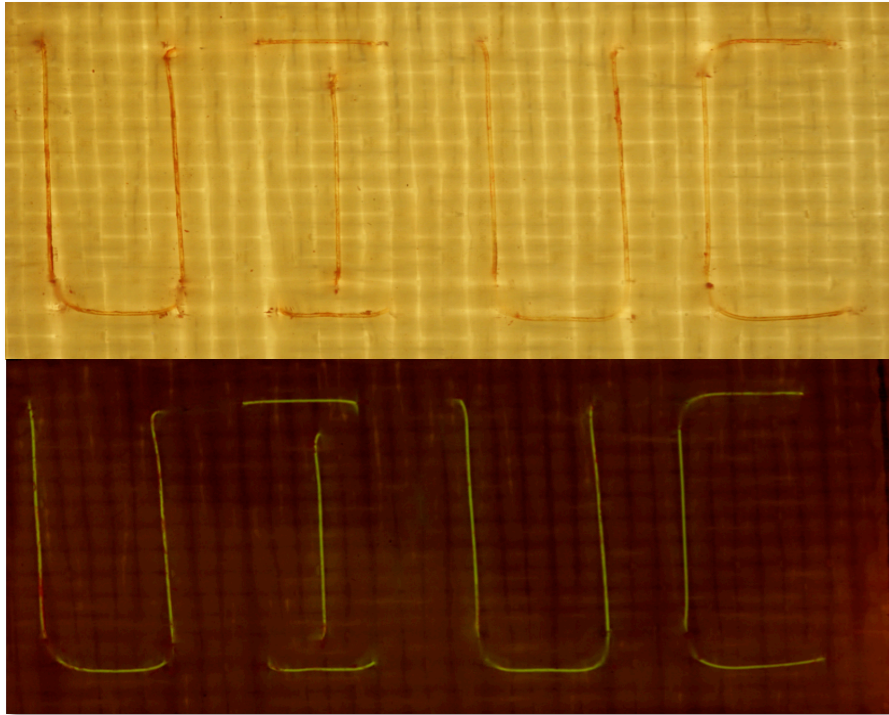


Celery Assembly



Fibers Can be Woven Into Composite Materials

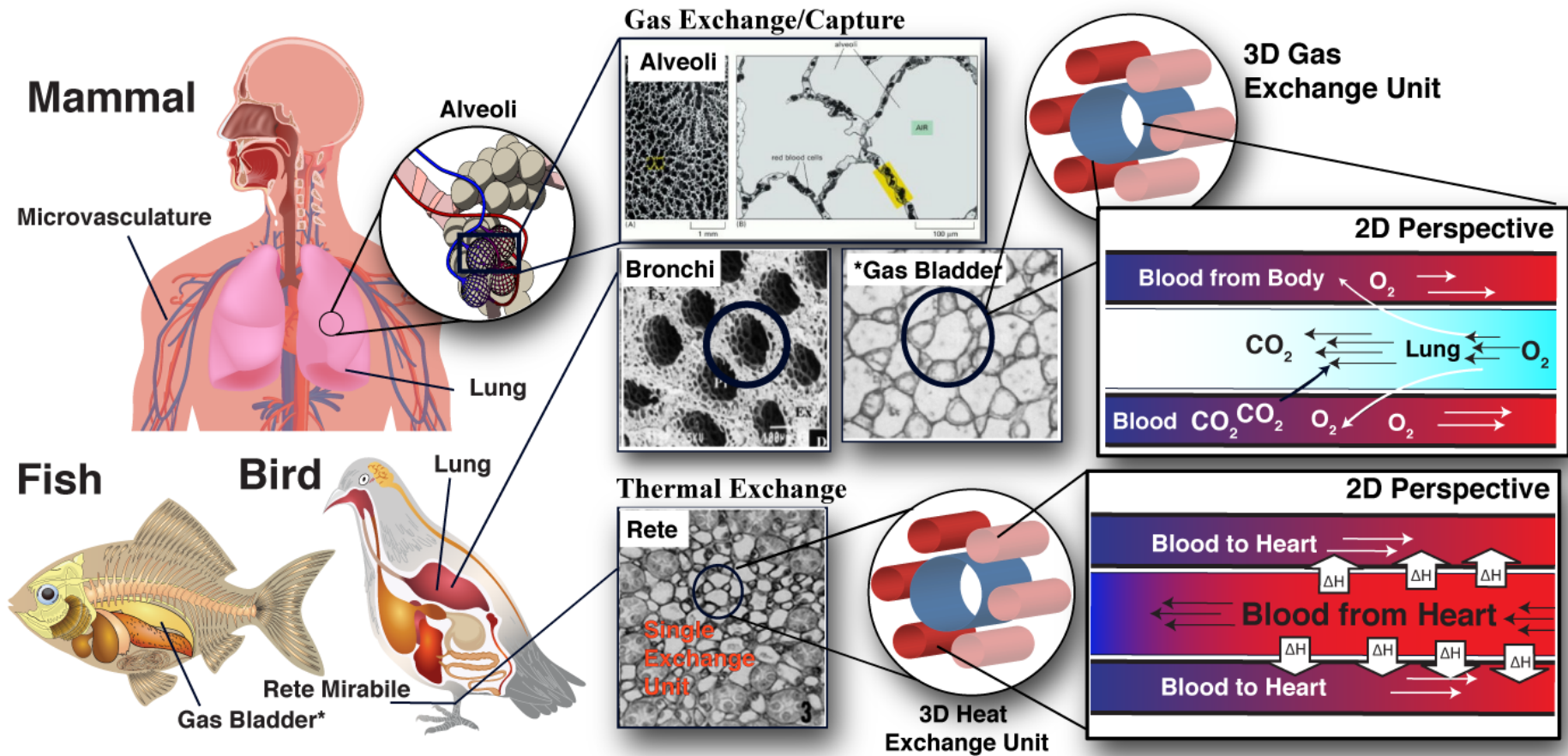
Channel extends
over 0.5 meter!



And Deformed to
Complex Geometries



Nature: A brilliant chemengineer



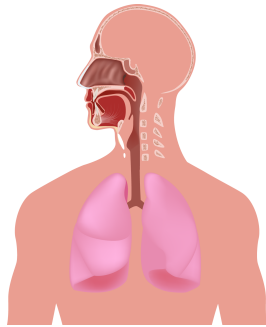
In Nature Thermal And Gas Exchange Are Based On Same Structures

Just how efficient are natural structures?



$2 \times 10^{12} \text{ kWh} \cdot \text{yr}^{-1}$

$85 \times 10^{10} \text{ L} \cdot \text{CO}_2 \cdot \text{yr}^{-1}$



Breathing Capacity of Lung

Resting $0.5 \cdot \text{L} \cdot \text{min}^{-1}$

Max. Cap. $3.0 \cdot \text{L} \cdot \text{min}^{-1}$

Lungs are some of the most efficient structures known

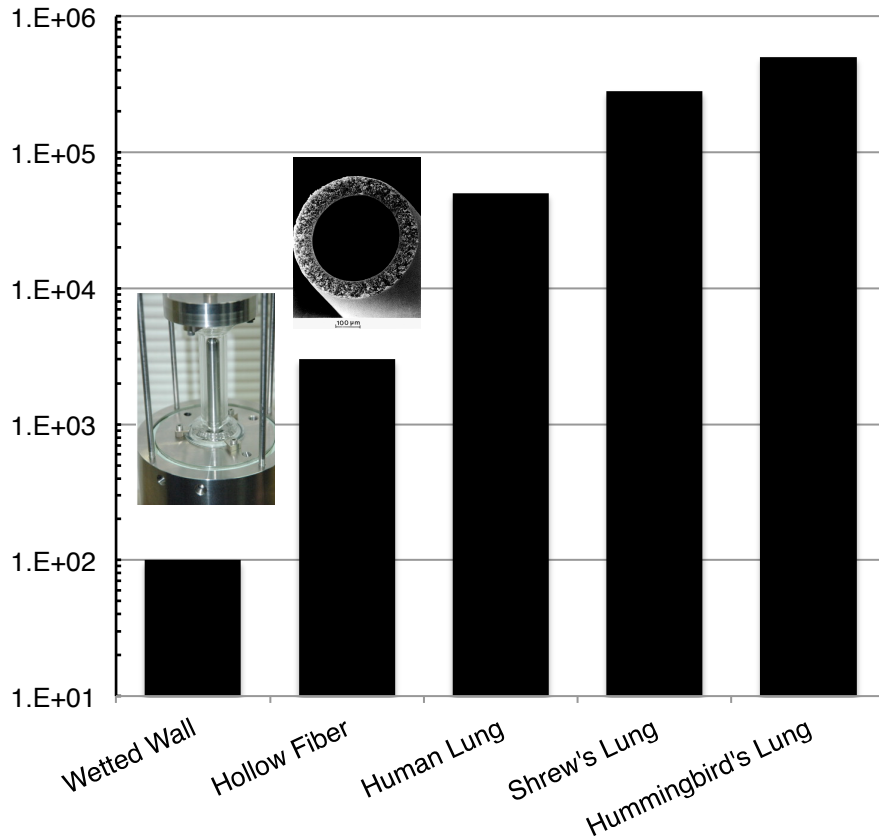
=

**3 million
(0.5 million max cap)**

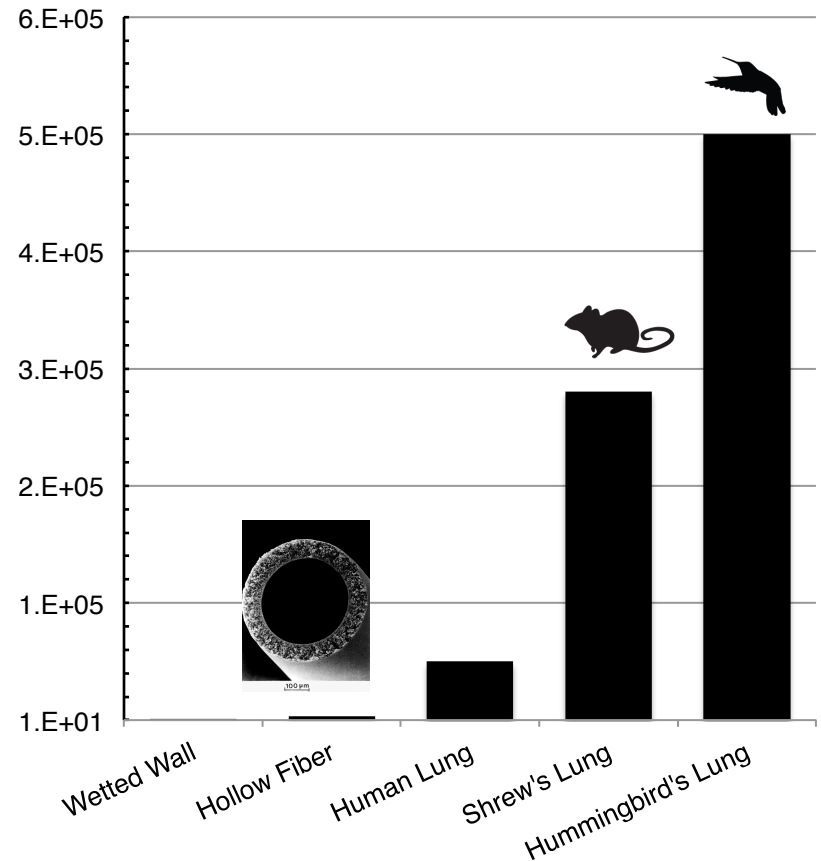
0.1% total energy

Man-Made Exchangers vs. Natural Exchangers

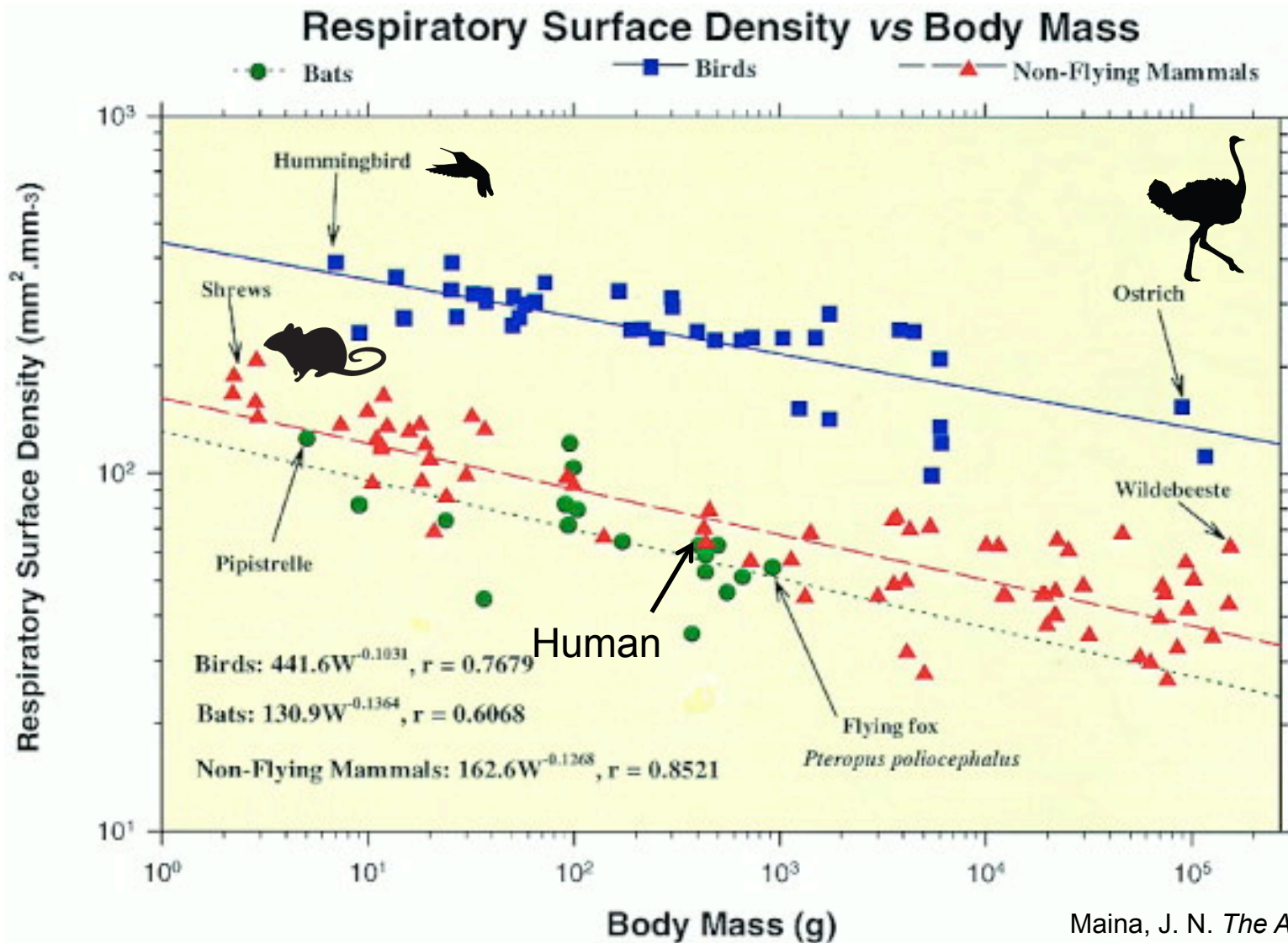
Log Plot Specific Surface Area
($\text{m}^2 \cdot \text{m}^{-3}$)



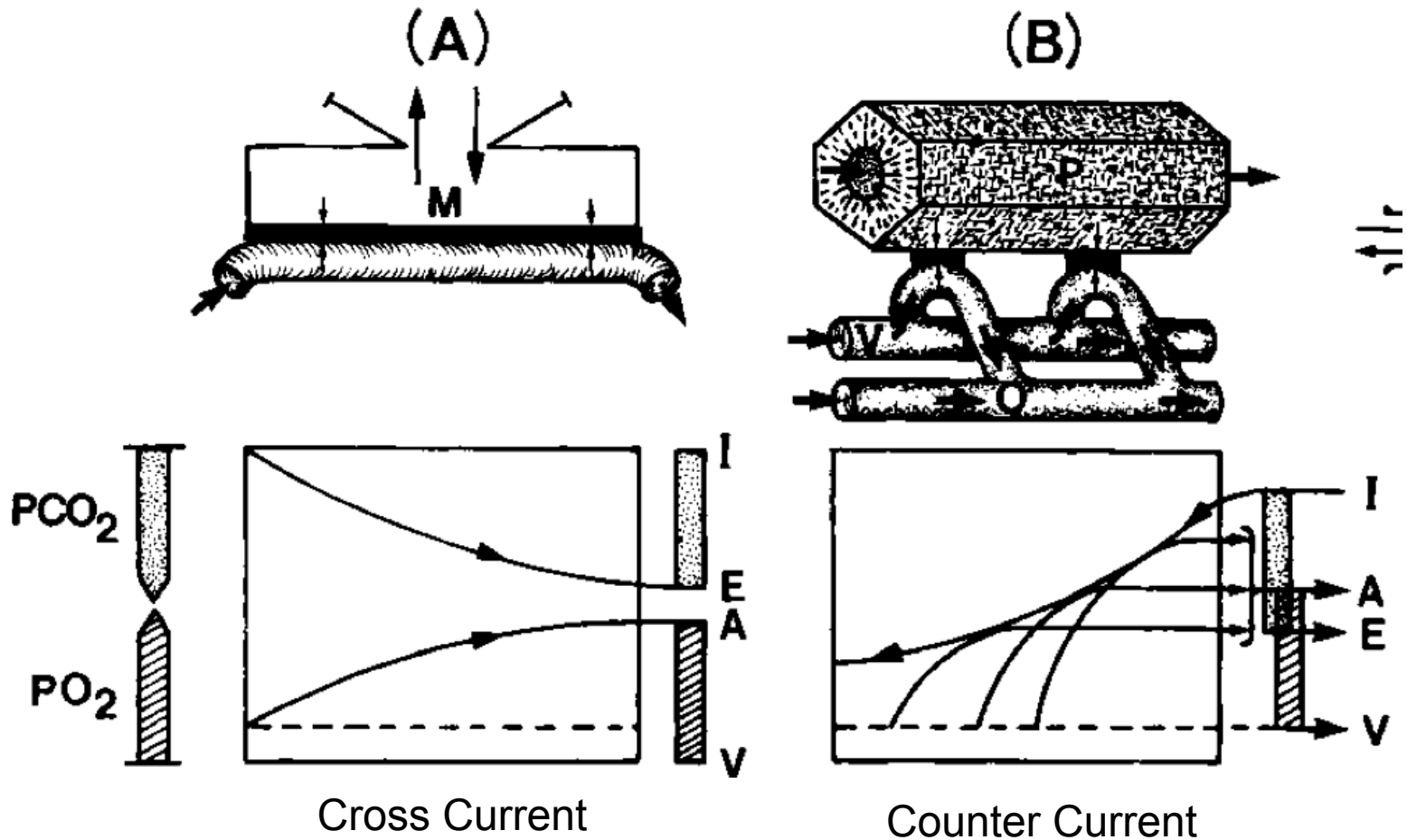
Specific Surface Area
($\text{m}^2 \cdot \text{m}^{-3}$)



Natural Systems – Scalable Solutions



What makes avian lung so appealing?

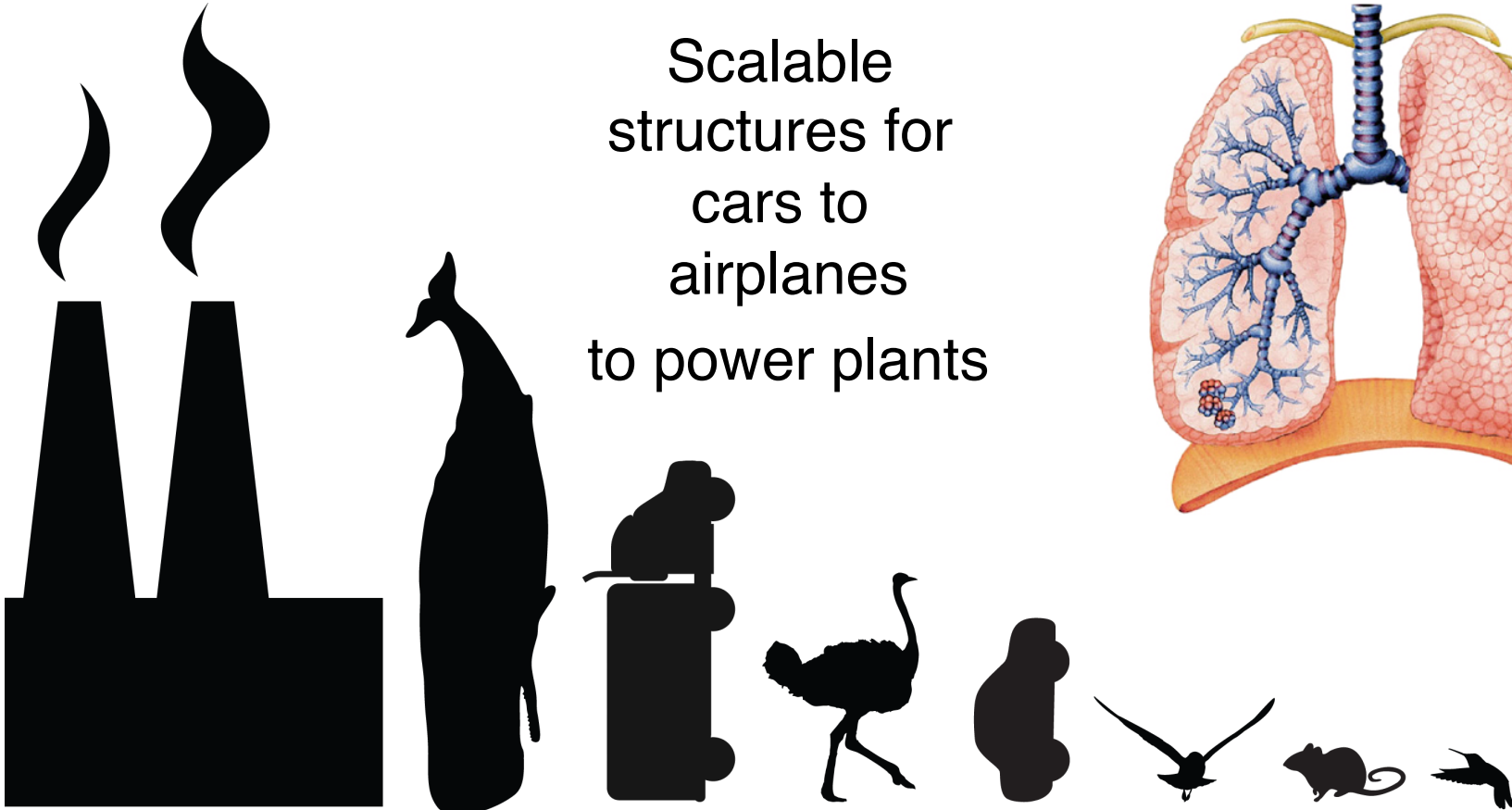
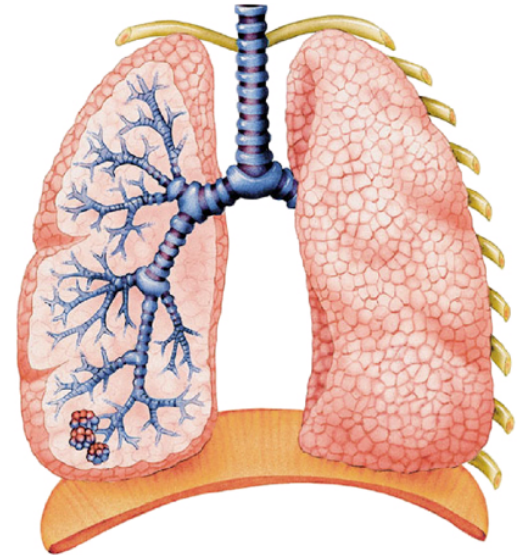


Building A Model Exchange Unit

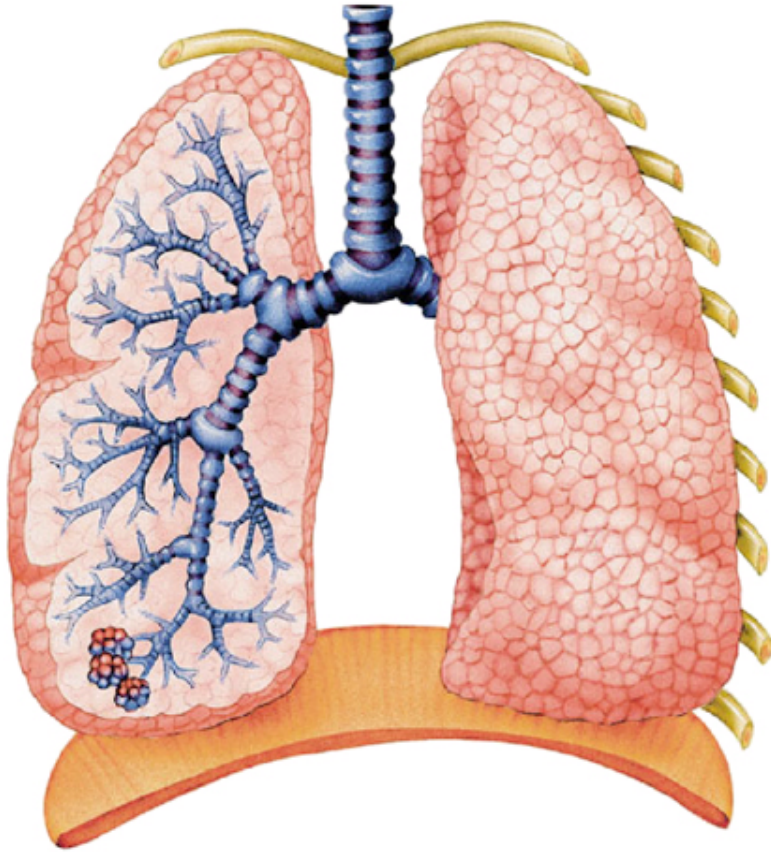
Each system has single, repeating Exchange Unit

Our Goal: *Develop Optimized Gas Exchange Unit*

Scalable
structures for
cars to
airplanes
to power plants



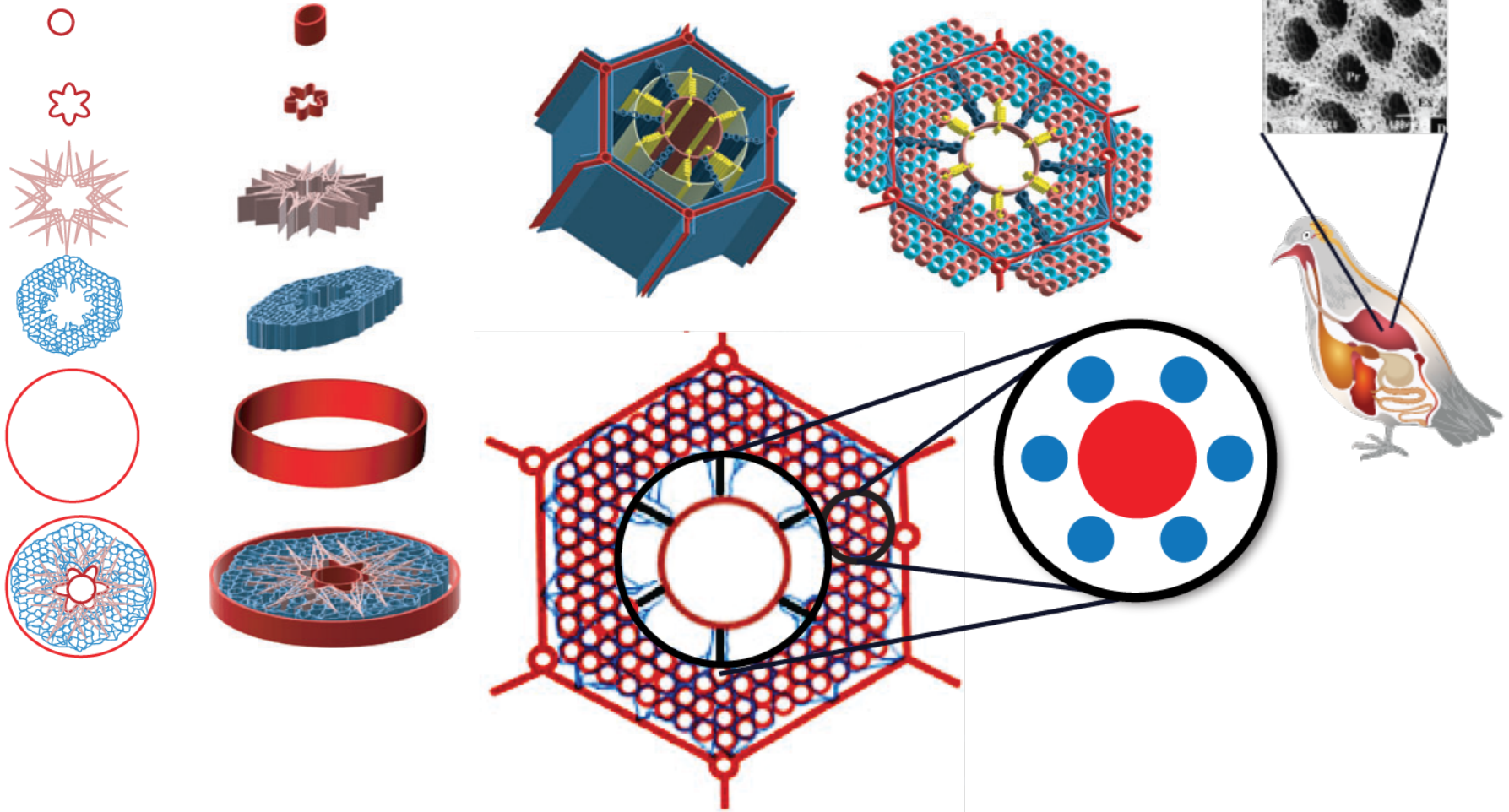
Applicable Properties of Natural System



- Surface Area
 - 3D arrangement
- Surface Chemistry
- Hierarchical Arrangement
- Compartmentalized Transfer
 - Heat transfer
 - Mass Transfer

What will our exchange unit look like?

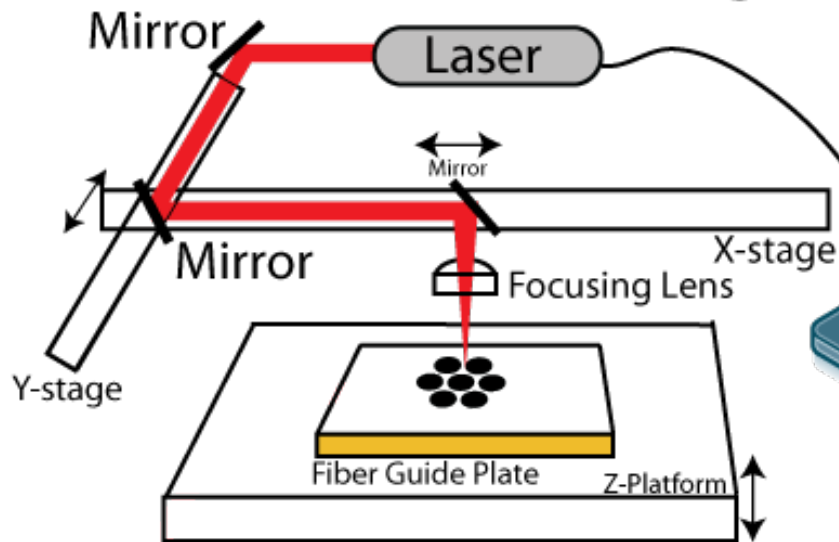
Transverse view Three dimensional view



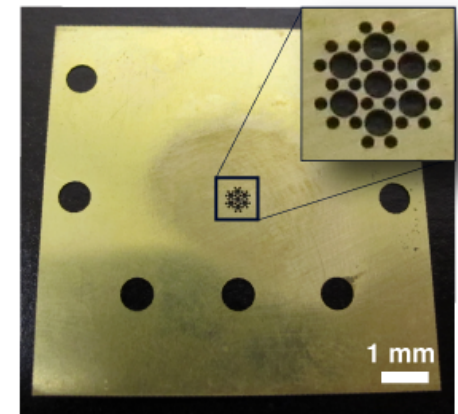
We Needed A Way to Create An Experimental Platform for Exploring Structure!

Making an Exchange Unit

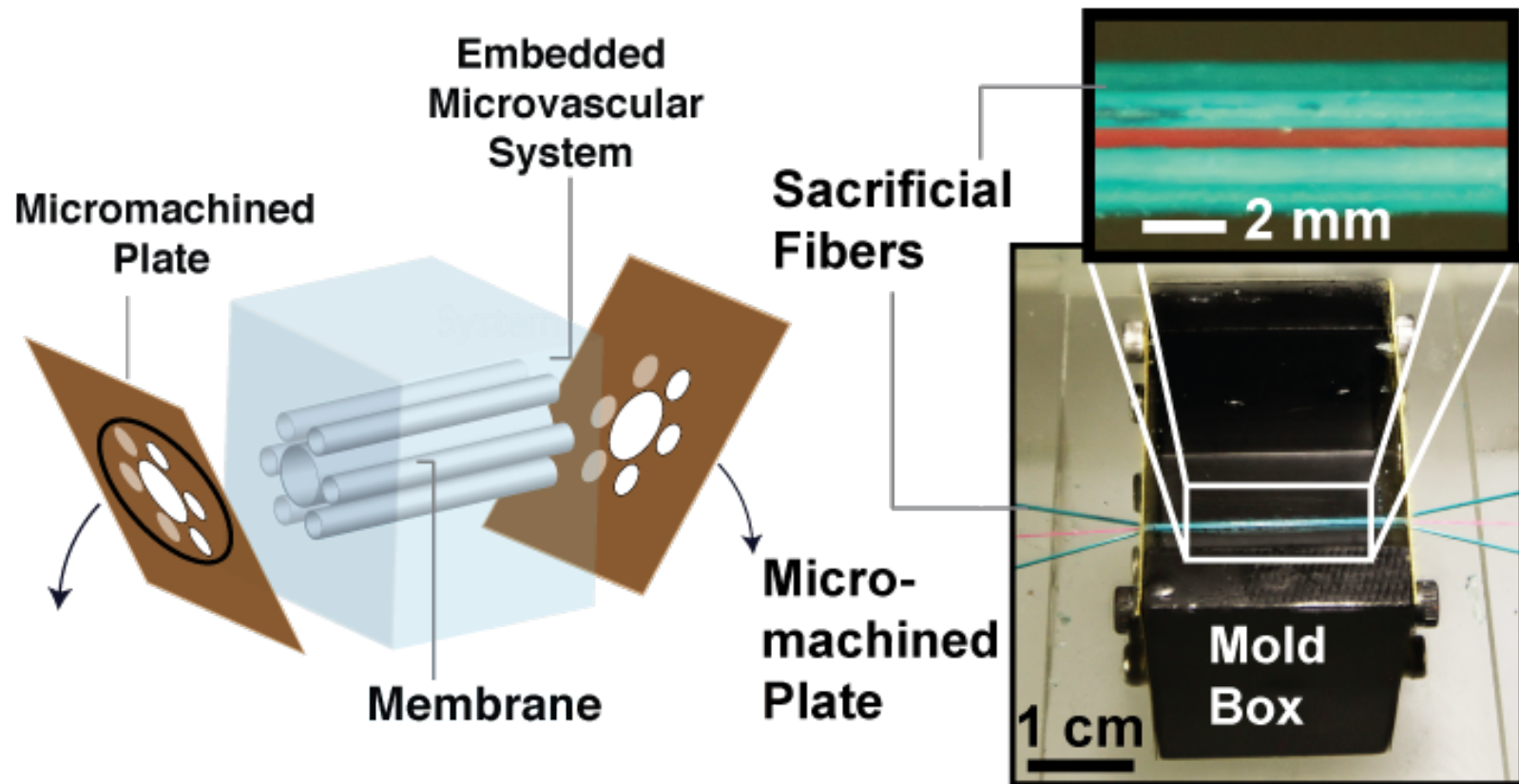
Computer Aided Micro-Machining



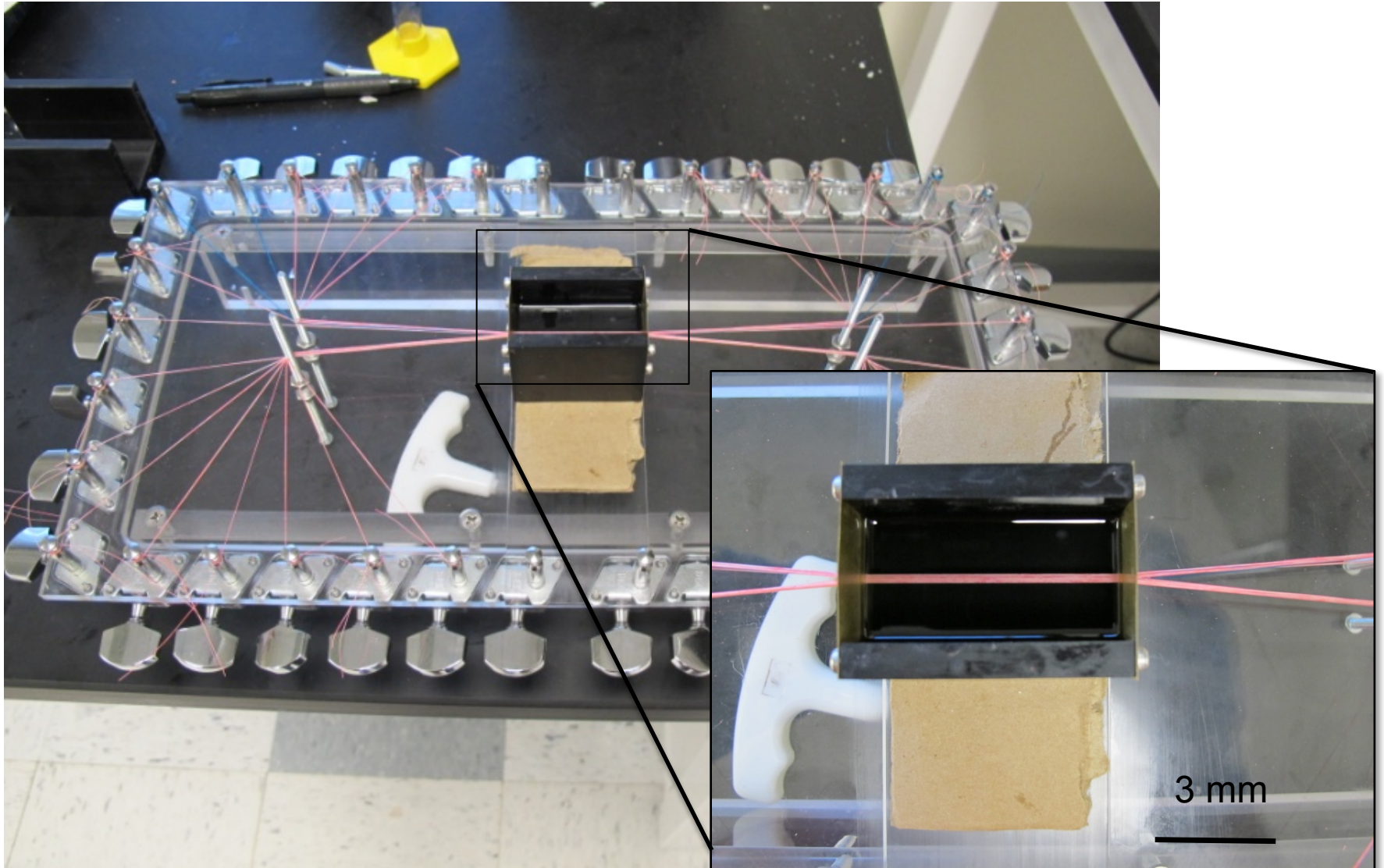
AutoCAD Design



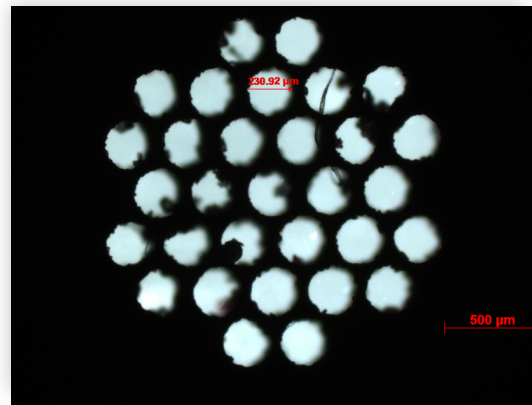
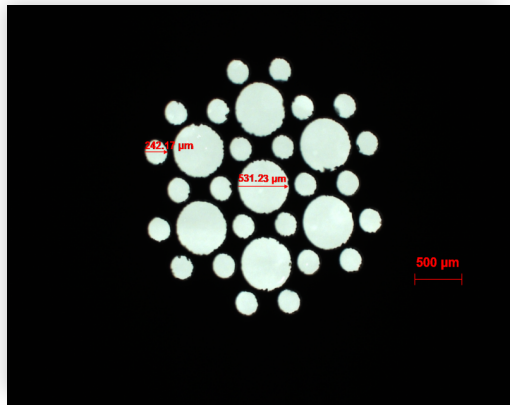
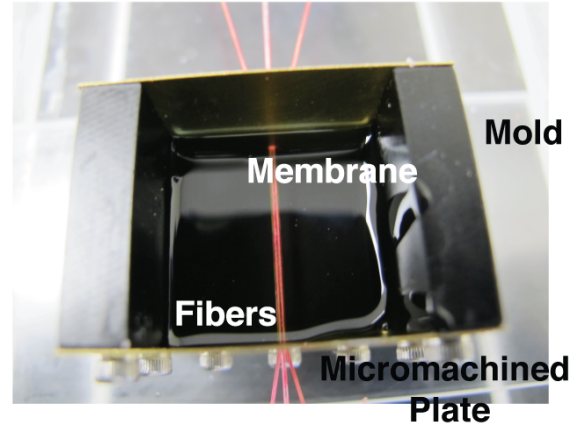
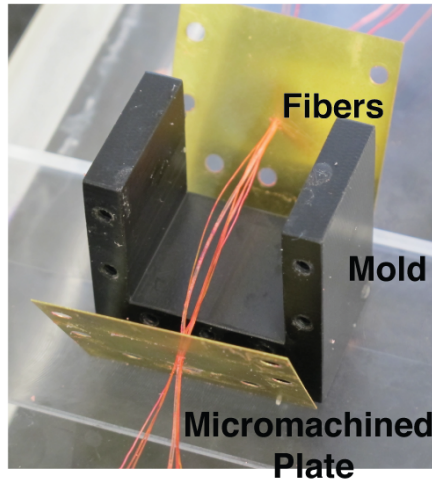
Patterning An Exchange Unit

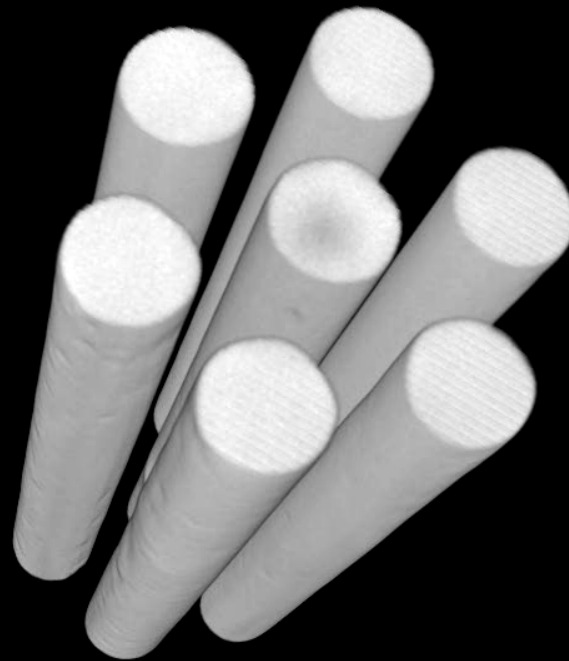


Established Fiber Tensioning Technology



Replication molding of natural patterns in 3D





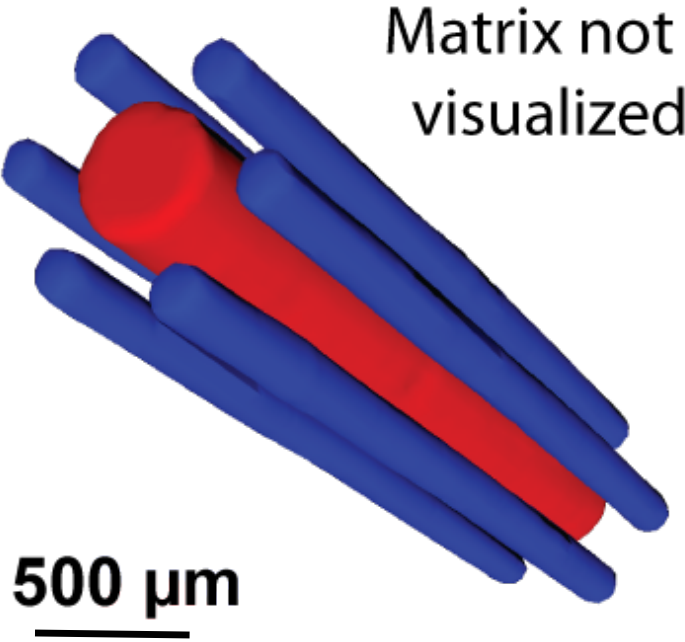
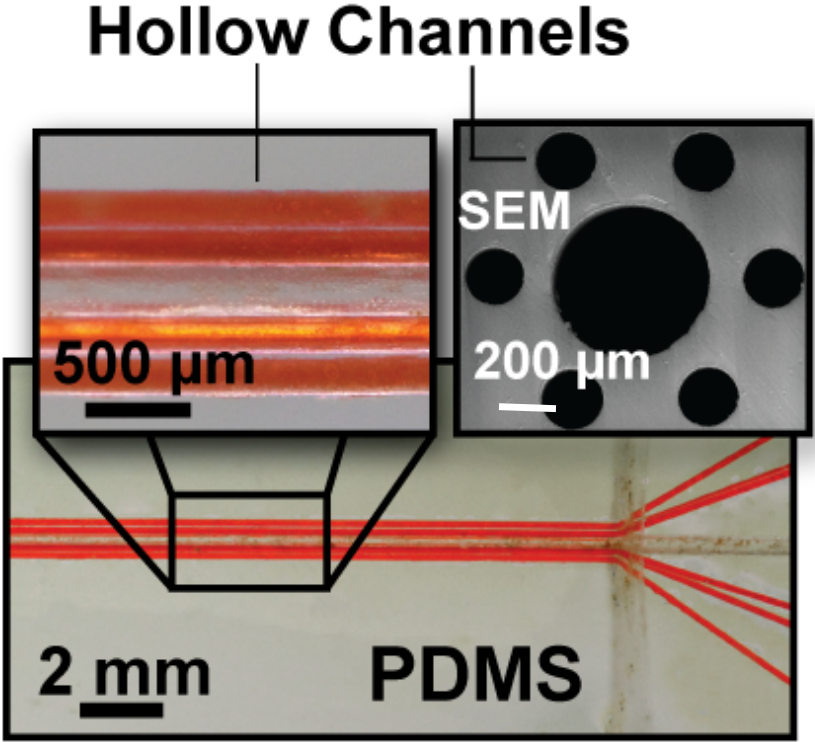
500 microns



Micro CT

Not Model

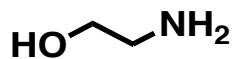
Analysis of Replication Molding



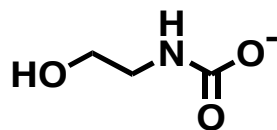
Observing CO₂ Absorption



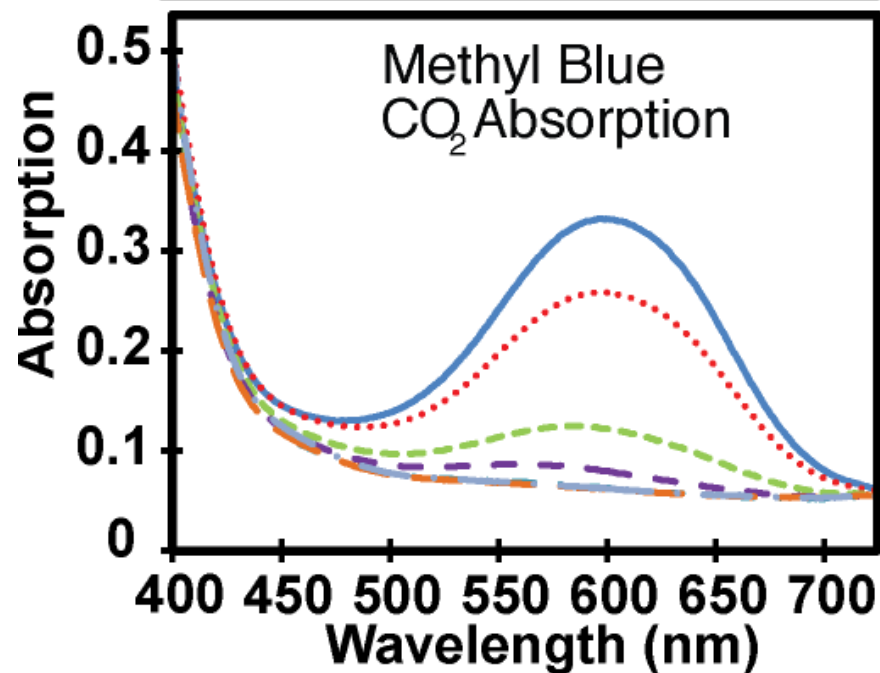
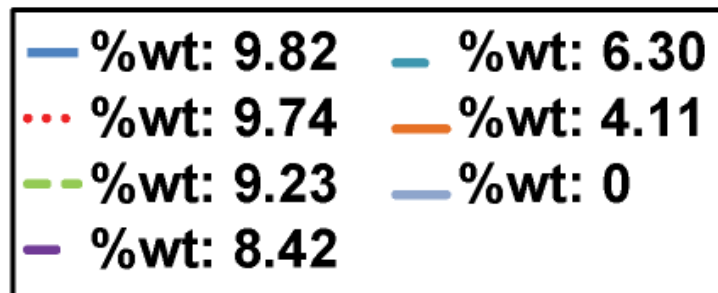
CO₂
→



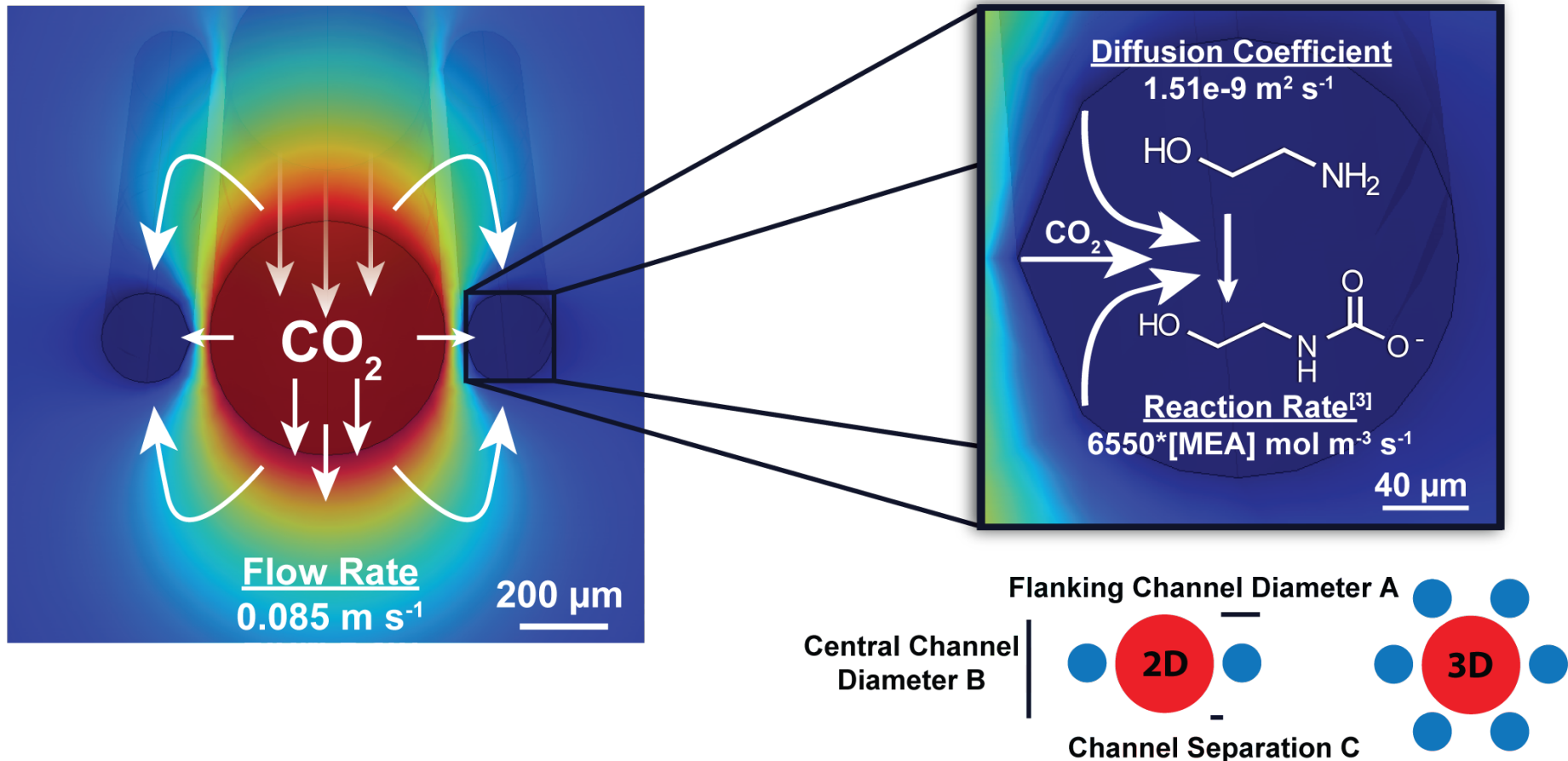
0 M CO₂



2.4 M CO₂



Modeling to Understand Experiment

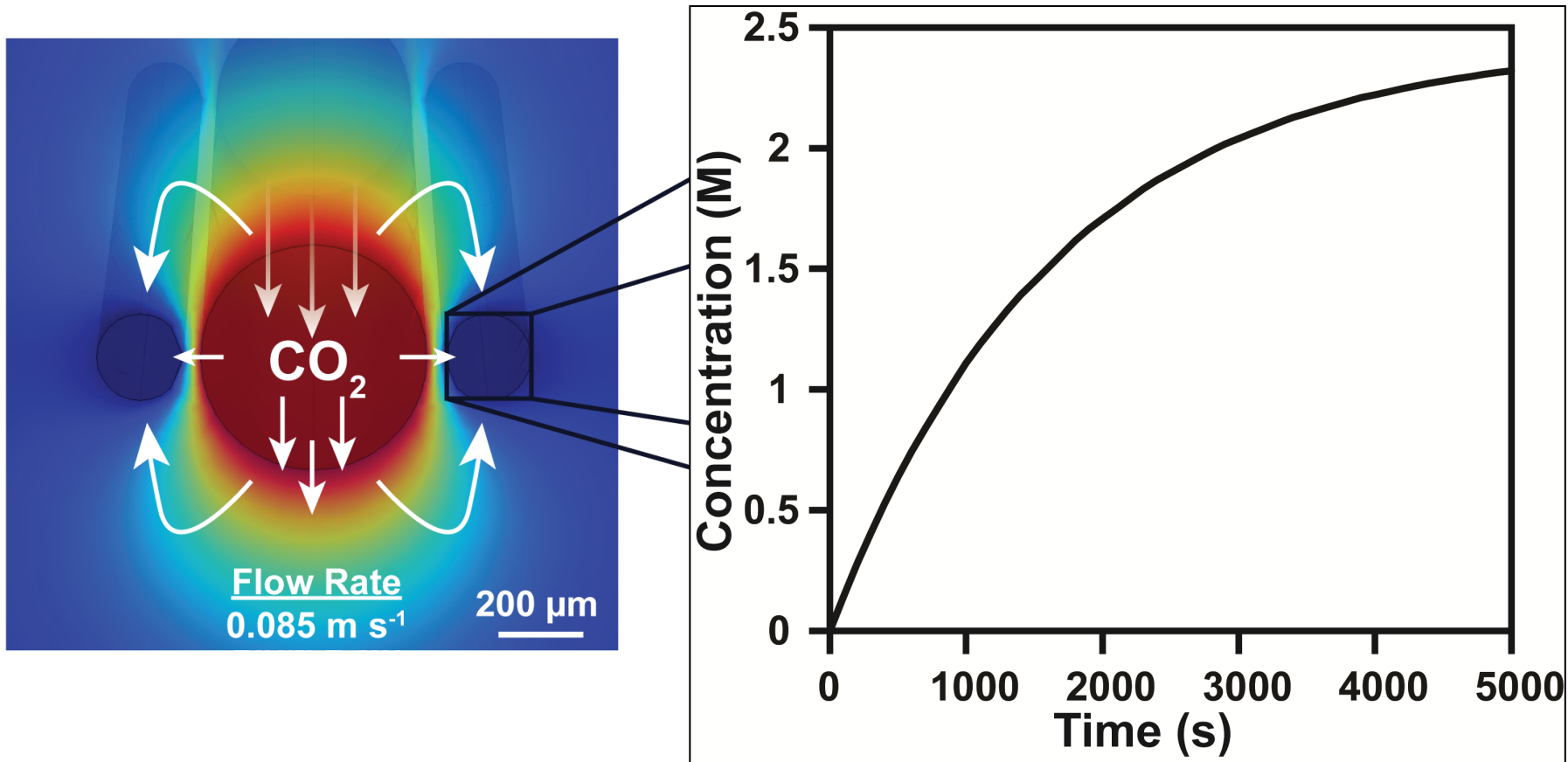


Dang, H.; Rochelle, G. T. Separation Science and Technology 2003, 38, 337.

Maceiras, R. Álvarez, E.; Cancela, M. Á. Chem. Eng. J. 2008, 138, 295-300.

Merkel, T. C. Bondar, V. I. Nagai, K. Freeman, B. D.; Pinnau, I. J. Polym. Sci., Part B: Polym. Phys. 2000, 38, 415-434.

Modeling to Understand Experiment

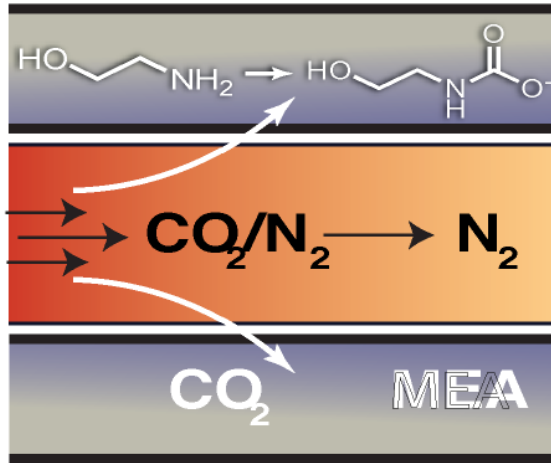




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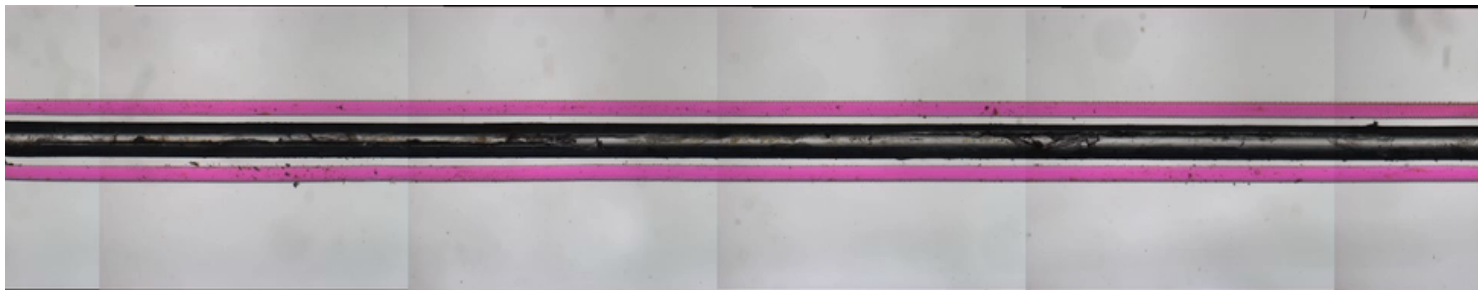
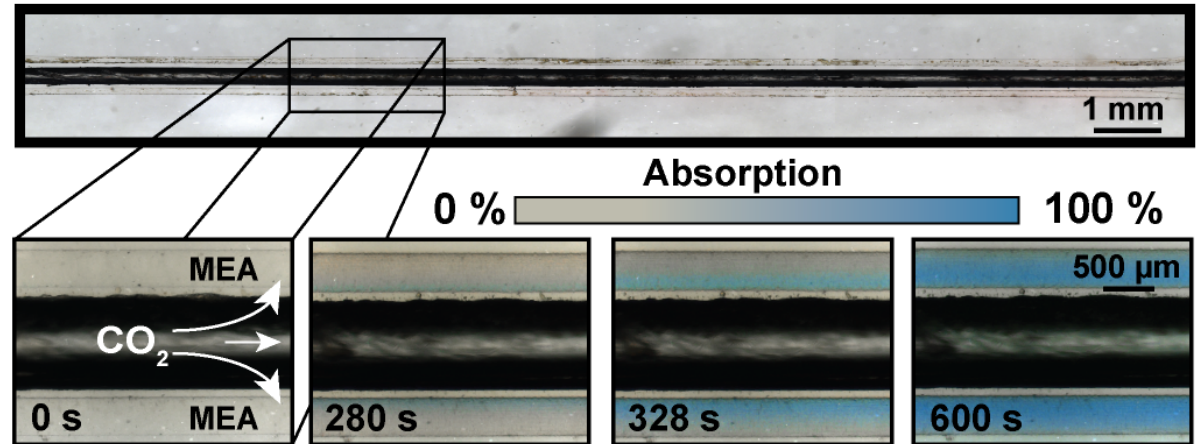
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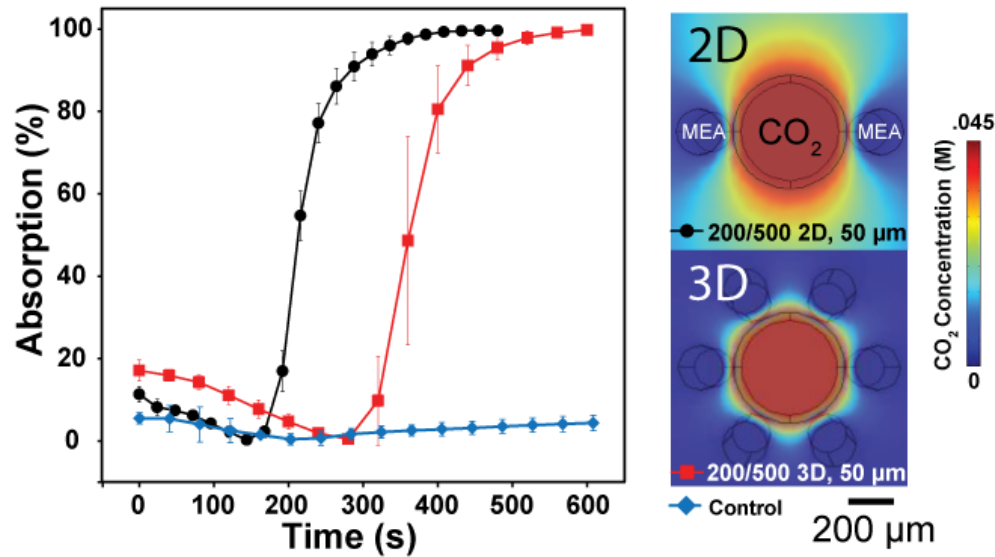
Spatio-Temporal Nature of Reaction



-  CO₂ Saturated Solution (pH ~8)
-  Empty (pH ~13)



2D vs. 3D : Visualizing Reactivity

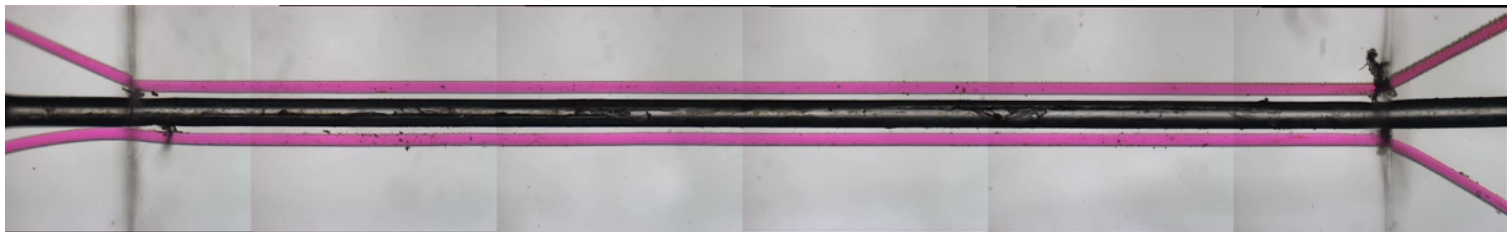


Mass Transfer Rate
Pure CO₂

1.66 ± .17 mol/m² hr

2.96 ± .35 mol/m² hr

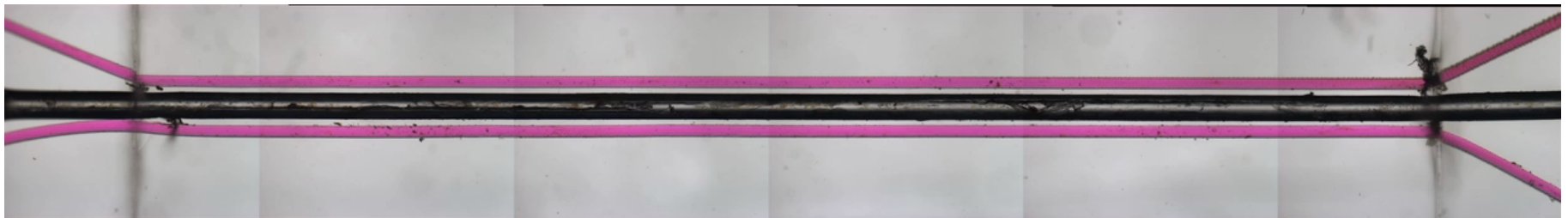
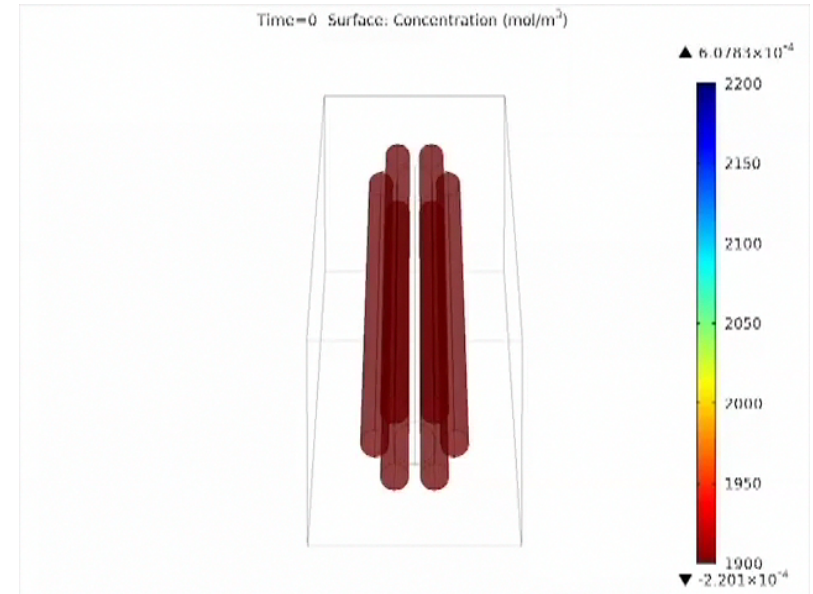
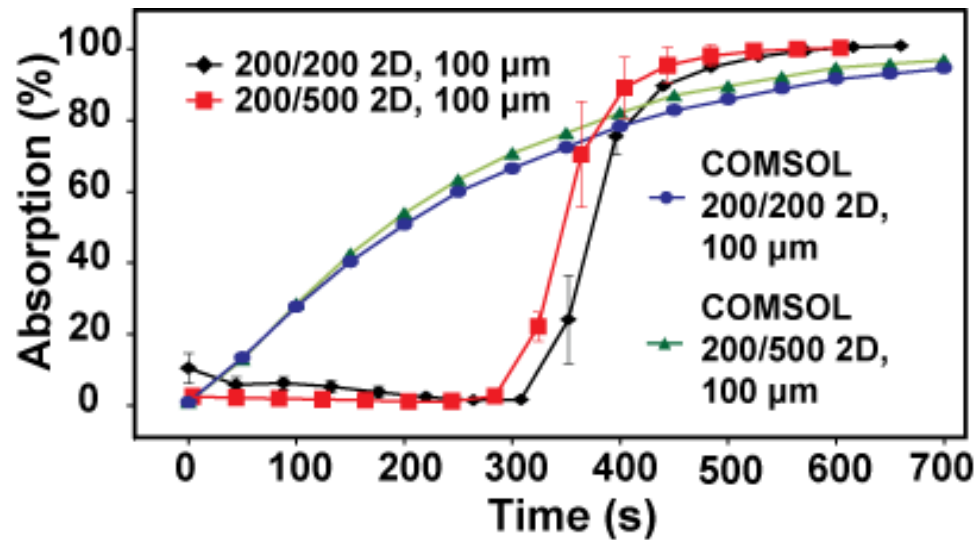
2D



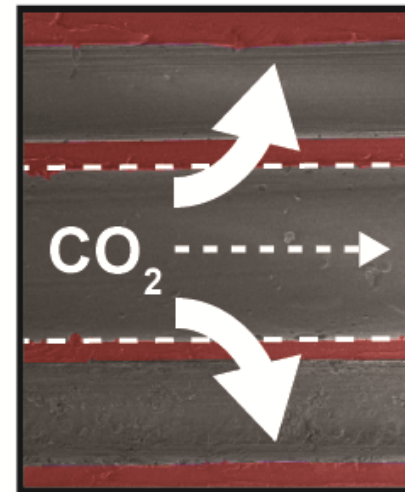
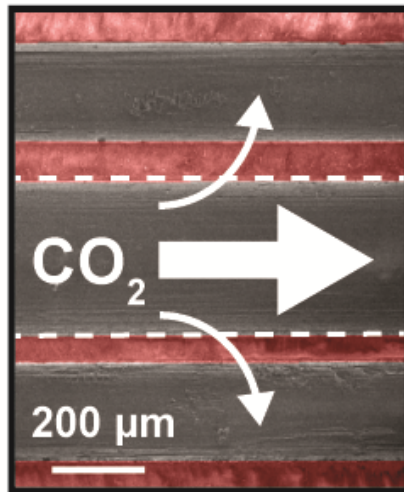
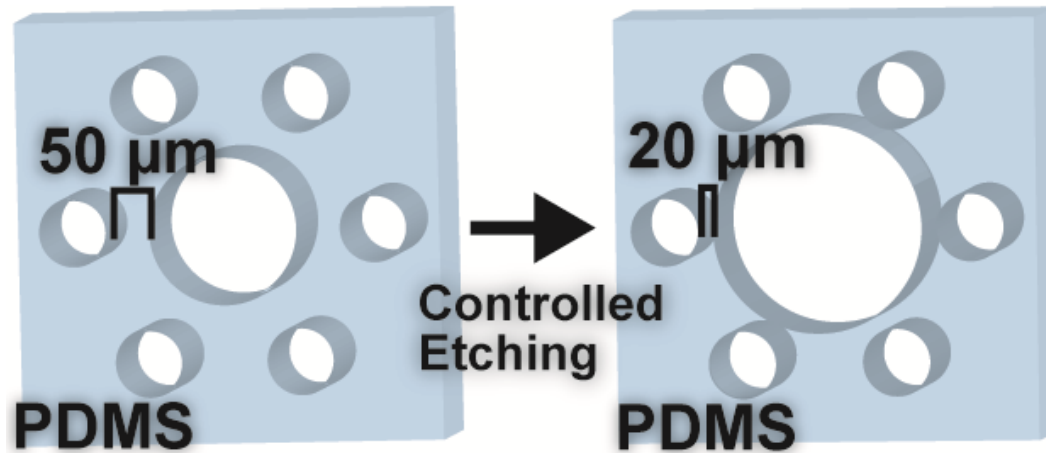
3D



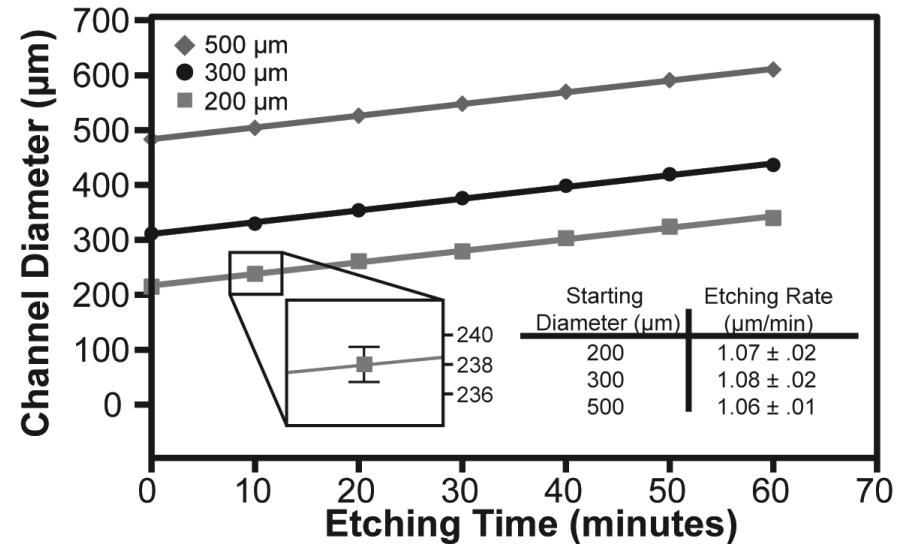
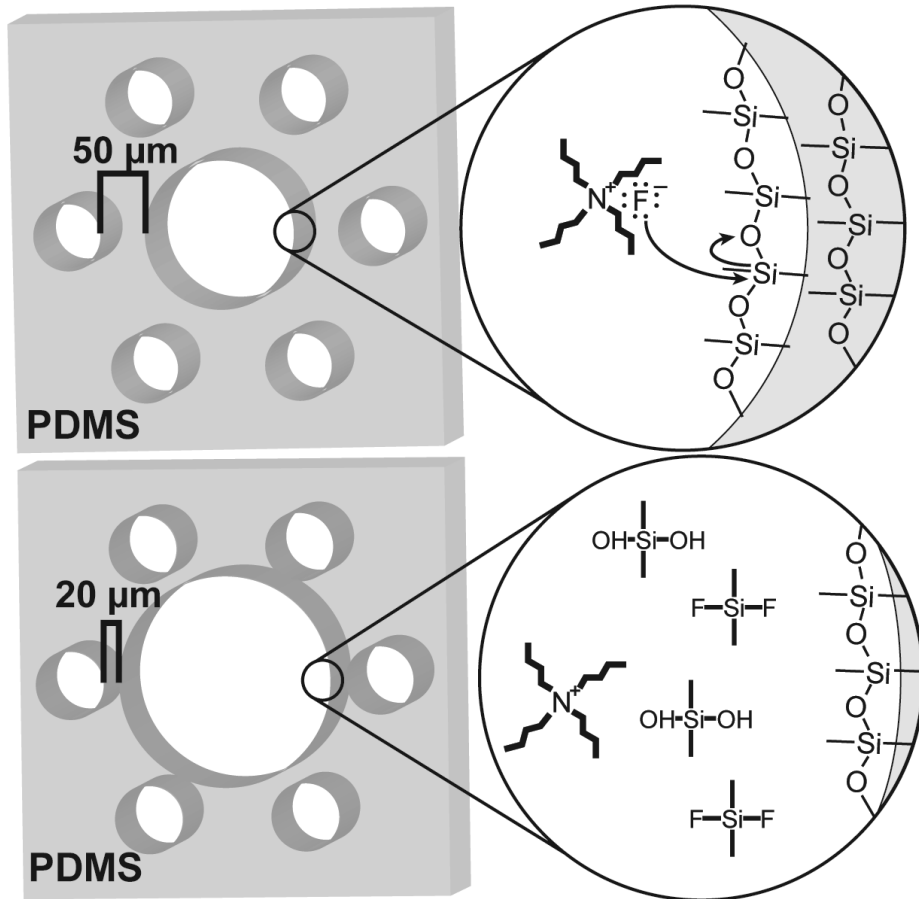
Matching Modeling and Experiment



Controlling Transfer By Changing Unit Geometry

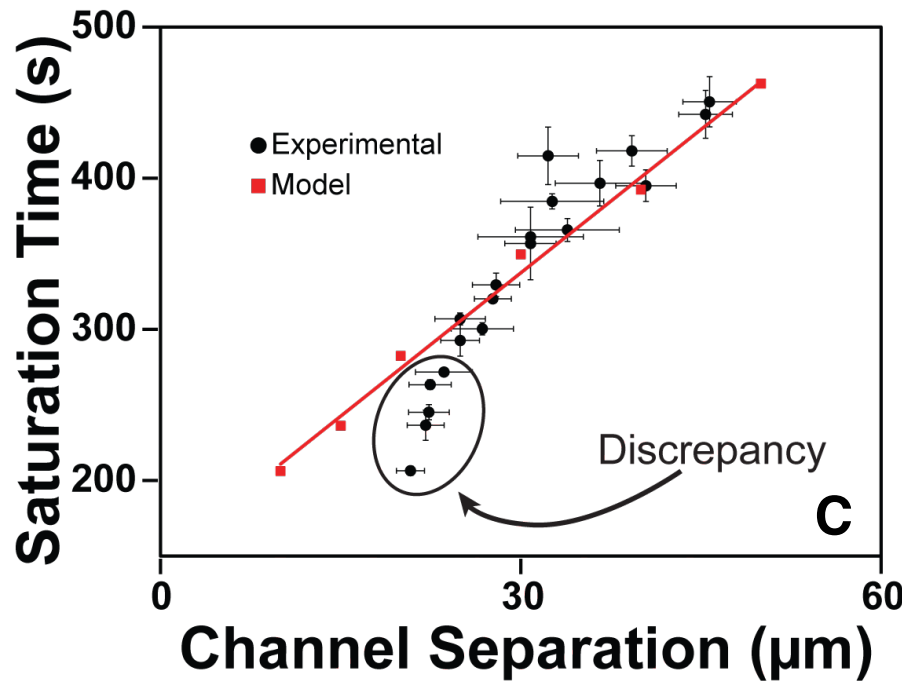
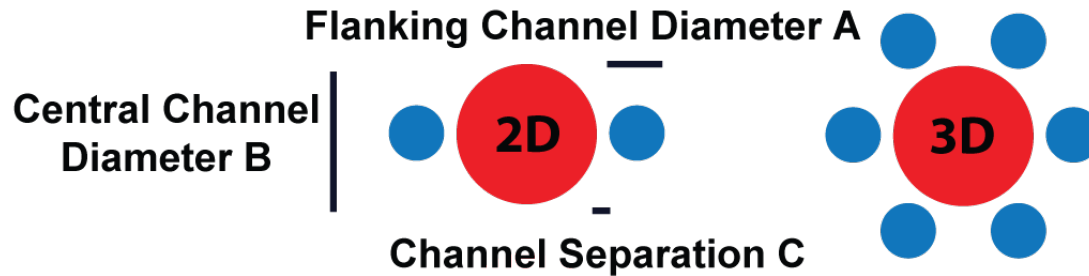


Etching with Micron Precision



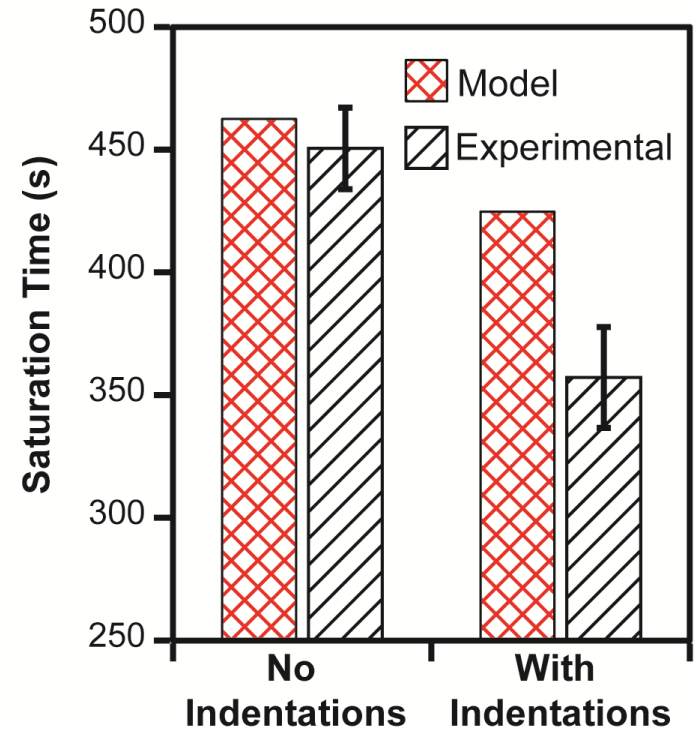
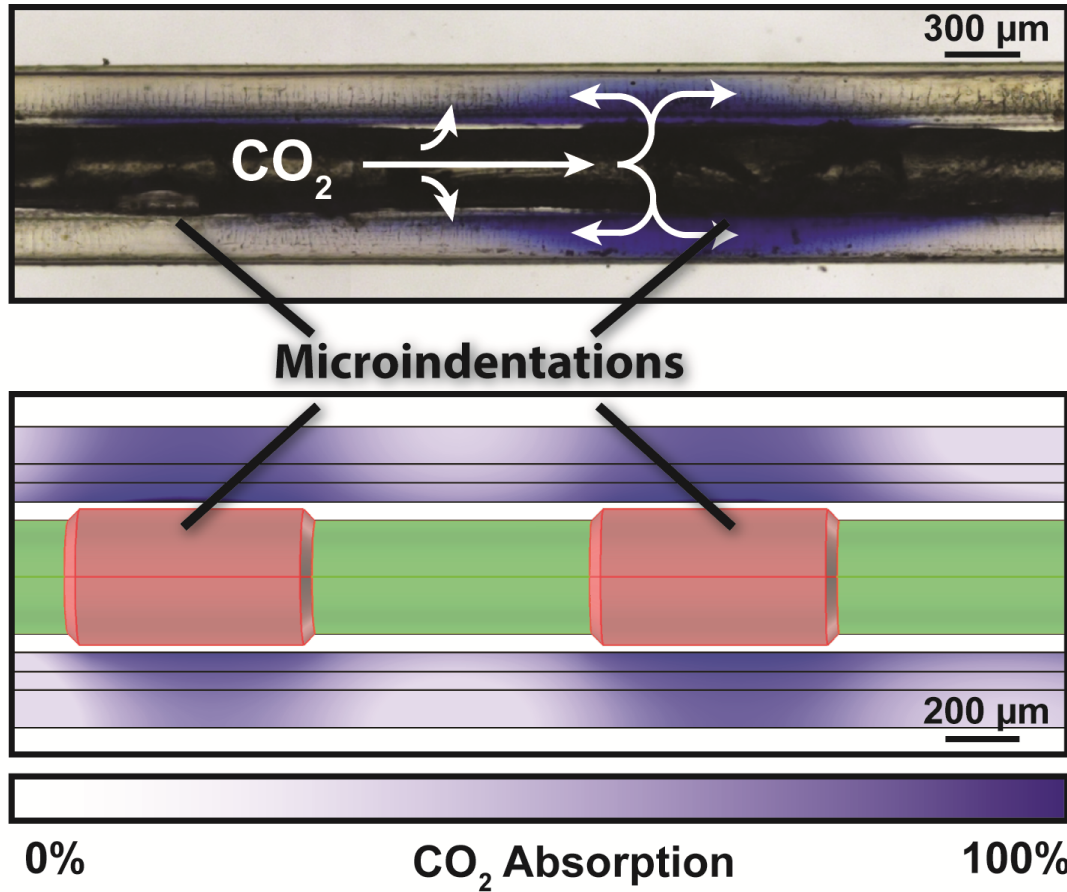
Flow Rate (mL min^{-1})	Etching Rate ($\mu\text{m min}^{-1}$)
2.00	$1.07 \pm .03$
1.00	$0.97 \pm .02$
0.50	$1.06 \pm .01$
0.25	$0.85 \pm .03$

Controlling Channel Separation

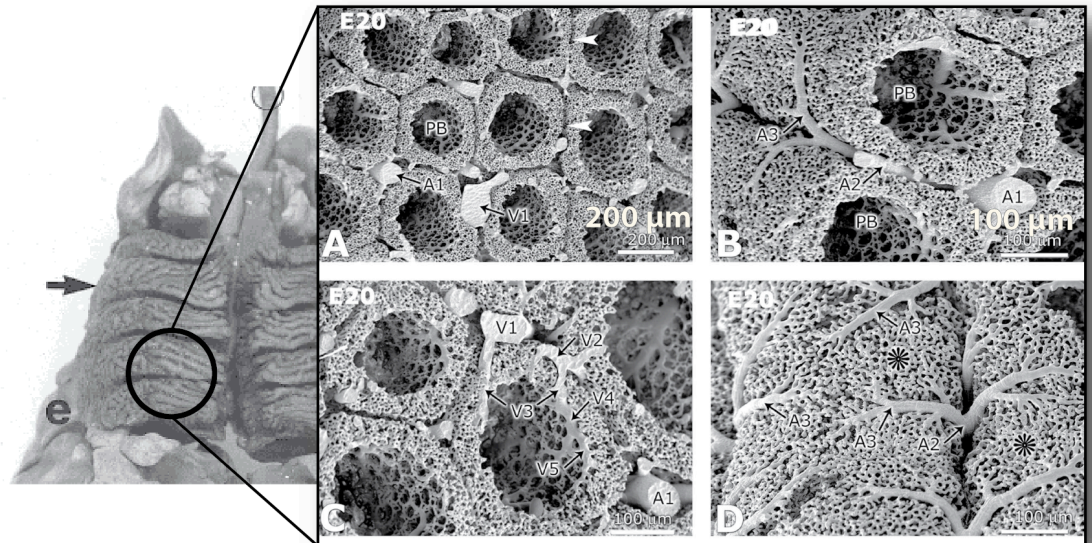
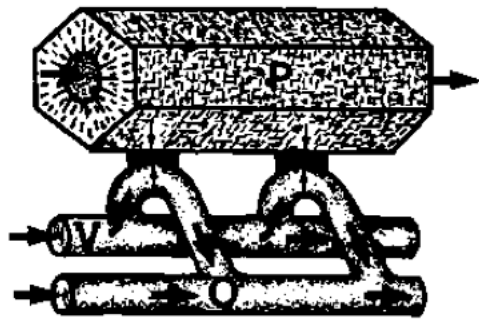


Etching Allows Control Over Reaction Rate

Modeling Reveal Micro-Indents are Key



How do we get to here?

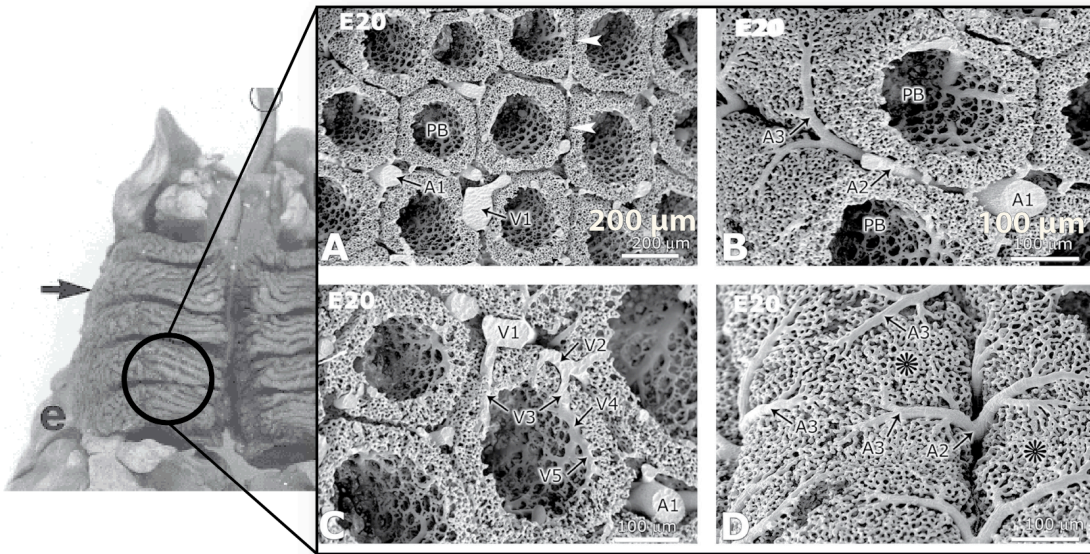


More Complex Structures

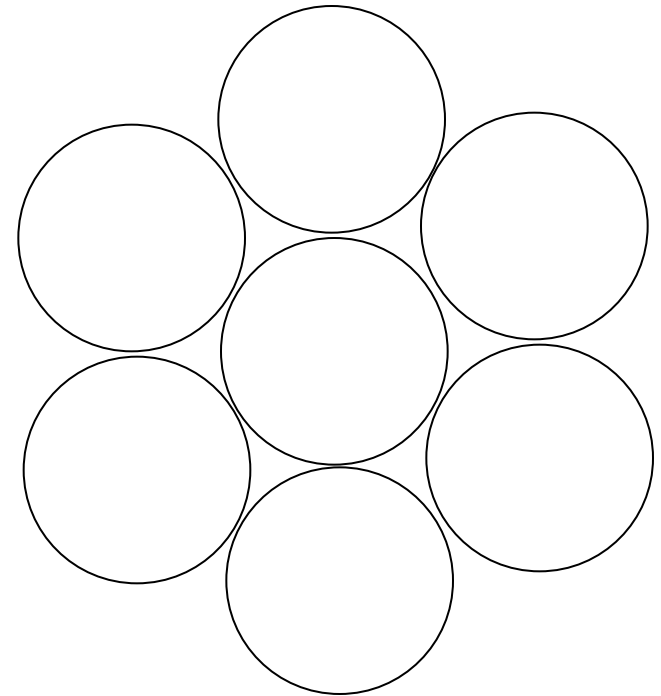
Specific Surface Area = $200,000 \text{ m}^2 \text{ m}^{-3}$

i.e) What's coming up next?

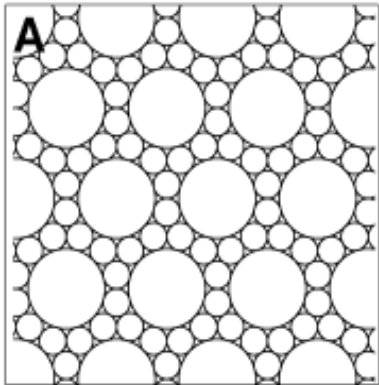
Packing to achieve efficiency



Specific Surface Area = $200,000 \text{ m}^2 \text{ m}^{-3}$

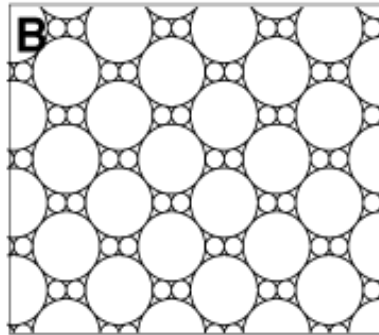


Searching for the optimized unit: A packing problem



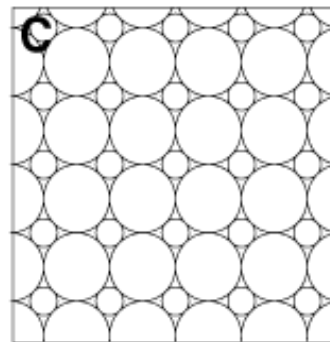
Compact Packing A

$$R_{\text{small}} = 0.35 \times (R_{\text{big}})$$



Compact Packing B

$$R_{\text{small}} = 0.28 \times (R_{\text{big}})$$



Compact Packing C

$$R_{\text{small}} = 0.42 \times (R_{\text{big}})$$

**Mass
Transfer
Unit**

**Specific
Surface Area**
 $\text{m}^2 \cdot \text{m}^{-3}$

Wetted Wall

100-300

Hollow Membrane
Contactor

~ 1500-3000

Our Previous
Pattern

~ 2000-2800

Dense, Compact
Pattern A

3549

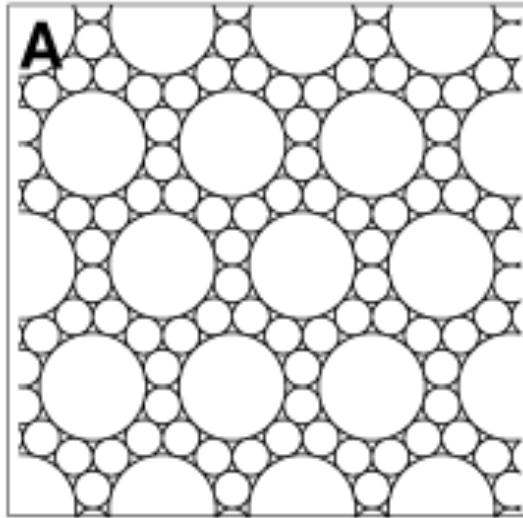
Dense, Compact
Pattern B

5180

Dense, Compact
Pattern C

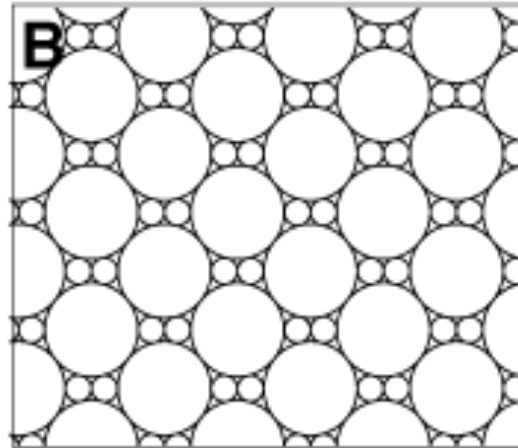
4601

Synthesizing Compact, Packed Geometry



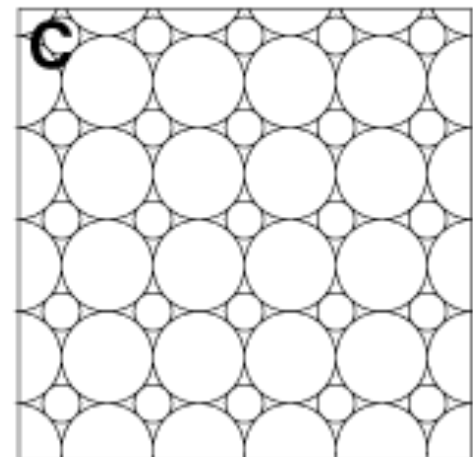
Compact Packing A

$$R_{\text{small}} = 0.35 \times (R_{\text{big}})$$



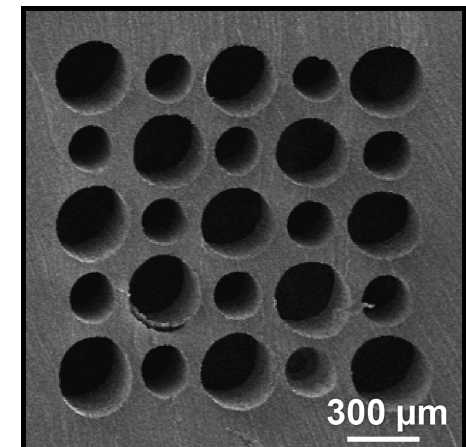
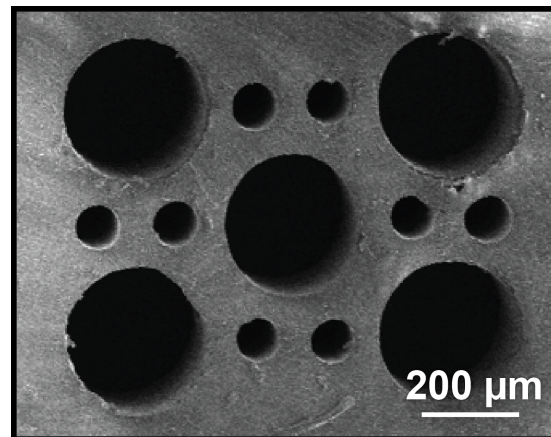
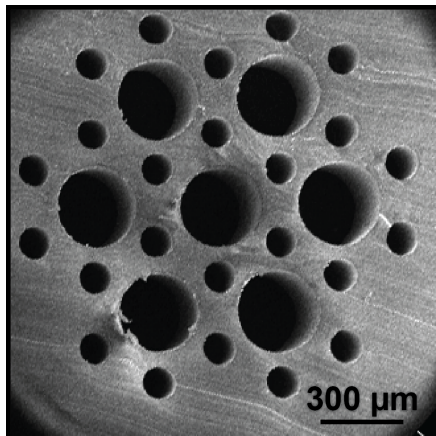
Compact Packing B

$$R_{\text{small}} = 0.28 \times (R_{\text{big}})$$



Compact Packing C

$$R_{\text{small}} = 0.42 \times (R_{\text{big}})$$



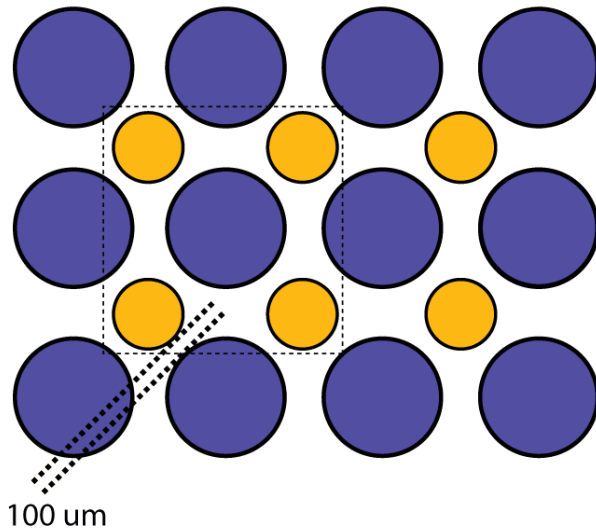
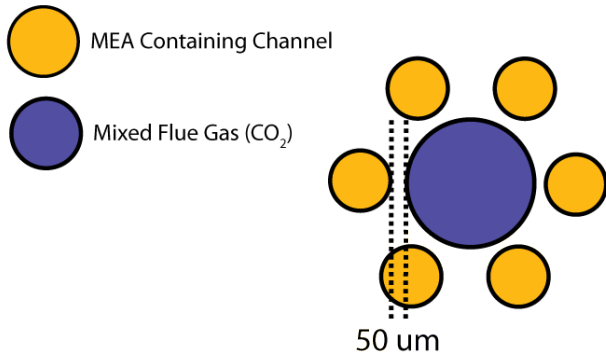
Comparison of Channel Arrangements

Mass Transfer Rate

Pure CO₂

$$\text{mol} \cdot \text{m}^{-2} \cdot \text{hr}^{-1}$$

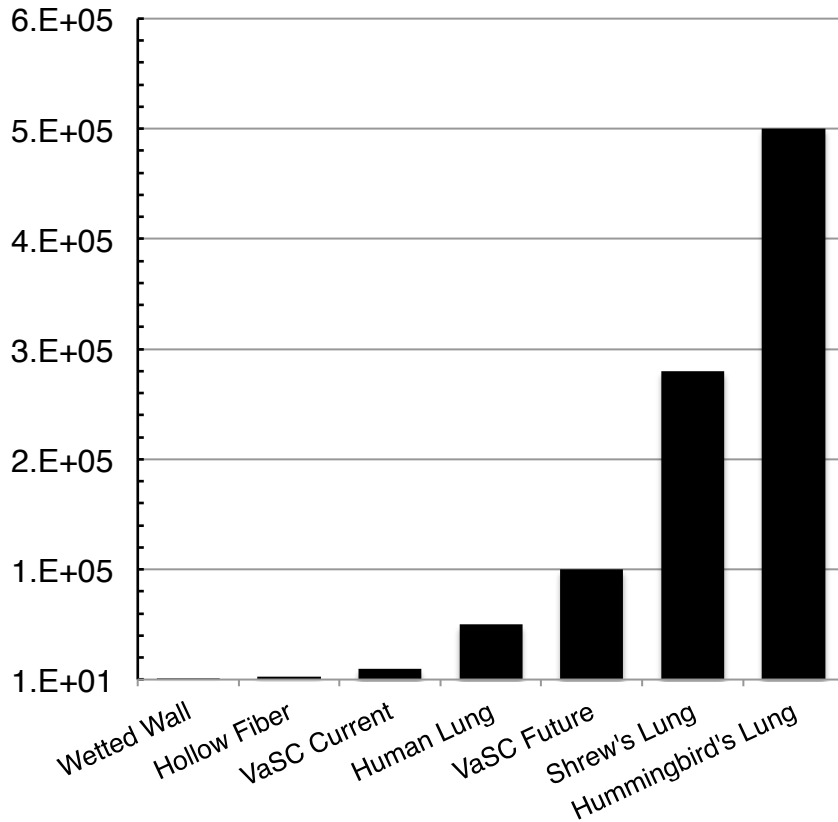
$$2.96 \pm 0.35$$



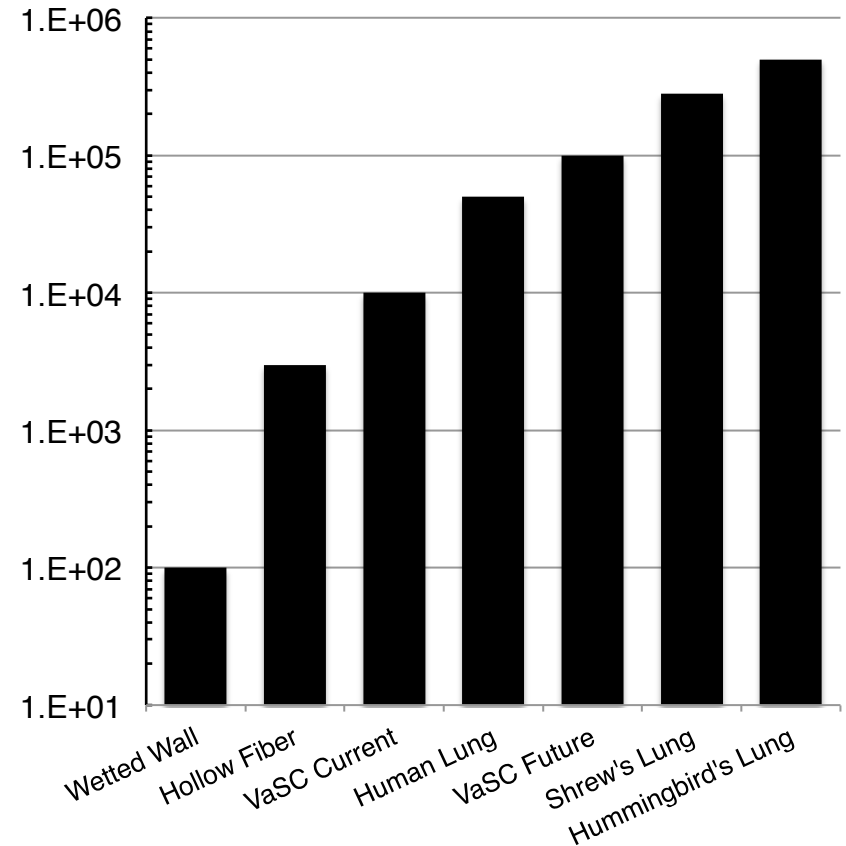
$$3.4 \pm 0.25$$

Where does VaSC fit in?

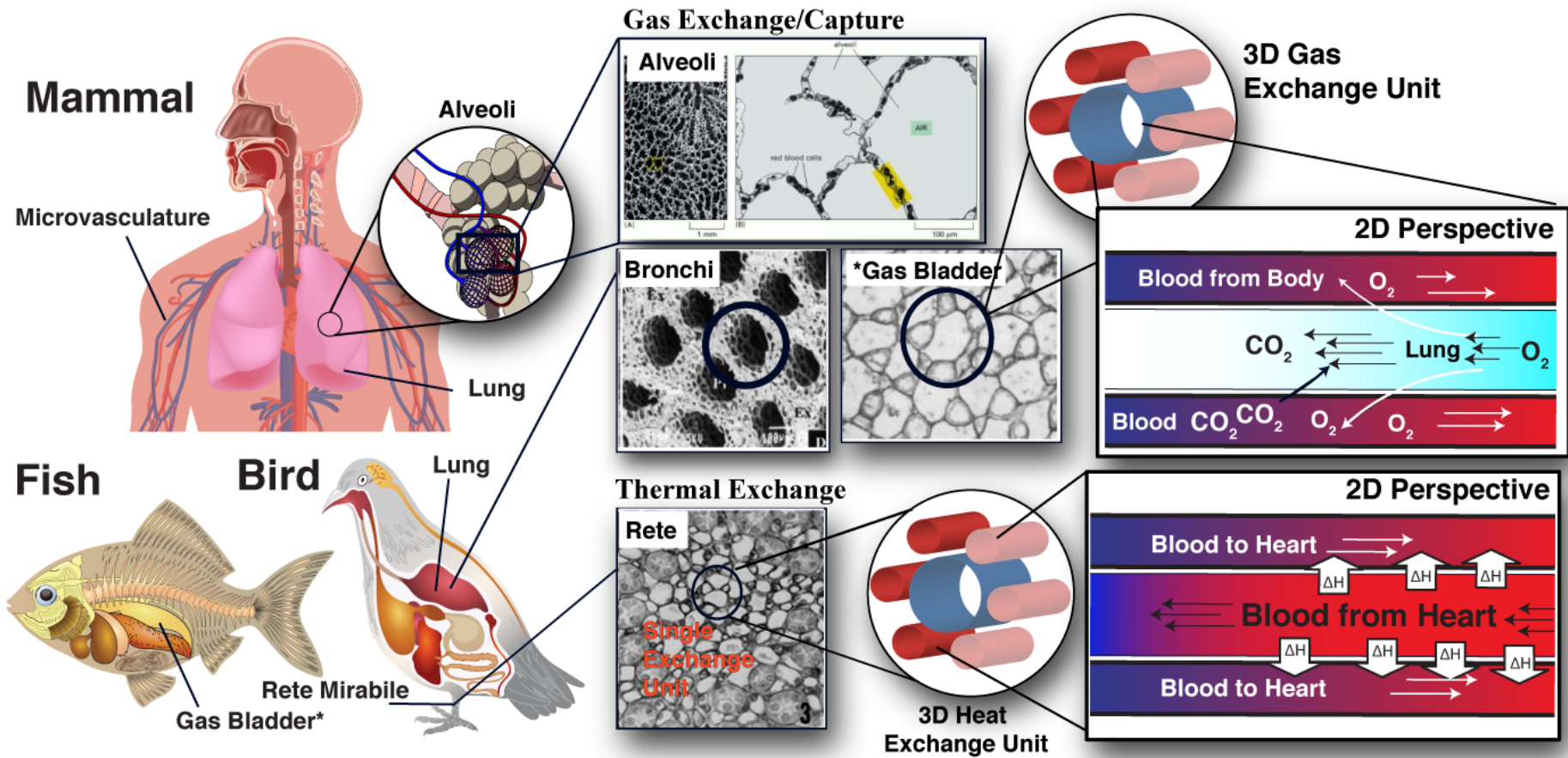
Specific Surface Area ($\text{m}^2 \cdot \text{m}^{-3}$)



Specific Surface Area Log scale

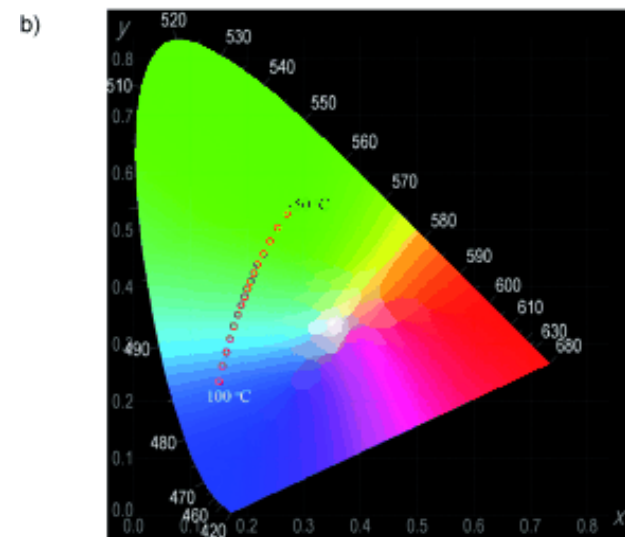
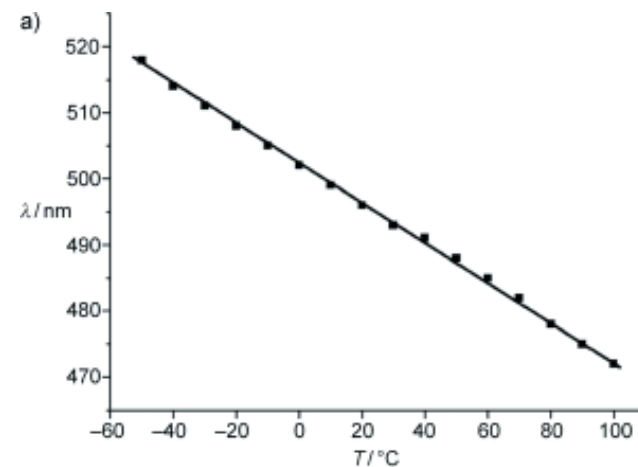
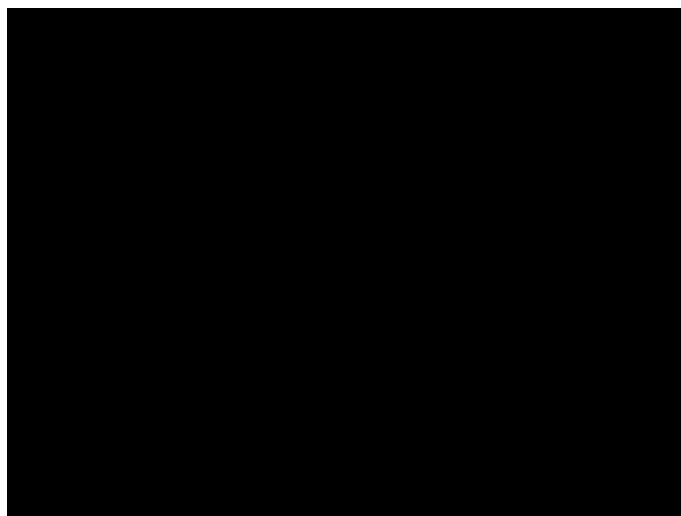
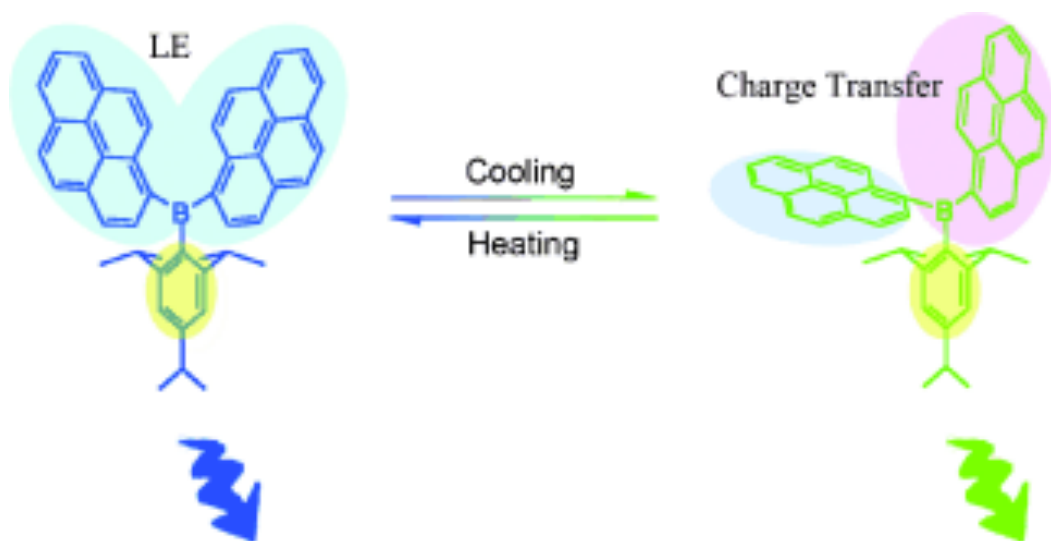


What about Heat Exchange?

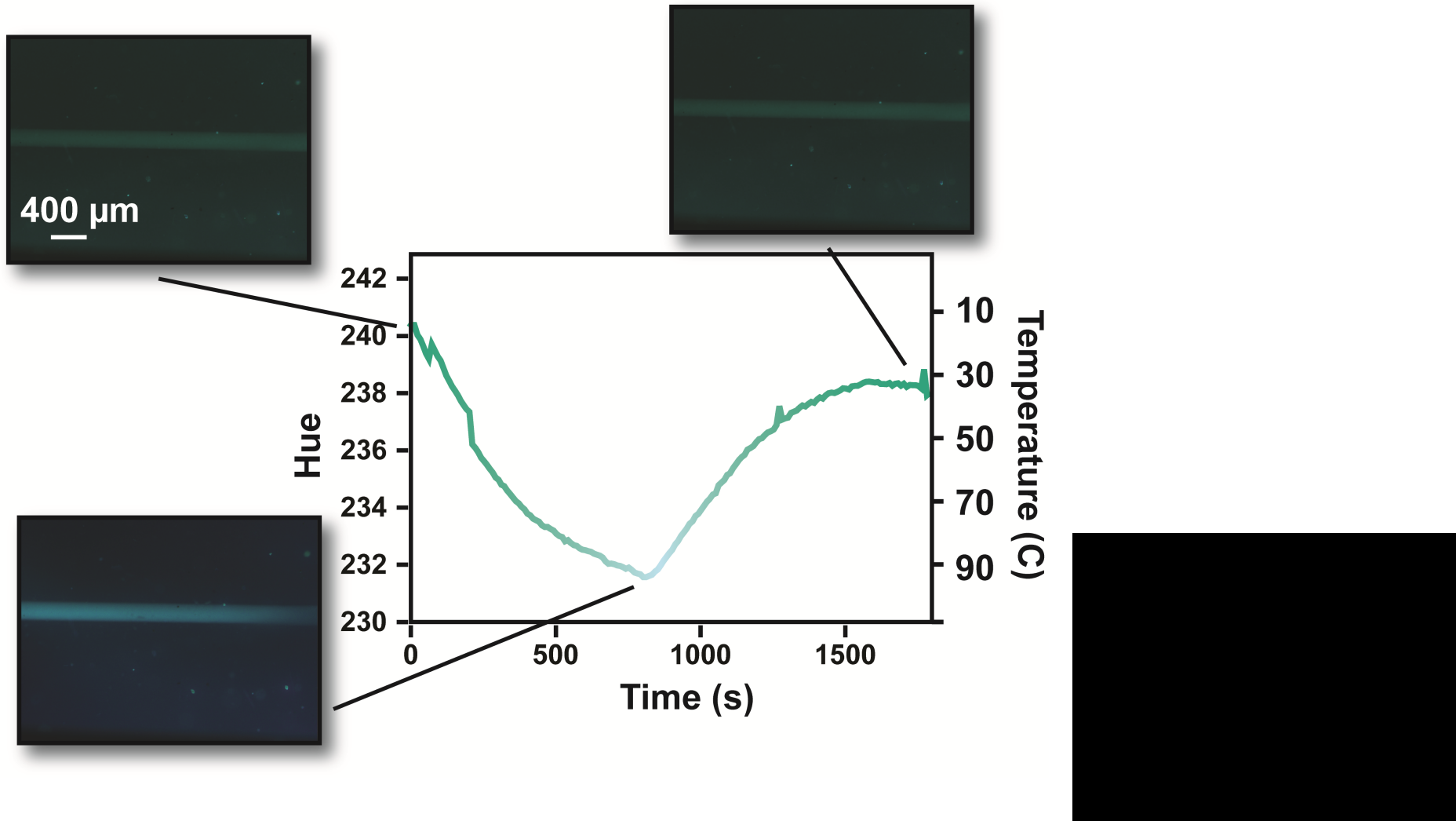


Thermal And Gas Exchange Are Based On Same Structures

A Fluorescent Thermometer

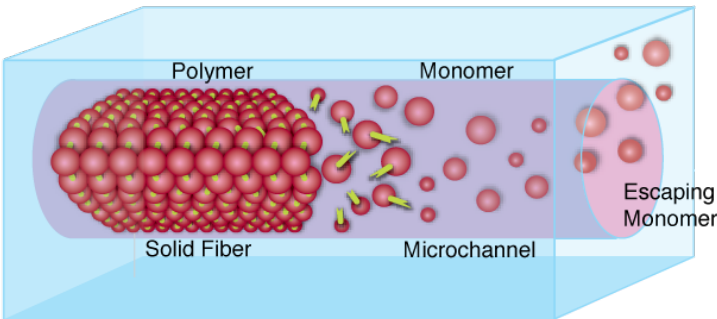


Temperature in Micro-Vascular Material

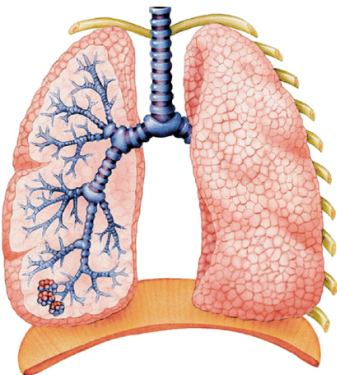


Micro-Vascular Exchange Units : Bio-Inspired Energy & Mass Transfer

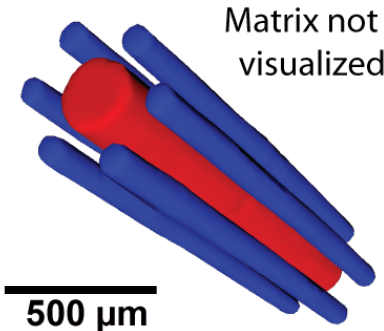
VaSC



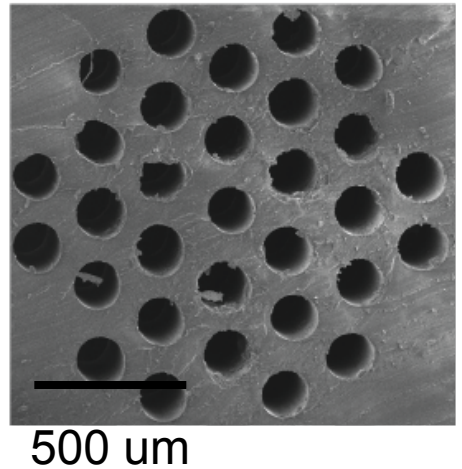
Our Motivation



Exchange Unit



Hierarchy



Next Year

Heat Transfer

Full Hierarchy

Acknowledgements



UCIRVINE

3M

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