Foam Generation and Propagation in Porous Media

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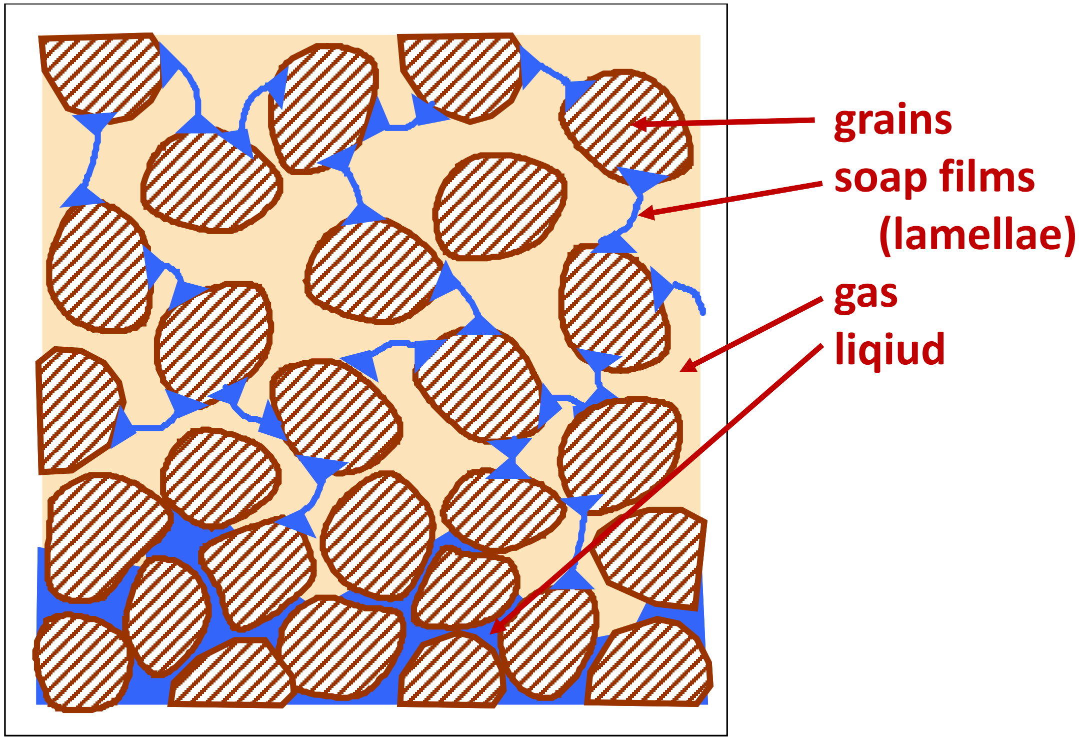
What is Foam Inside Porous Media?

- Liquid films separate gas bubbles, reduce gas mobility (“viscosify” the gas)
- Foam is not a new phase, but a two-phase flow phenom-enon that drastically reduces gas mobility
- Bubbles are as big as pores



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Applications of Foam in Porous Media

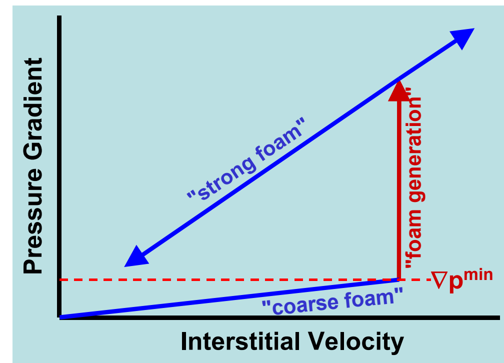
- Gas diversion in enhanced/improved oil recovery
- Acid diversion in well stimulation
- CO_2 Sequestration
- Liquid or gas diversion in aquifer remediation

In these all cases, foam behavior in pore space is key

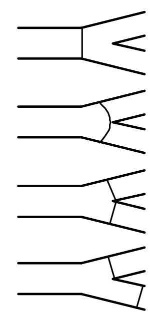
Goal: reduce gas mobility, redirect flow of fluids through geological formations

Foam Generation in Steady Flow

- Experiments find minimum ∇p for foam generation in steady gas-liquid flow: ***Why?***
- "Lamella division" is crucial step in foam generation
  - requires moving lamellae
  - requires Δp across throat > $(2\sigma/R_t)$
- What is minimum ∇p to mobilize lamellae in pore network?
- Model based on percolation theory predicts a minimum ∇p for lamella division, foam generation



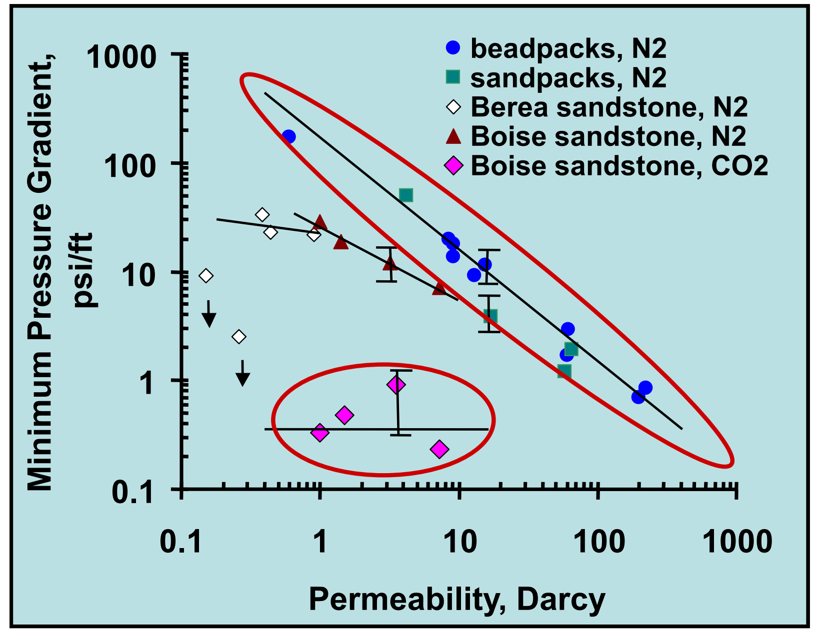
LAMELLA DIVISION

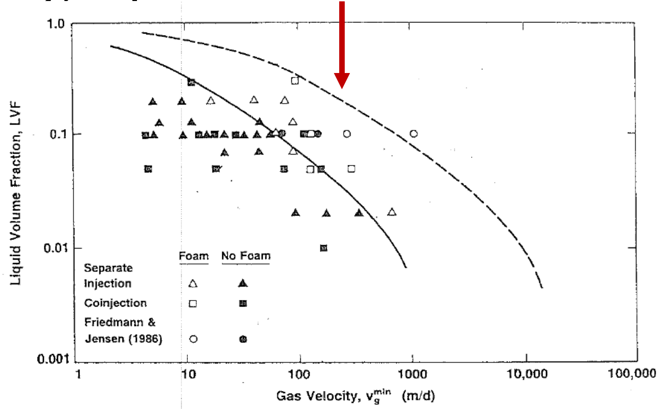


Rossen and Gauglitz, *AIChE J.* 36, 1176 (1990)

Results of Percolation Model

- Predicts ∇p_{min} ~ 1/k, in agreement with N_2 data in sandpacks
- Predicts ∇p_{min} lower for hi-p CO_2 because of low σ
- Model (w adjustable param) fits data for foam generation as function of velocity, liquid volume fraction





Rossen and Gauglitz,
***AIChE J.* 36, 1176 (1990)**

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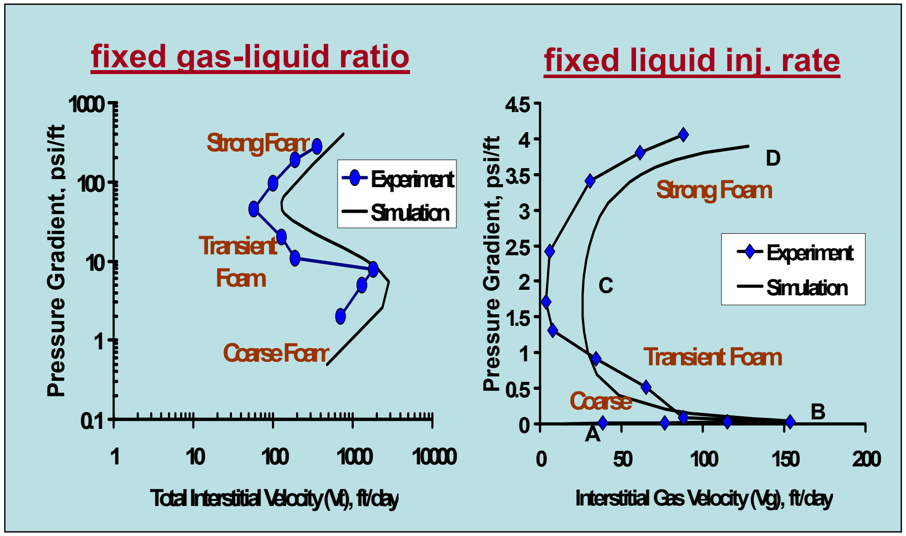
Foam Propagation

- Foam propagation is advance of foam throughout geological formation
- Propagation depends on convection of bubbles, *and* creation/destruction of bubbles at foam front
- Advance of foam front depends on forward movement of bubbles, plus creation and destruction of bubbles at foam front
- In radial flow from injection well, velocity decreases with distance from well
- Does decreasing velocity hamper ability of foam to advance outward into formation?

Population-Balance Model for Foam Generation as Function of ∇p

- Population-balance foam models represent foam bubble size as explicit variable, resulting from rates of lamella creation, destruction and transport
- Population-balance model of Kam et al. represents lamella creation as function of ∇p
- Fits data for foam generation at fixed gas fraction and fixed liquid injection rate



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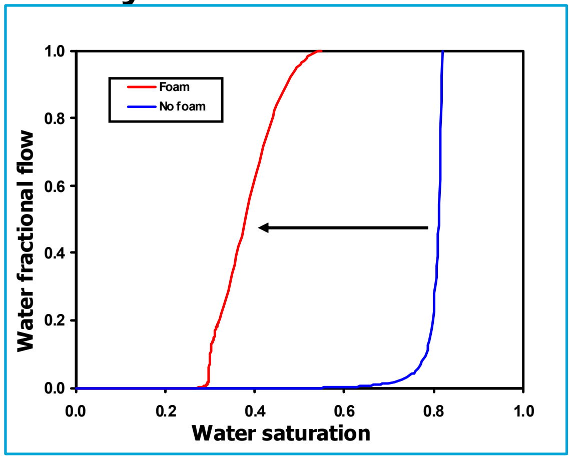
Kam et al., *SPEJ* **8**, 417 (2003); **12**, 35 (2007)

Method of Characteristics & Foam

- Consensus: local equilibrium between lamella generation and destruction applies to foam displacements on field scale and even lab scale: exceptions near injection face, at shock fronts
- If local equilibrium applies, and make additional simplifying assumptions, can describe displacement with Method of Characteristics (fractional flow theory, Buckley-Leverett theory)
- Solution depends on behavior at small scale at "traveling wave" at shocks
- Many simplifying assumptions, but useful for insights into complex displacements



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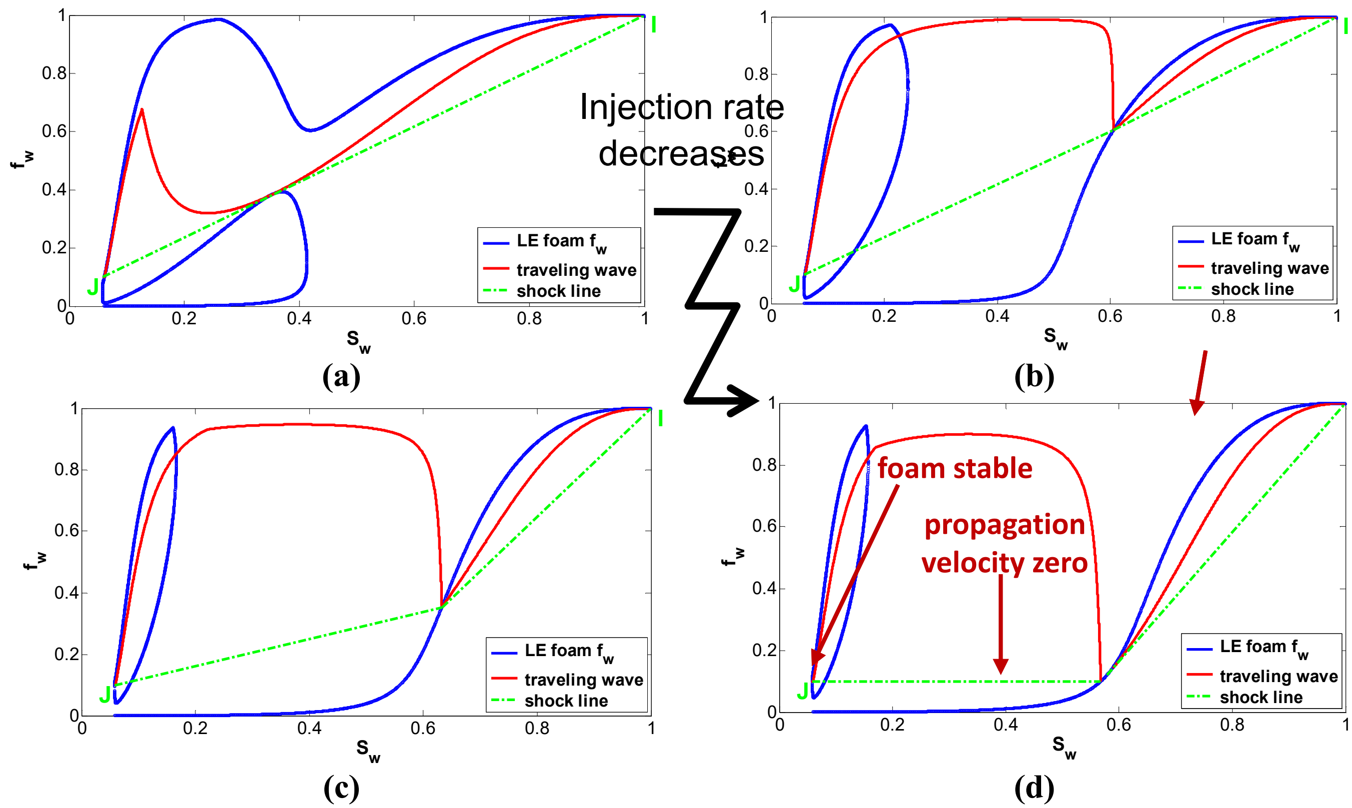
Riemann solutions for Shocks

total superficial velocity u:
(a) $u=4.5\times10^{-5}$ m/s,
(b) $u=2.798\times10^{-5}$ m/s,
(c) $u=1.5\times10^{-5}$ m/s,
(d) $=1.351\times10^{-5}$ m/s ,
all with $f_{wJ}=0.1$

Foam propagation stops at a velocity (d) at which foam itself is still stable



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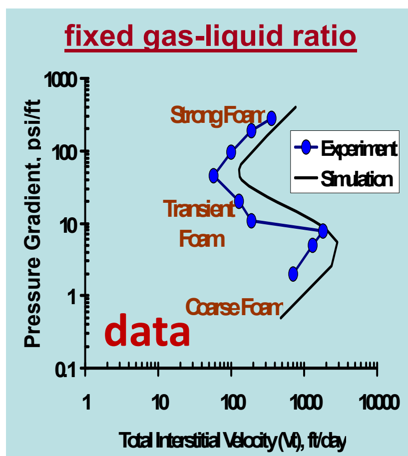
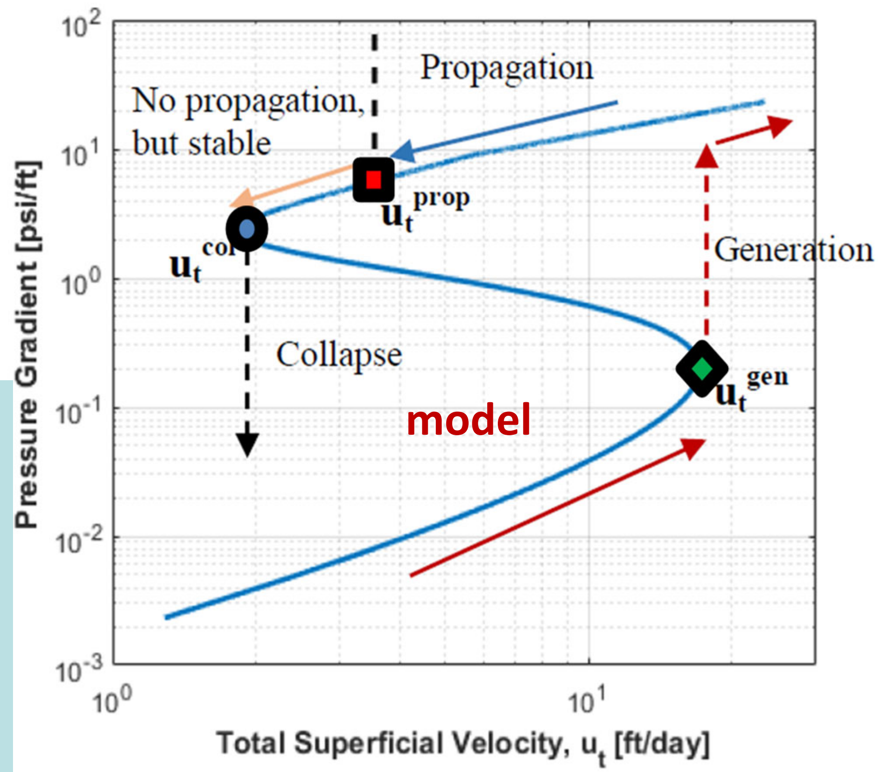
Ashoori et al., **17**, 1231 (2012)

Implications

- There are three separate velocity/∇p thresholds: for foam generation, propagation and stability
- Can foam propagate long distances from an injection well at decreasing velocity, ∇p?





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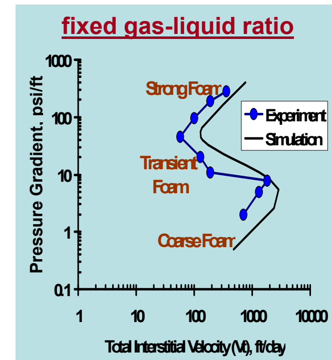
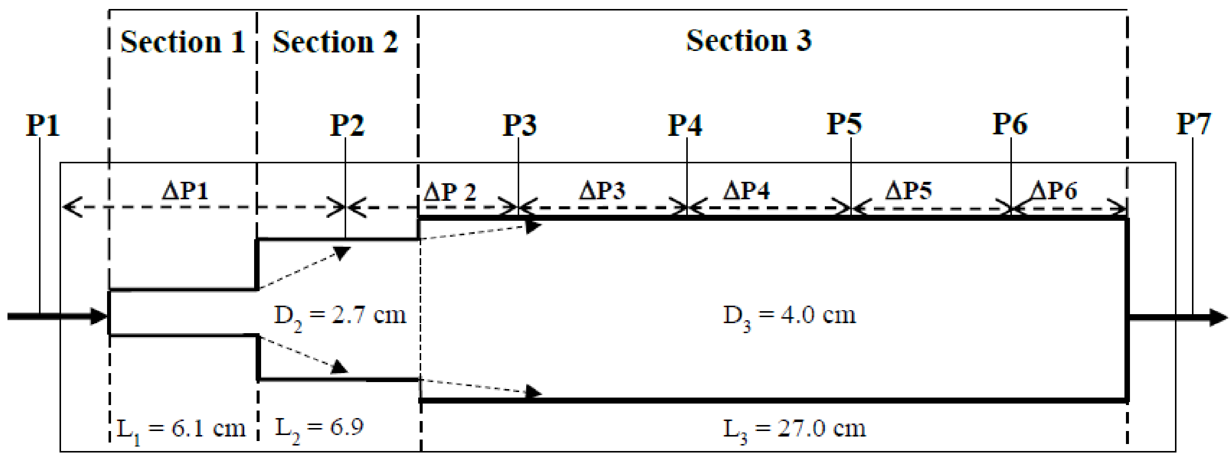
Laboratory Study of Foam Propagation



- Previous experimental studies suggested lower limiting velocity for foam propagation (Friedmann et al., 1986, 1991, 1994)
- Population-balance model suggests lower limiting velocity for stable foam; is this the limit for propagation as well?
- Approach: generate foam at high superficial velocity in-situ, observe foam propagation to sections of larger diameter and smaller u_t. Capillary continuity guaranteed.
- Diameter ratio (left to right): 1.0 : 2.7 : 4.0
- Superficial velocity
- ratio (left to right): 16.0 : 2.2 : 1.0



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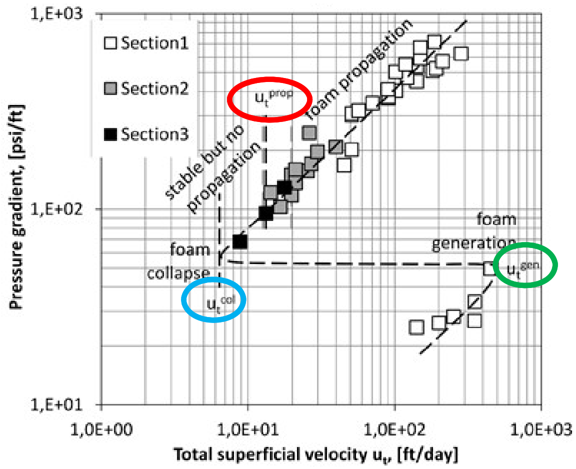
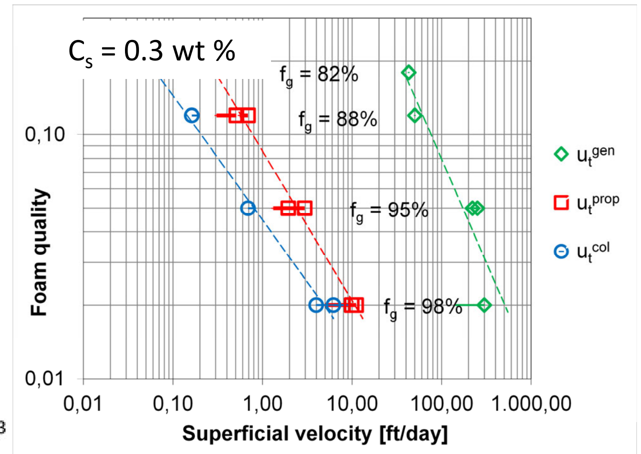
Results

- Three limiting superficial velocities:.
  - u_t^{gen} – critical velocity for foam generation
  - u_t^{prop} – critical velocity for foam propagation.
  - u_t^{col} – critical velocity for foam collapse.





- Find lower limiting velocities for propagation and foam stability; confirms prediction of theory. Foam propagation stops before foam stability limit.
- Study conducted under idealized conditions, w/ stable foam and very high ∇p
- Need to extend and test results at more-realistic field conditions

Yu et al., *SPEJ* (June 2020), 2020; EAGE IOR Symp. 2019

Summary

- Many studies find minimum velocity or pressure gradient for creation of low-mobility foam state in steady two-phase flow
- There are two states at same injection velocity, depending on history: low-mobility foam state and high-mobility coarse or no-foam state
- A population balance model can represent this behavior; suggests also minimum velocity to maintain foam
- Analysis of advancing foam front with this model suggests possible problem with foam propagation far from injection well, based on ∇p effect on lamella creation; distinct from minimum velocity to maintain foam
  - Need to extend results to more-realistic conditions
  - (There are other ways to place foam far from an injection well besides direct propagation)

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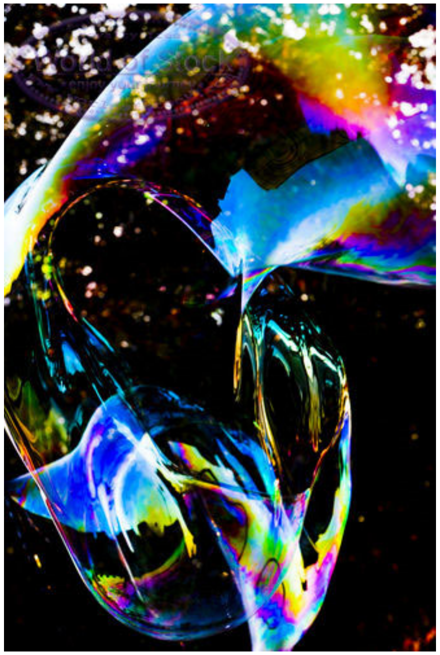
Questions?



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