

HARVARD
School of Engineering
and Applied Sciences



Physics of Cooking

Dave Weitz
Harvard

Naveen Sinha
Helen Wu

UCB – Public Lecture 7/19/12

The changing world of modern cuisine



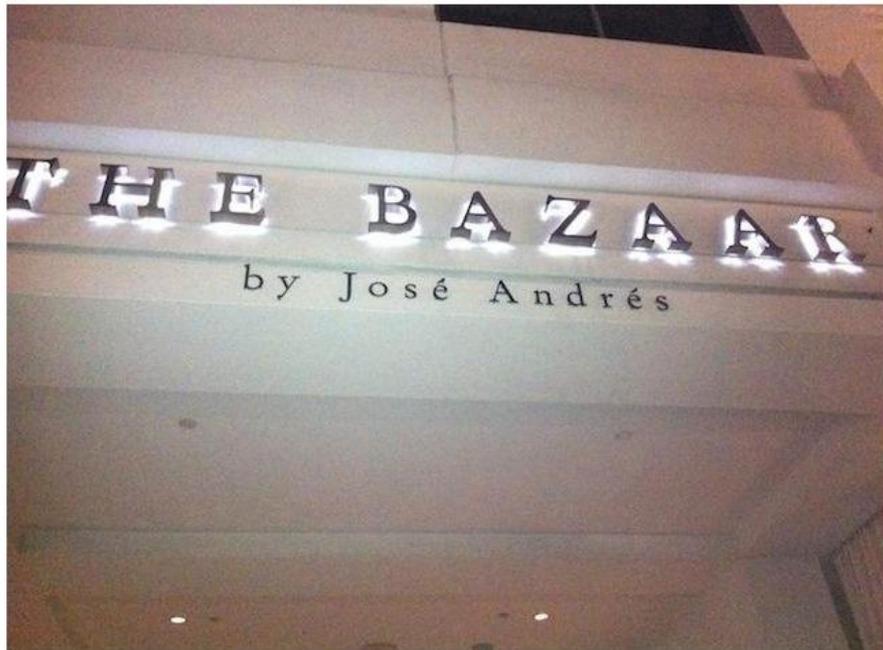
Jose Andres



Jose Andres



Jose Andres



Ferran Adrià







Ferran Adria



September 9, 2008



chef of El Bulli, Ferran Adria, has a fascinating relationship between science and modern cuisine. He met "the Salvador Dalí of the kitchen," the physicist and chemist Juan Luis Arsuaga, at the birth of molecular gastronomy. He then discusses his own work, which he calls "molecular cooking." He explores the use of hydrocolloids to enable a delicate fruit to be turned into a dense gel, and how he uses spherification, creating a liquid (as in a pea soup held in a gel) rather than itself.

He is one of the most creative individuals in the world. Adria views preparing food as an art that is based on scientific principles. He says, "Cooking is my own special alphabet. From this alphabet, I create my own dishes. Our role as chefs is to offer the world new recipes."



Ferran Adrià

Ferran Adrià is the head chef of the restaurant **El Bulli**, located on the coast of Catalonia near the city of Barcelona. Perhaps best known for creating "culinary foam," Adrià's stated goal is to "provide unexpected contrasts of flavor, temperature and texture. The idea is to provoke, surprise and delight the diner." **El Bulli** has 3 Michelin stars and is considered among one of the best restaurants in the world.



HARVARD

School of Engineering and Applied Sciences

Cooking and Science

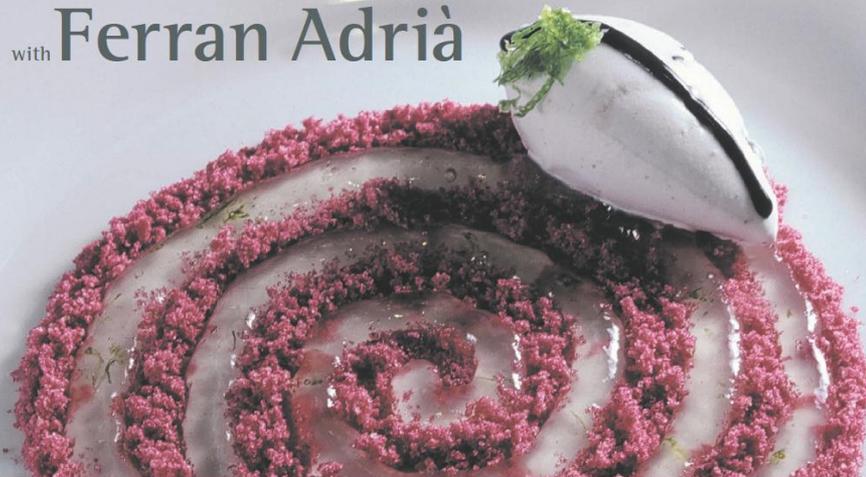
Ferran Adria lecture at Harvard



Sponsored by the Materials Research Science and Engineering Center (MRSEC) at Harvard. Hosted by the Harvard Department of Physics and Harvard School of Engineering and Applied Sciences.

COOKING & SCIENCE

with Ferran Adrià



A CONVERSATION ON CREATIVITY



FREE
public talk
Seating is on a
first-come
first-served basis.
No exceptions.



Tuesday
December 9, 2008
6:30 p.m.

Harvard University
Jefferson Hall
Physics Department
Room 250



The world acclaimed chef of El Bulli, Ferran Adrià, will discuss the fascinating relationship between modern science and modern cuisine. Adrià, called by *Gourmet* "the Salvador Dalí of the kitchen," will trace the birth of molecular gastronomy, manipulating the physical and chemical processes of cooking, and then discuss his own adventures in what he calls "molecular cooking." In particular, he will explore the use of hydrocolloids, or "gums" that enable a delicate fruit puree to be transformed into a dense gel, and deconstruct techniques like spherification, creating a resistant skin of liquid (as in a pea soup held in a pod of nothing more than itself). Considered one of the most creative individuals in any profession, Adrià views preparing food as a language "to transmit impressions, feelings, sensations, and experiences." He says, "Cooking is a language with its own special alphabet. From one alphabet, each cook creates his or her own unique conversation. Our role as chefs is to expand this dialogue, offering the world new forms of culinary expression."

Ferran Adrià

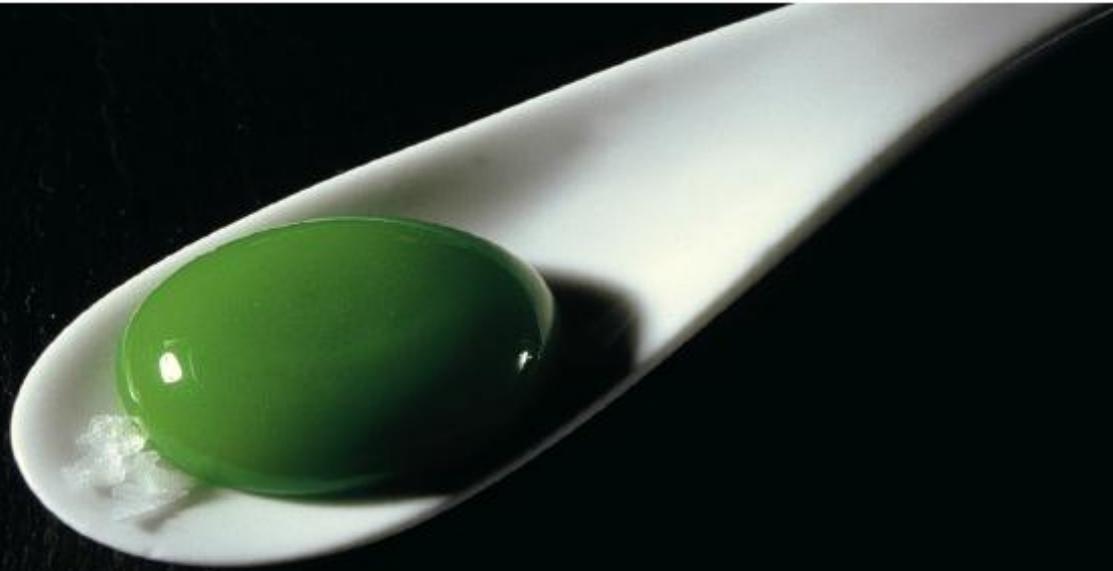
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and Applied Sciences

Cooking and Science





Harvard School of Engineering and Applied Sciences presents ...

SCIENCE & COOKING

Lecture Series

Members of the general public have an opportunity to attend free lectures given by the guest chefs and faculty affiliated with a new Harvard College General Education science course, "Science and Cooking: From Haute Cuisine to the Science of Soft Matter." The talks may or may not contain material relevant to the course. The talks are meant to inform and inspire.

- free and open to the public
- first come, first seated
- all lectures begin at 7:00pm
- lectures take place in the Science Center (except for the first event)

www.seas.harvard.edu/cooking

SEPTEMBER 7, TUESDAY

Science & Cooking: A Dialogue

Harold McGee; Ferran Adrià, *elBulli*; José Andrés (*ThinkFoodGroup*), *Jaleo*
Loeb Drama Center

NOTE: This is a ticketed event. Contact the Harvard Box Office for details.

SEPTEMBER 13, MONDAY

Sous-vide Cooking: a State of Matter

Joan Roca, *El Celler de Can Roca*

SEPTEMBER 20, MONDAY

Brain Candy: How Desserts Slow the Passage of Time

Bill Yosses, *White House Pastry Chef*

SEPTEMBER 27, MONDAY

Olive Oil & Viscosity

Carles Tejedor, *Via Veneto*

OCTOBER 4, MONDAY

Heat, Temperature, & Chocolate

Enric Rovira, *Master Chocolatier*

OCTOBER 11, MONDAY

Reinventing Food Texture & Flavor

Grant Achatz, *Alinea*

OCTOBER 18, MONDAY

Emulsions: Concept of Stabilizing Oil & Water

Nandu Jubany, *Can Jubany*

OCTOBER 25, MONDAY

Gelation

José Andrés (*ThinkFoodGroup*), *Jaleo*

NOVEMBER 1, MONDAY

Browning & Oxidations

Carme Ruscalleda, *Sant Pau, Sant Pau de Tòquio*

NOVEMBER 8, MONDAY

Meat Glue Mania

Wylie Dufresne, *wd-50*

NOVEMBER 15, MONDAY

Cultivating Flavor

Dan Barber, *Blue Hill*



JOSE ANDRES
THINKFOOD
GROUP



ESADE
Business School

Harvard Business School

HARVARD

School of Engineering
and Applied Sciences



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A science class Based on cooking

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Olive Oil & Viscosity

Carles Tejedor, *Via Veneto*

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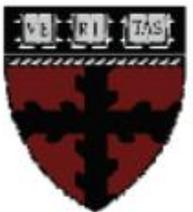
JOSE ANDRES
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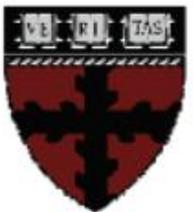
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www.seas.harvard.edu/cooking



A science class
Based on cooking
Motivated by cooking
But still real science

HARVARD
School of Engineering
and Applied Sciences



GROUP

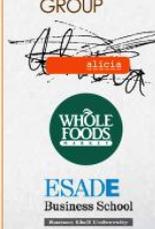


Gelation
José Andrés (*ThinkFoodGroup*), *Jaleo*

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Dan Barber, *Blue Hill*



Michael
Brenner



A team of teachers



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Cooking and Science

Wide coverage in the press

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The all-new
9-5 Luxury Sport Sedan.



At Harvard, the Kitchen as Lab



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What's Popular Now

Electoral
Oath
Struggled



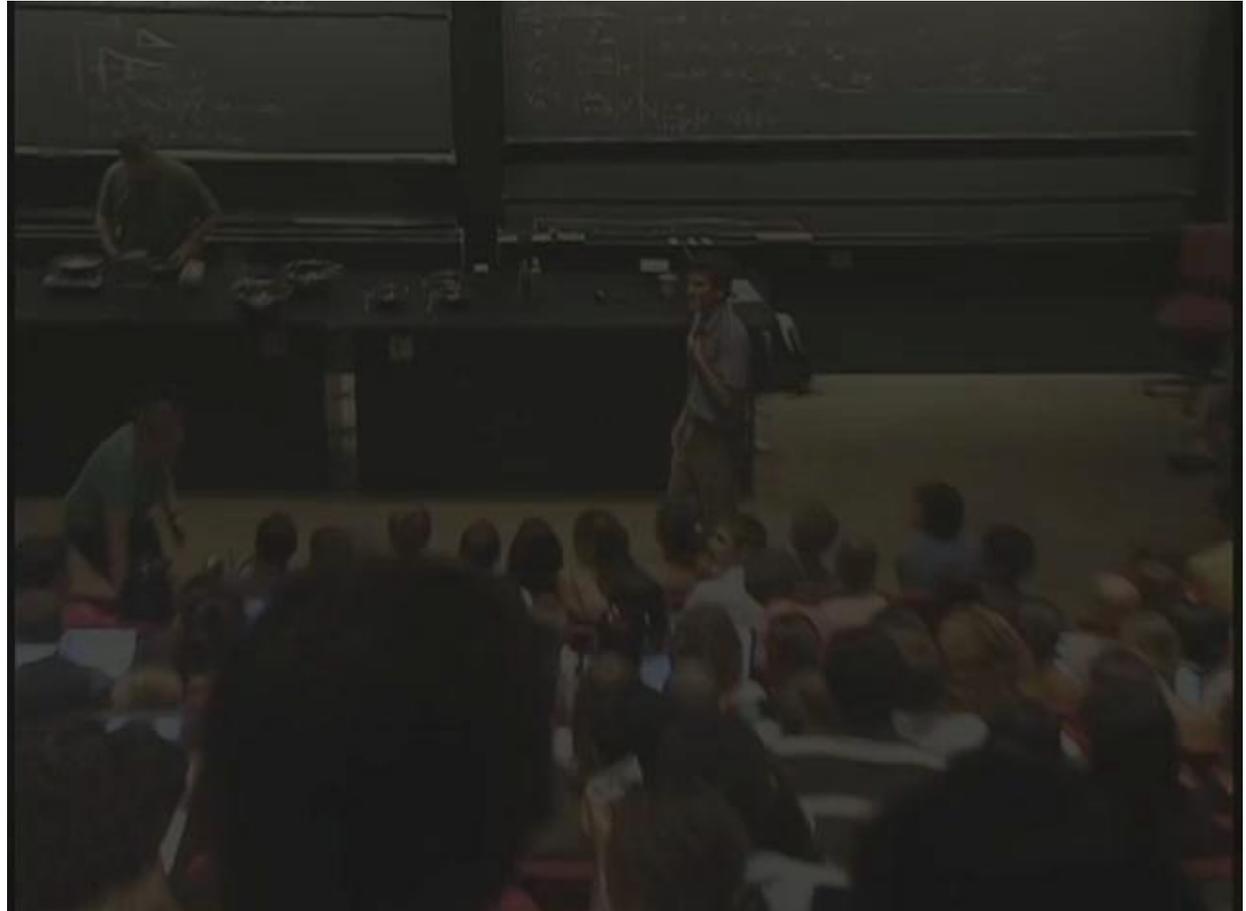
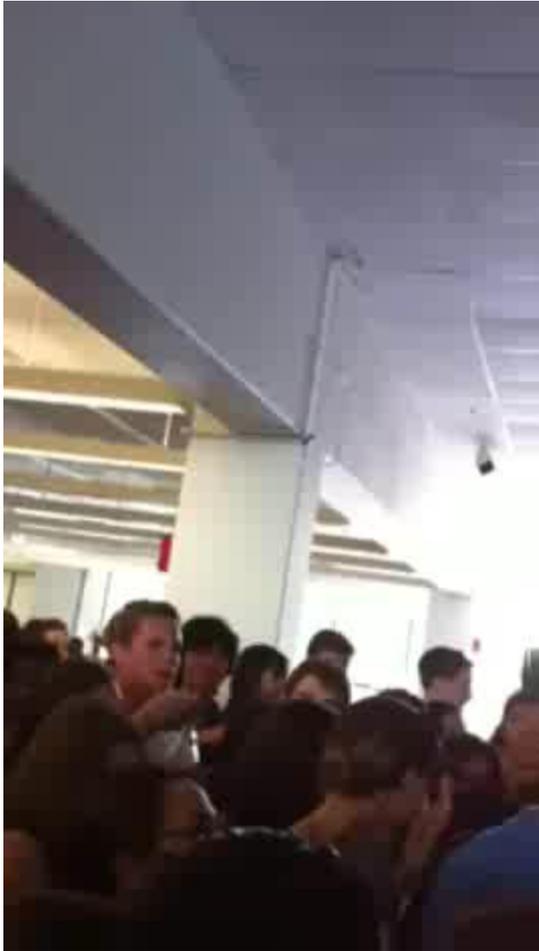
The Way We
Treat Our Troops



The all-new
9-5 Luxury Sport Sedan.



The crowds



700 students signed up for the class

Mathematics Review

Here is a warm-up: [orders of magnitude]

Mathematics Review

Here is a warm-up: [orders of magnitude]

Odds of getting into SPU 27 $300/697 = 43\%$

Mathematics Review

Here is a warm-up: [orders of magnitude]

Odds of getting into SPU 27 $300/697 = 43\%$

Odds of getting into Harvard $\sim 10\%$

Mathematics Review

Here is a warm-up: [orders of magnitude]

Odds of getting into SPU 27 $300/670 = 44\%$

Odds of getting into Harvard $\sim 10\%$

Odds of getting a reservation at El Bulli: $8000/2000000 = 0.5\%$

Why I took the course



The lab



The lab



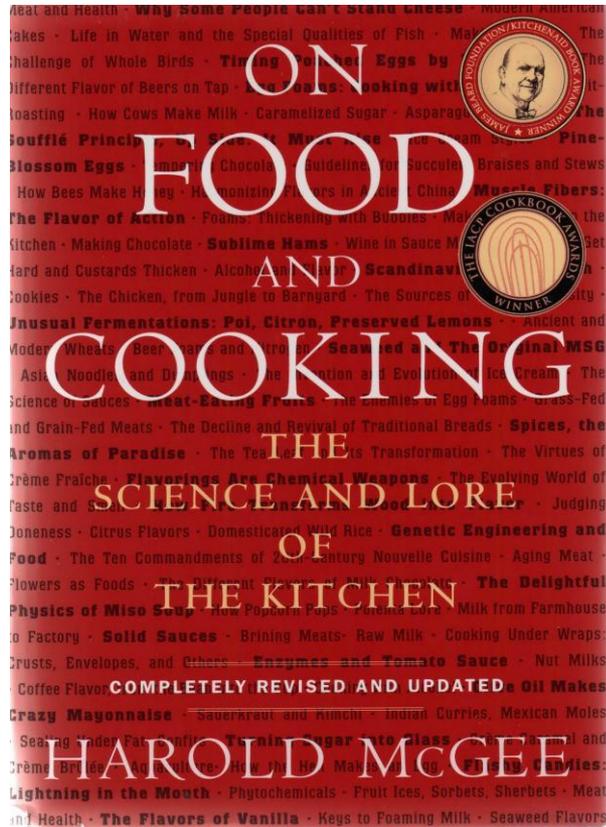
Recipe of the week

The lab



On Food and Cooking

Harold McGee



This will be the only required textbook for the course.

Other cookbooks/food science books are on reserve.



The Equation of the Week

Clap when you see an equation



How often have you had undergrad
non-science majors
clap every time they see an equation?



SCIENCE & COOKING LECTURE SERIES

The Many Faces of Chocolate

Ramon Morató, *Aula Chocovic*

September 19

7:00 PM

www.seas.harvard.edu/cooking







Bill Yosses



Bill Yosses

White House Pastry Chef

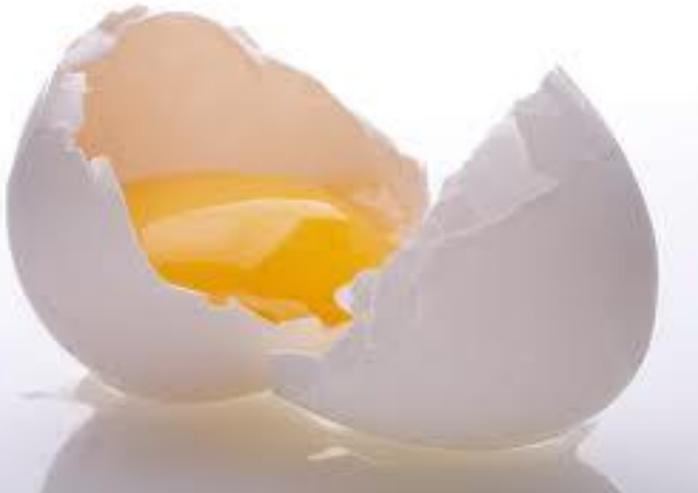


What is cooking?

Cooking an egg



Liquid → Solid



Phases transitions:

A Physicist's View of Cooking

Phases of water

A macro-scale view



SOLID



LIQUID



GAS



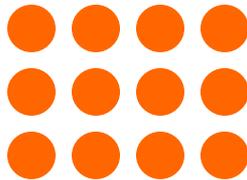
0 °C

100 °C

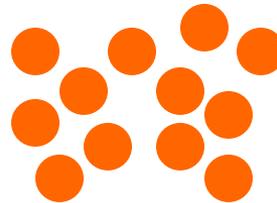
Temperature

Phases of water

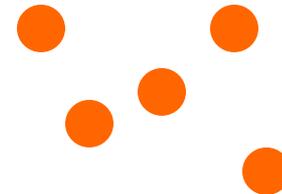
A Micro-scale View



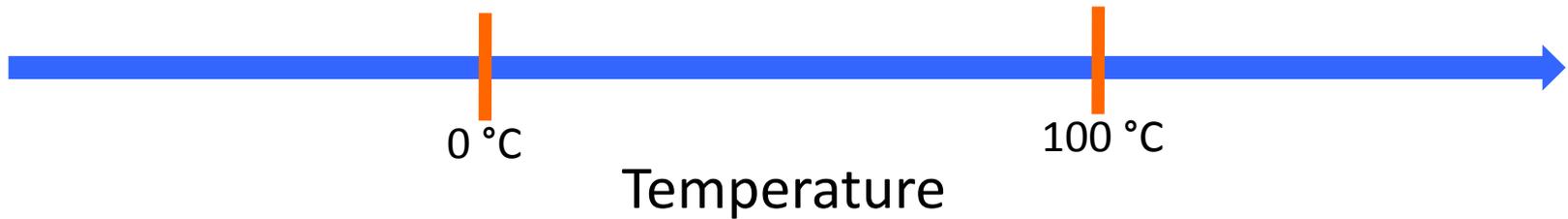
SOLID



LIQUID

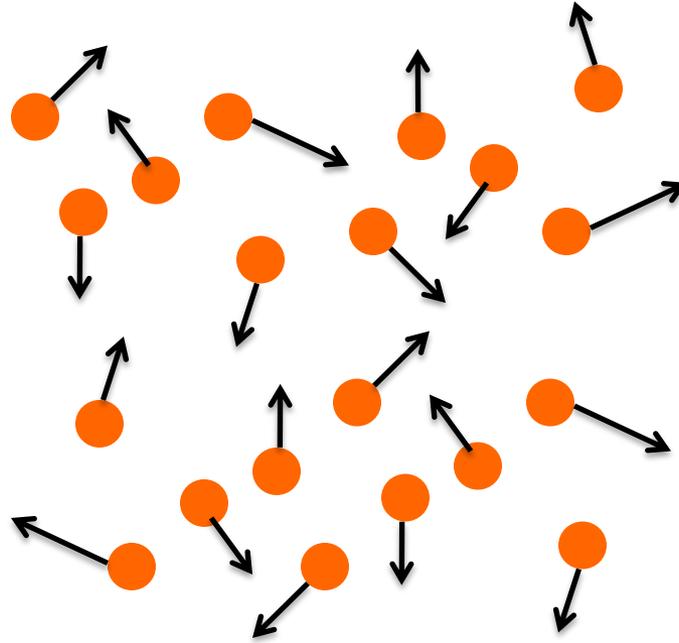


GAS



What is temperature?

A scientific definition



Temperature is a measure of the energy in the motion of the molecules in the material.

Cook an egg → Solidify it



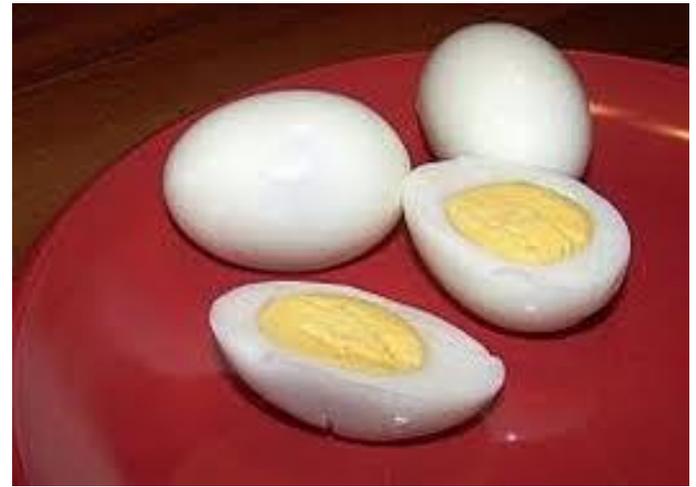
Frozen



Cook an egg → Solidify it

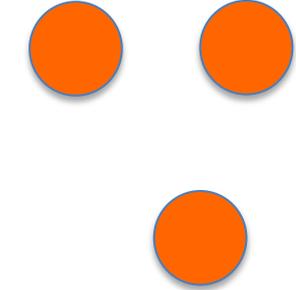


Frozen

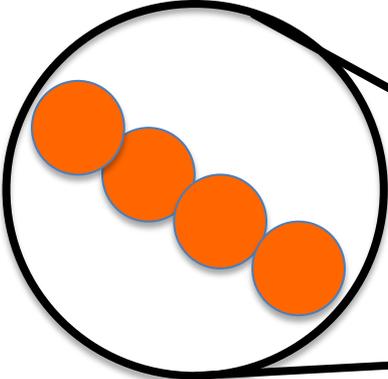


Boiled

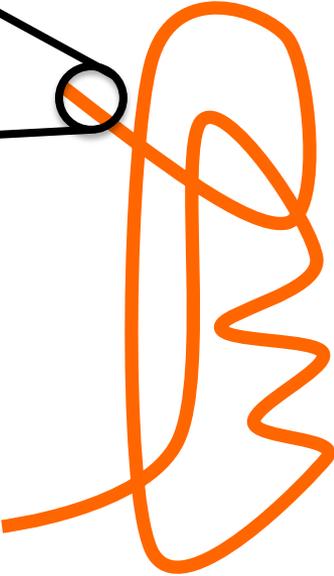
Molecular structure of proteins



Free Amino Acids

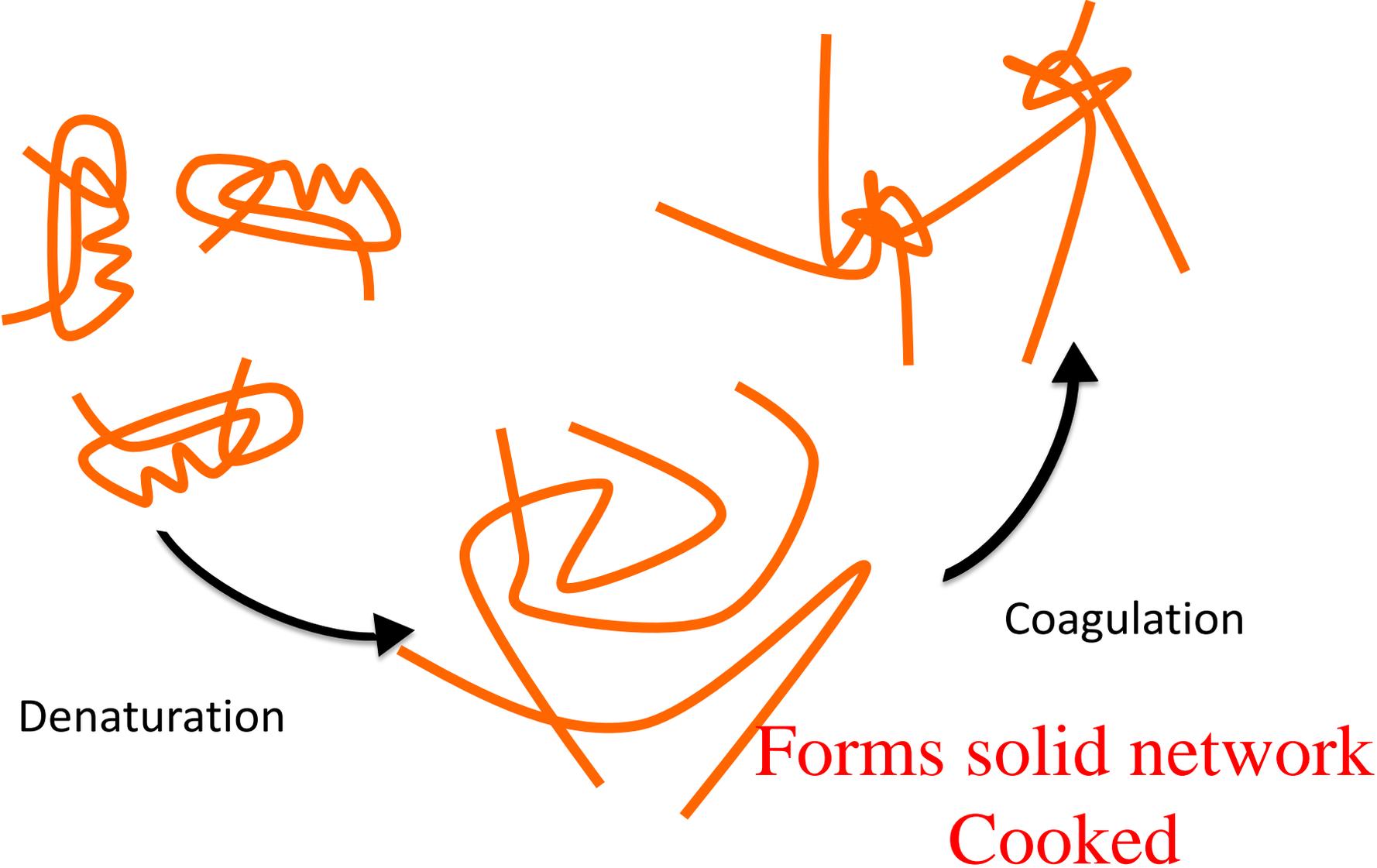


Assembled



Folded

Protein Denaturation & Coagulation

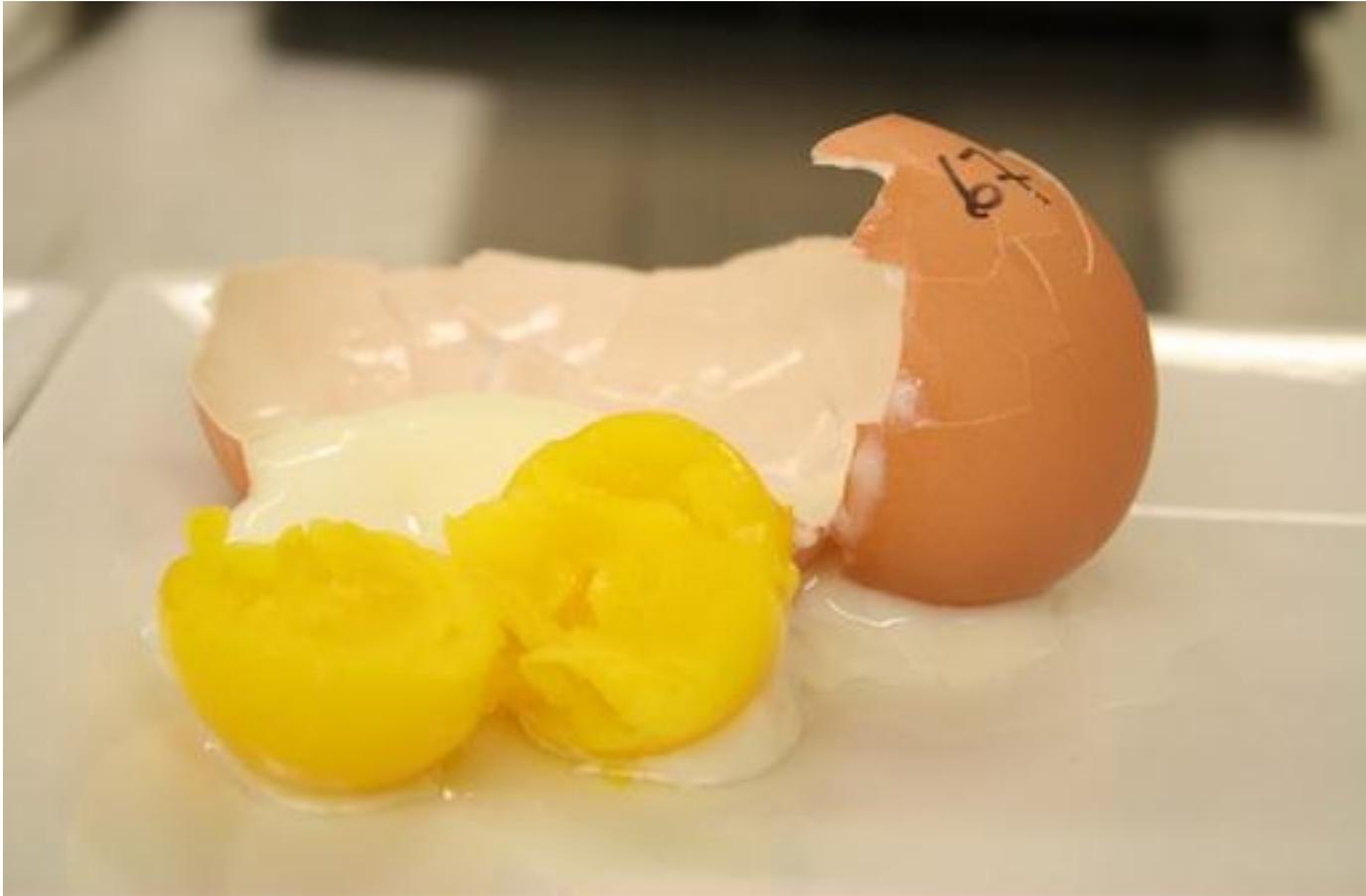


New ways to cook: Sous Vide



Sous vide eggs

Novel textures are possible at lower temperatures



Phase transitions in food

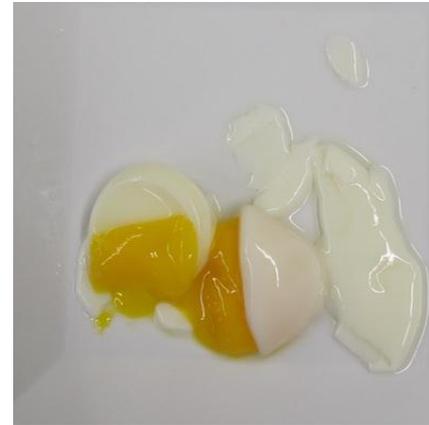
Egg in temperature-controlled bath

59 °C

61 °C

63 °C

67 °C



What about other parameters?

Effect of pressure



Effect of Pressure

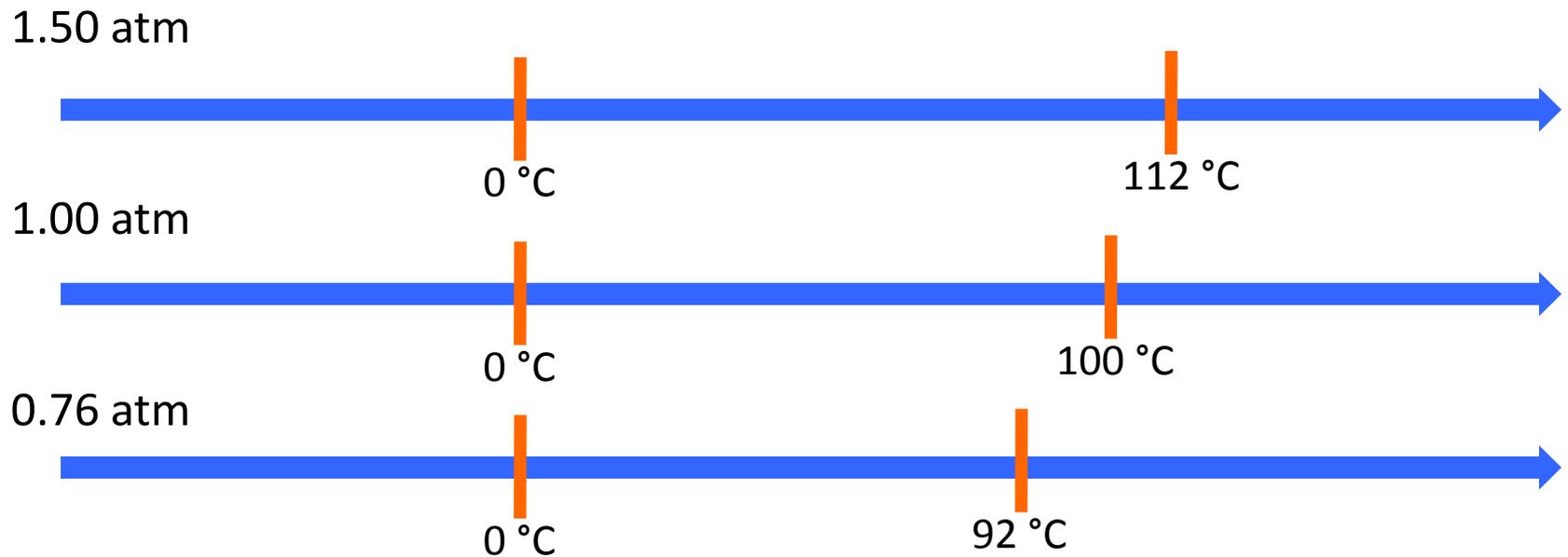
What about other parameters?



Pressure at high elevation is greatly reduced:
At 16,000 ft, pressure is 56% of that at sea level.

Phases of water

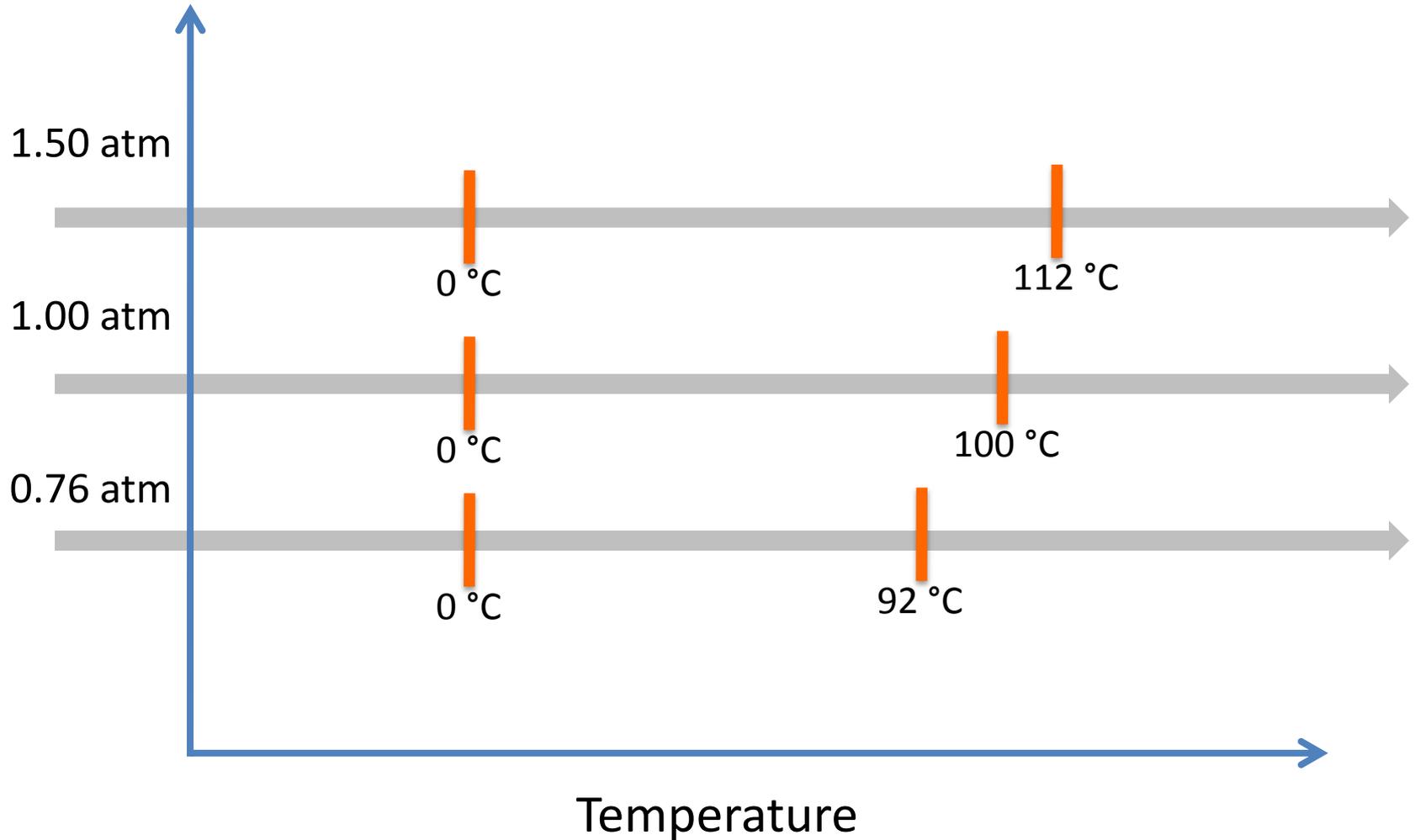
Melting/boiling points at different pressures



Temperature

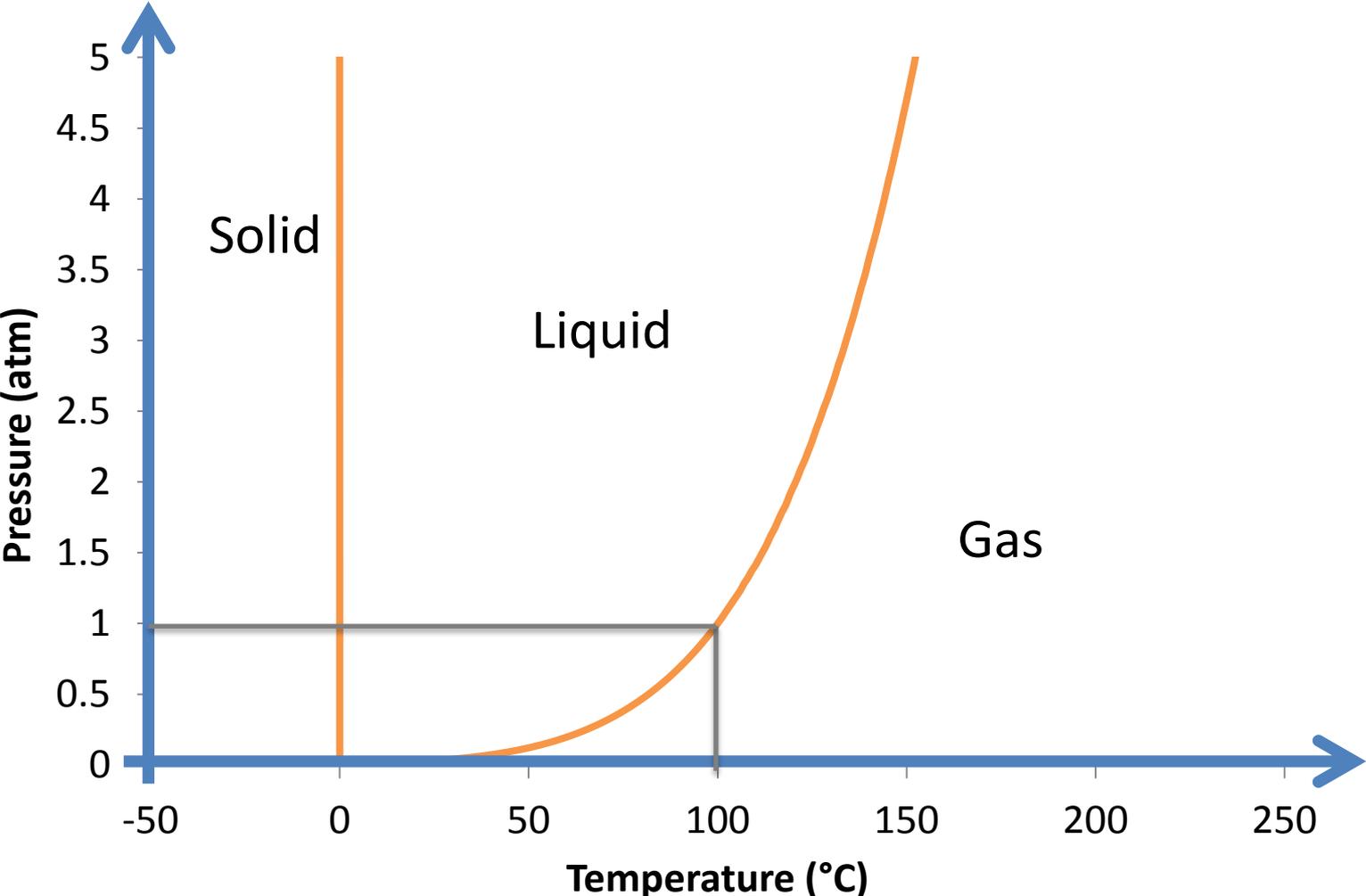
Phases of water

Melting/boiling points at different pressures



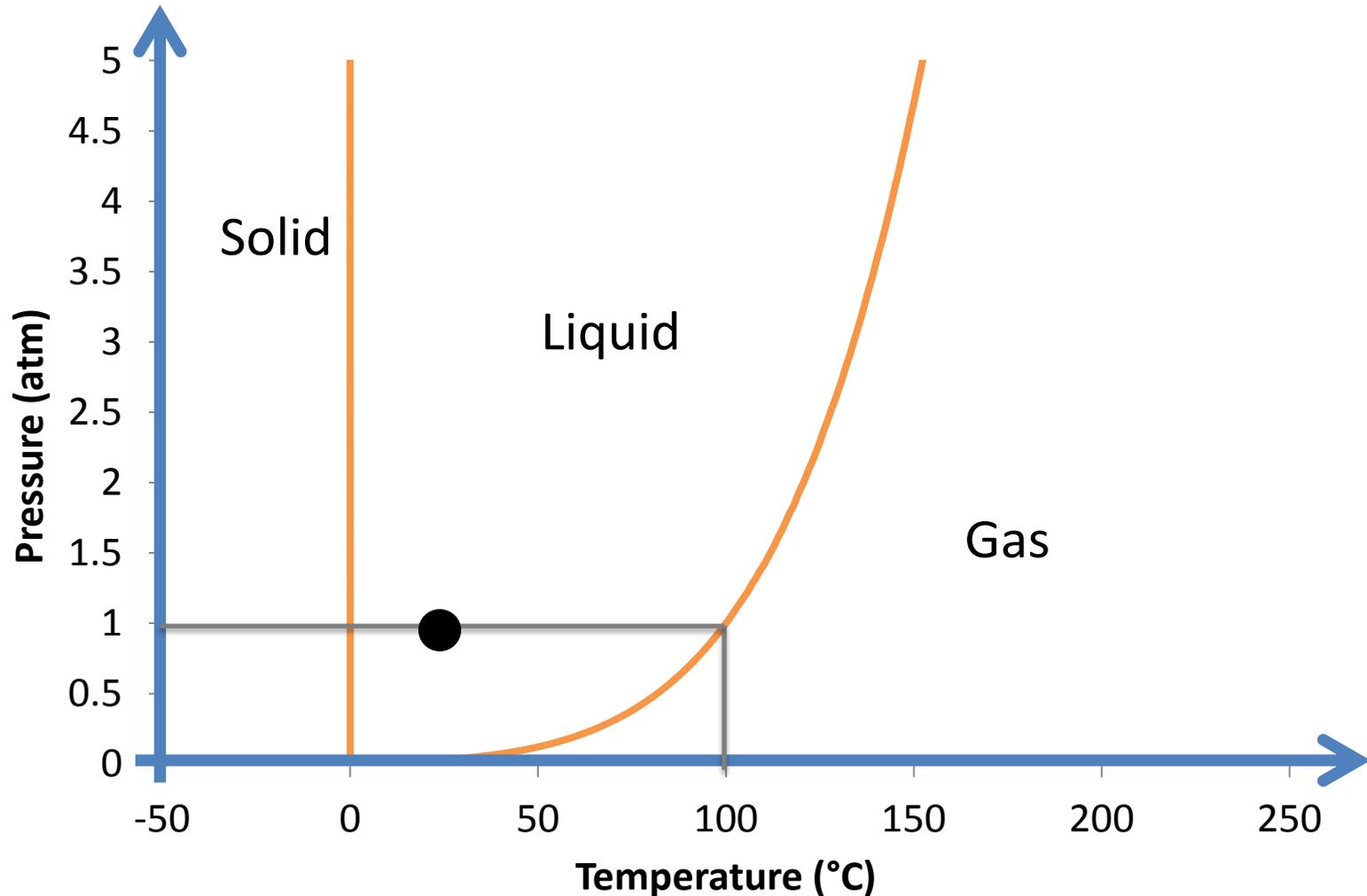
Phases of Water

Solid, liquid, and gas



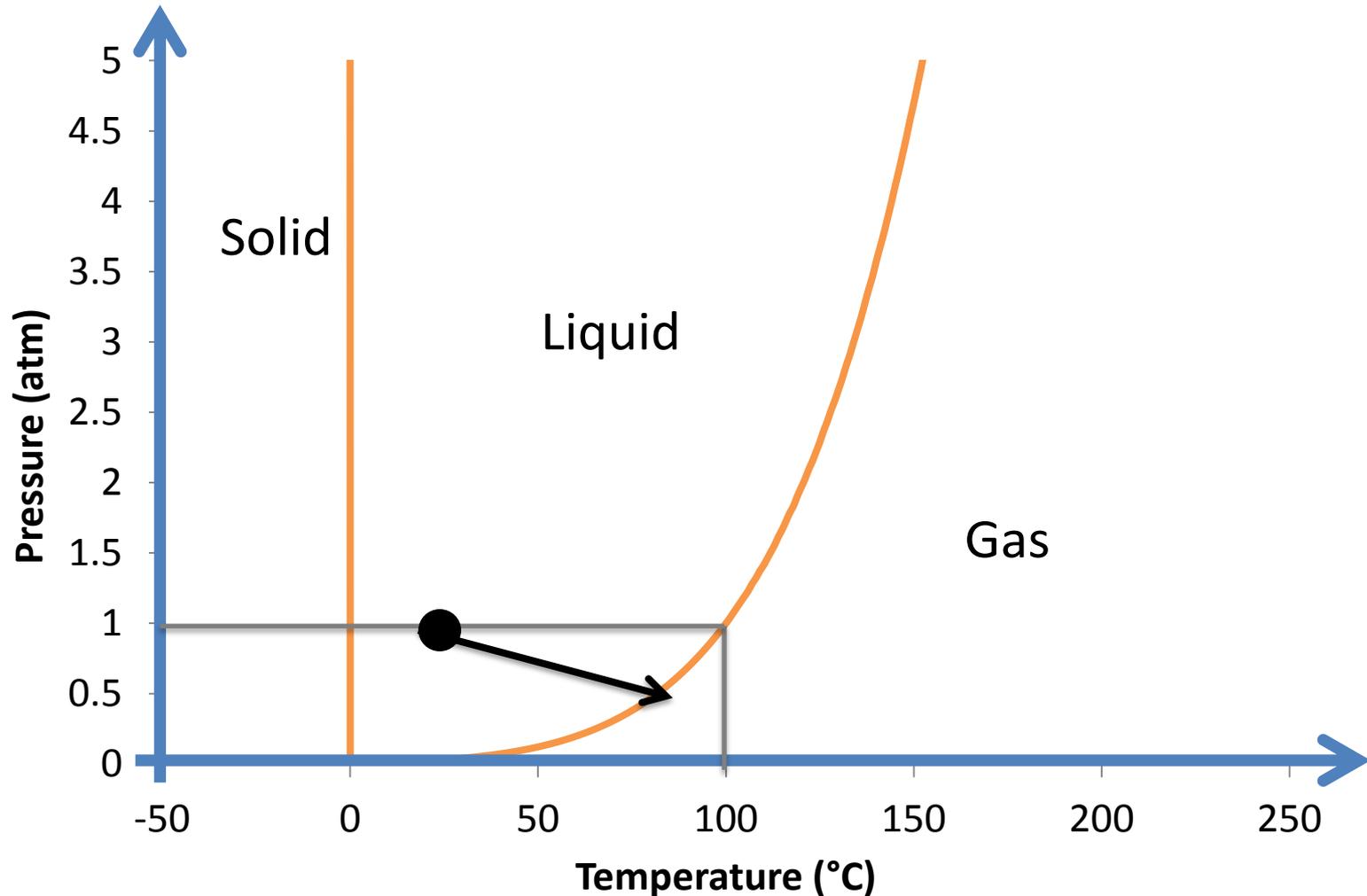
Applications of the Phase Diagram

Standard Temperature and Pressure = STP



Applications of the Phase Diagram

High elevation lowers the boiling point



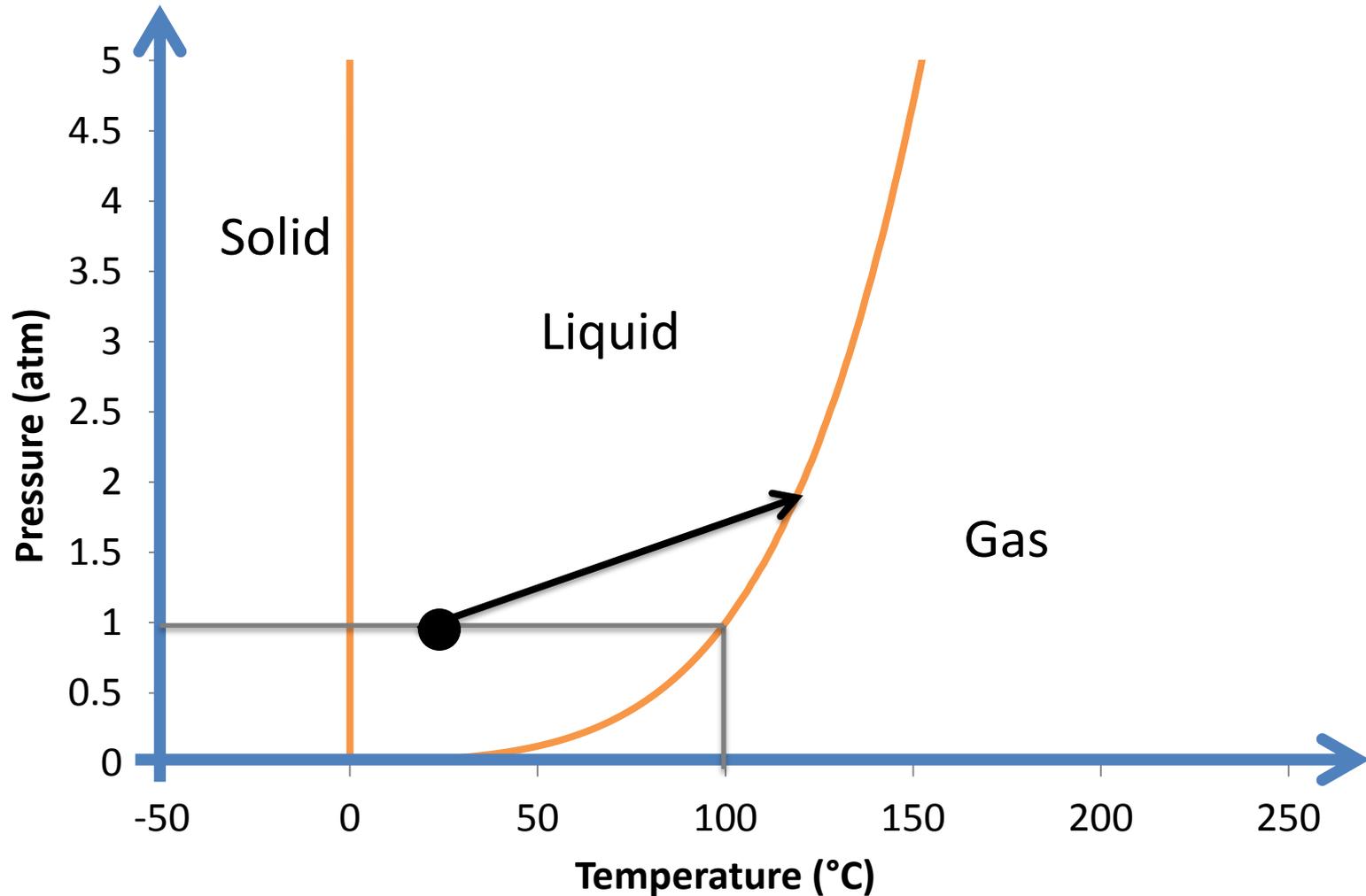
Applications of the Phase Diagram

Pressure cookers increase the boiling point



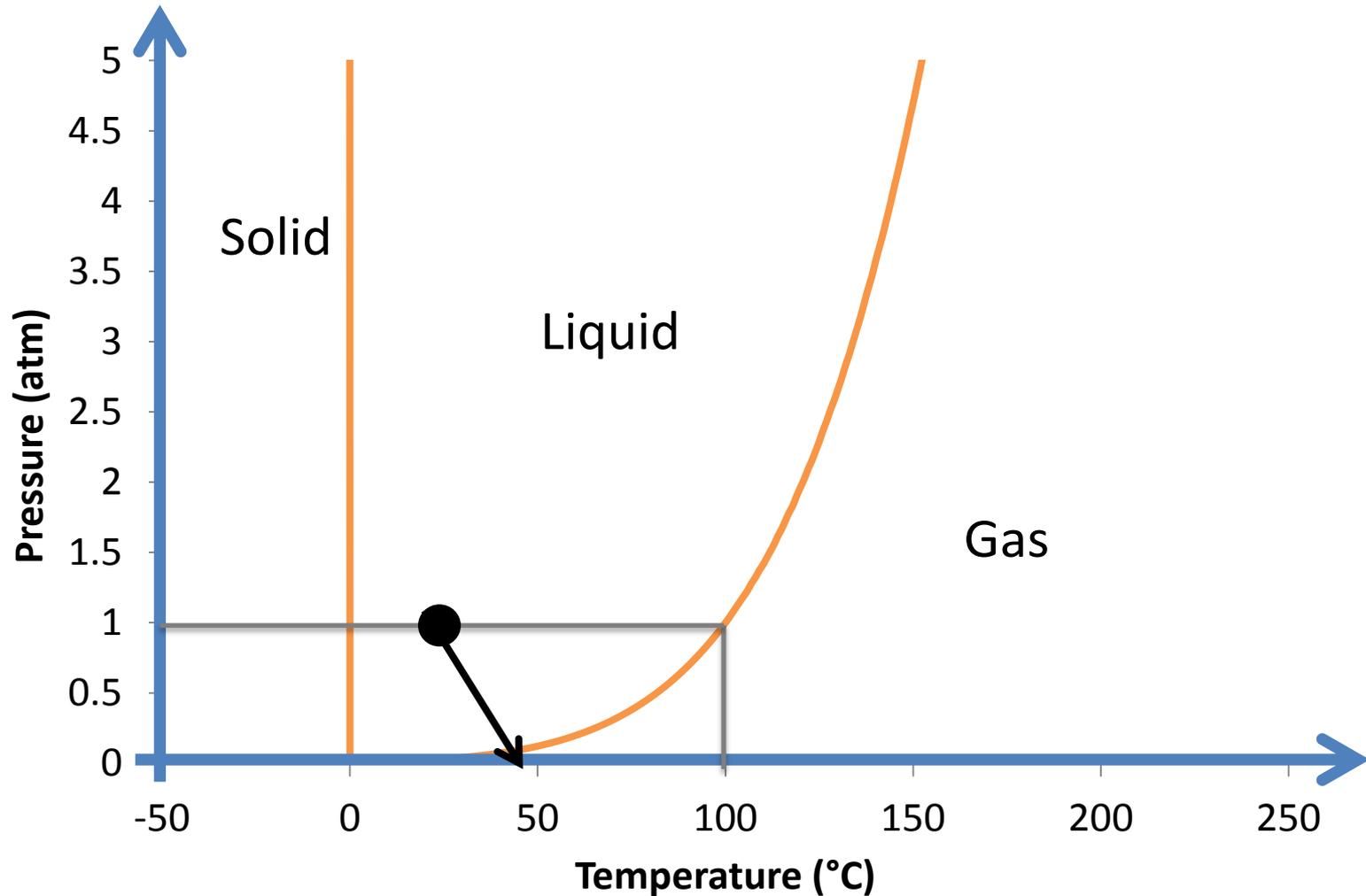
Applications of the Phase Diagram

Pressure cookers increase boiling point



Applications of the Phase Diagram

Rotary evaporators lower the boiling point

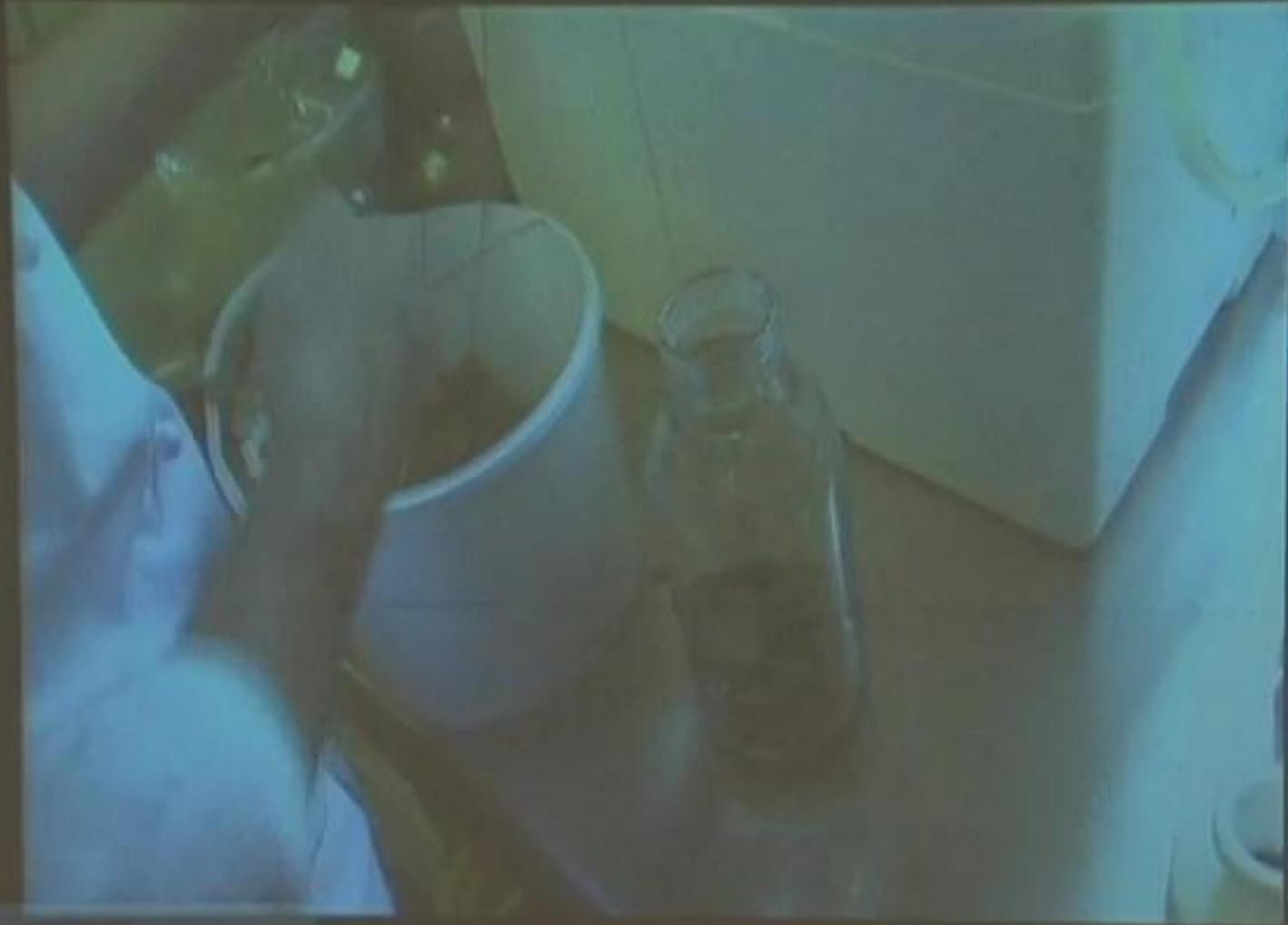


Applications of the Phase Diagram

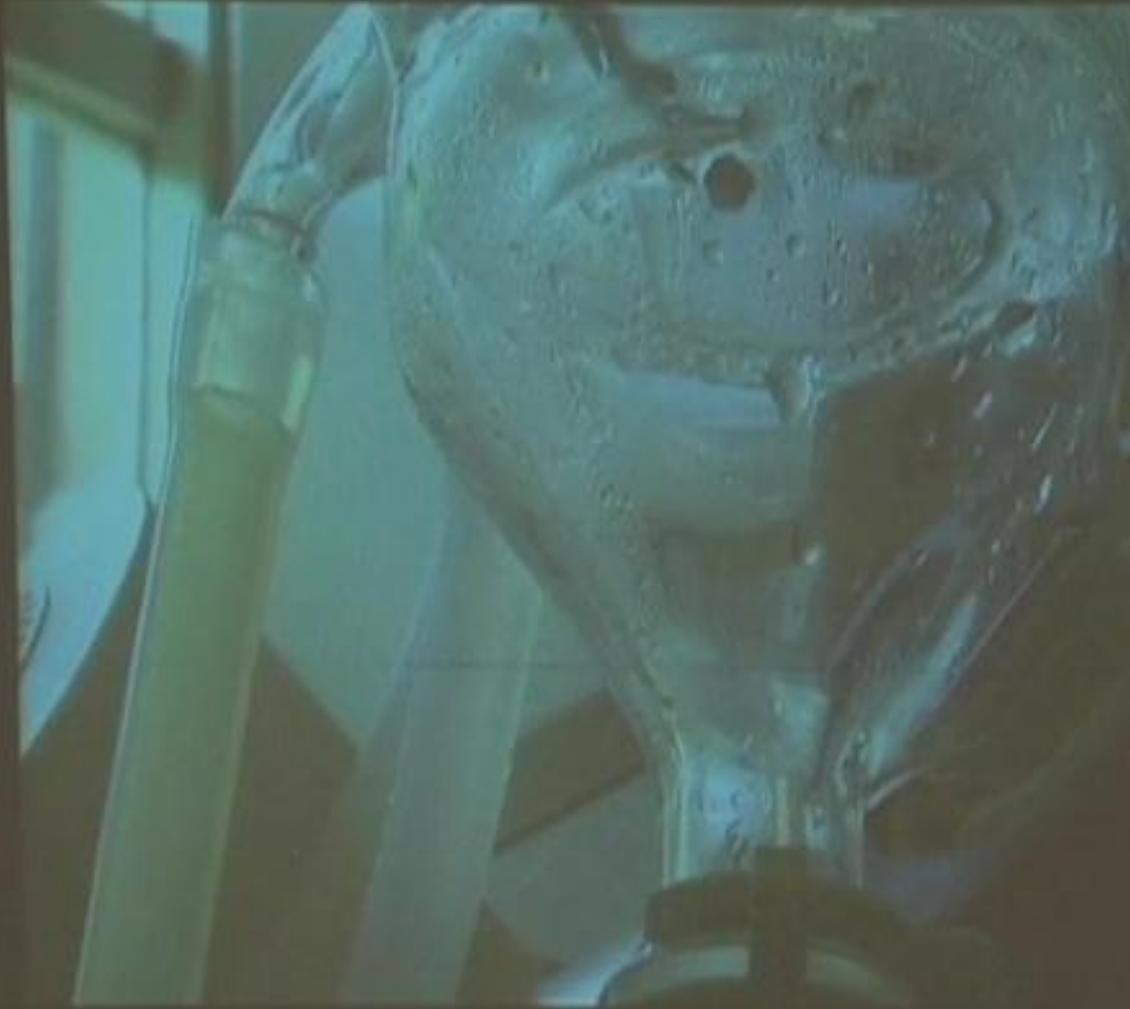
Rotary evaporators lower the boiling point



Super cool dessert



Super cool dessert



Super cool dessert



Clap when you see a great dessert

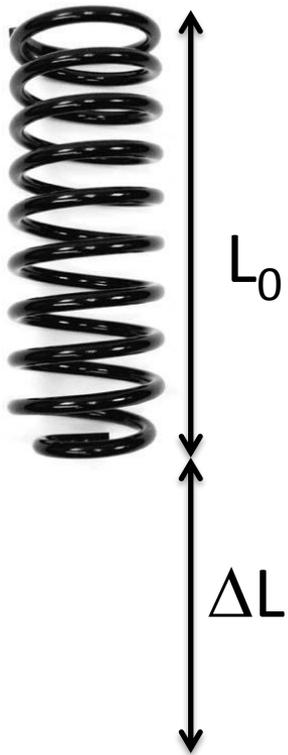


Elasticity:

Applications to mouthfeel

Elasticity of a spring

Hooke's Law



$$F = -k\Delta L$$

$$k = -\frac{F}{\Delta L}$$

F = force [N]

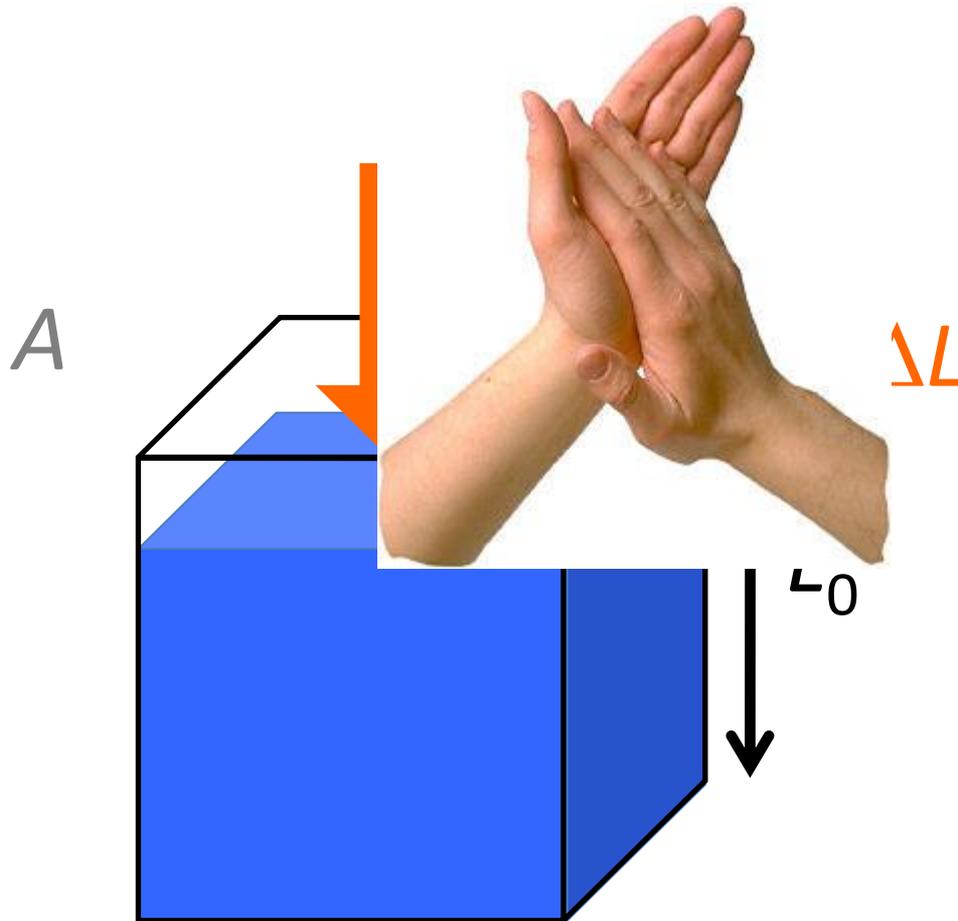
k = spring constant [N/m]

ΔL = displacement [m]



Elastic constant of a material

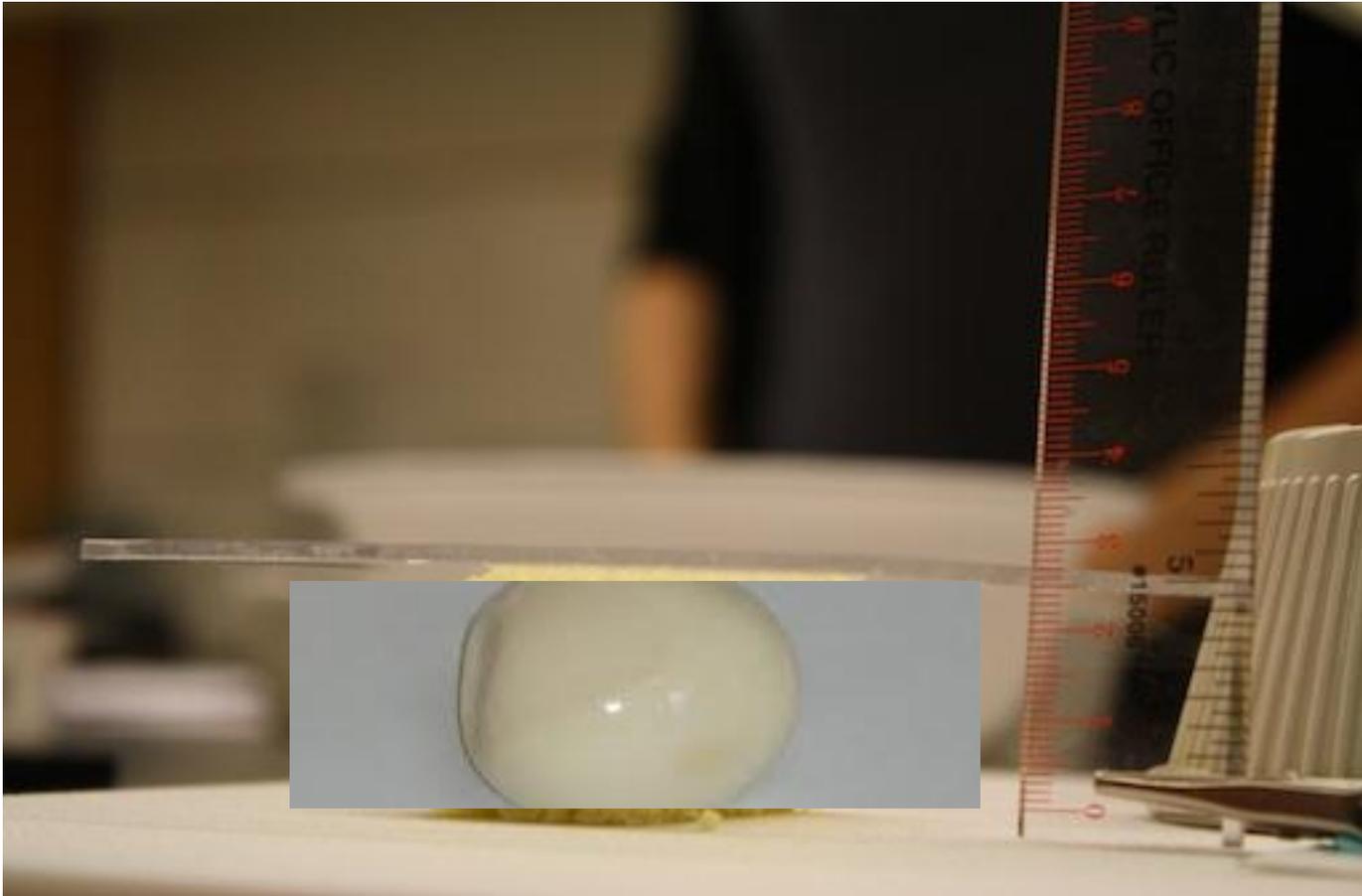
Intrinsic quantity of a material



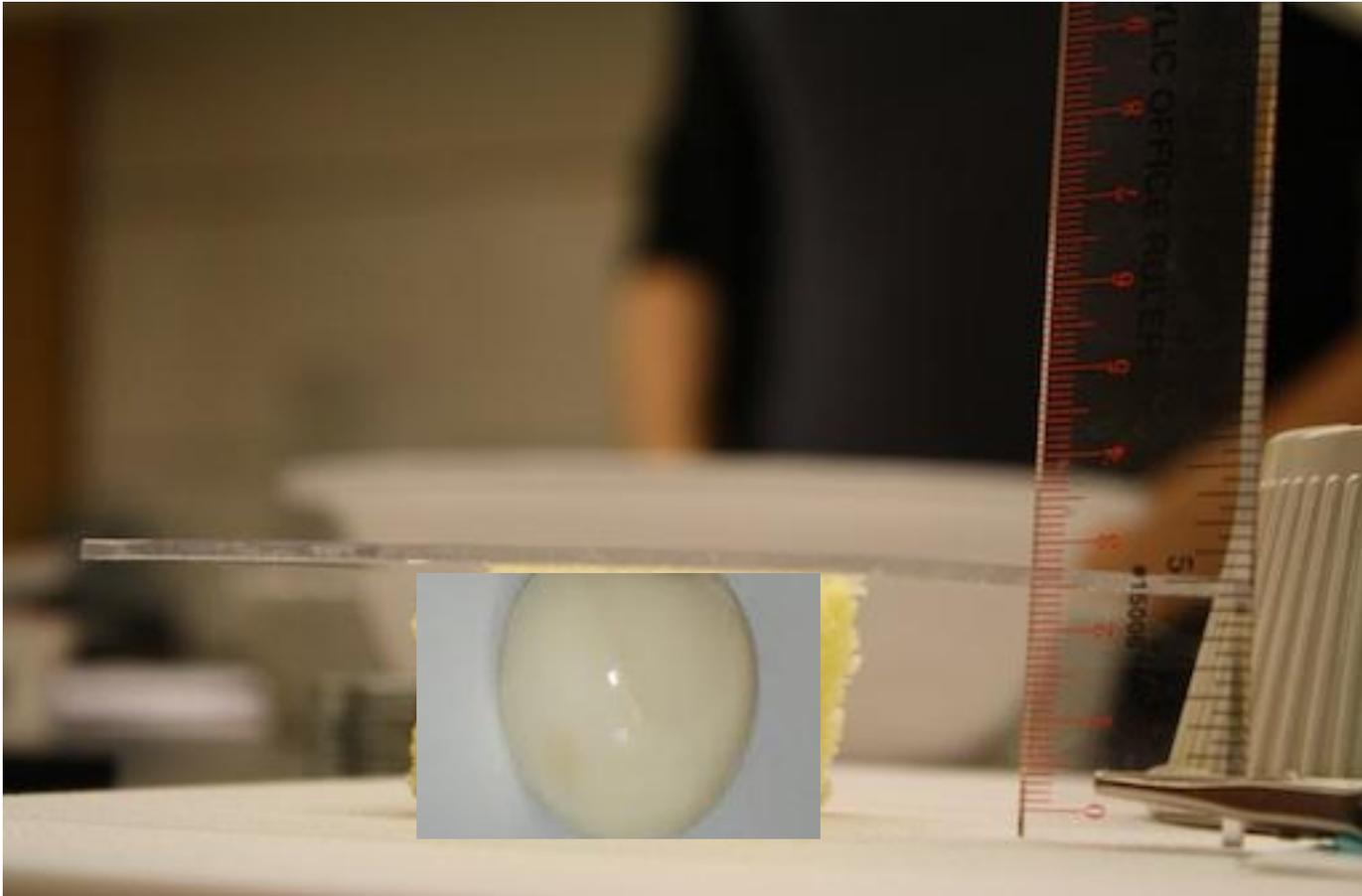
$$E = \frac{\text{stress}}{\text{strain}}$$
$$= \frac{F/A}{\Delta L/L_0}$$

- E = Elastic modulus [Pa]
- F = Force [N]
- A = Area [m^2]
- ΔL = change in length [m]
- L_0 = initial length [m]

Elasticity of a hard-boiled egg



Elasticity of a hard-boiled egg



Elasticity of a hard-boiled egg



Measurement

Elasticity of faux shark fin

We need to measure:

- Force applied
- Area of egg
- Deformation

Calculation

Elasticity of faux shark fin

$$E = \frac{F/A}{\Delta L/L_0}$$



Calculation

Elasticity of hard-boiled egg

$$E = \frac{F/A}{\Delta L / L_0}$$

Weight used: 1.0 kg

Radius of egg: 2.0 cm

Height of egg: 1.9 cm

Deformation: 0.3 cm

Calculation

Elasticity of hard-boiled egg

$$E = \frac{F/A}{\Delta L/L_0}$$

$$F = mg = 1.0\text{kg} \times 10\text{m/s}^2 = 10\text{N}$$

$$A = \pi r^2 = 3.14 \times 0.02^2 = 1.3 \times 10^{-3} \text{m}^2$$

Calculation

Elasticity of hard-boiled egg

$$E = \frac{F/A}{\Delta L/L_0}$$

$$F = mg = 1.0\text{kg} \times 10\text{m/s}^2 = 10\text{N}$$

$$A = \pi r^2 = 3.14 \times 0.02^2 = 1.3 \times 10^{-3}\text{m}^2$$

$$\Delta L/L_0 = (0.3)/1.9 = 0.16$$

Calculation

Elasticity of hard-boiled egg

$$E = \frac{F/A}{\Delta L/L_0}$$

$$E = \frac{10\text{N}}{0.16 \times 1.3 \times 10^{-3} \text{m}^2} = 4.8 \times 10^4 \text{Pa}$$

Calculation

Elasticity of hard-boiled egg

$$E = \frac{F/A}{\Delta L/L_0}$$

$$E = \frac{10\text{N}}{0.16 \times 1.3 \times 10^{-3} \text{m}^2} = 4.8 \times 10^4 \text{Pa}$$

$$E = 48 \text{kPa}$$

Elasticity of a cooked steak

Depends on how well cooked it is

Rare



$$E = 45 \text{ kPa}$$

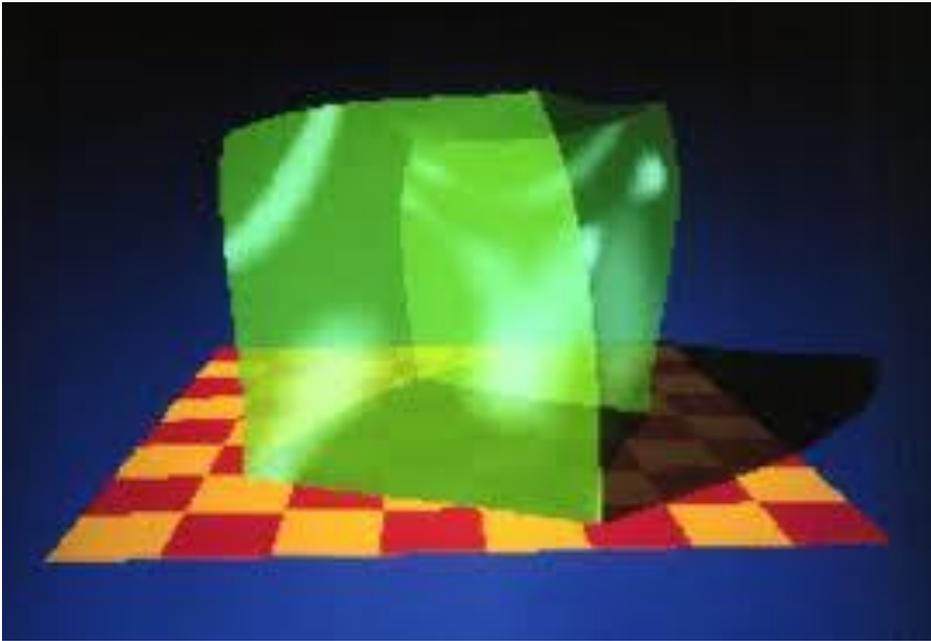
Well-done



$$E = 63 \text{ kPa}$$

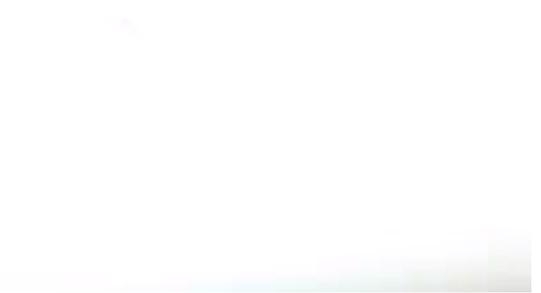
Gels

Mainly water



Elasticity of a gel

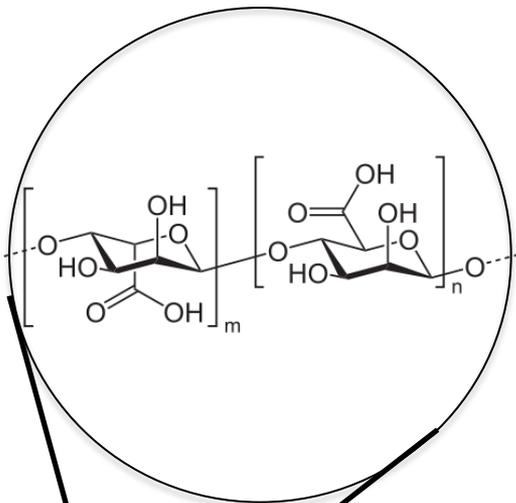
Ex: bouncing gelatin cube (*Modernist Cuisine*)



<http://youtu.be/4n5AfHYST6E>

Gel is made from polymers

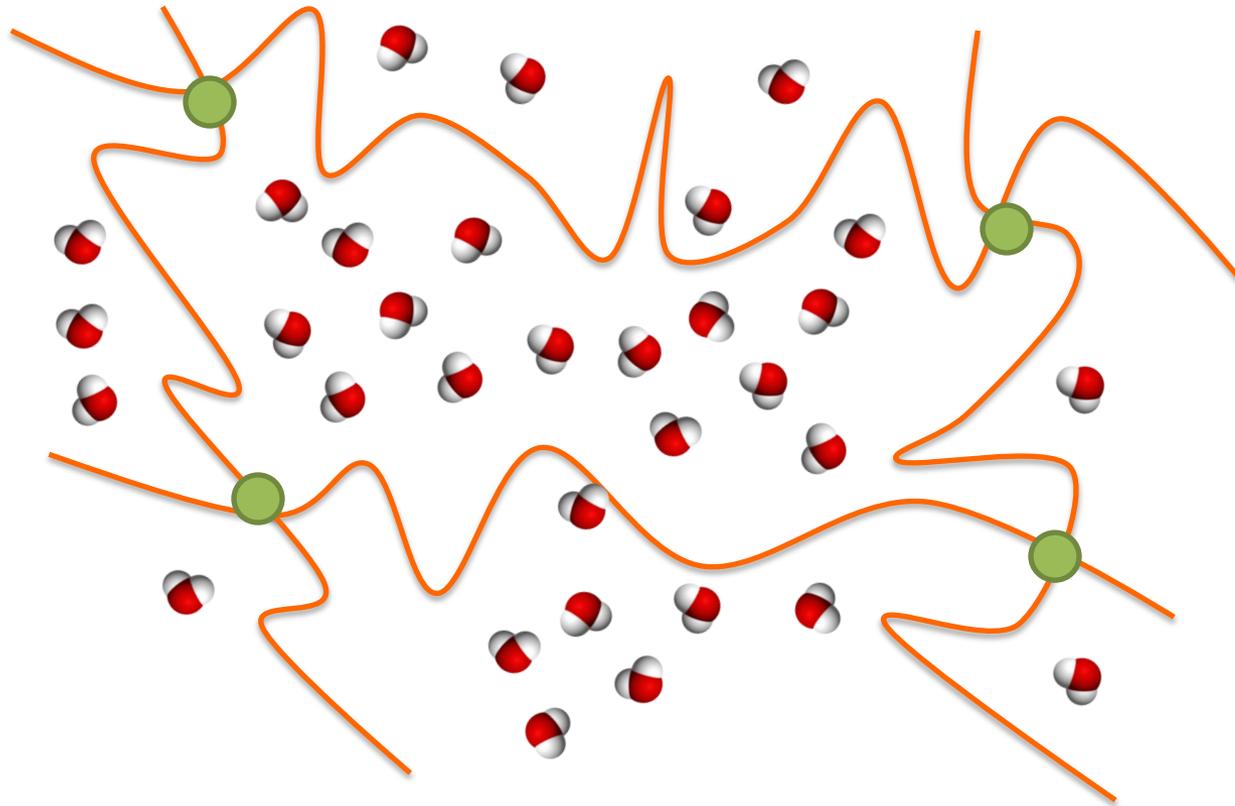
Chains of units or monomers



Alginate → from seaweed

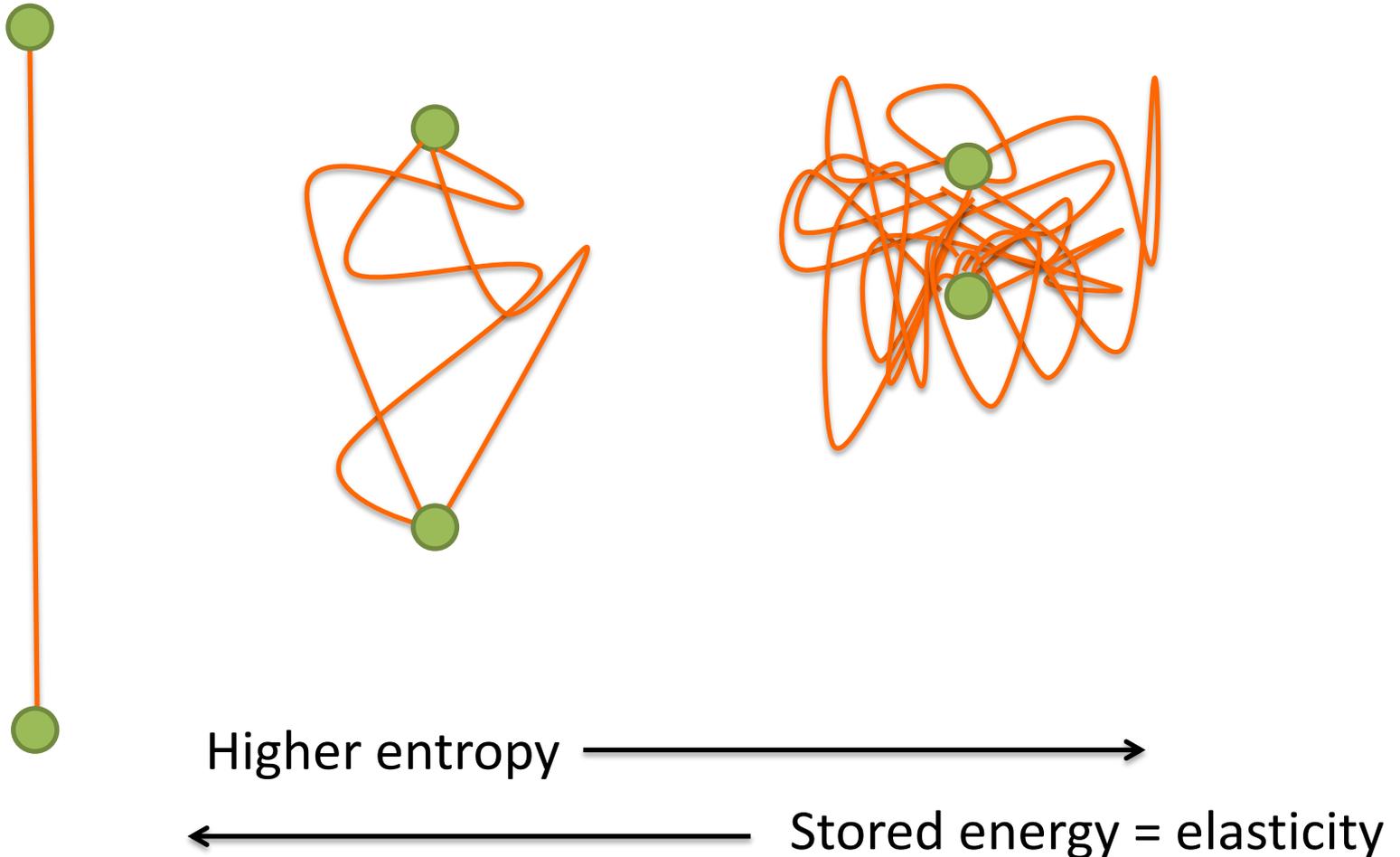
Gel are mainly water

But behave like solids



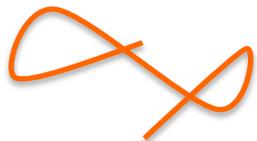
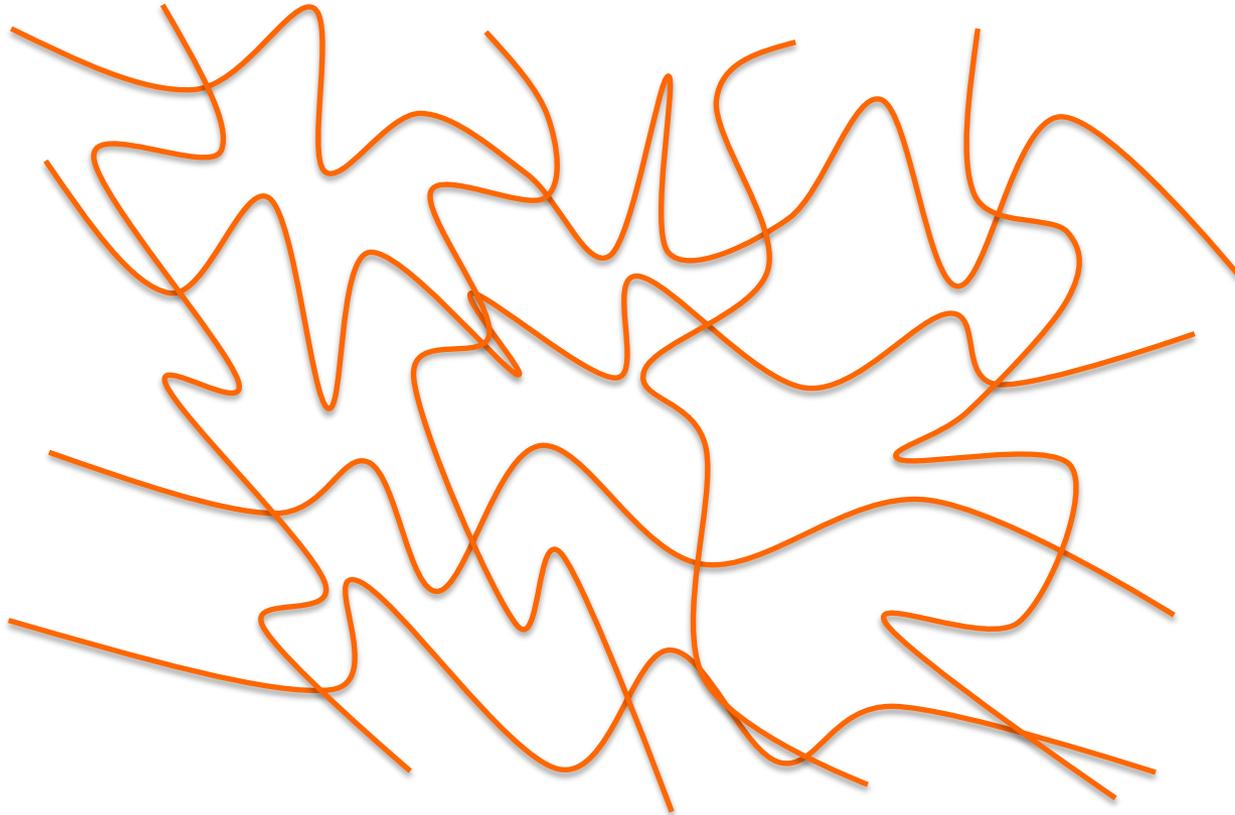
Entropy of polymers leads to elasticity

Stretching polymers reduces the number of states



Polymers chains form a network

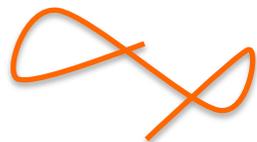
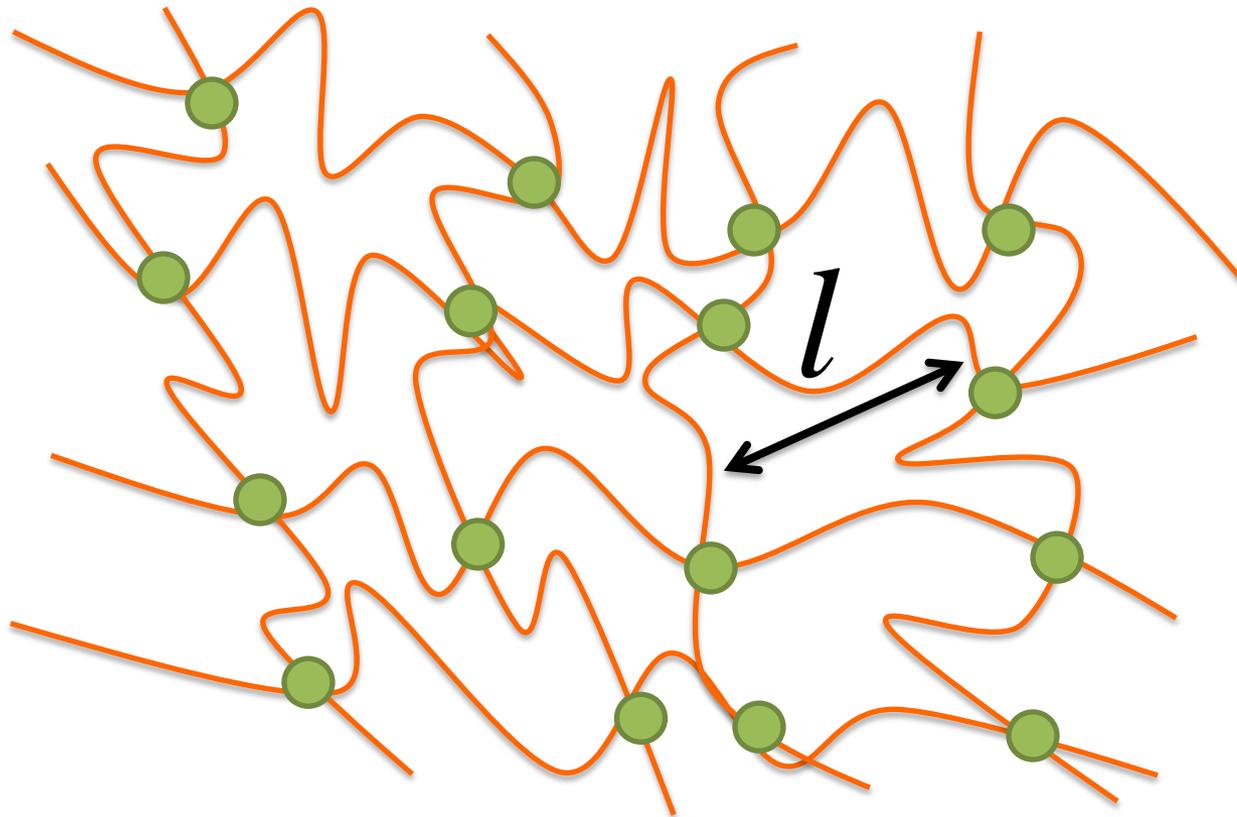
Entangled chains



= polymer strand

Polymers can cross-link to form a gel

Form chemical bond where polymers cross



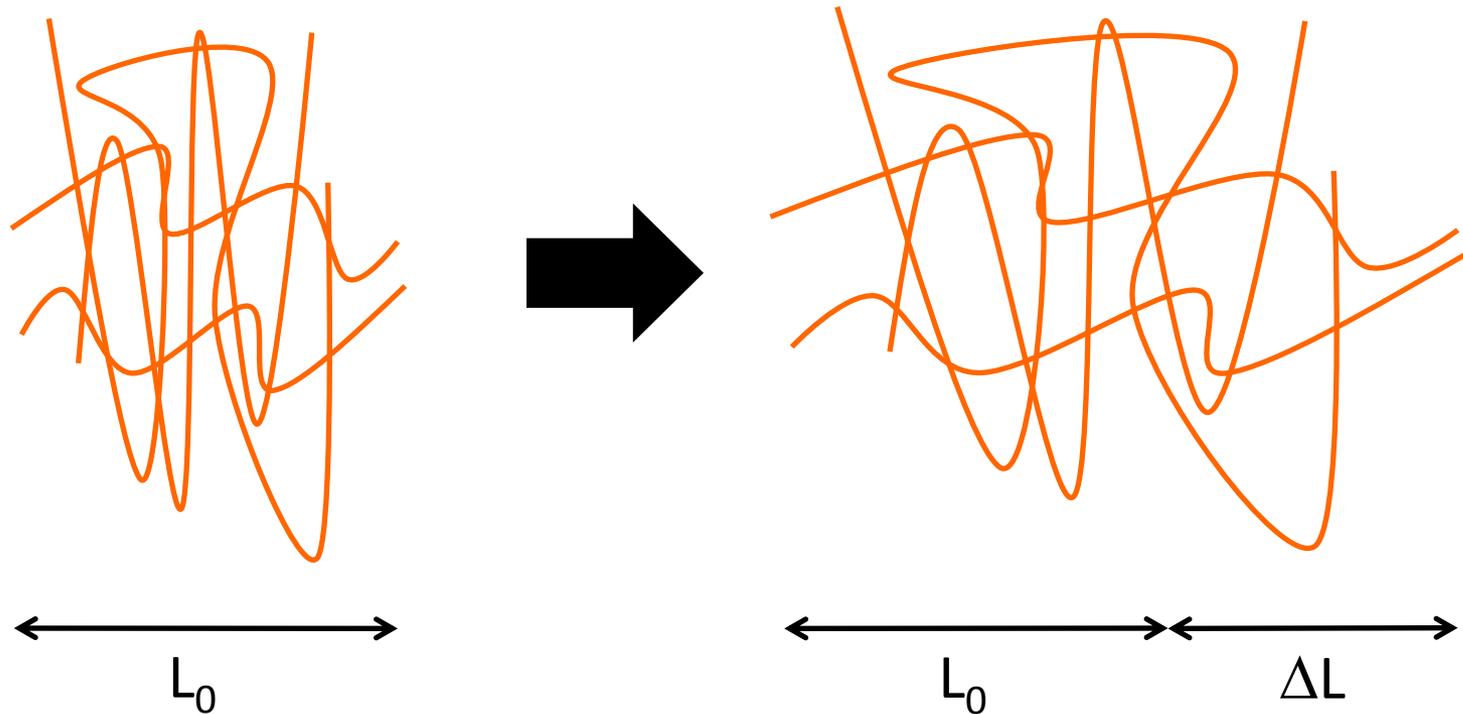
= polymer strand



= permanent bond between
polymer strands

Microscopic view

Deformations in the network causes elasticity



Long molecules straighten out as the material is stretched.

Equation of the week

Elasticity of a gel depends on cross-link spacing

$$E = \frac{k_B T}{l^3}$$



E = elasticity [Pa]

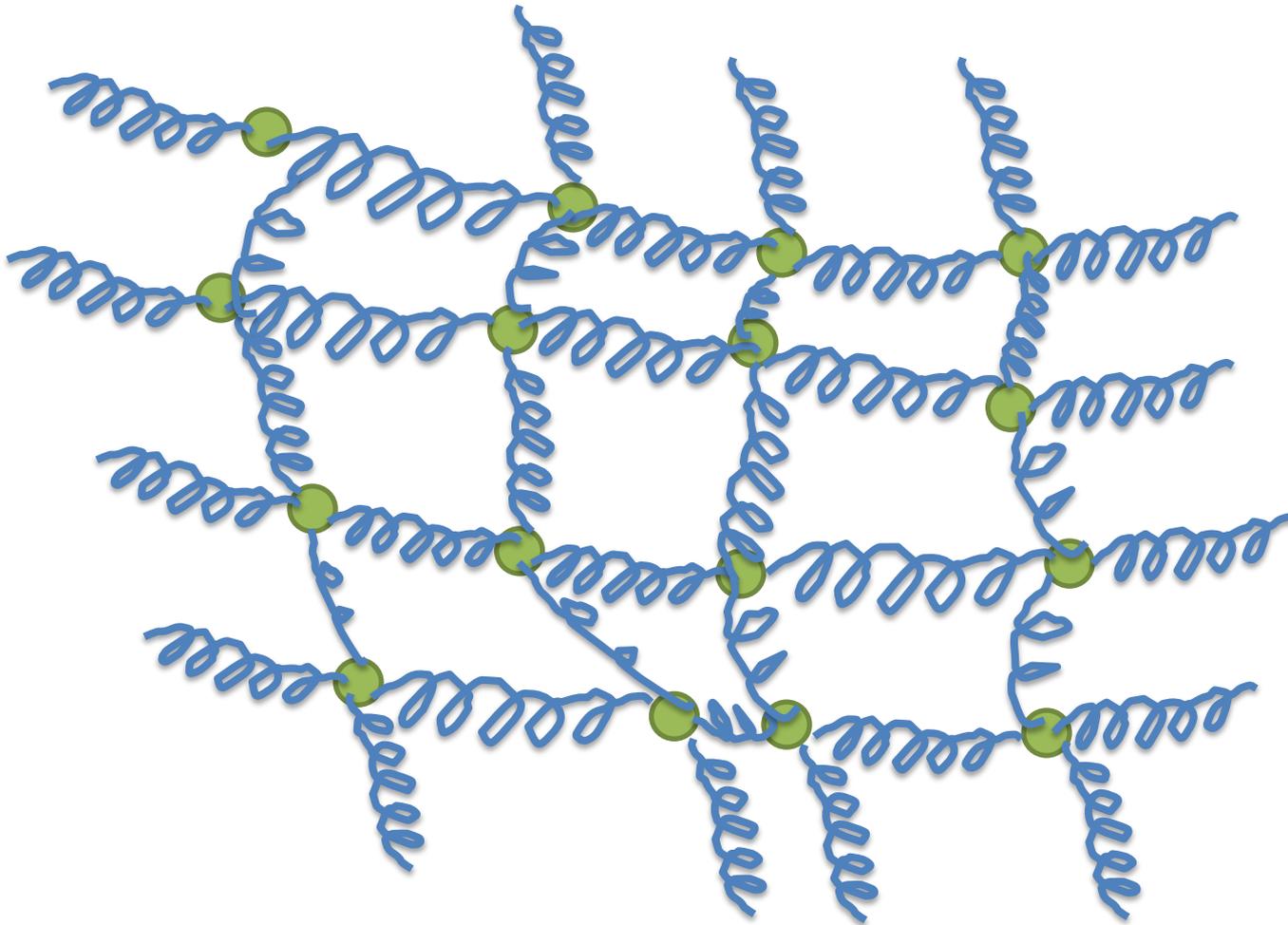
k_B = Boltzmann's constant [J/K]

T = temperature [k]

l = mesh spacing [m]

Sodium alginate gel

Cross link with calcium



Elasticity is due to the spring-like connections of the polymer strands

Spherification:

Diffusion-limited gelation

Spherification: a use of gelation

Green pea ravioli / el Bulli and Alícia Foundation



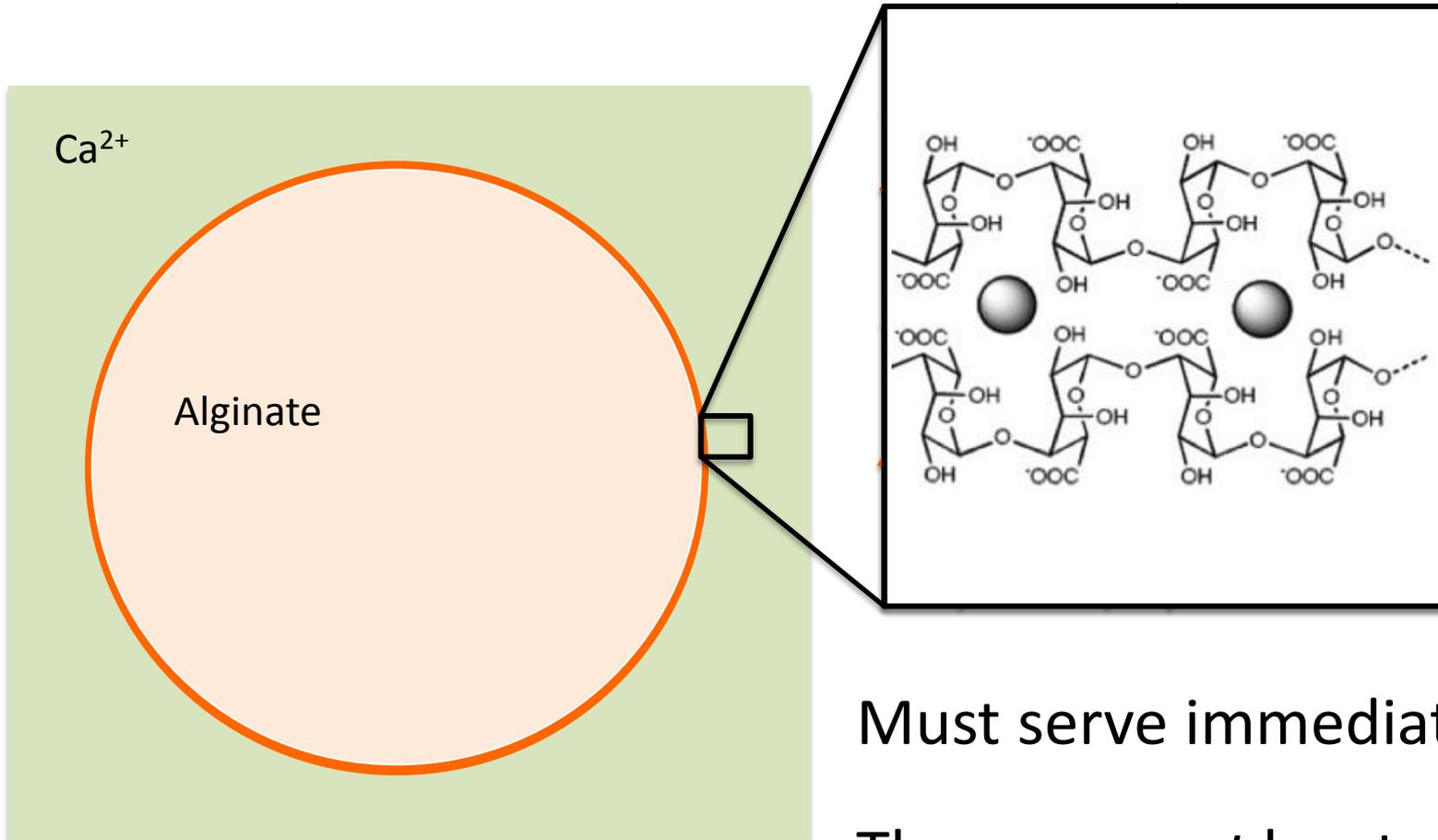
Spherification

Yogurt spheres



Spherification: Direct

Alginate drop forms gels with Ca^{2+} in solution

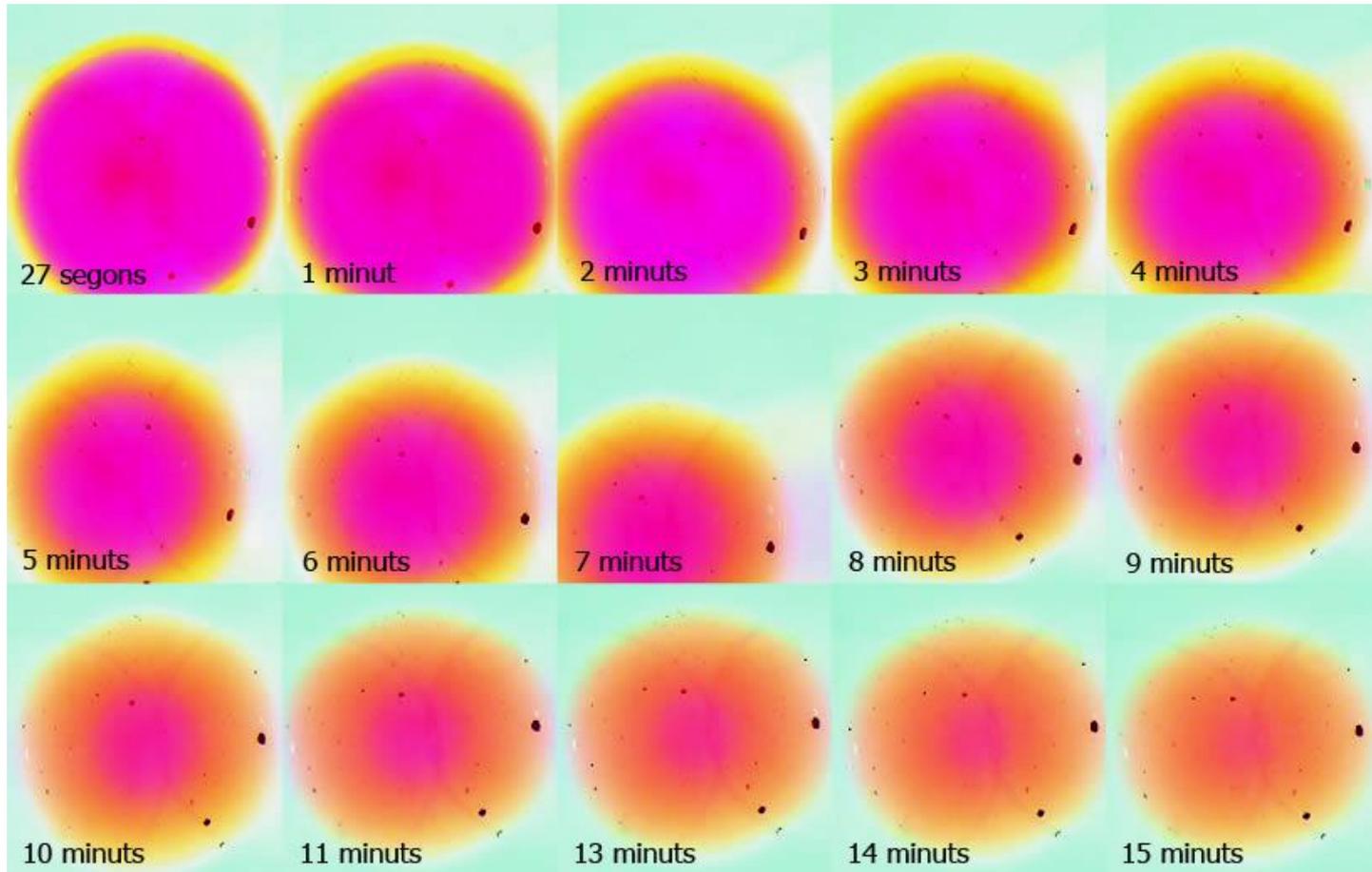


Must serve immediately

These can *not* be stored

Internal view of spherification

Shell thickens with time in the Ca^{2+} bath

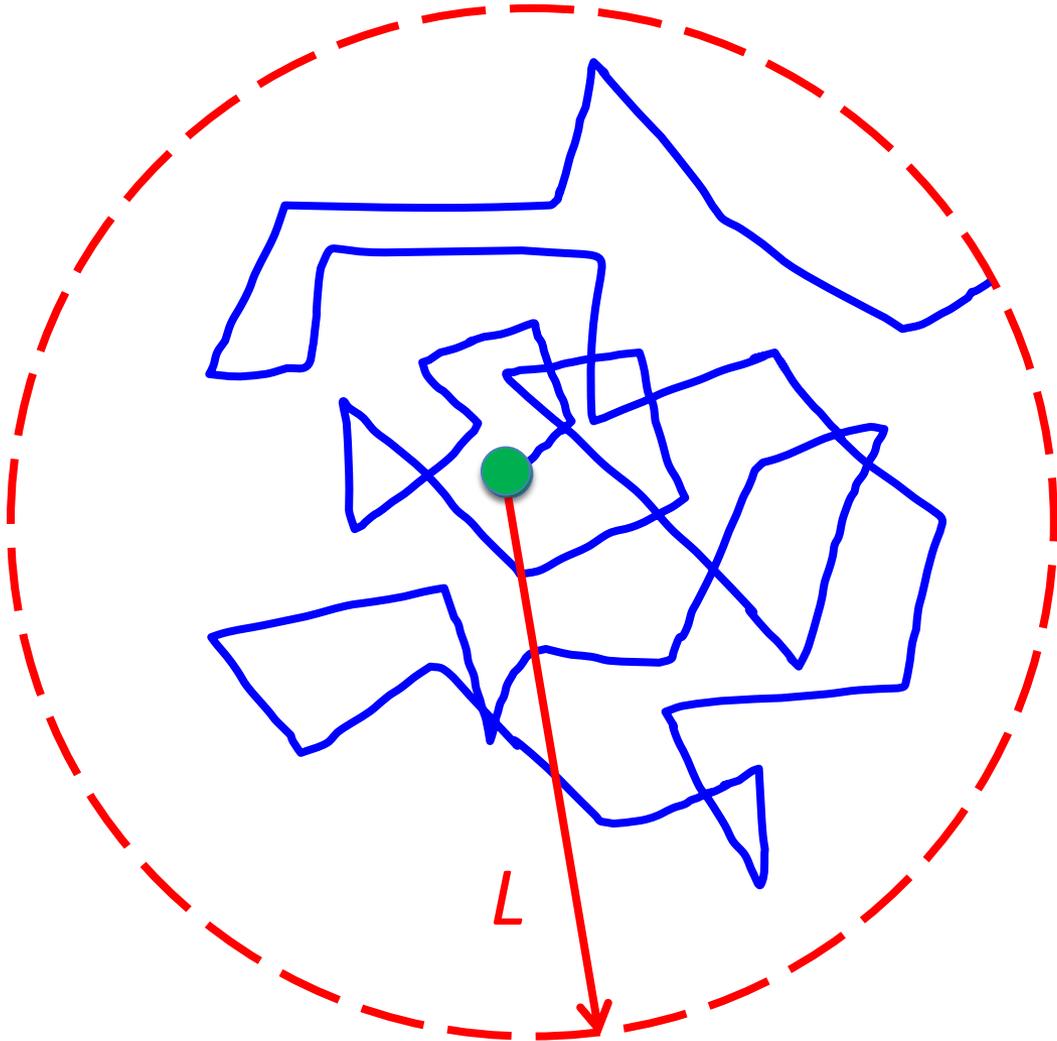


(F. Sapiña y E. Martinez, Universitat de València)



Random walk in two-dimensions

Motion takes much longer because path is longer



Number of steps: n

Particle radius: a

Total path length: s

$$n = \left(\frac{L}{a} \right)^2$$

$$s = na = \left(\frac{L}{a} \right)^2 a$$

Diffusion equation

Diffusion time is proportional to distance squared

$$t = \frac{L^2}{D}$$

t = time to diffuse [sec]

L = distance of diffusion [m]

D = diffusion coefficient [m²/sec]



Time scale for spherification

Diffusion of Ca^{2+} ions in water: $D = 7 \times 10^{-10} \text{ m}^2/\text{sec}$

10 micron shell



100 micron shell



$$t = \frac{L^2}{D} = \frac{(10 \cdot 10^{-6} \text{ m})^2}{7 \cdot 10^{-10} \text{ m}^2/\text{s}}$$

$$t = 0.1 \text{ sec}$$

$$t = \frac{L^2}{D} = \frac{(100 \cdot 10^{-6} \text{ m})^2}{7 \cdot 10^{-10} \text{ m}^2/\text{s}}$$

$$t = 10 \text{ sec}$$

Time scale for spherification

Diffusion of Ca^{2+} ions in water: $D = 7 \times 10^{-10} \text{ m}^2/\text{sec}$

10 micron shell



1 mm shell



$$t = \frac{L^2}{D} = \frac{(10 \times 10^{-6} \text{ m})^2}{7 \times 10^{-10} \text{ m}^2/\text{s}}$$

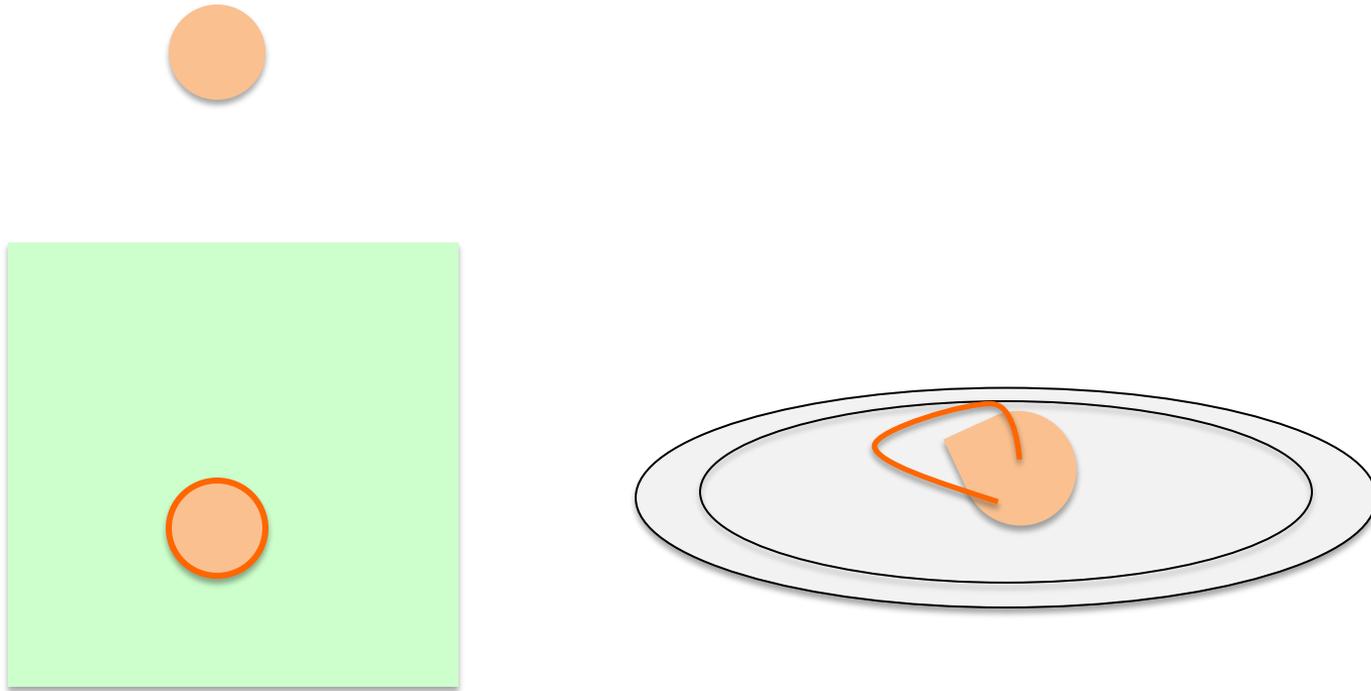
$$t = 0.1 \text{ sec}$$

$$t = \frac{L^2}{D} = \frac{(10^{-3} \text{ m})^2}{7 \times 10^{-10} \text{ m}^2/\text{s}}$$

$$t = 1000 \text{ sec} = 20 \text{ min}$$

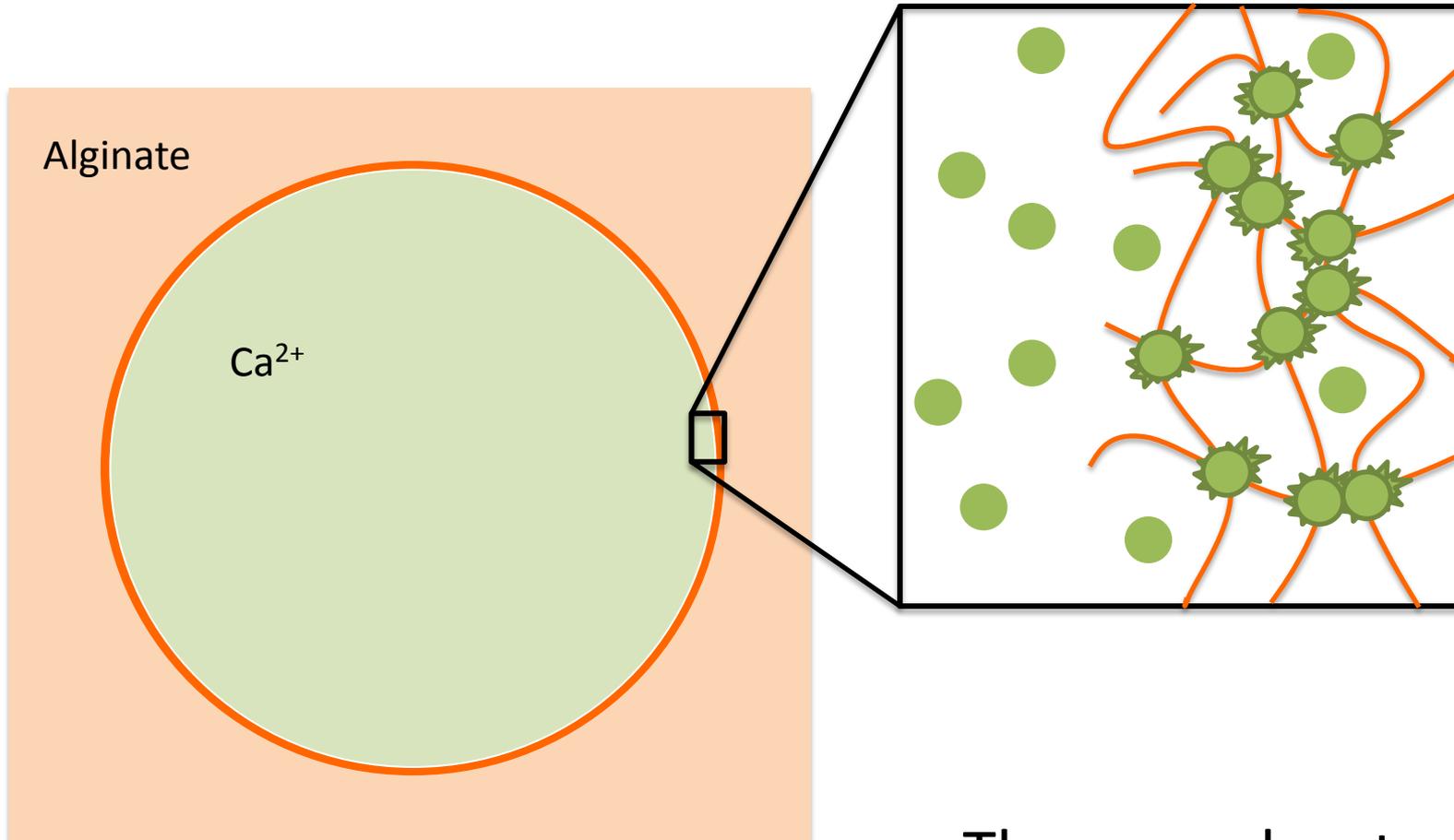
Inverse spherification

Form thin layer of gel around droplet



Inverse spherification

Ca²⁺ solution forms gels with aqueous alginate



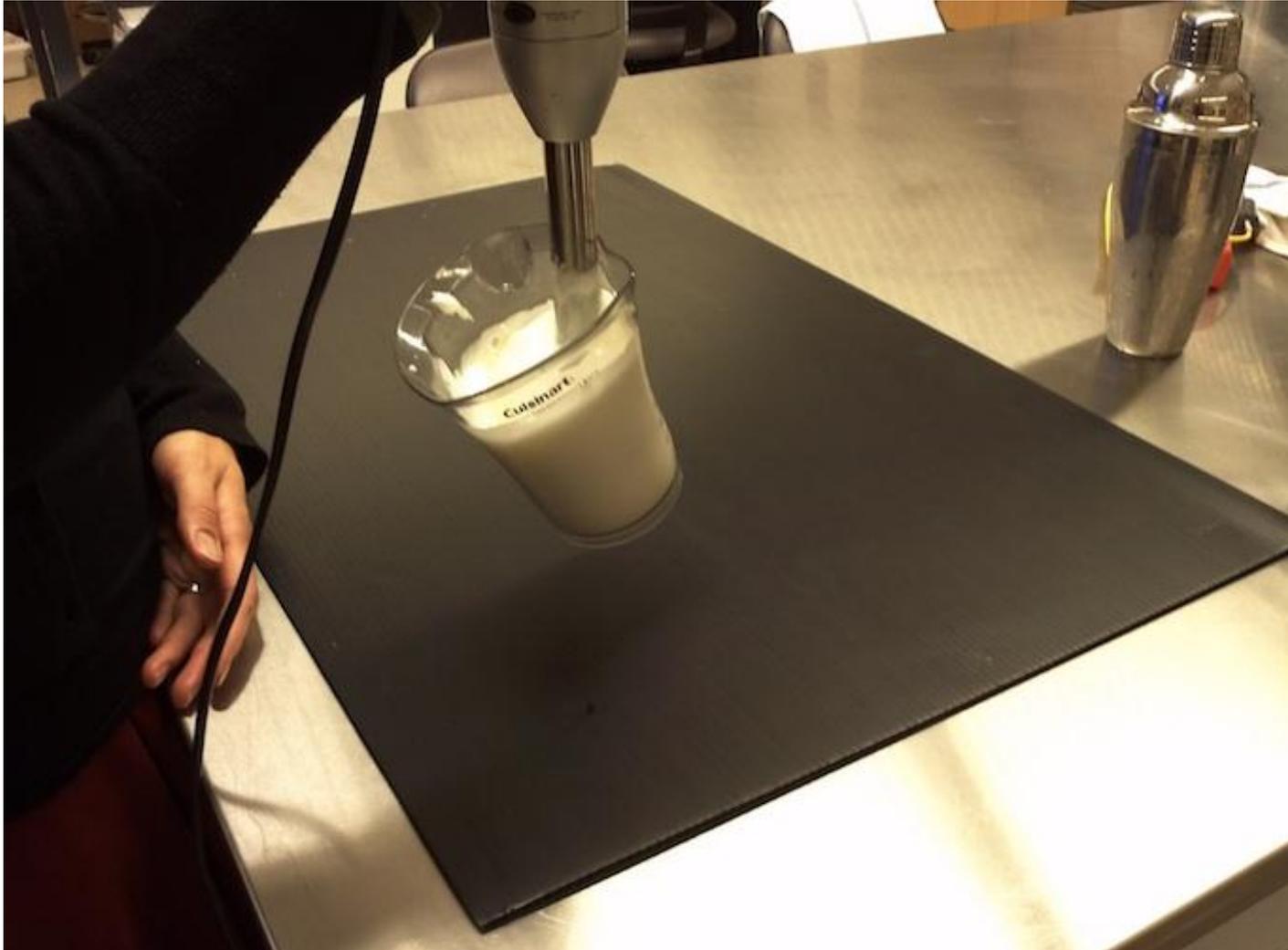
These *can* be stored

Emulsion:

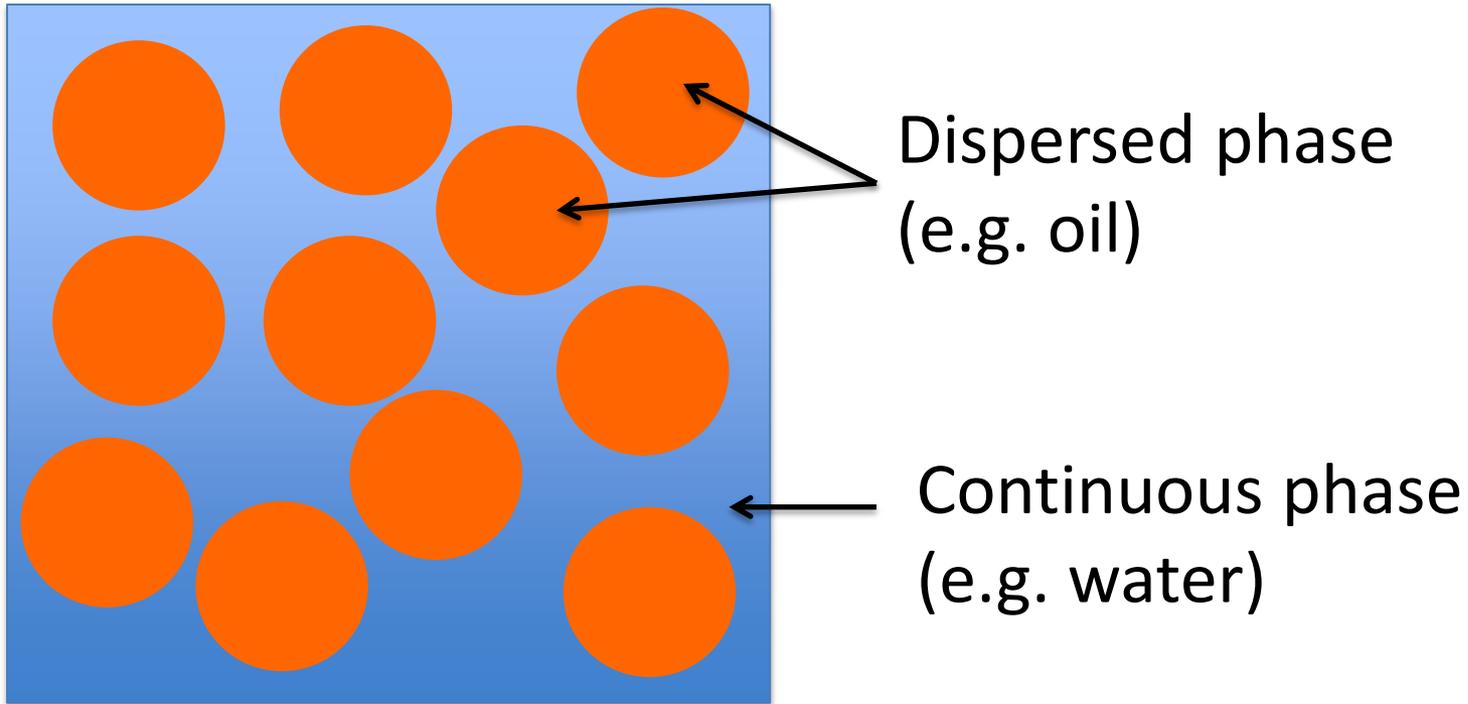
Mixing oil and water

Mayonnaise

Water and oil can create a stable emulsion with egg as surfactant



Emulsion: Drops of one fluid in another



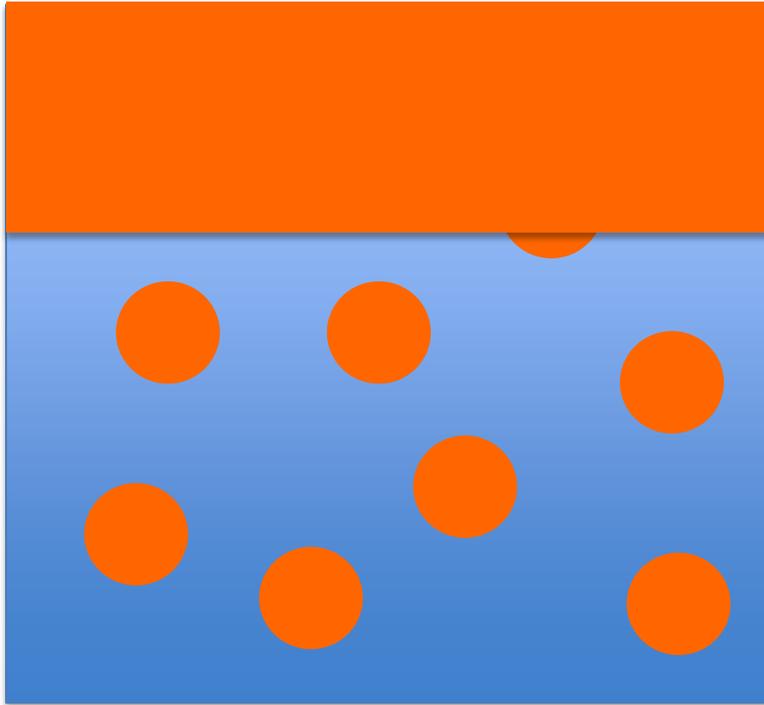
Formation of emulsions

Droplets of one liquid are formed within another.



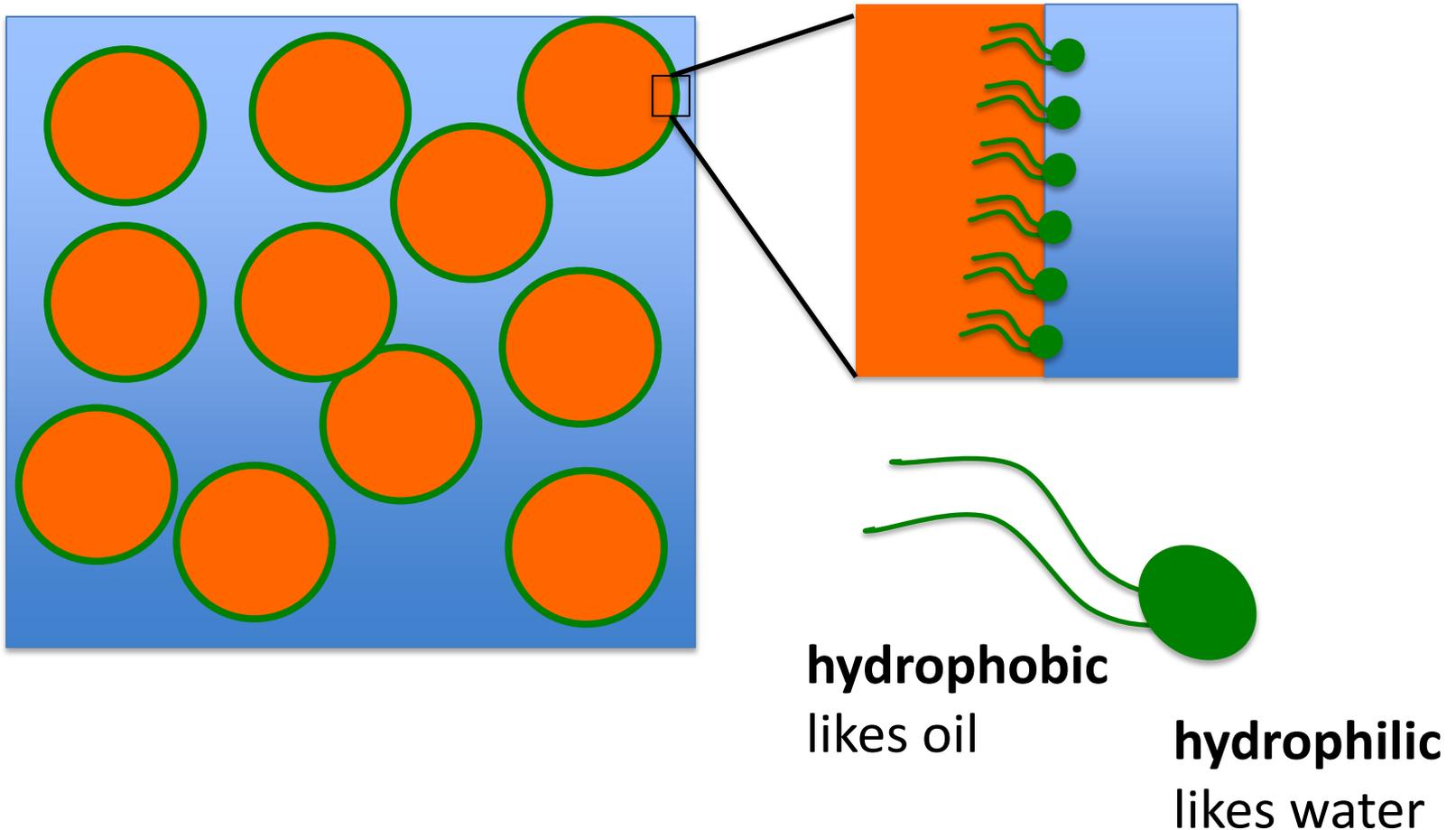
Formation of emulsions

Droplets of one liquid are formed within another.



Surfactants stabilize emulsions

Surfactants: surface-active molecules



Surfactants stabilize emulsions.

Ampiphilic molecules attach to the interfaces.



Microscopic view of the interface between drops

Concentrated emulsions are solids

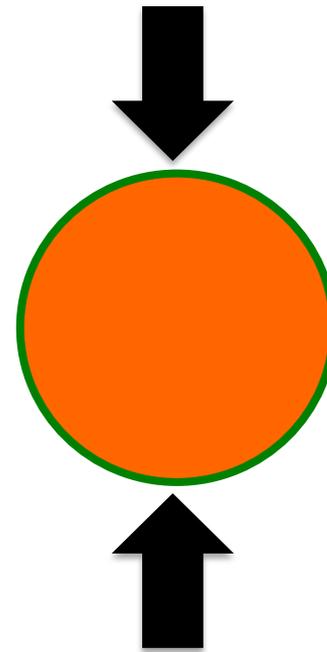
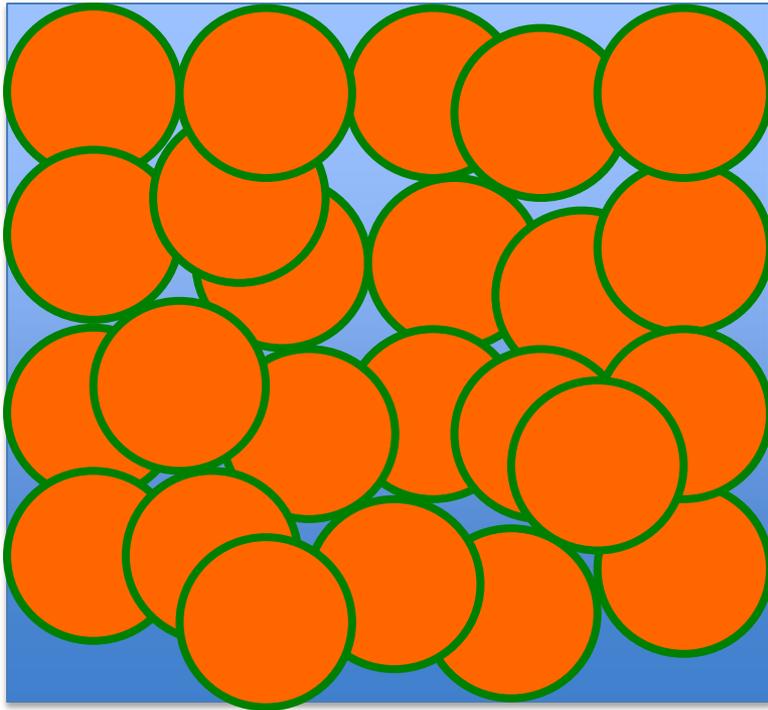
Two liquids mixed together become a solid!



Microscopic view of the interface between drops

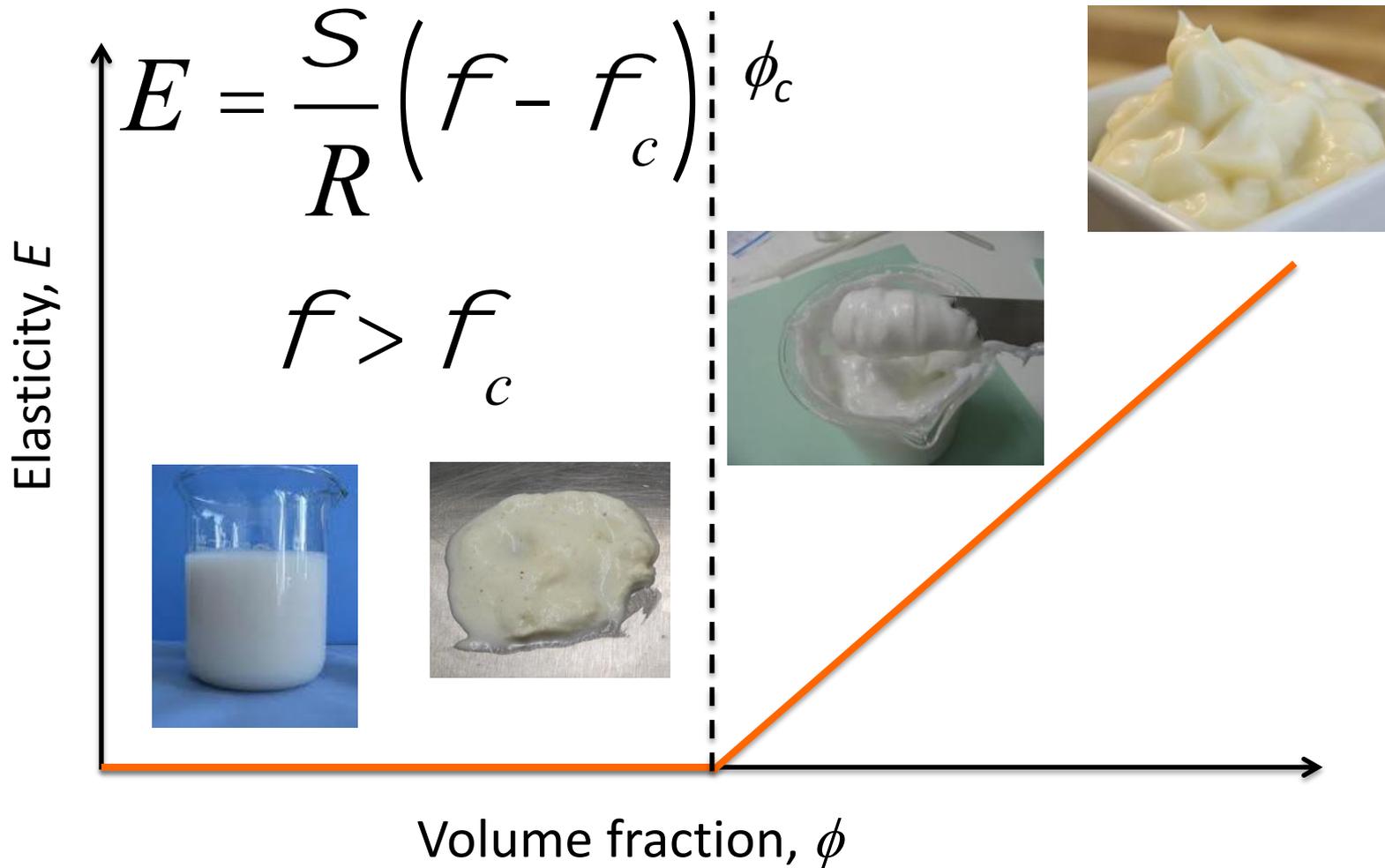
Emulsions can be solids

Compressed droplets resist deformation.



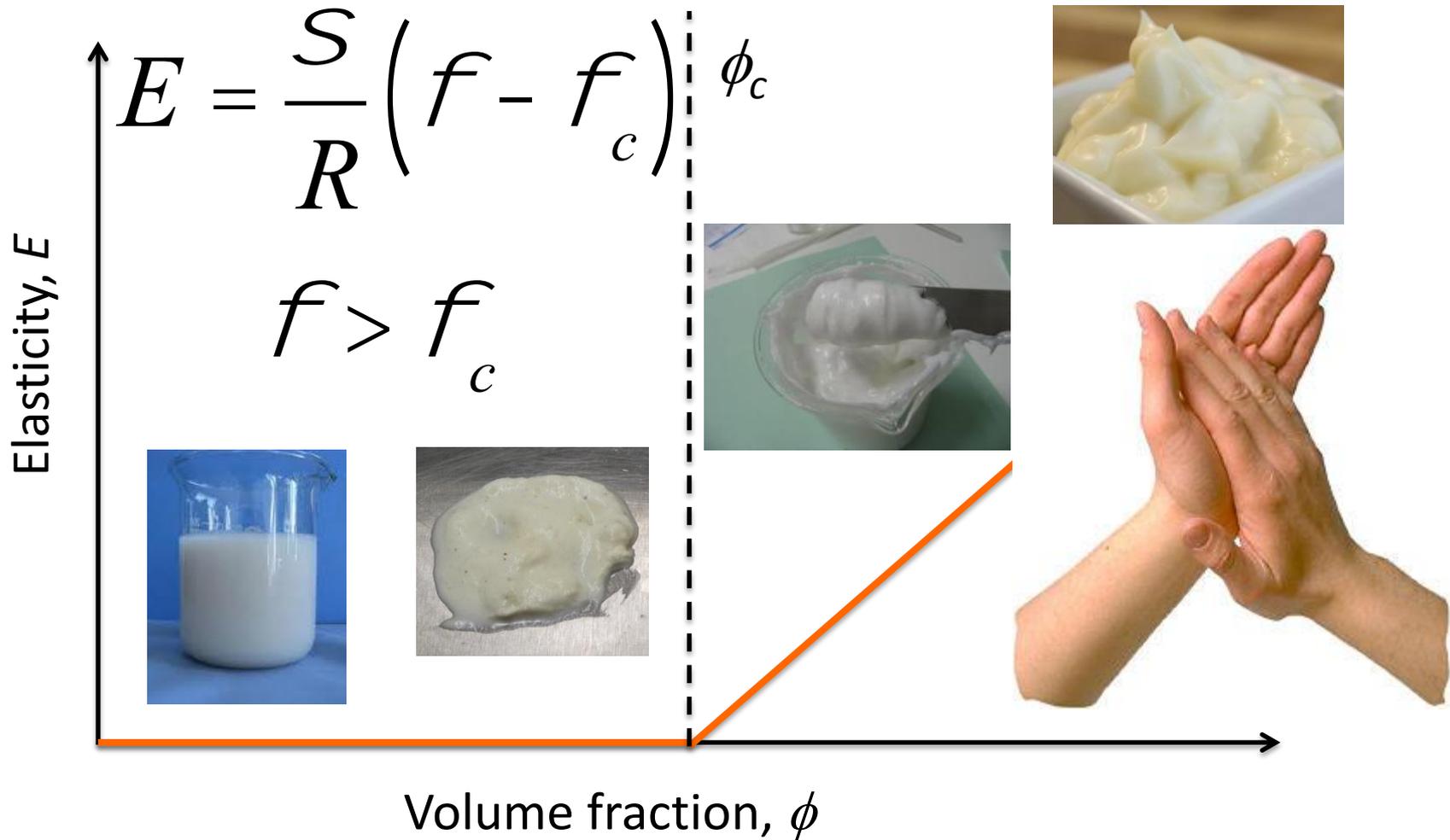
Elasticity as a function of ϕ

Emulsions are elastic above critical volume fraction.



Elasticity as a function of ϕ

Emulsions are elastic above critical volume fraction.



Foams:

Liquid + Gas = Solid

Example: beer foam

Gas becomes trapped by surfactants in the drink.



Foam production

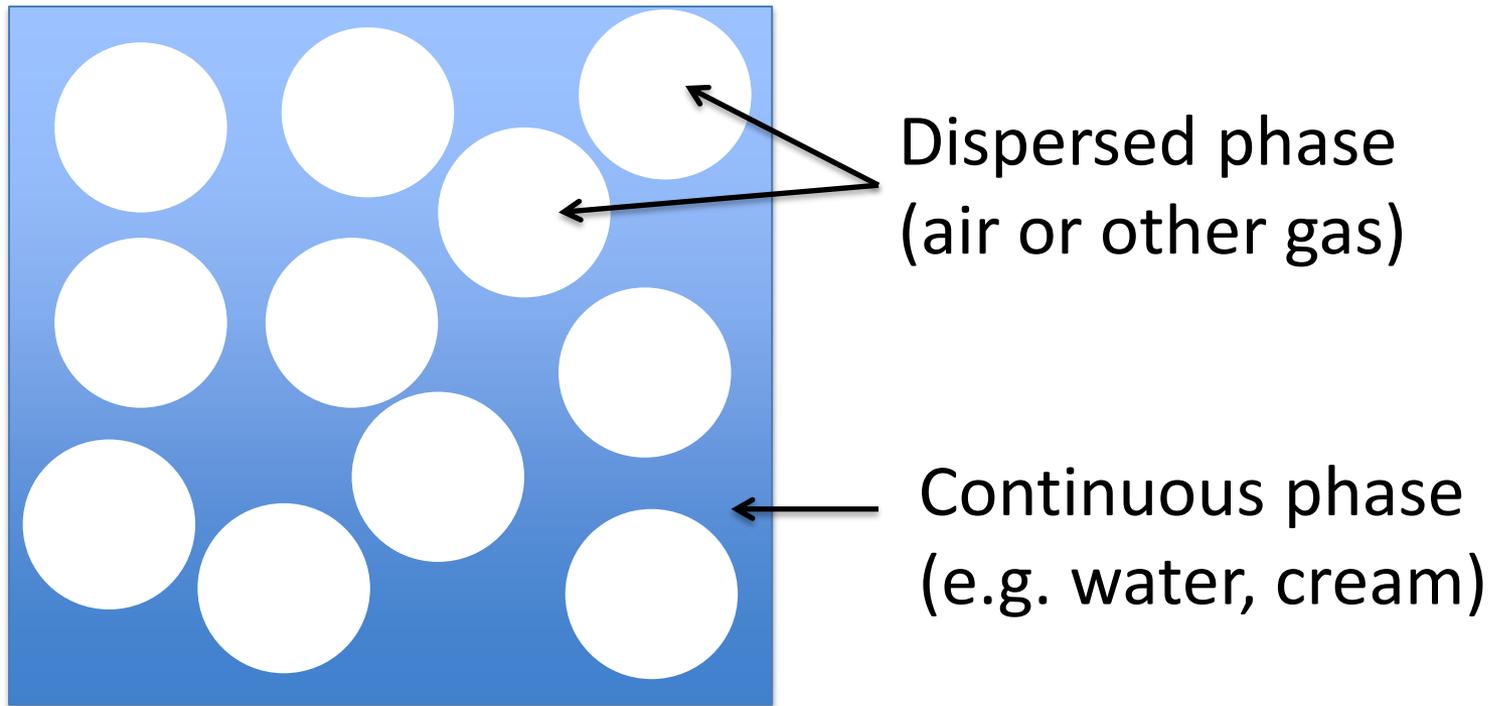
Incorporate air into fluid



Mix

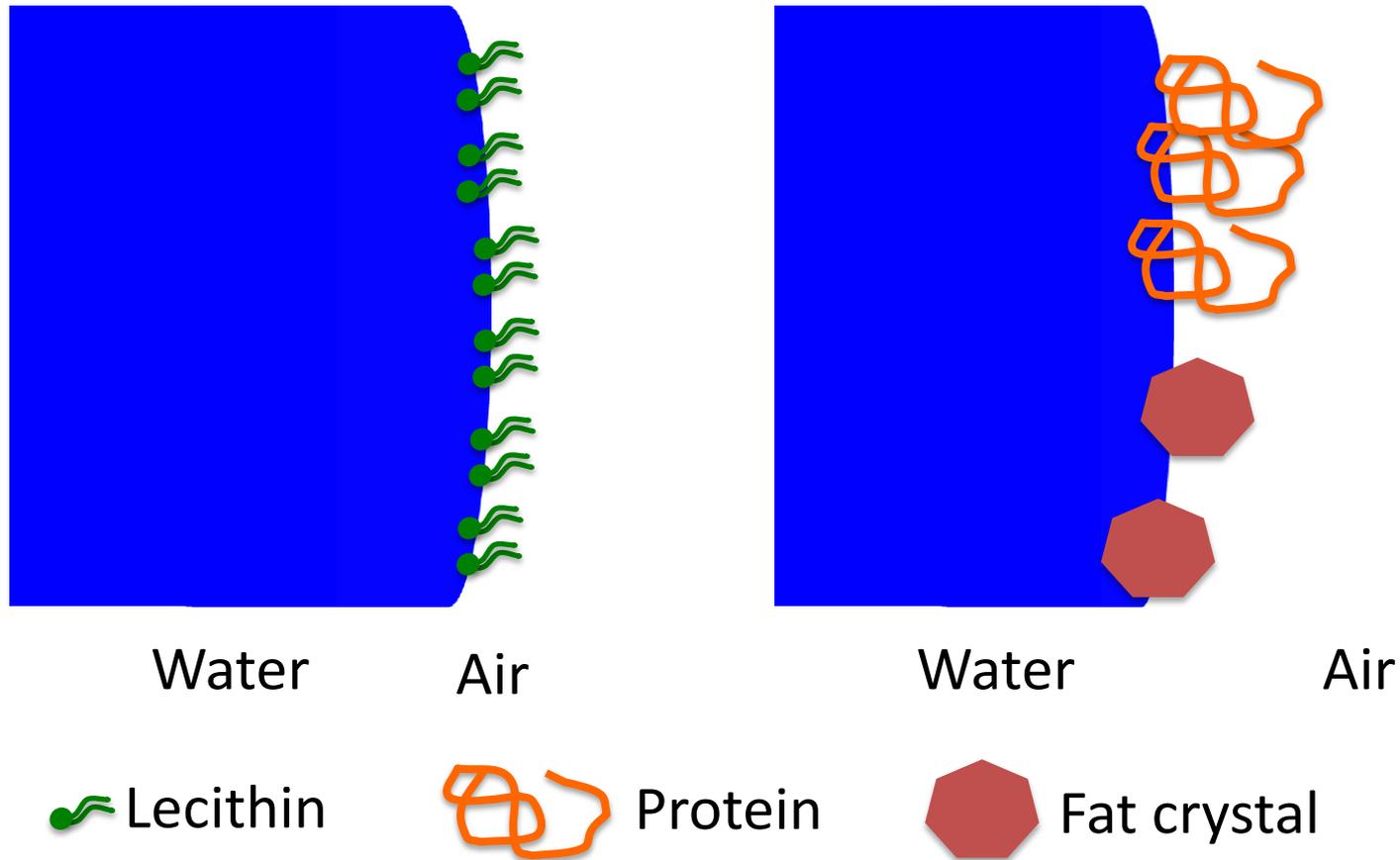
Foam: Bubbles of gas in a liquid

Emulsions with a dispersed phase of gas.



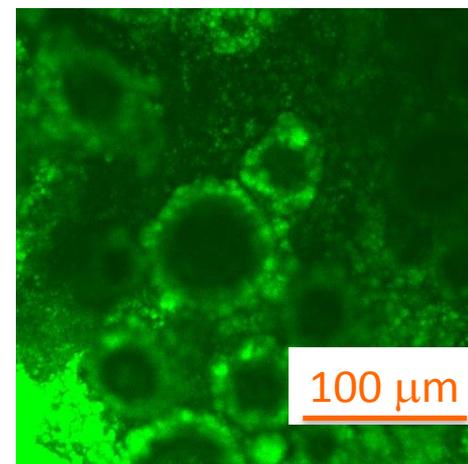
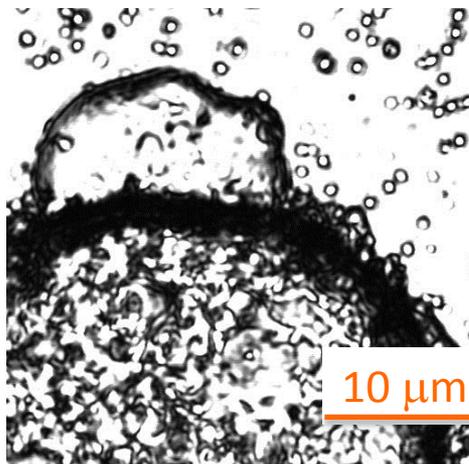
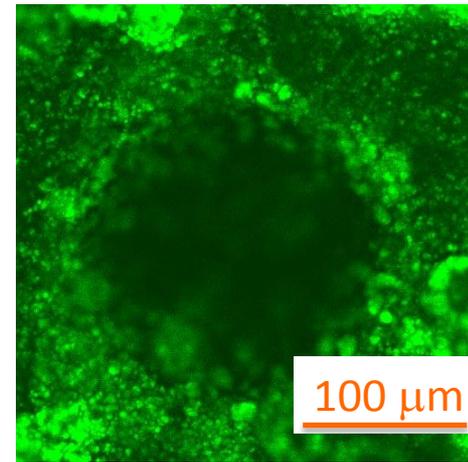
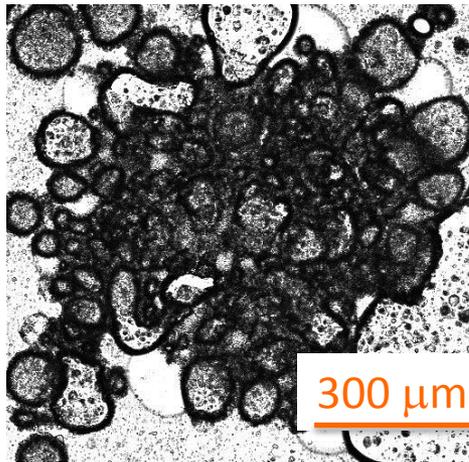
Role of surfactants

Proteins, starches, and fats can act as surfactants



Foam micro-structure

There are several methods for incorporating air.



Foam production

Incorporate air into fluid



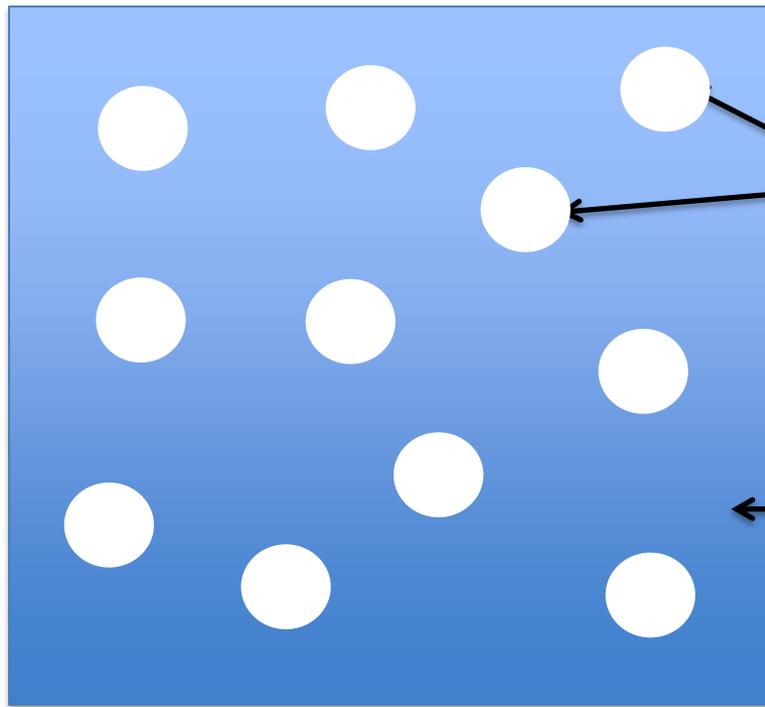
Mix



Add high-pressure gas

Foam: Mix compressed gas with fluid

Compressed gas is liquid – forms emulsion with fluid



Emulsion of compressed gas in fluid

Foam forms upon release of pressure

Foam production

The resulting products differ in appearance.



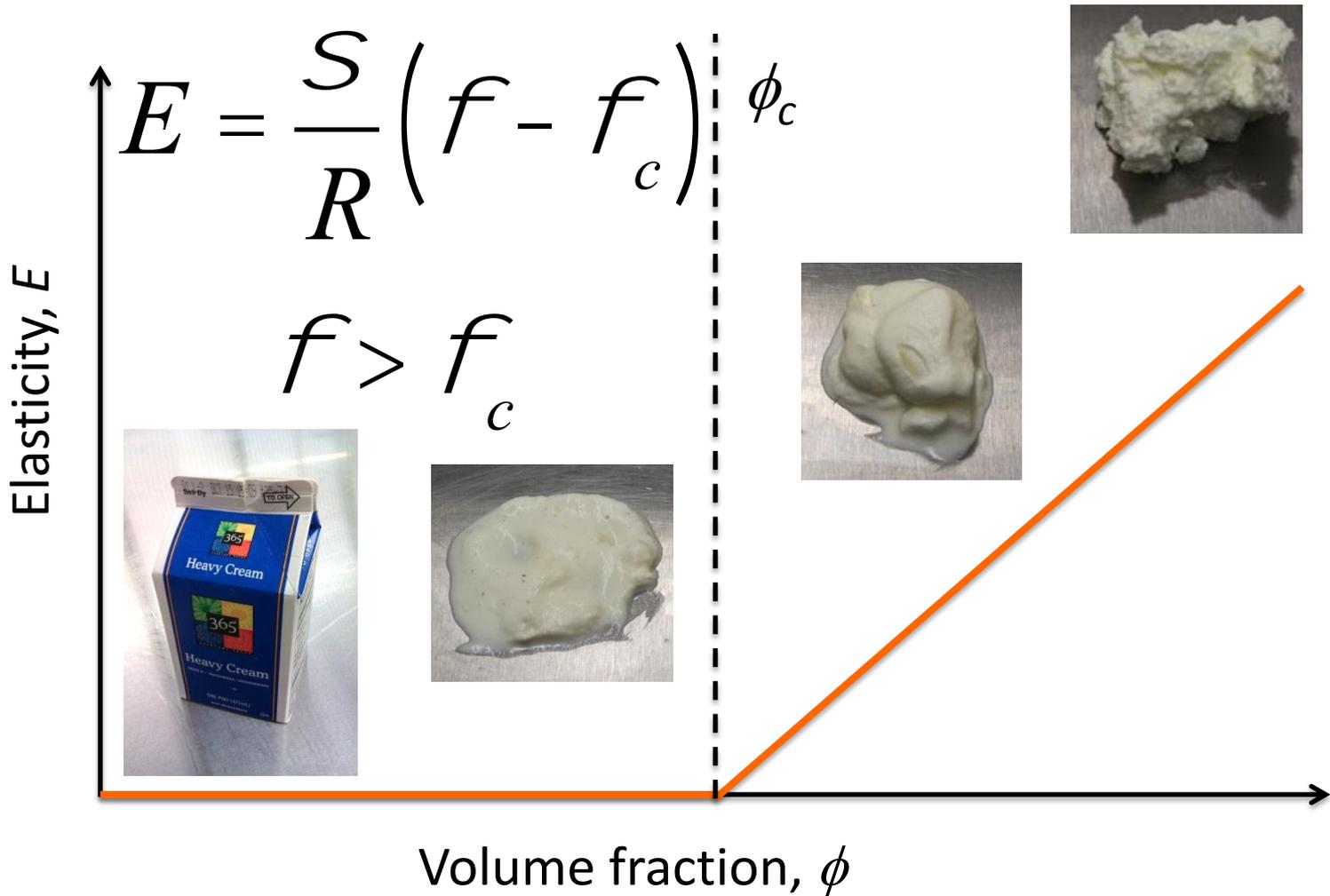
KitchenAid
(short time)

iSi Whip

KitchenAid
(long time)

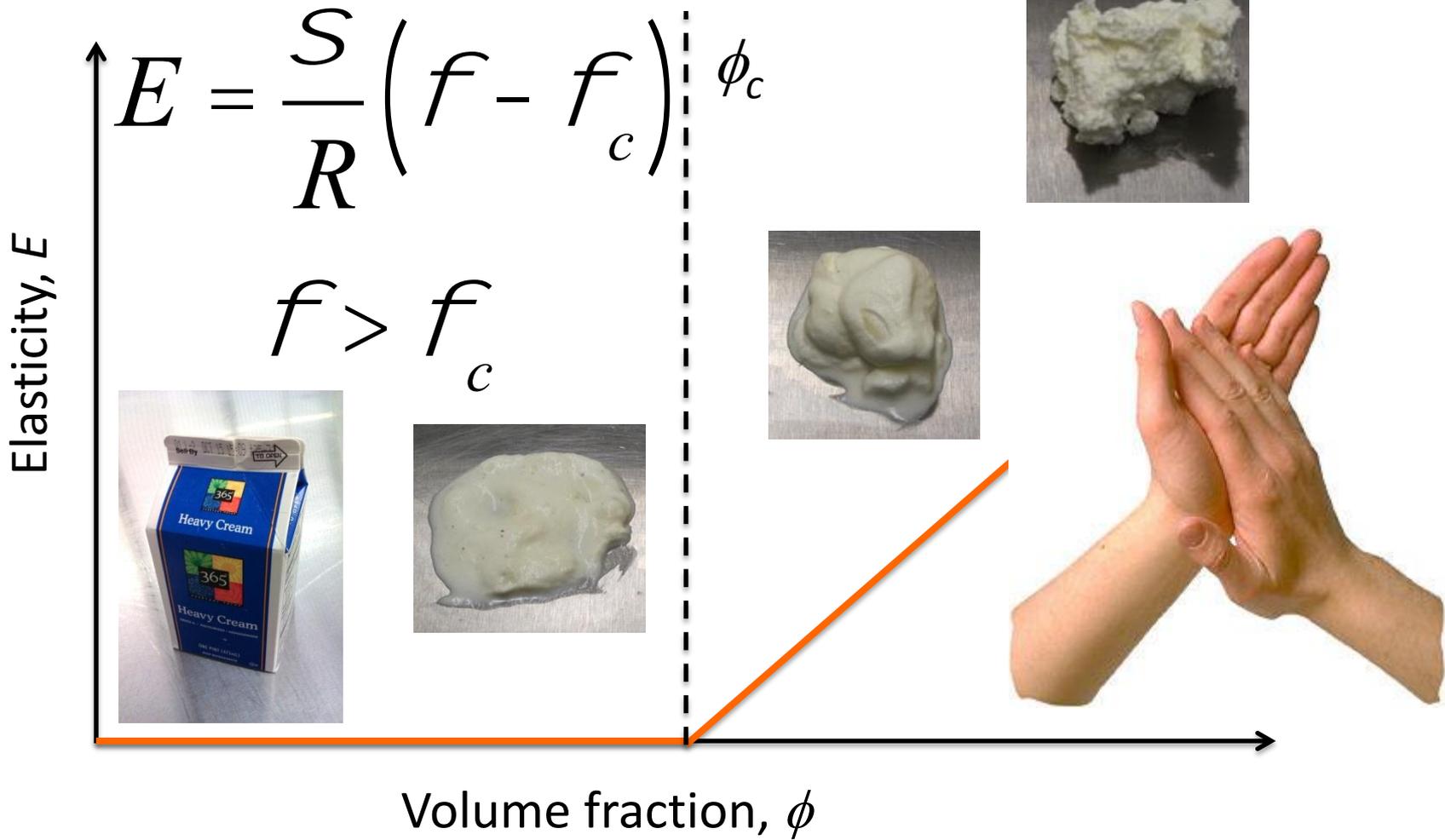
Elasticity as a function of ϕ

Foams are elastic above critical volume fraction.



Elasticity as a function of ϕ

Foams are elastic above critical volume fraction.

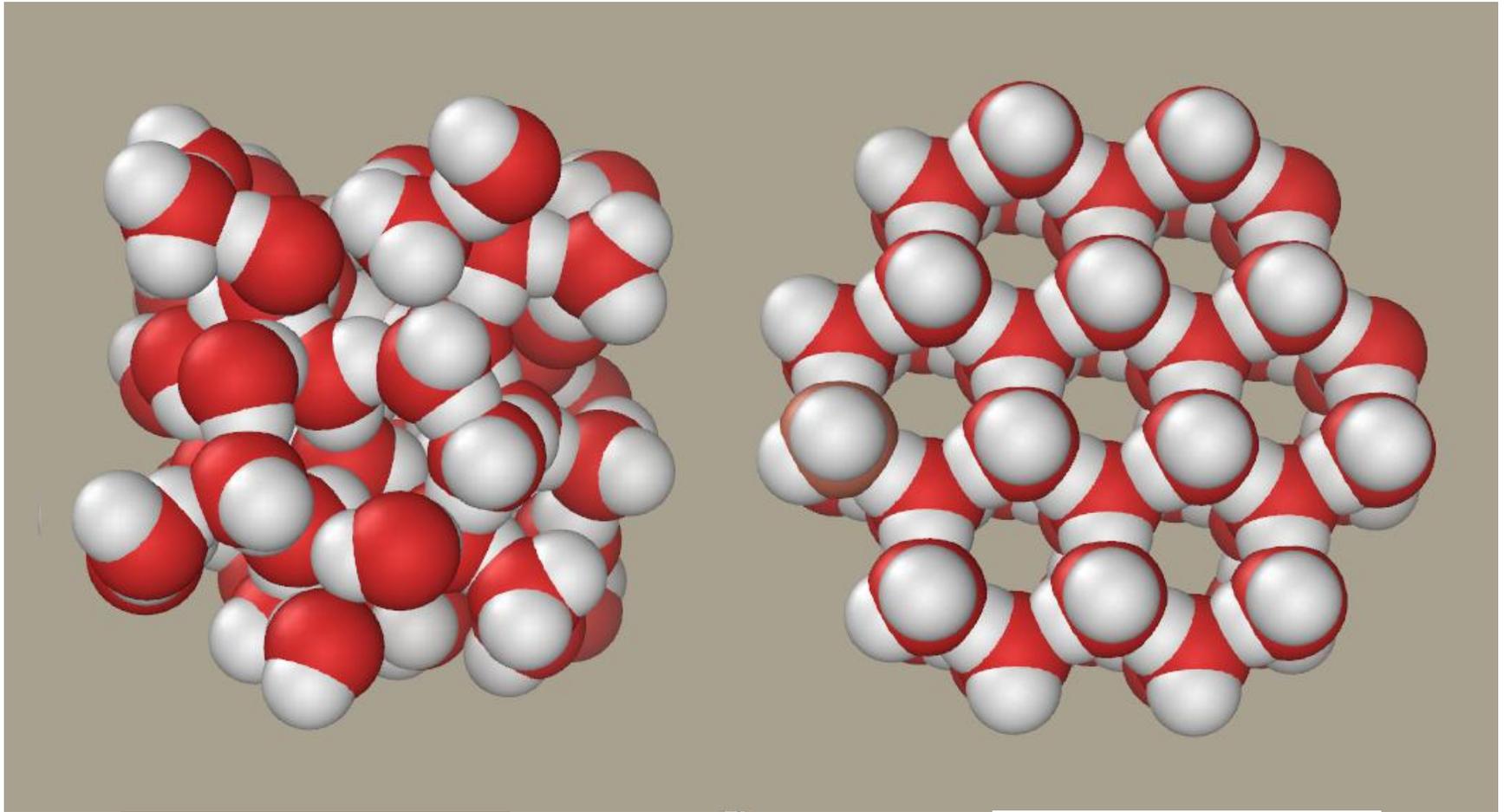


Cocktails:

Cooling and Dilution

Molecular viewpoint

Ice is in a lower entropy state than water.



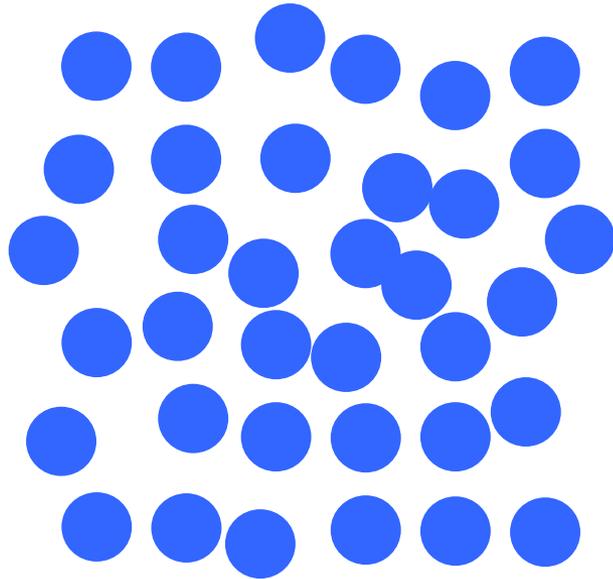
Liquid

Ice

Molecular viewpoint

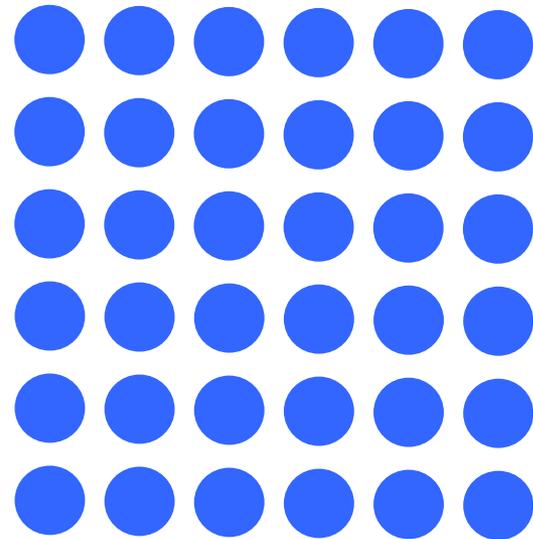
Ice is in a lower energy state than water

Higher energy



Liquid

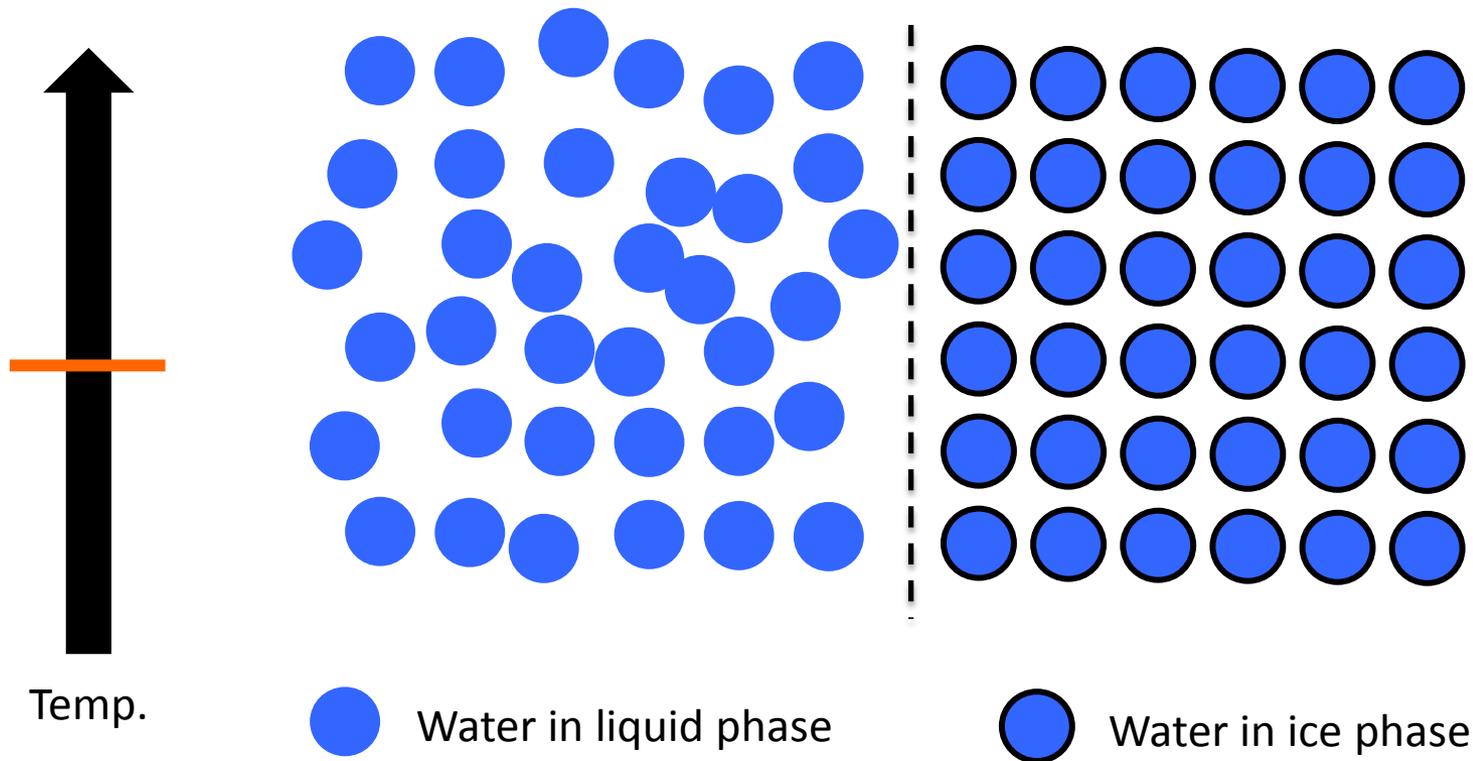
Lower energy



Ice

Molecular viewpoint

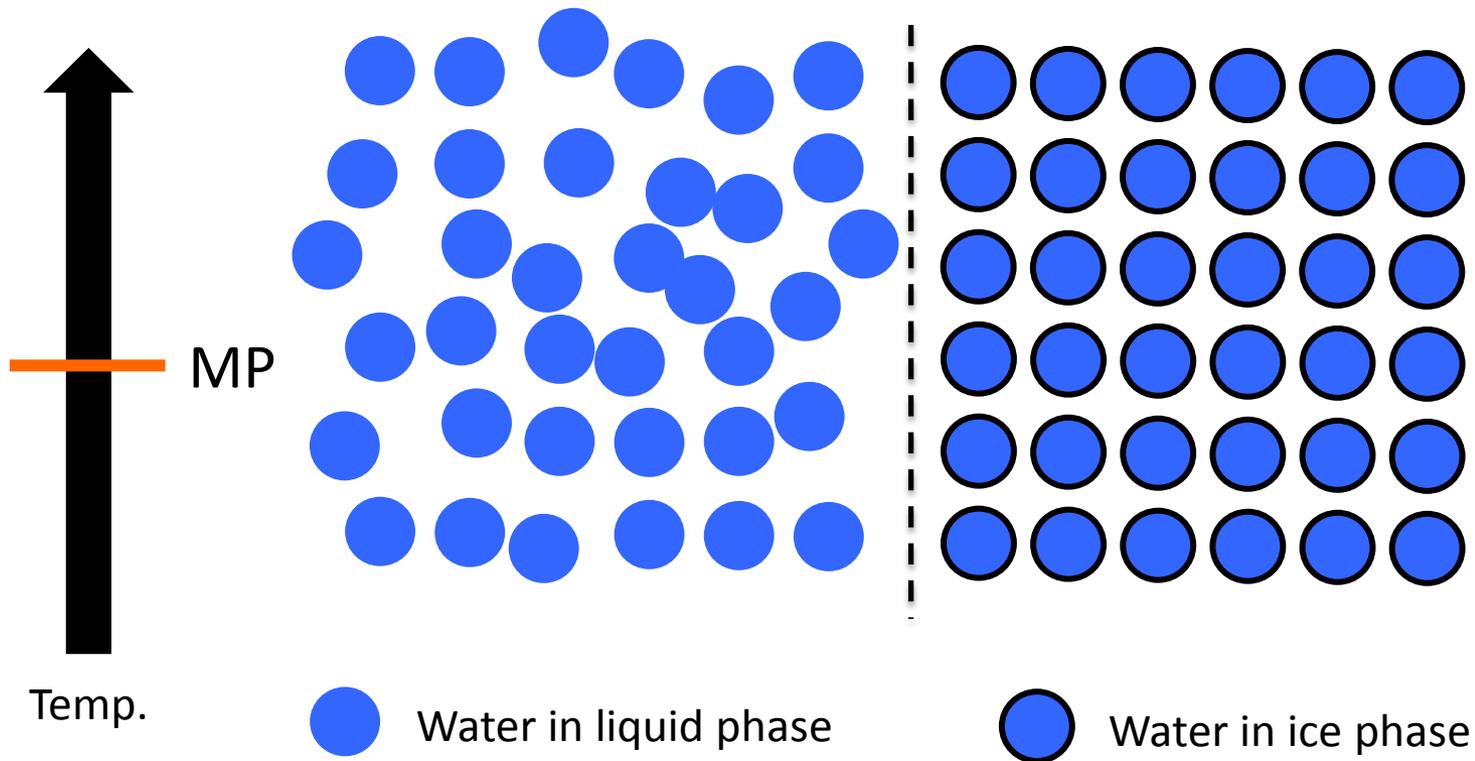
The interface continually exchanges molecules.



All the water molecules are chemically identical.

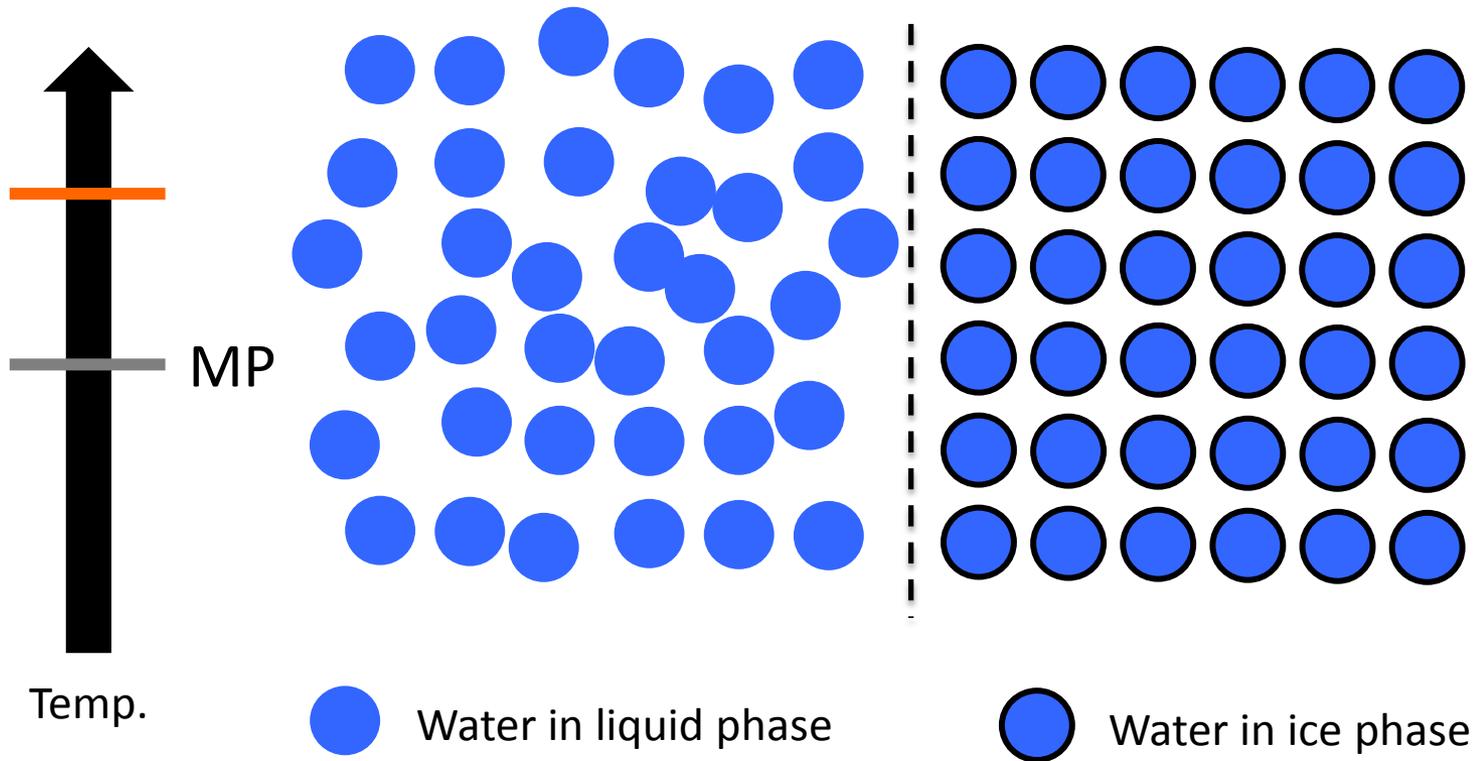
Equilibrium: at melting point

The same numbers leave and enter the ice.



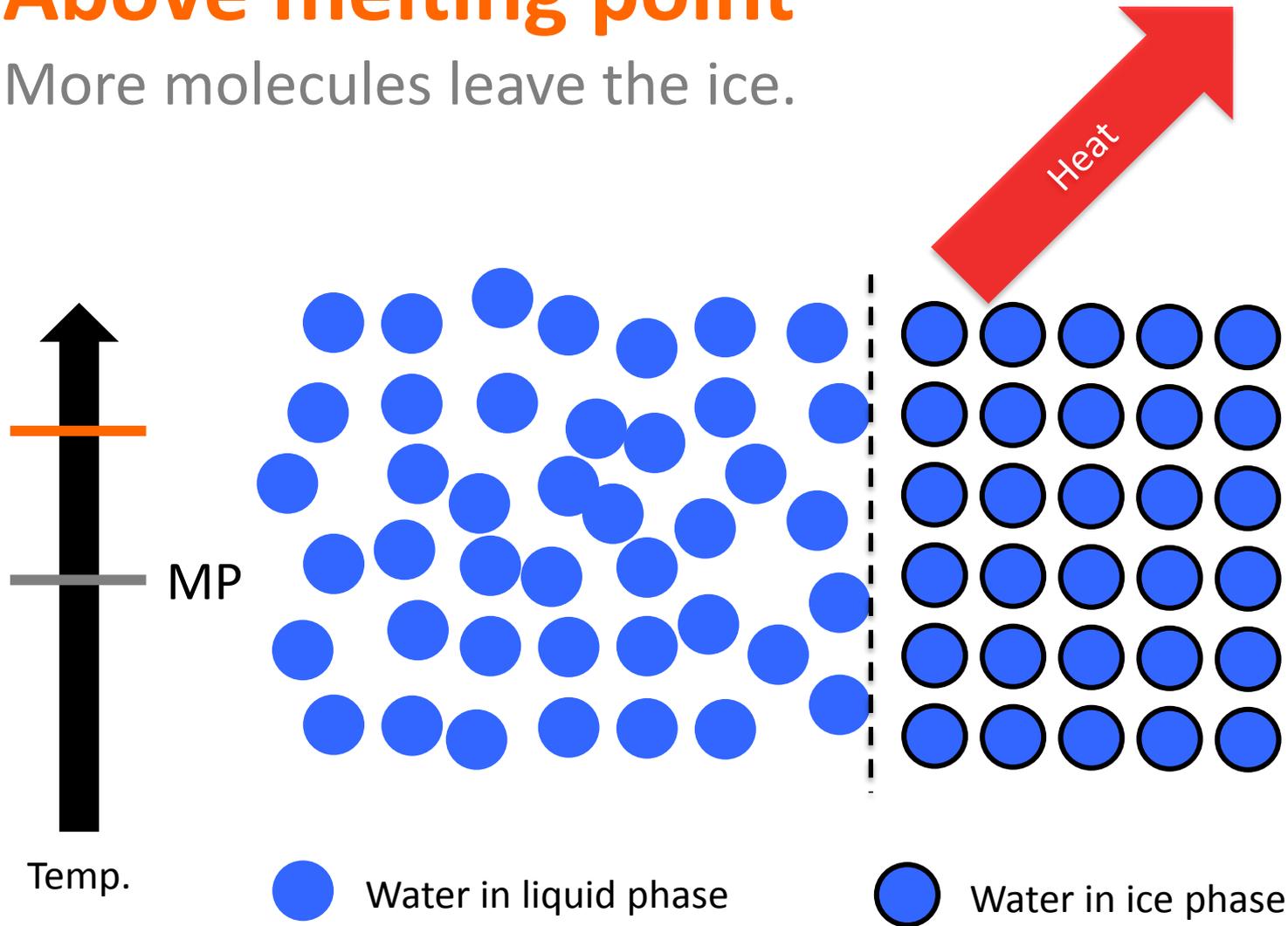
Above melting point

More molecules leave the ice.



Above melting point

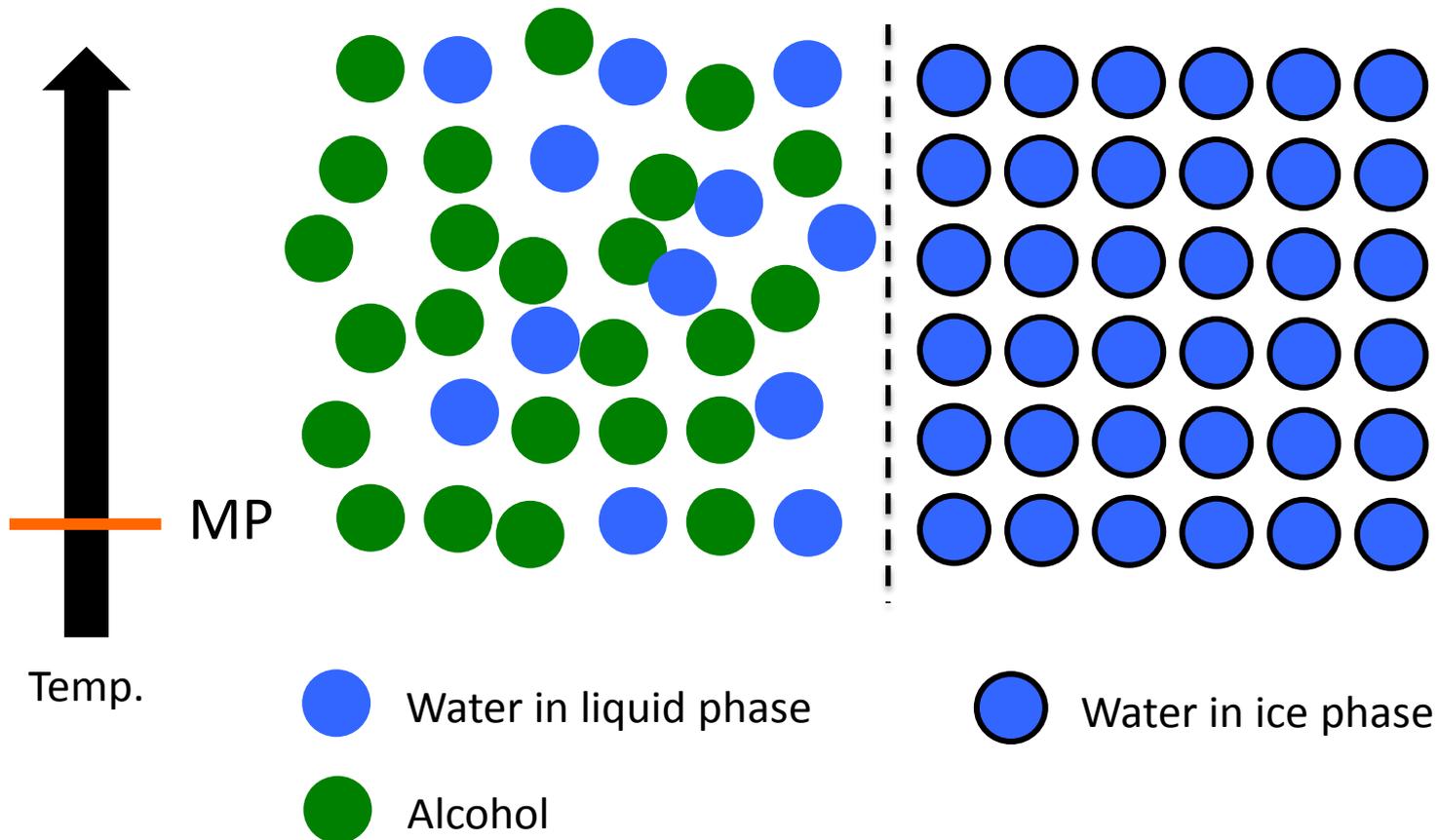
More molecules leave the ice.



Heat is required to melt the ice → fluid is cooled

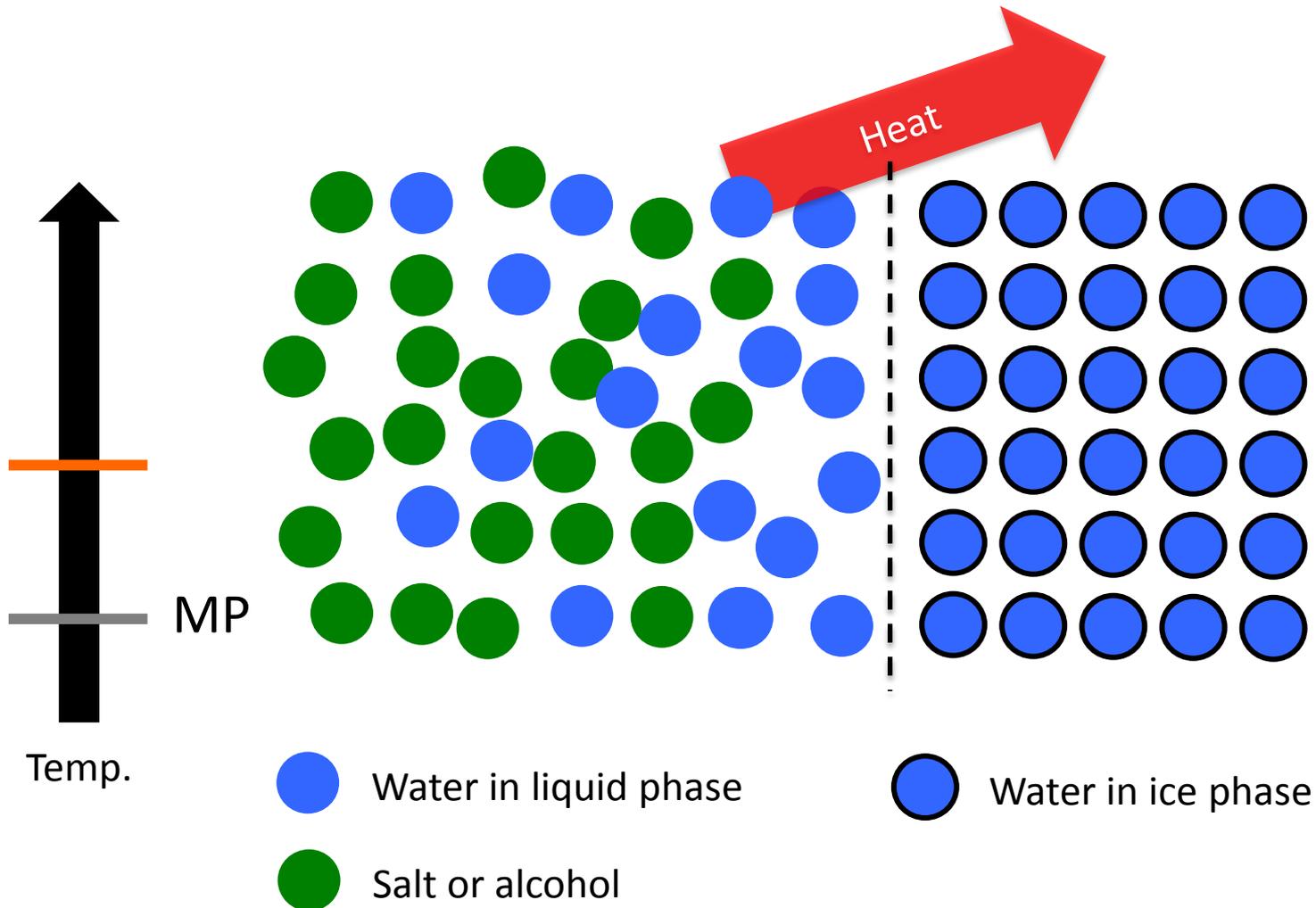
Solutes lower the melting point

Alcohol reduces the equilibrium temperature.



Heat energy leaves the liquid phase

In a closed system, the temperature decreases.



Example: Ramos Gin Fizz

Egg whites and cream create a stiff foam



- 2 ounces gin
- 1 ounce Simple Syrup
- 1/2 ounce fresh lemon juice
- 1/2 ounce fresh lime juice
- 1 ounce heavy cream
- 1 large egg white
- 4 drops of orange flower water
- Ice
- 1 ounce chilled club soda

Thank you for your attention

A. Rosenthal

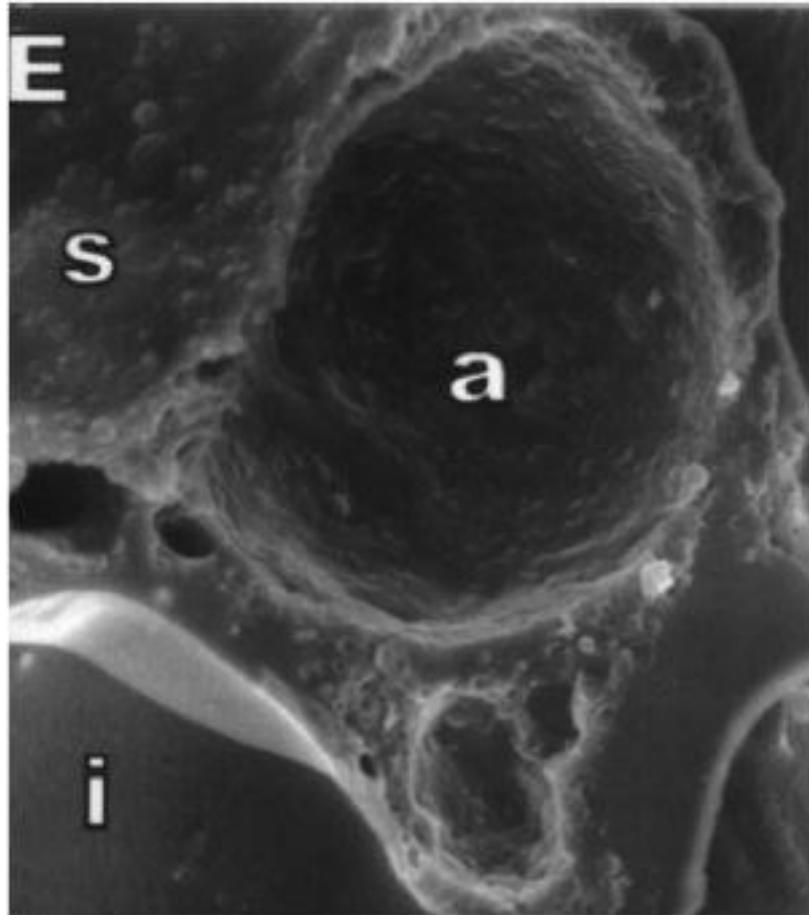
Food and Wine, 2007

Encore:
Ice cream

Foams, emulsions, and crystallization

Microscopic structure of ice cream

Fat globules are stabilized by proteins



D Goff , “Colloidal Aspects of Ice Cream” *Int. Dairy J.* 1997.

Phase diagram of salt water

At 0°C, a saltwater solution is super-heated.

