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Physics of Cooking

Dave Weitz
Harvard

Naveen Sinha
Helen Wu

UCB – Public Lecture 7/19/12

The changing world of modern cuisine

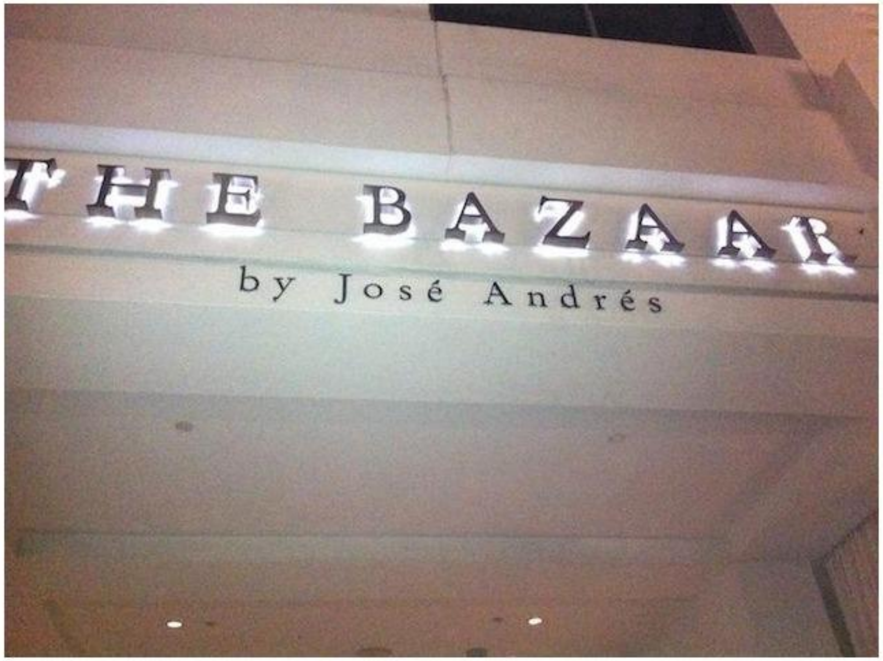





Jose Andres

Jose Andres

Jose Andres



Ferran Adrià

Ferran Adria

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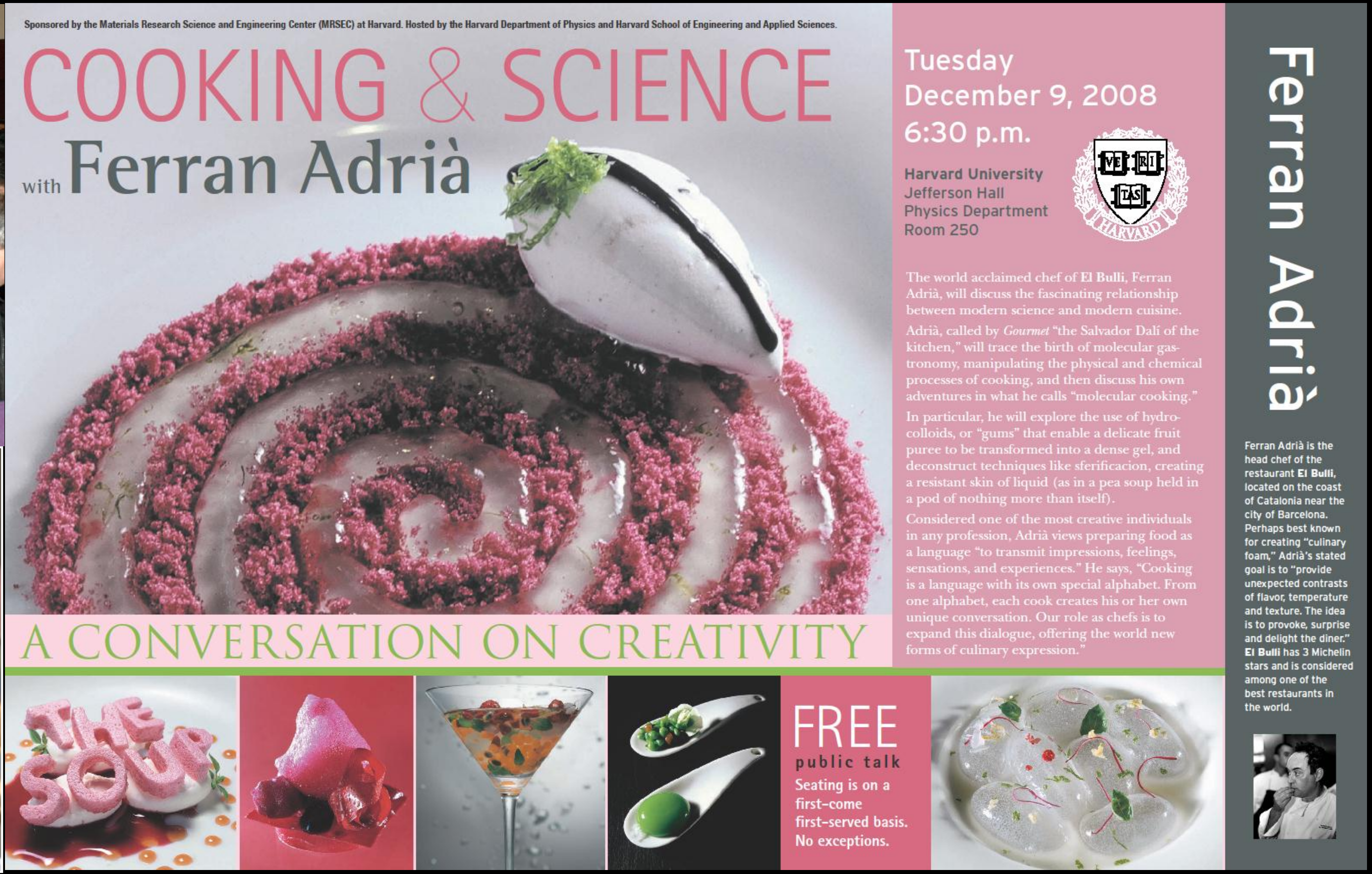
Cooking and Science

Ferran Adria lecture at Harvard



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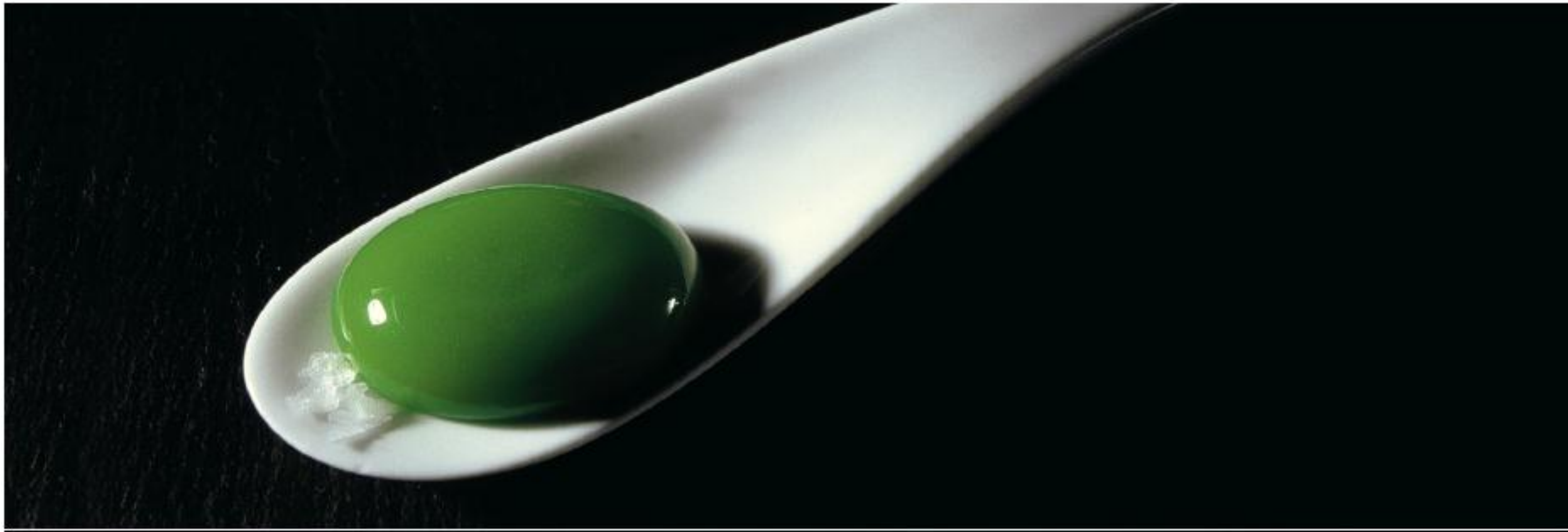
Cooking and Science



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A science class
Based on cooking

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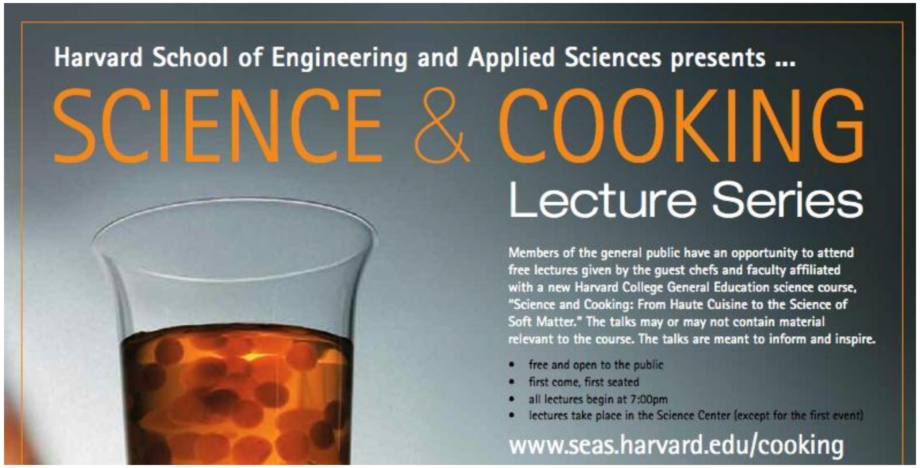

A science class

Based on cooking

Motivated by cooking

But still real science

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Michael
Brenner

A team of teachers

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Cooking and Science

Wide coverage in the press


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At Harvard, the Kitchen as Lab

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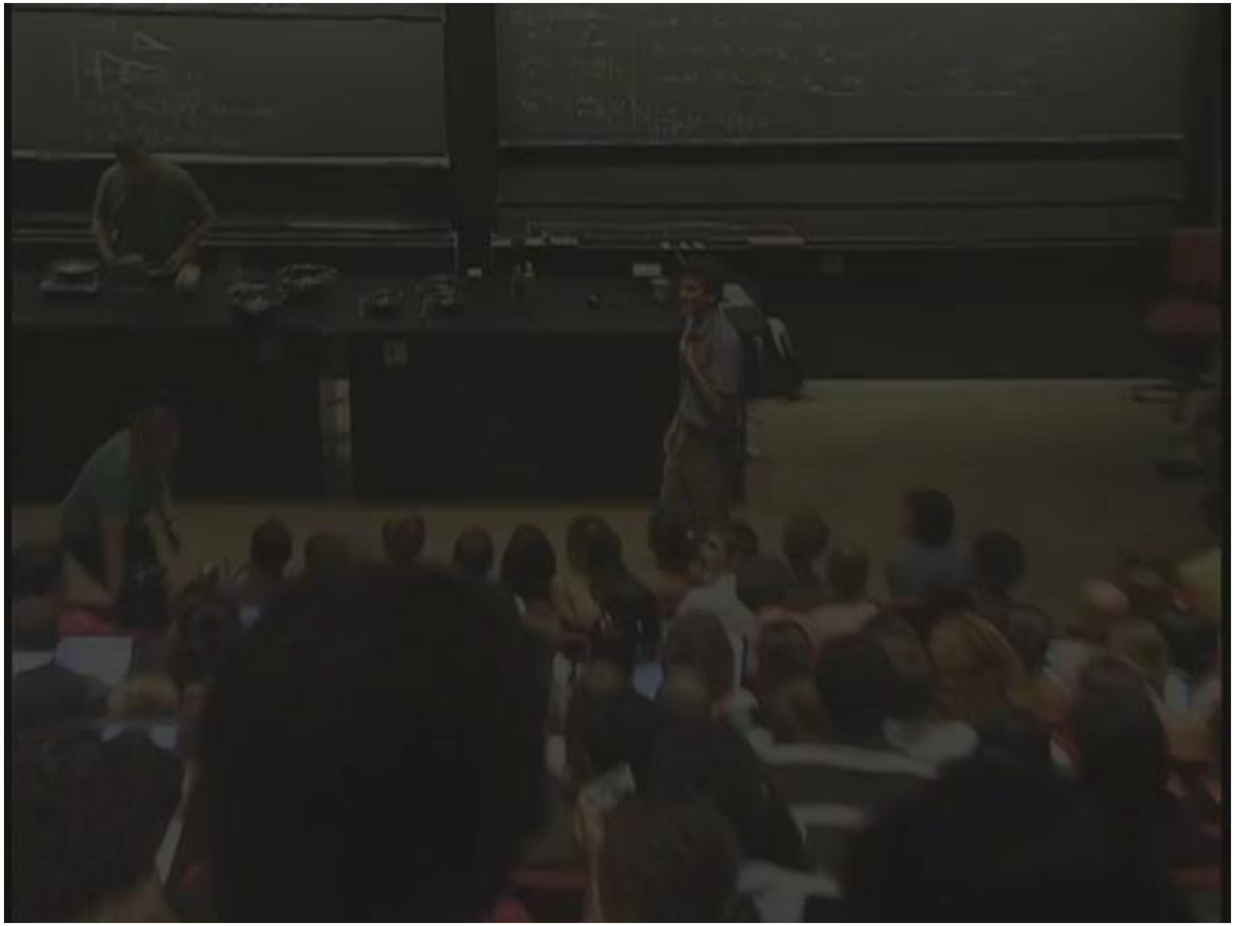
What's Popular Now

Elections: Oshkosh Shrugged

The Way We Treat Our Troops

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 ~ 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 ~ 10%

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

Why I took the course

The lab

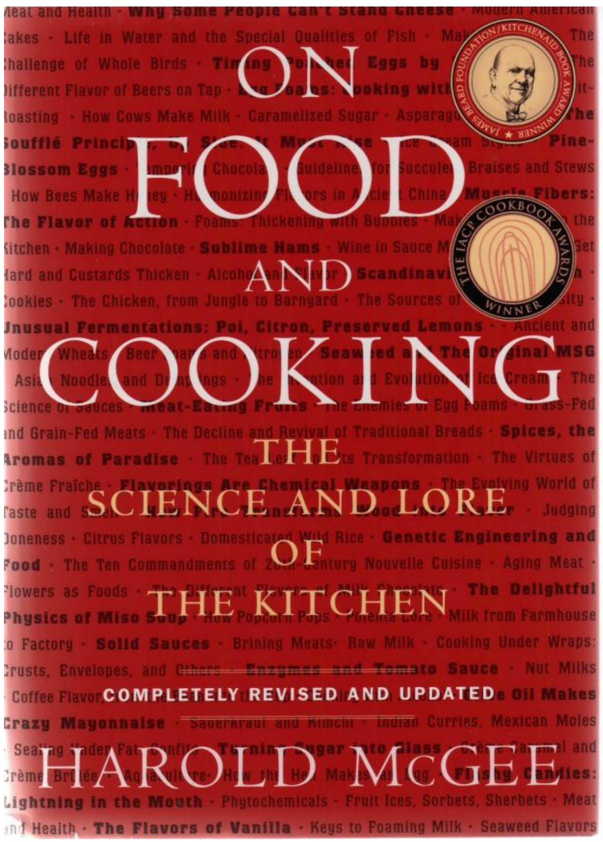
The lab

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
7:00PM

www.seas.harvard.edu/cooking

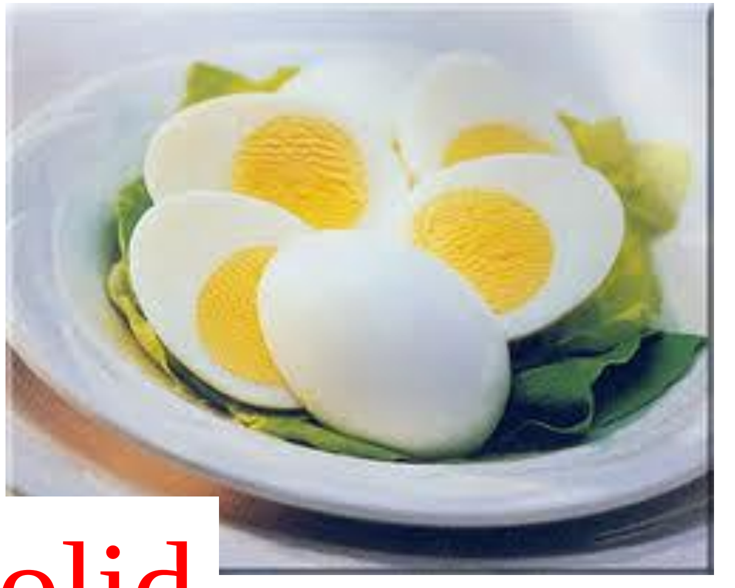
Bill Yosses

Bill Yosses

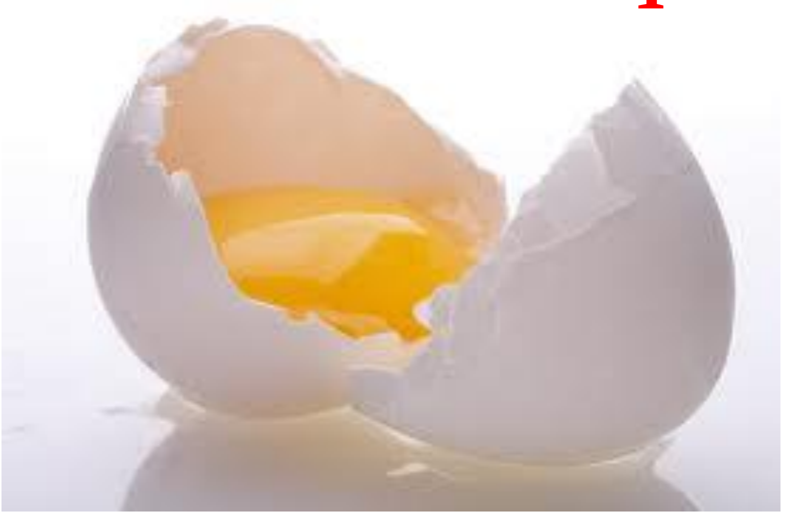
White House Pastry Chef

What is cooking?

Cooking an egg



Liquid → Solid



Phases transitions:

A Physicist's View of Cooking

Phases of water

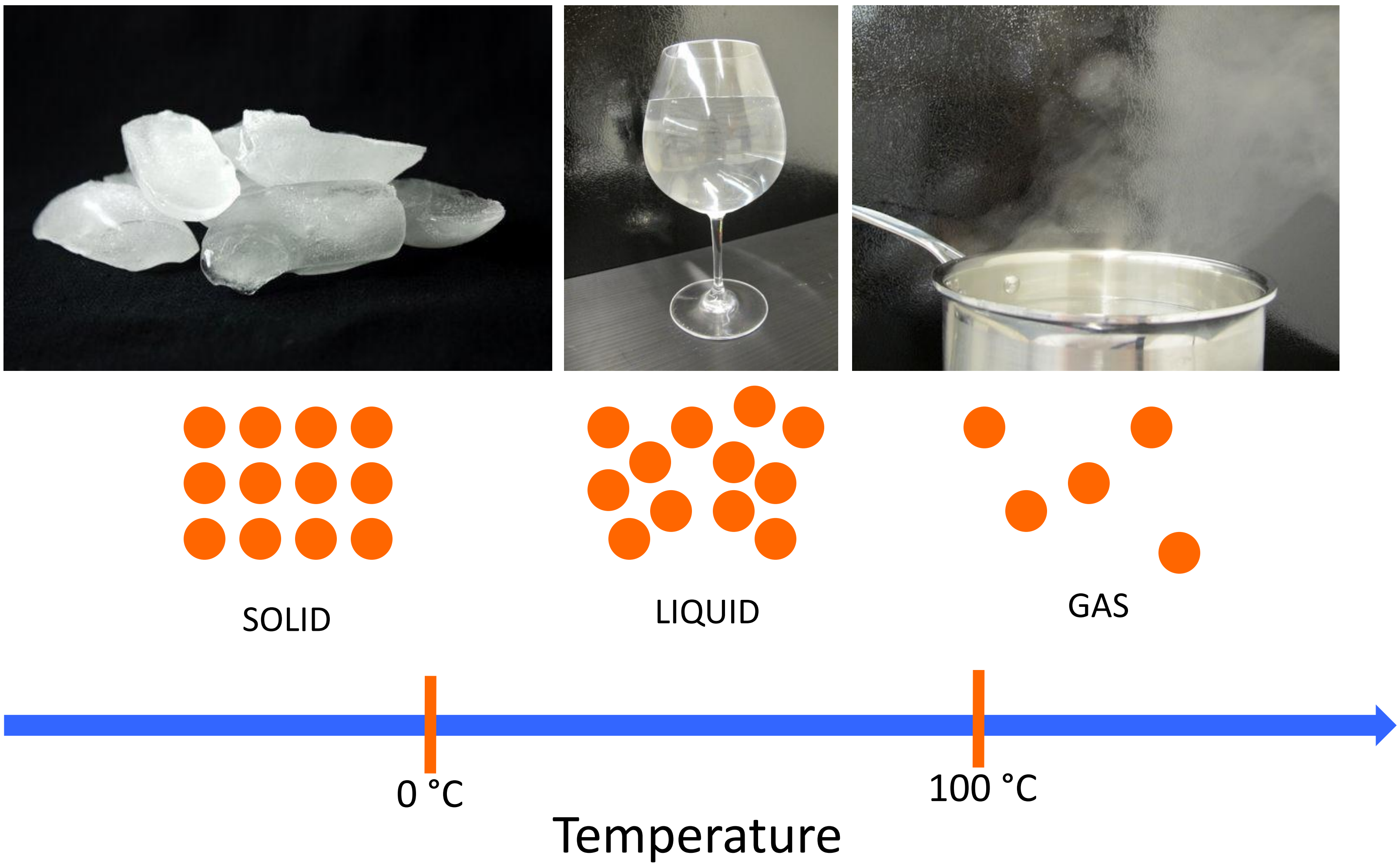
A macro-scale view

SOLID LIQUID GAS

Temperature

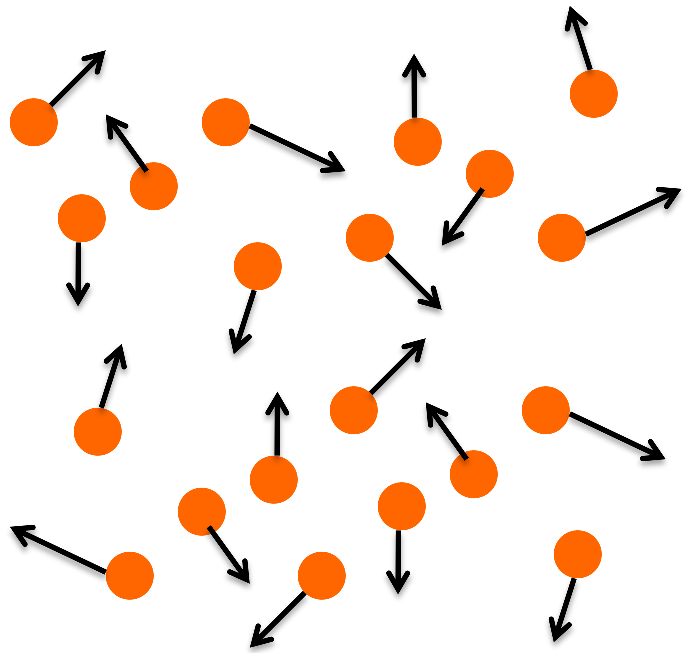
Phases of water

A Micro-scale View



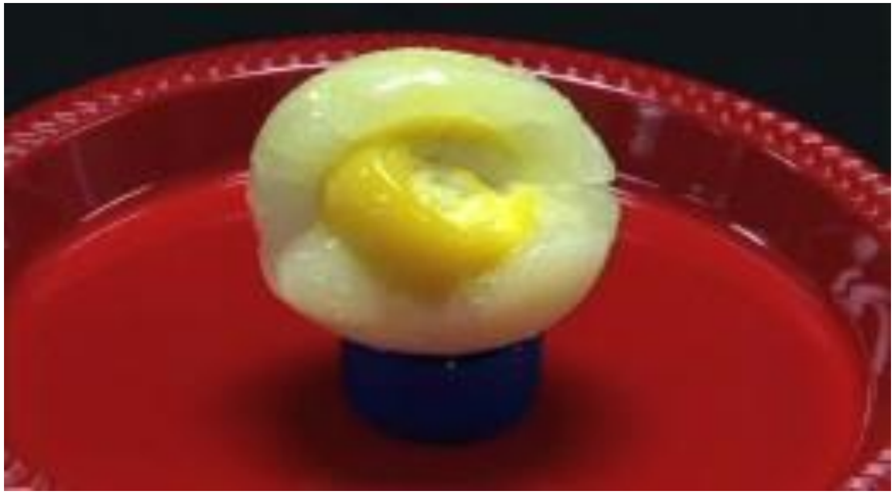
What is temperature?

A scientific definition

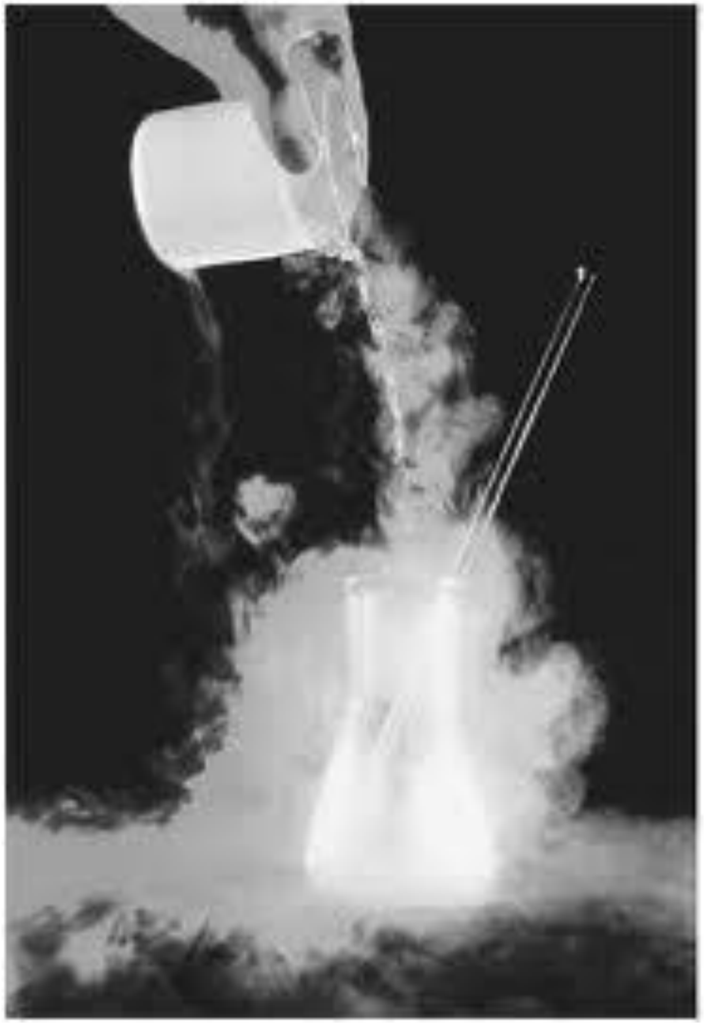


Temperature is a measure of the energy in the motion of the molecules in the material.

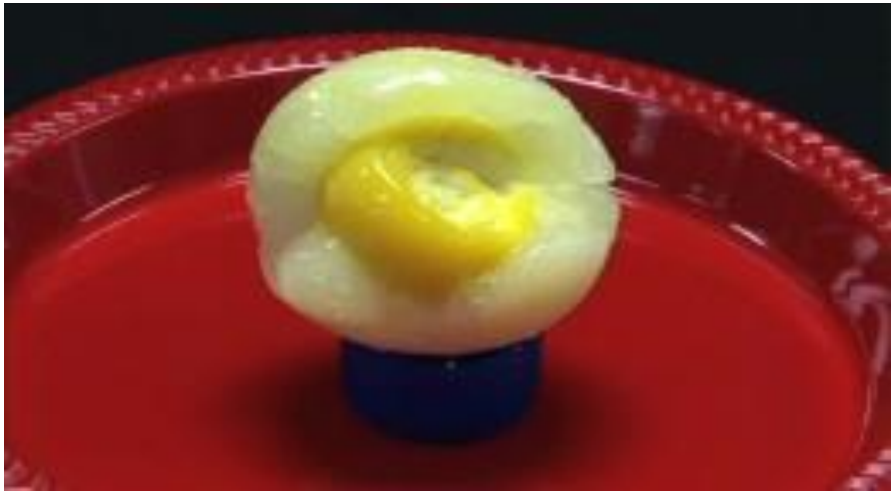
Cook an egg → Solidify it



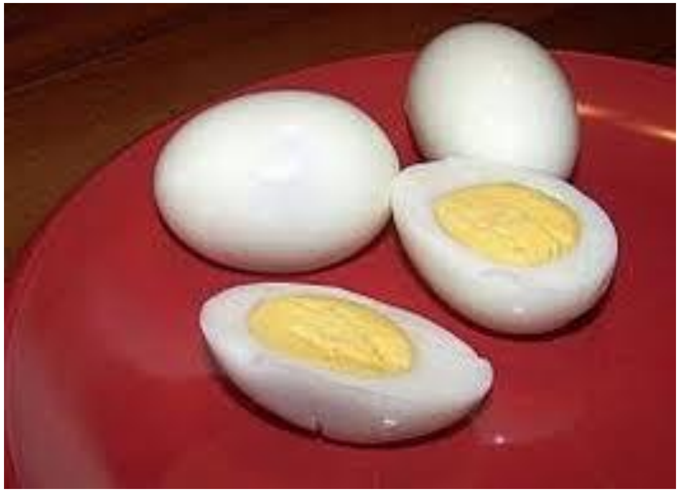
Frozen



Cook an egg → Solidify it

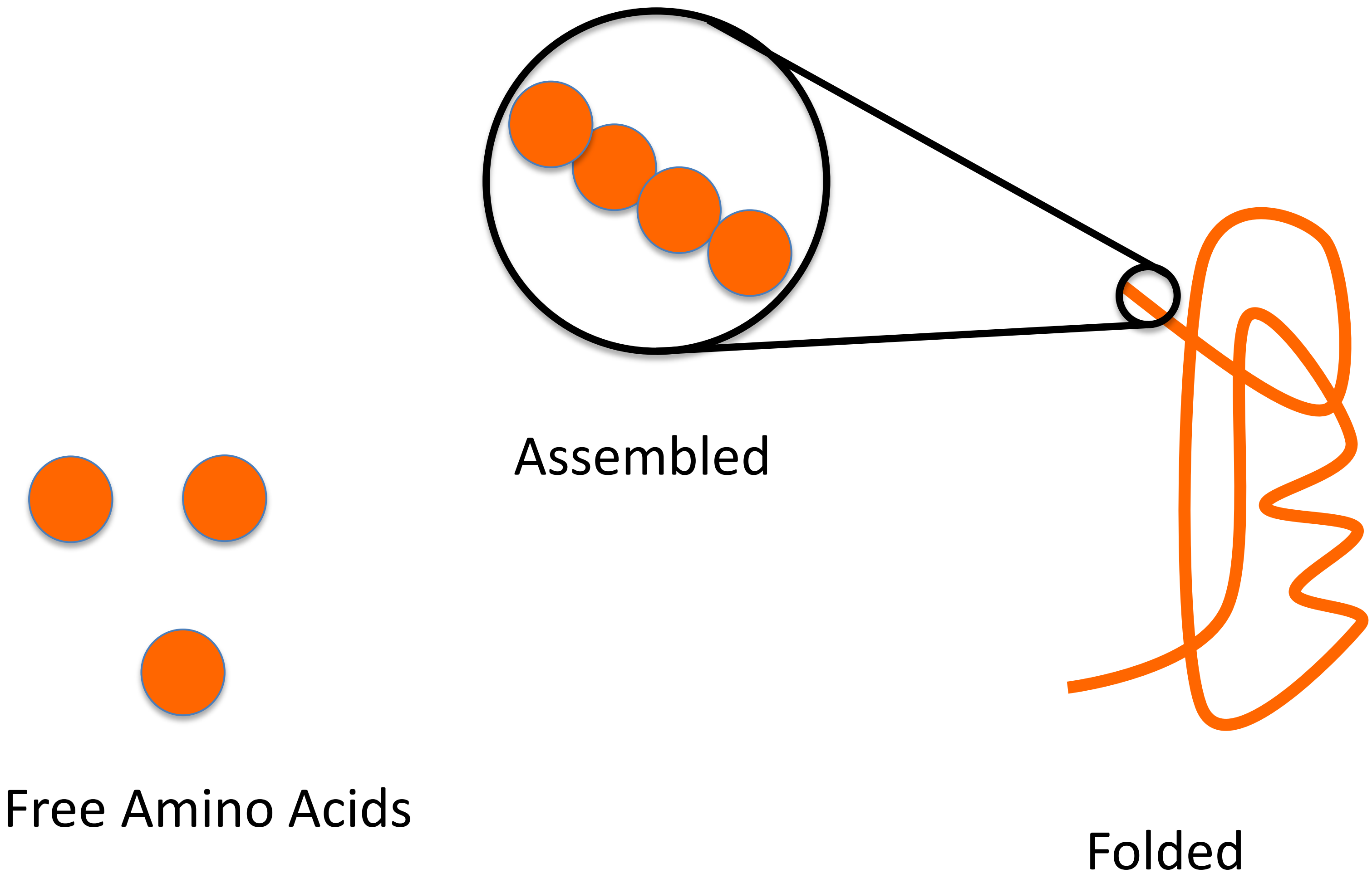


Frozen

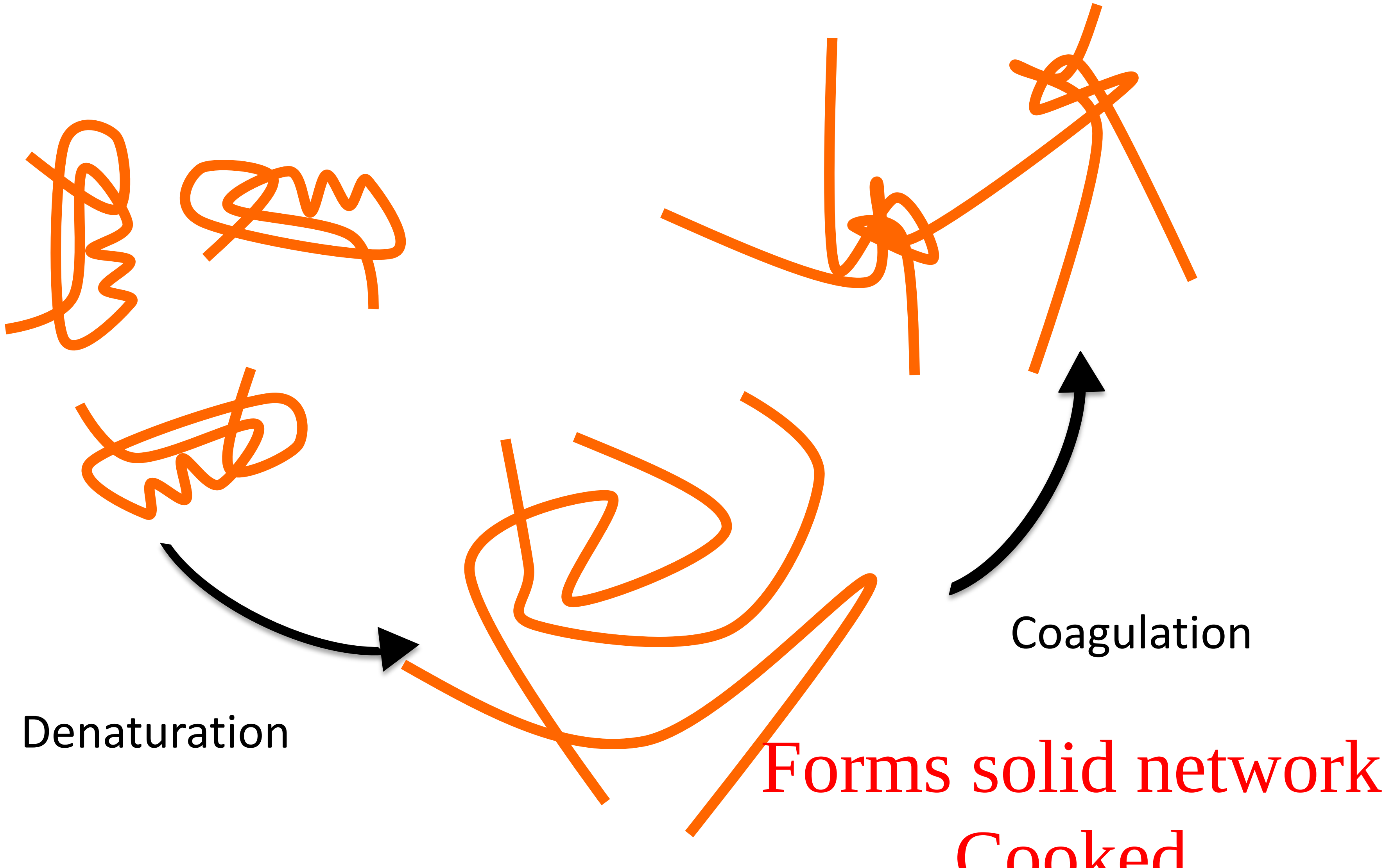


Boiled

Molecular structure of proteins



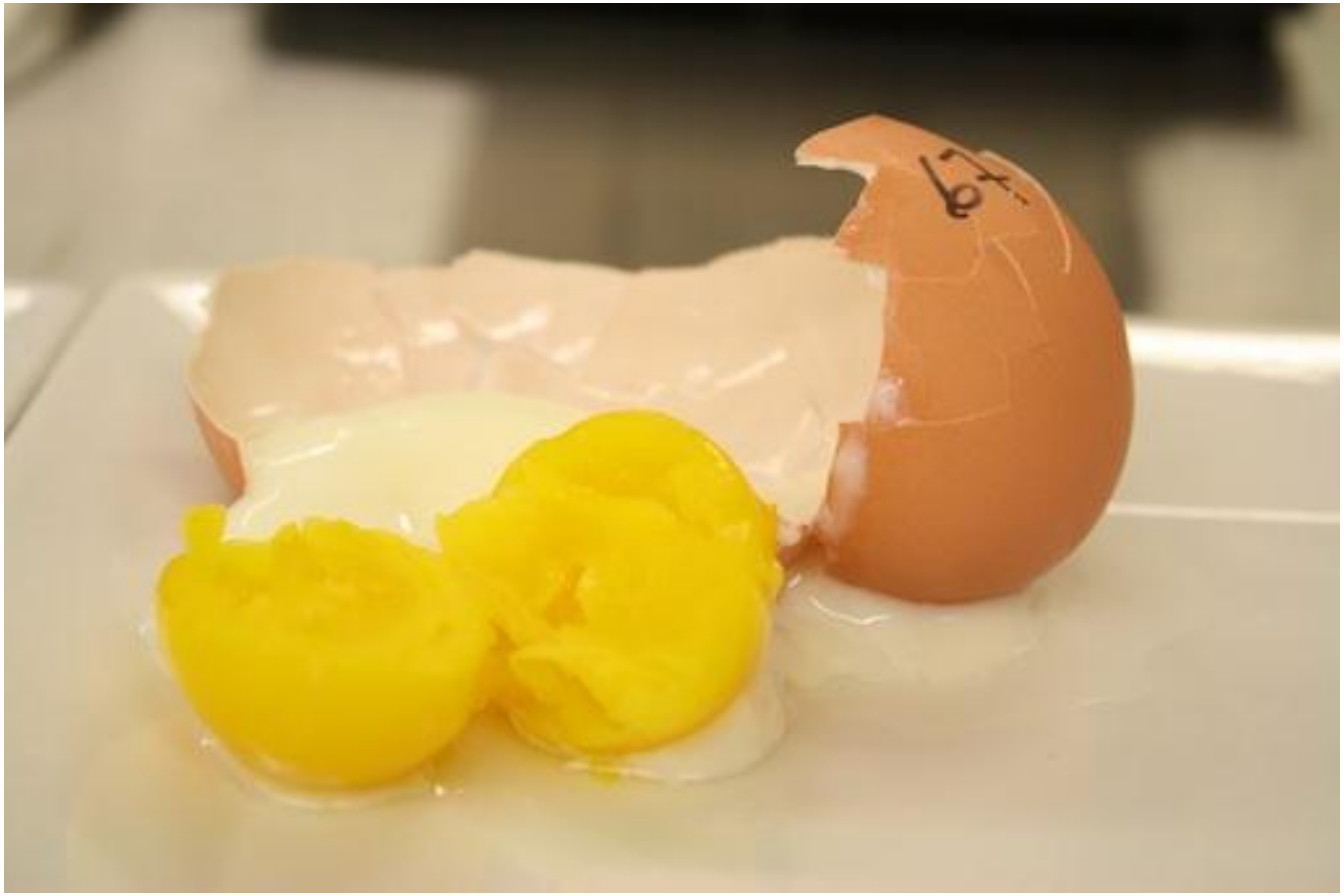
Protein Denaturation & Coagulation



New ways to cook: Sous Vide

Sous vide eggs

Novel textures are possible at lower temperatures



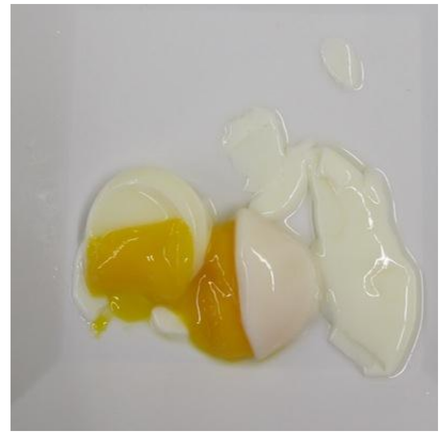
Phase transitions in food

Egg in temperature-controlled bath

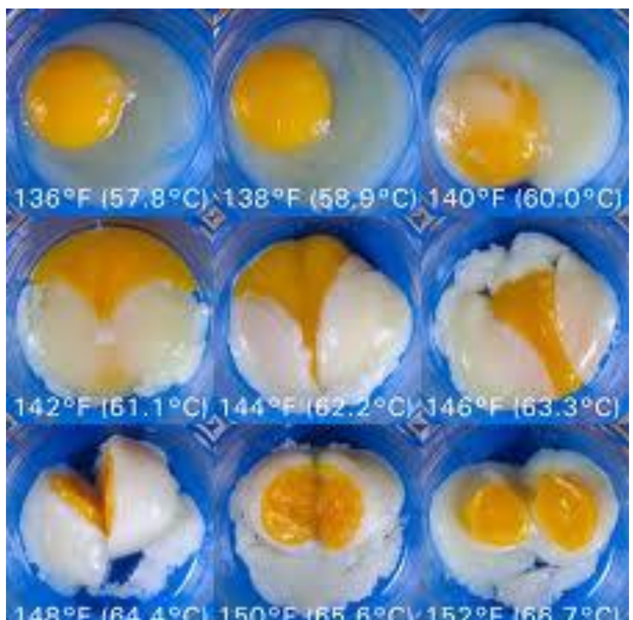
59 °C

61 °C

63 °C



67 °C



Héloïse Vilaseca

What about other parameters?

Effect of pressure

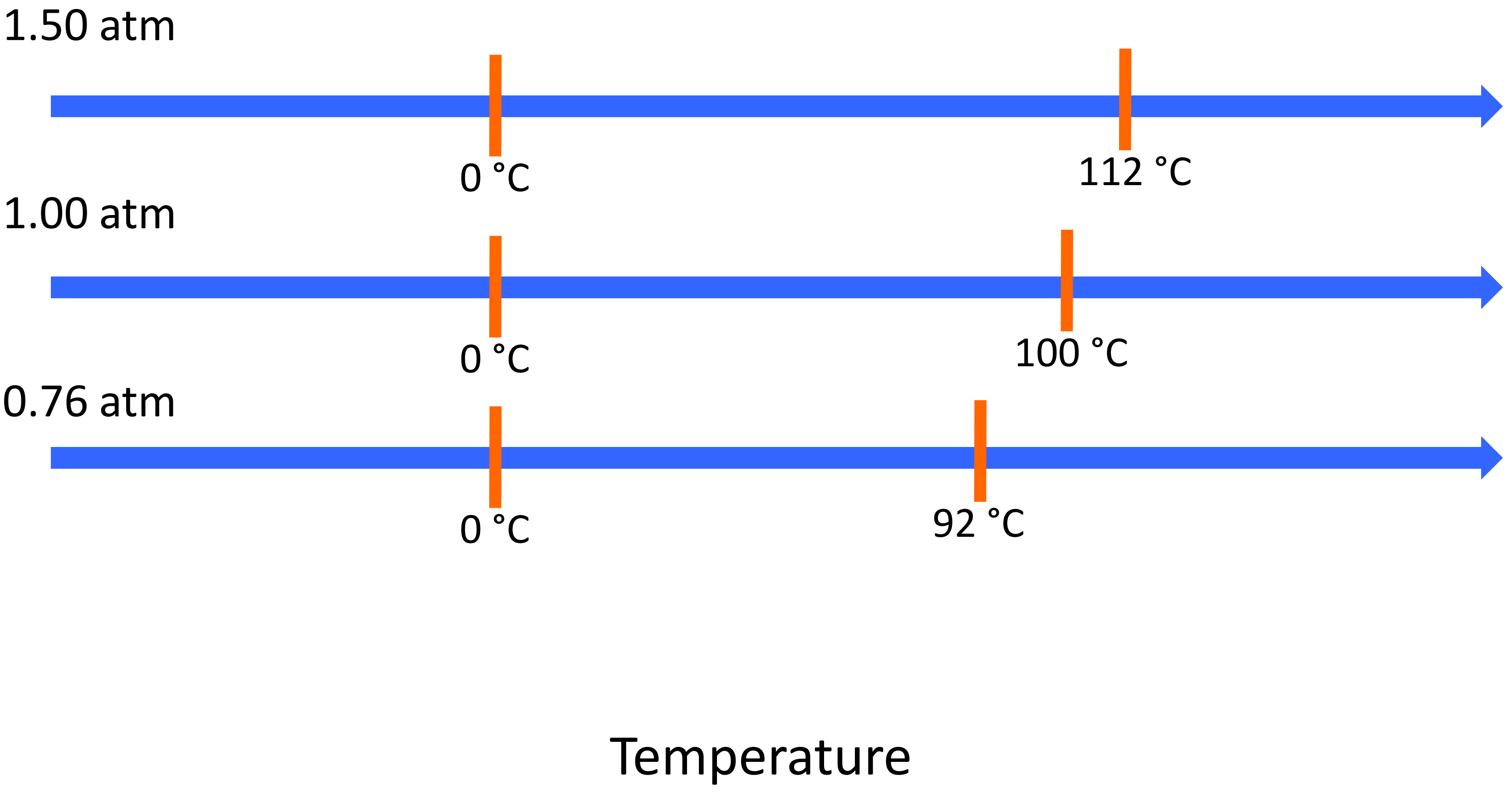
Effect of Pressure

What about other parameters?

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

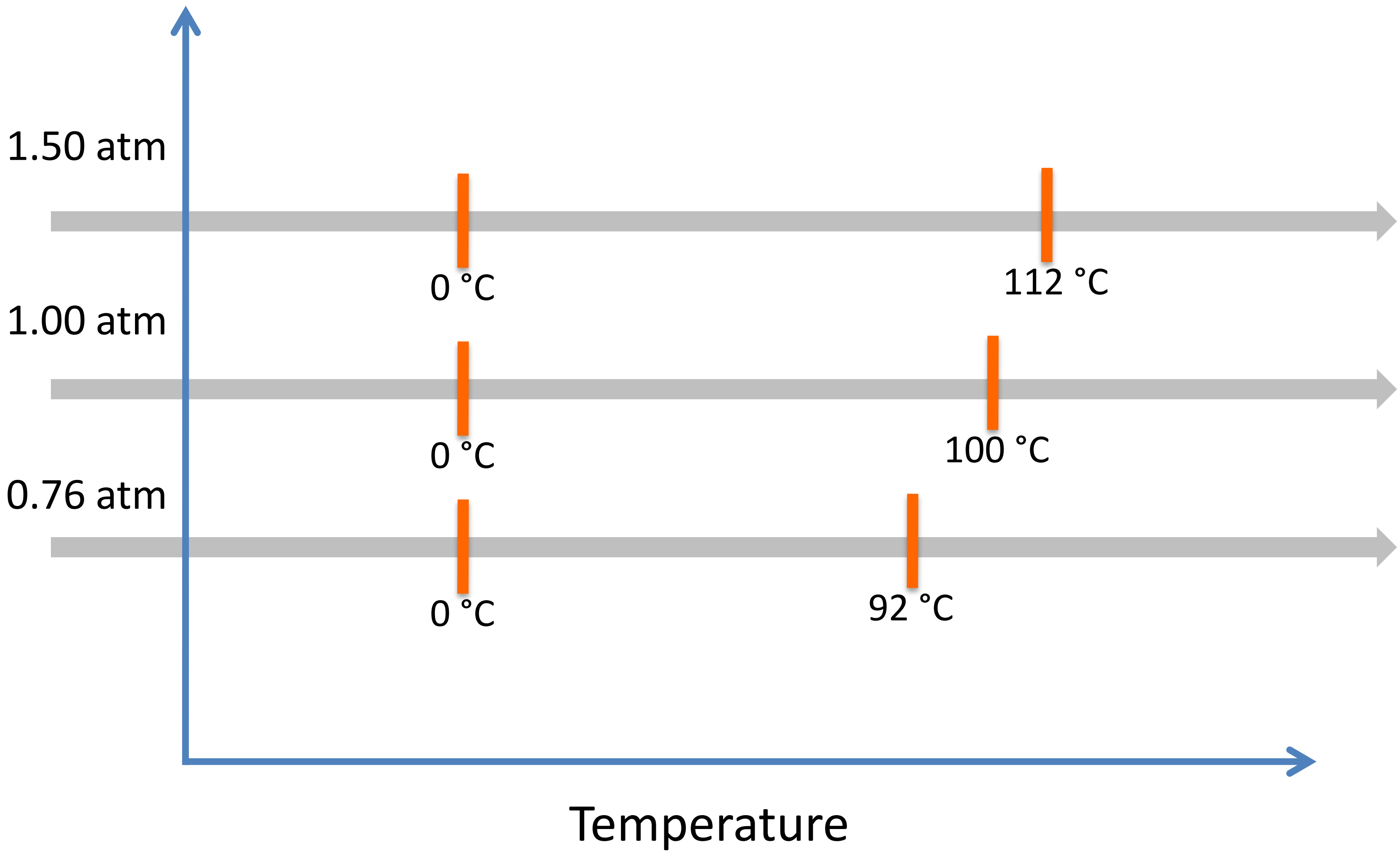
Phases of water

Melting/boiling points at different pressures



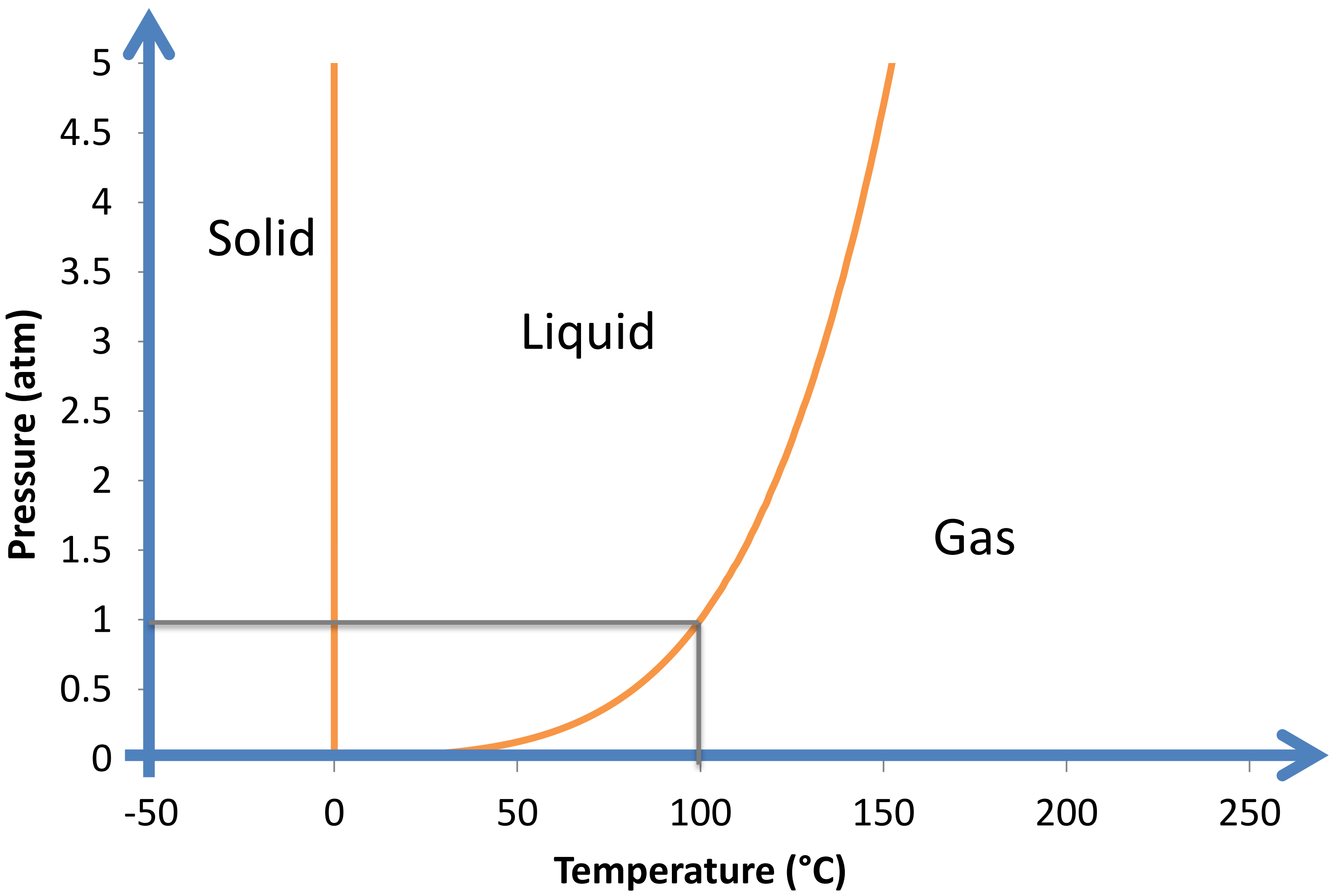
Phases of water

Melting/boiling points at different pressures



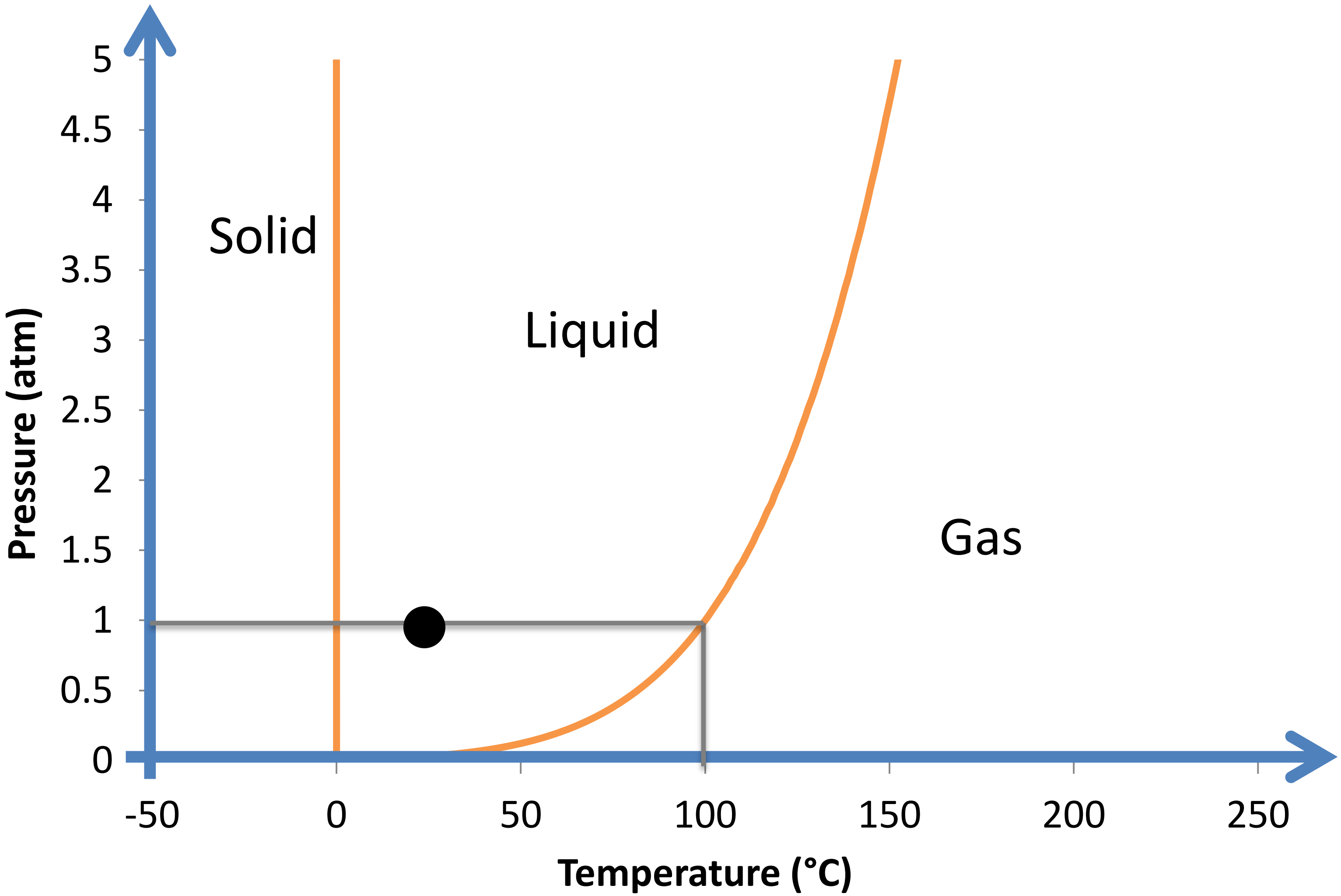
Phases of Water

Solid, liquid, and gas



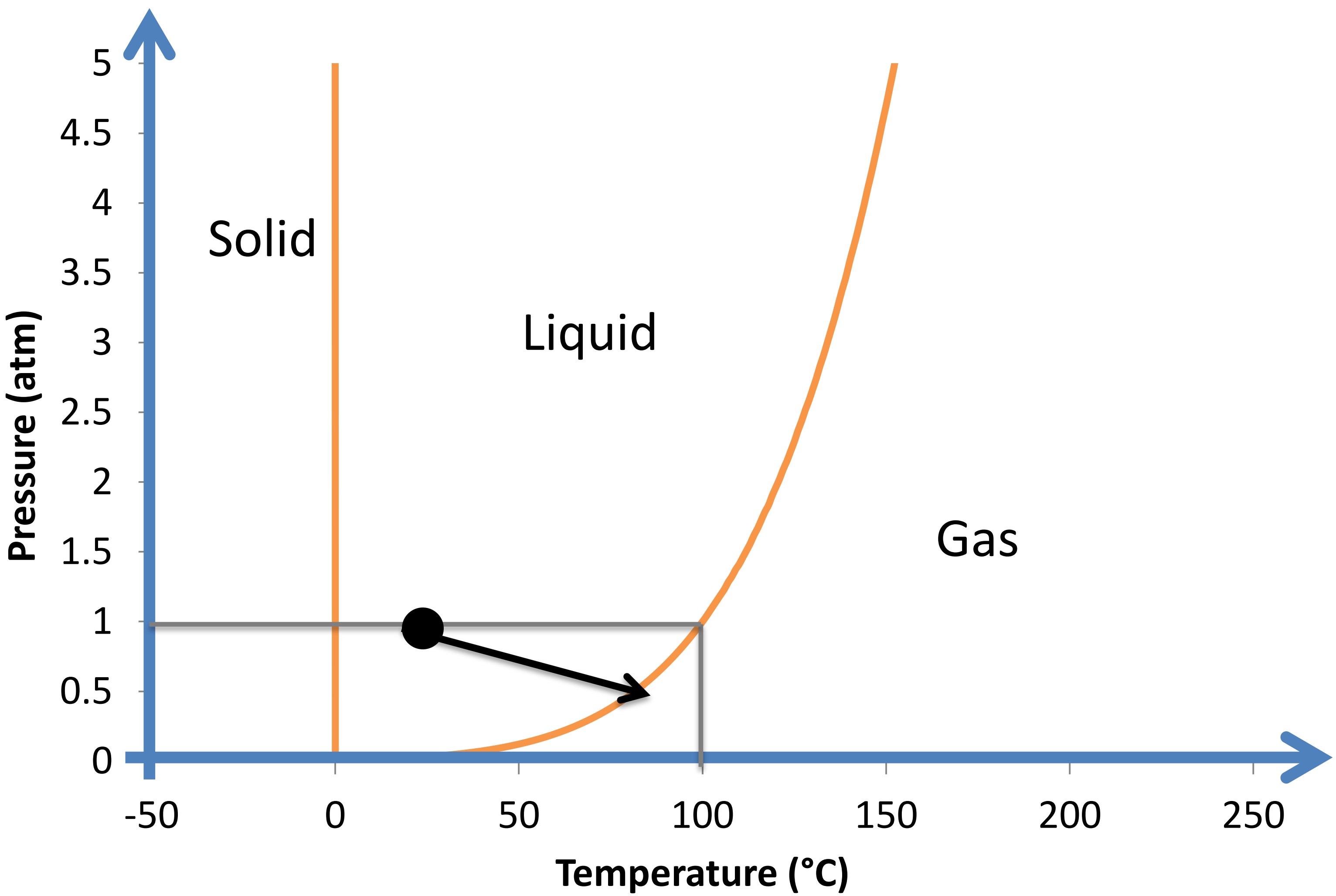
Applications of the Phase Diagram

Standard Temperature and Pressure = STP



Applications of the Phase Diagram

High elevation lowers the boiling point

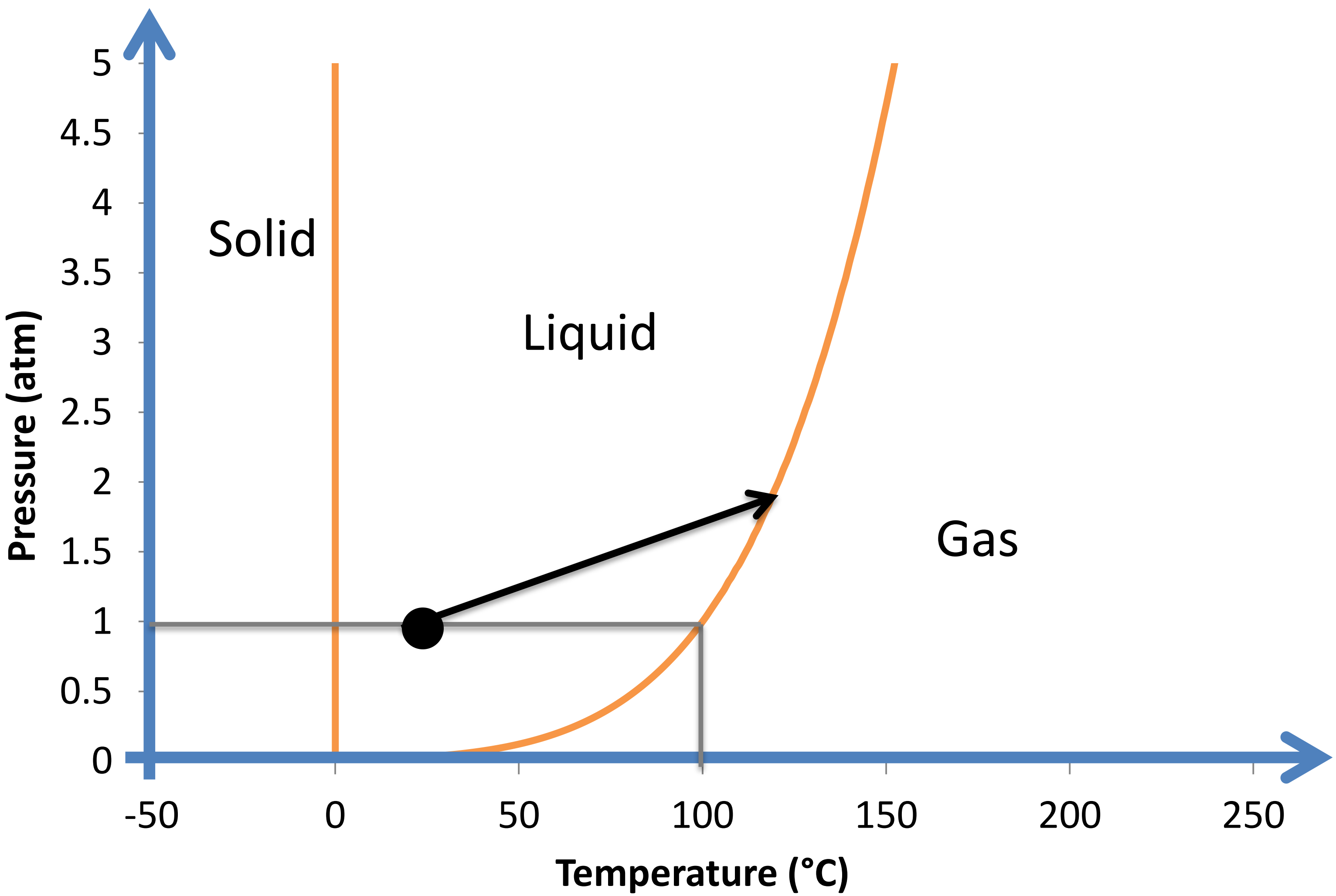


Applications of the Phase Diagram

Pressure cookers increase the boiling point

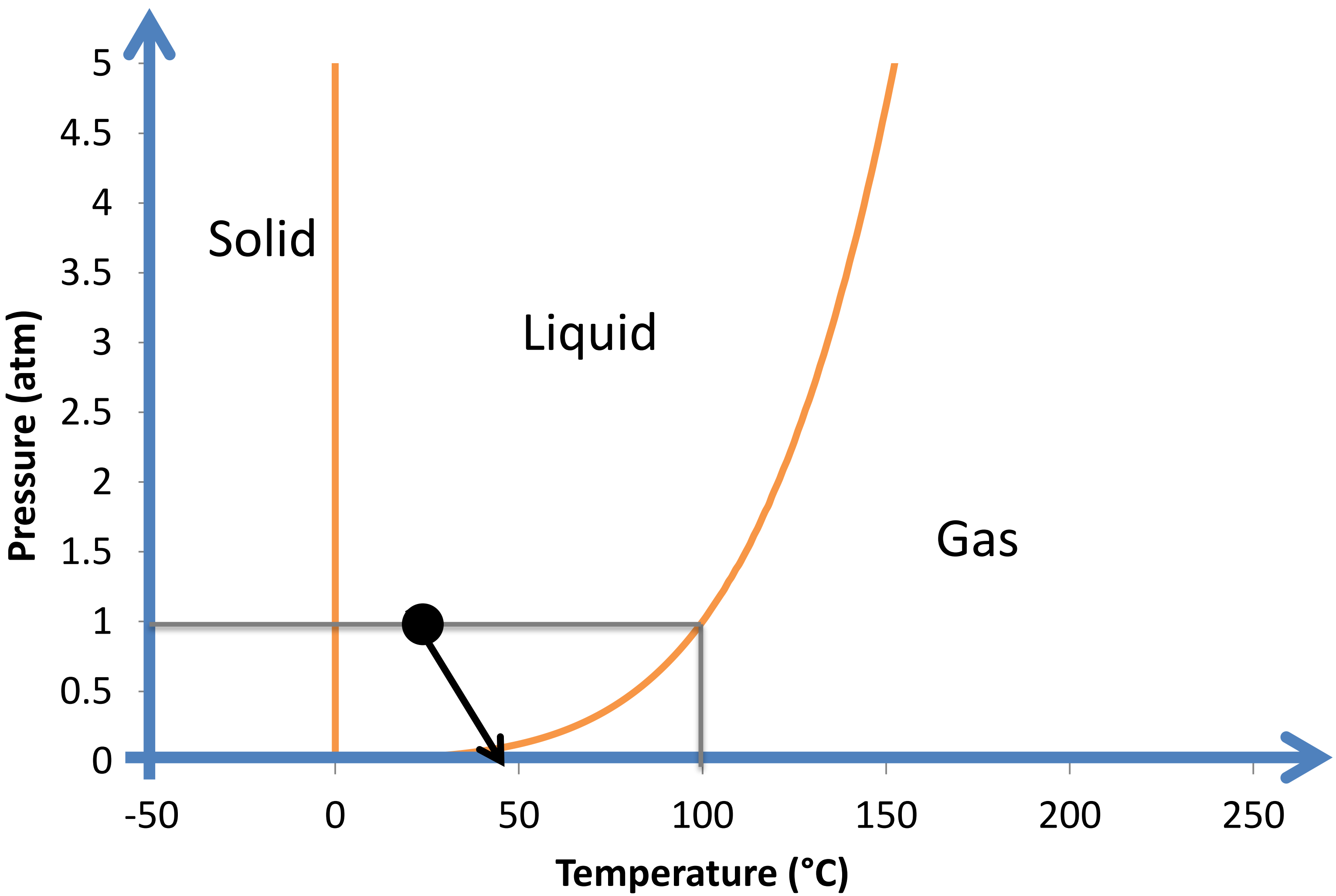
Applications of the Phase Diagram

Pressure cookers increase boiling point



Applications of the Phase Diagram

Rotary evaporators lower the boiling point

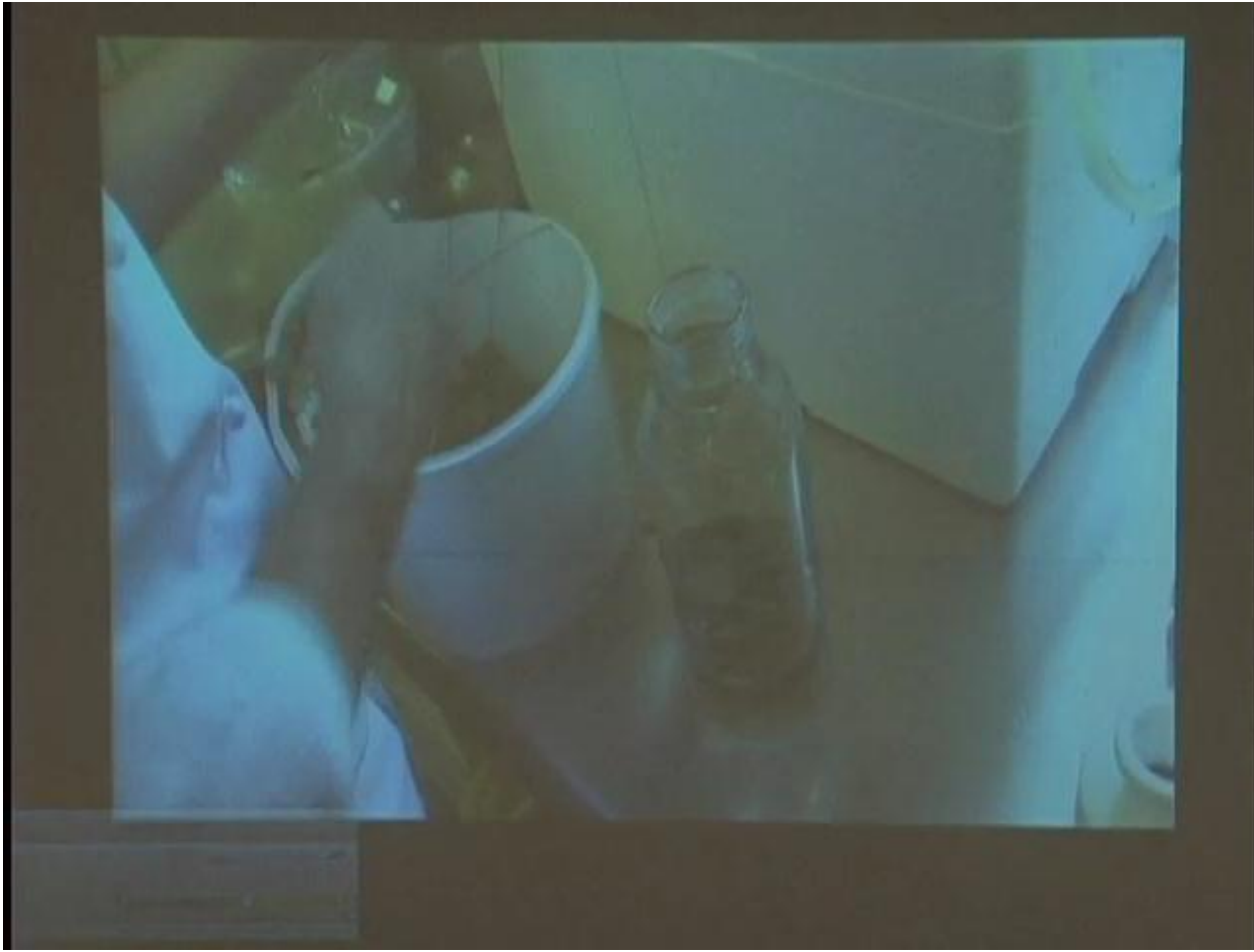


Applications of the Phase Diagram

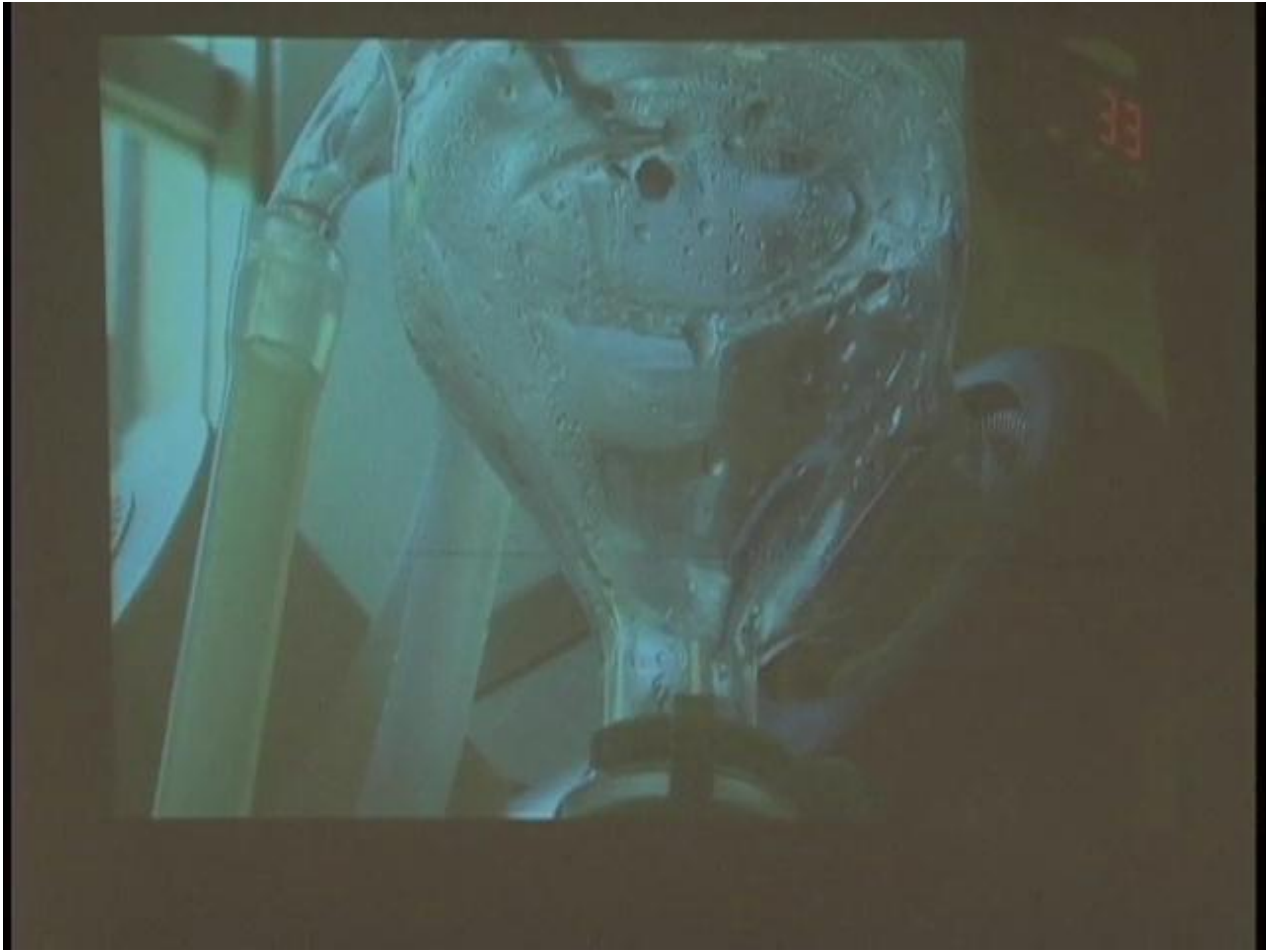
Rotary evaporators lower the boiling point

D Arnold, *Cooking Issues*

Super cool dessert



Super cool dessert



Super cool dessert

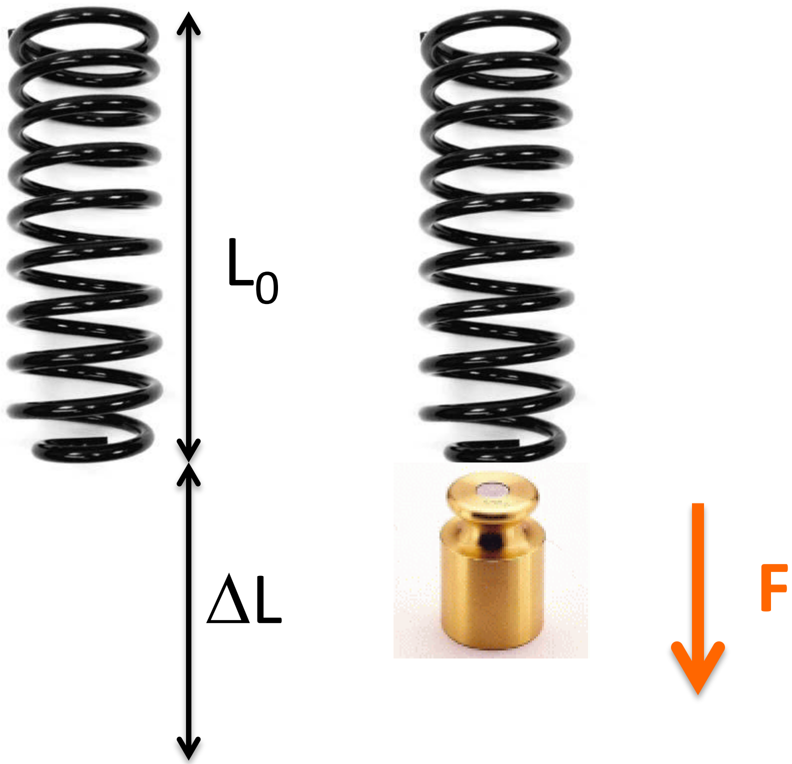
Clap when you see a great dessert

Elasticity:

Applications to mouthfeel

Elasticity of a spring

Hooke's Law



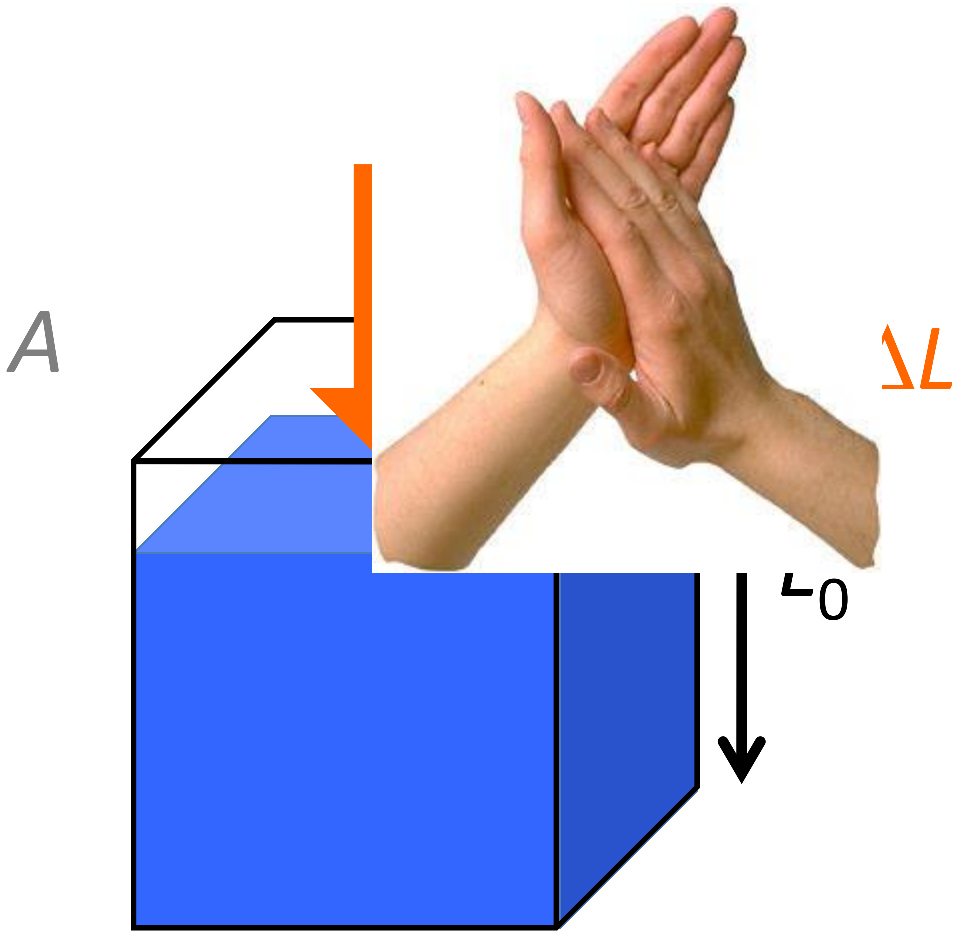
$$F = -k\Delta L$$

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

F = force [N]
k = spring constant [N/m]
Δ*L* = 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]

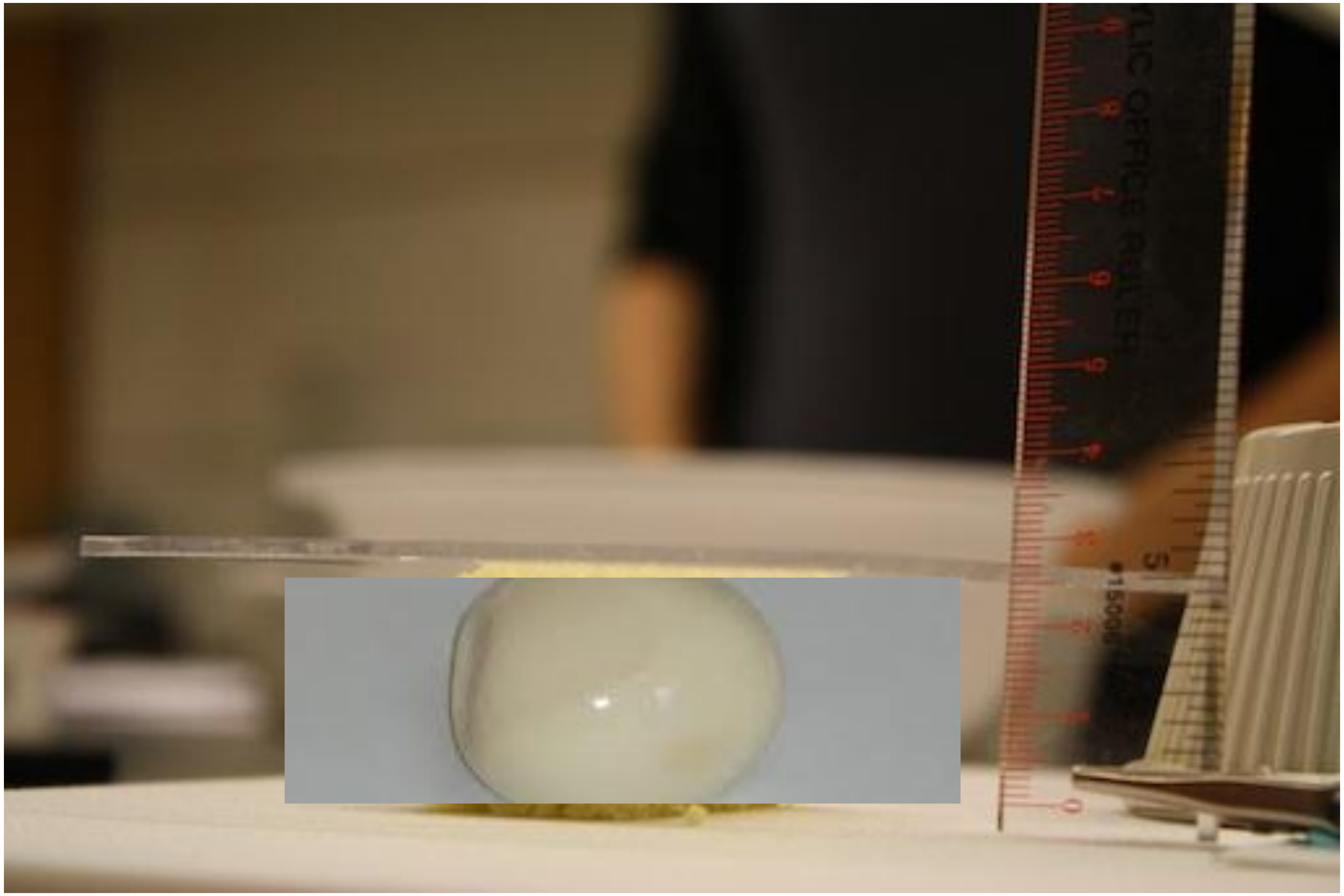
F = Force [N]

A = Area [m^2]

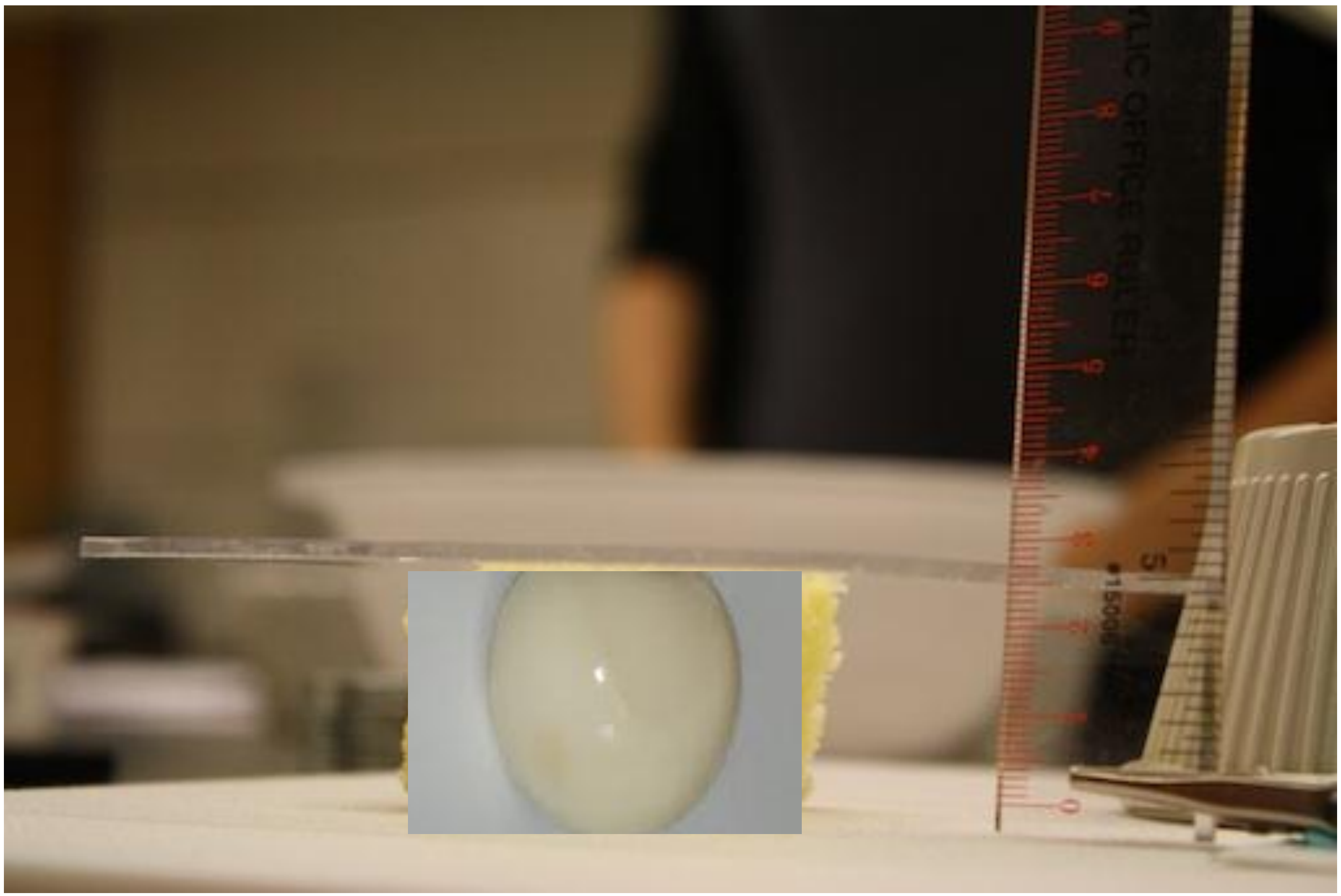
ΔL = change in length [m]

L_0 = initial length [m]

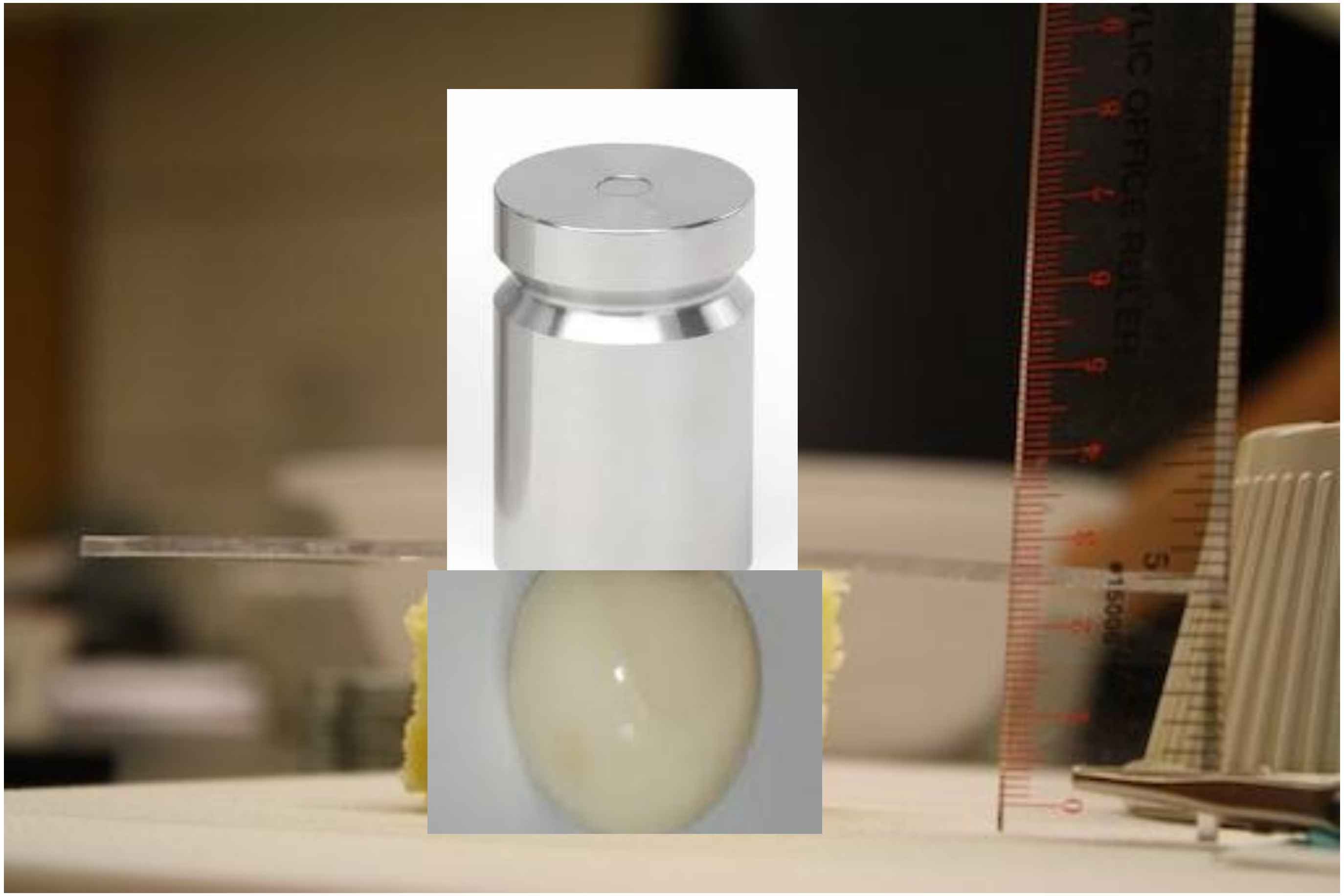
Elasticity of a hard-boiled egg



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

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

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

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

Calculation

Elasticity of hard-boiled egg

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

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

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

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

Calculation

Elasticity of hard-boiled egg

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

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

Calculation

Elasticity of hard-boiled egg

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

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

$$E = 48\,\mathrm{kPa}$$

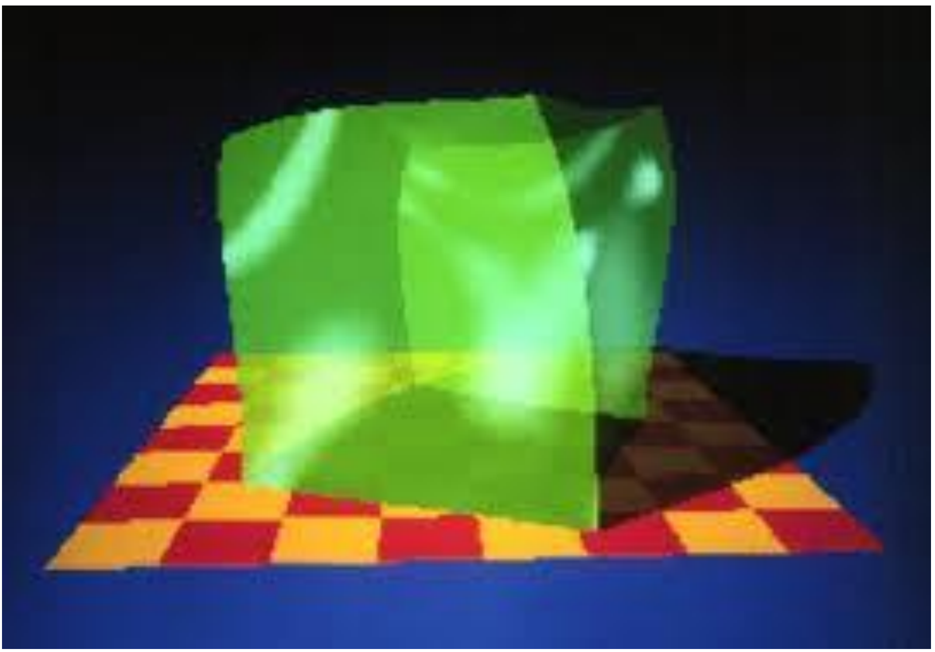
Elasticity of a cooked steak

Depends on how well cooked it is

Rare	Well-done
	
$E = 45\ \text{kPa}$	$E = 63\ \text{kPa}$

Gels

Mainly water



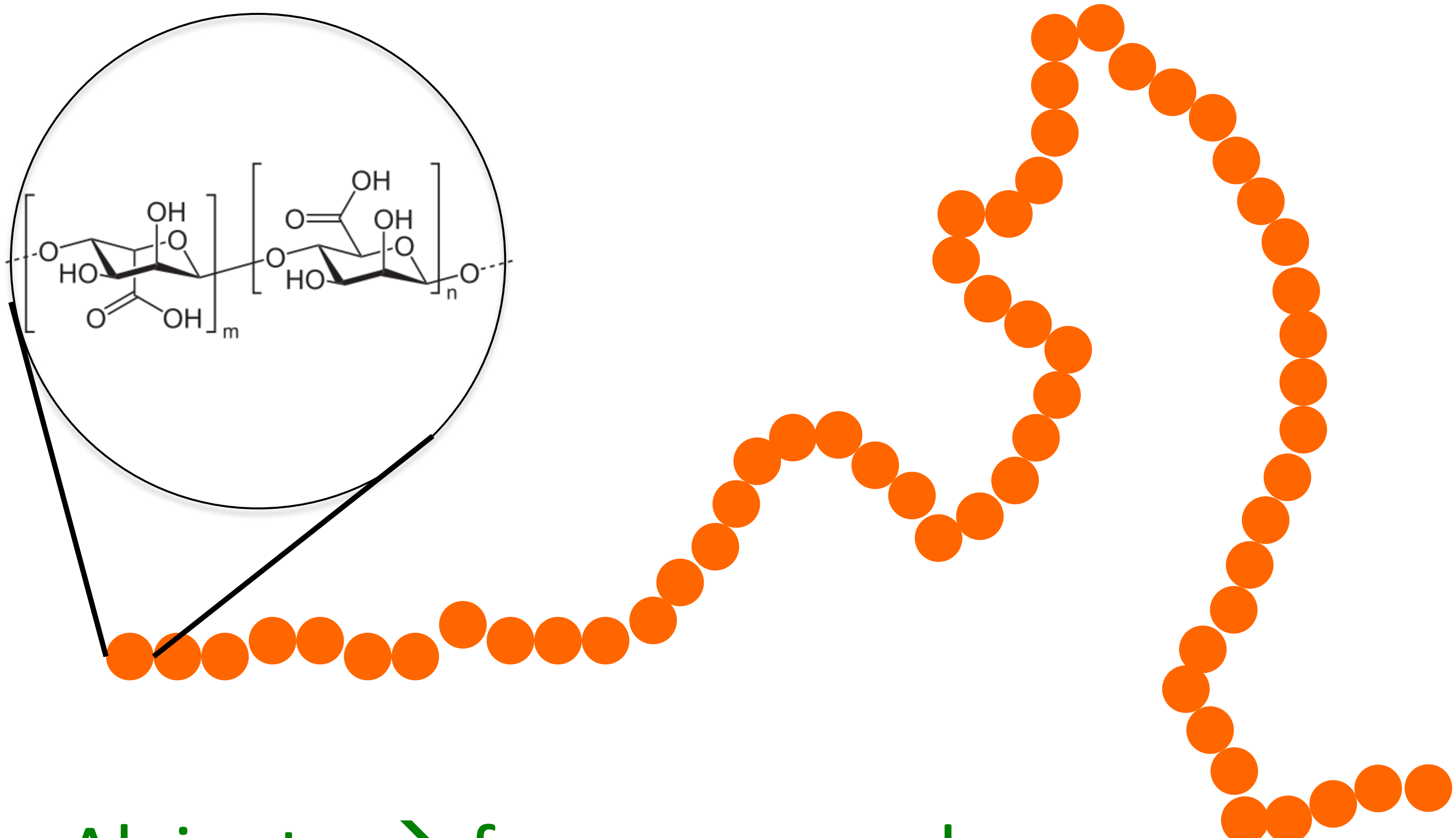
Elasticity of a gel

Ex: bouncing gelatin cube (*Modernist Cuisine*)

http://youtu.be/4n5AfHYST6E

Gel is made from polymers

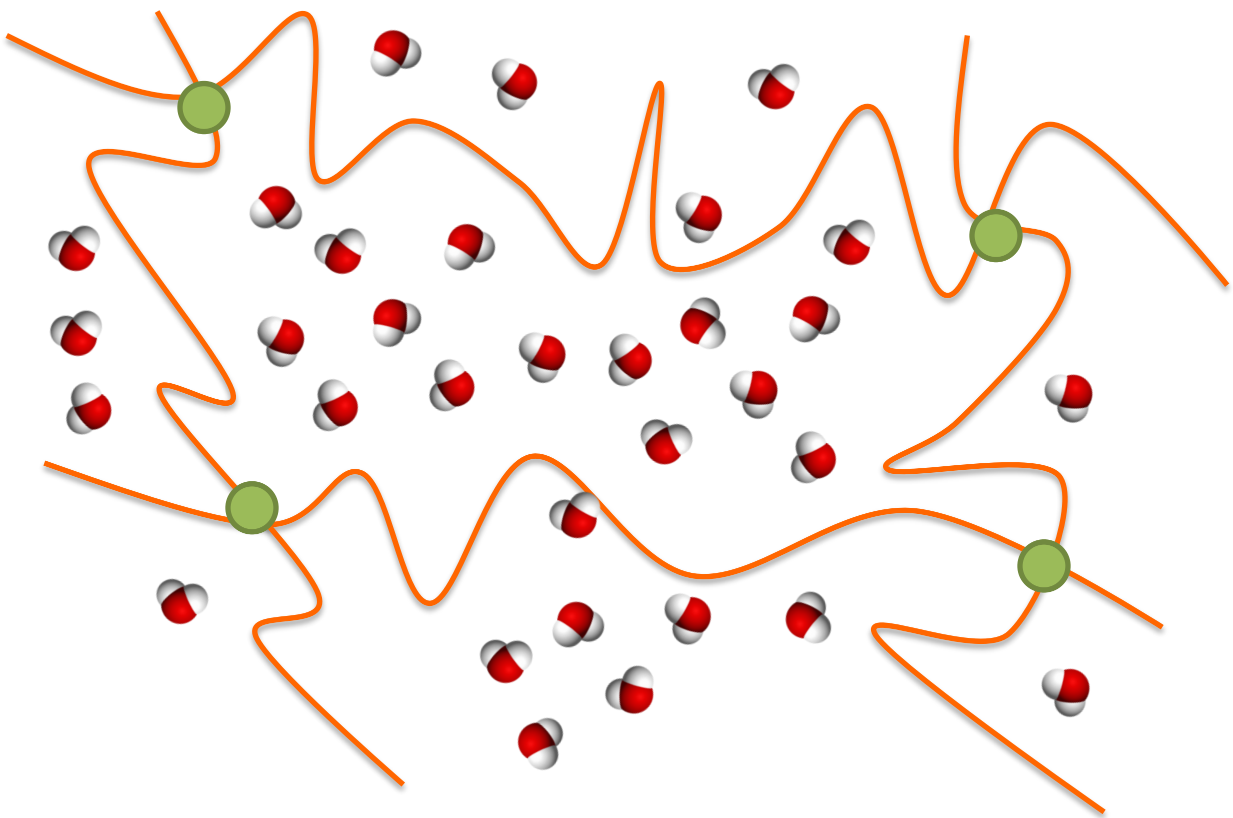
Chains of units or monomers



Alginate → from seaweed

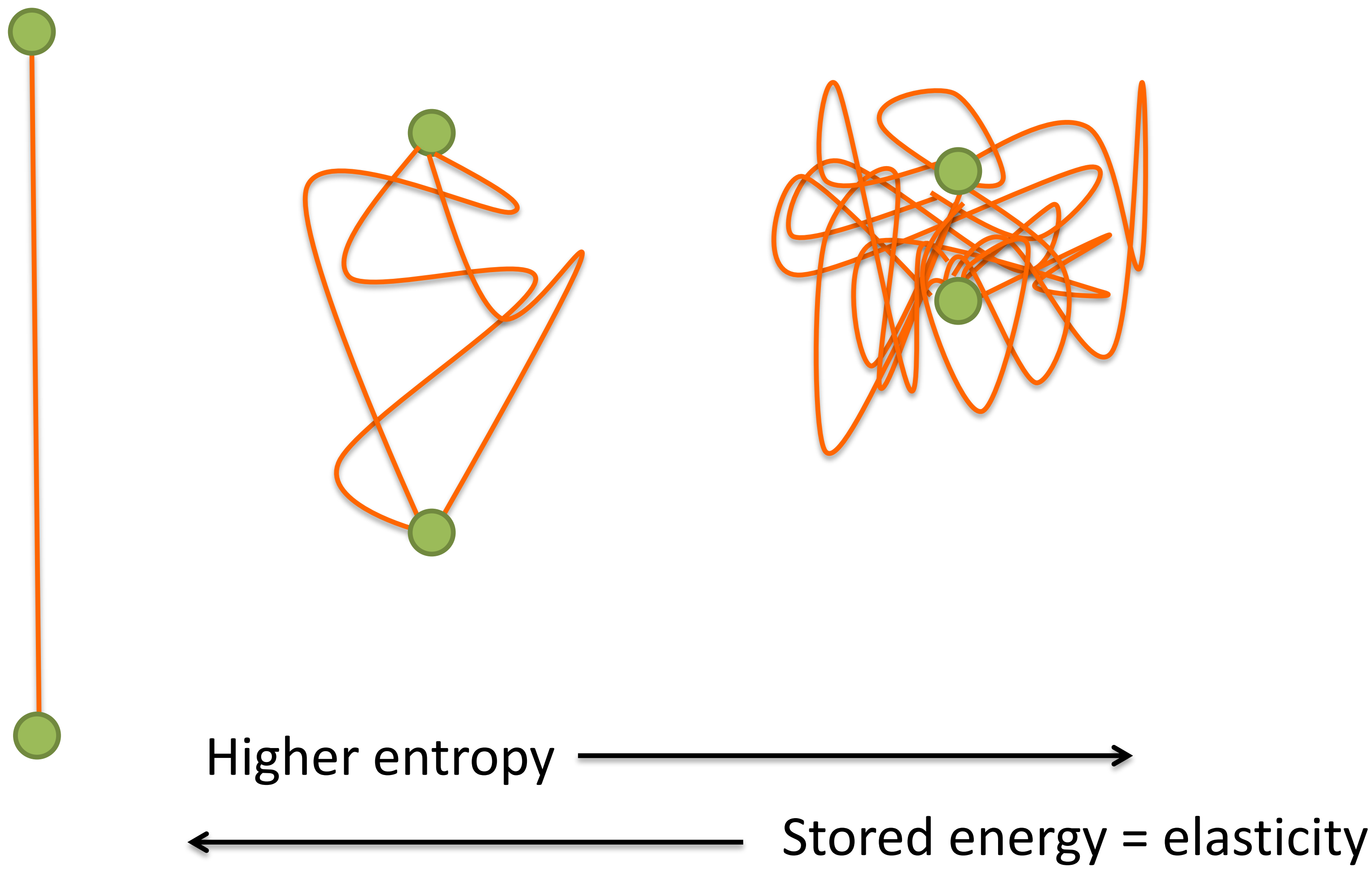
Gel are mainly water

But behave like solids



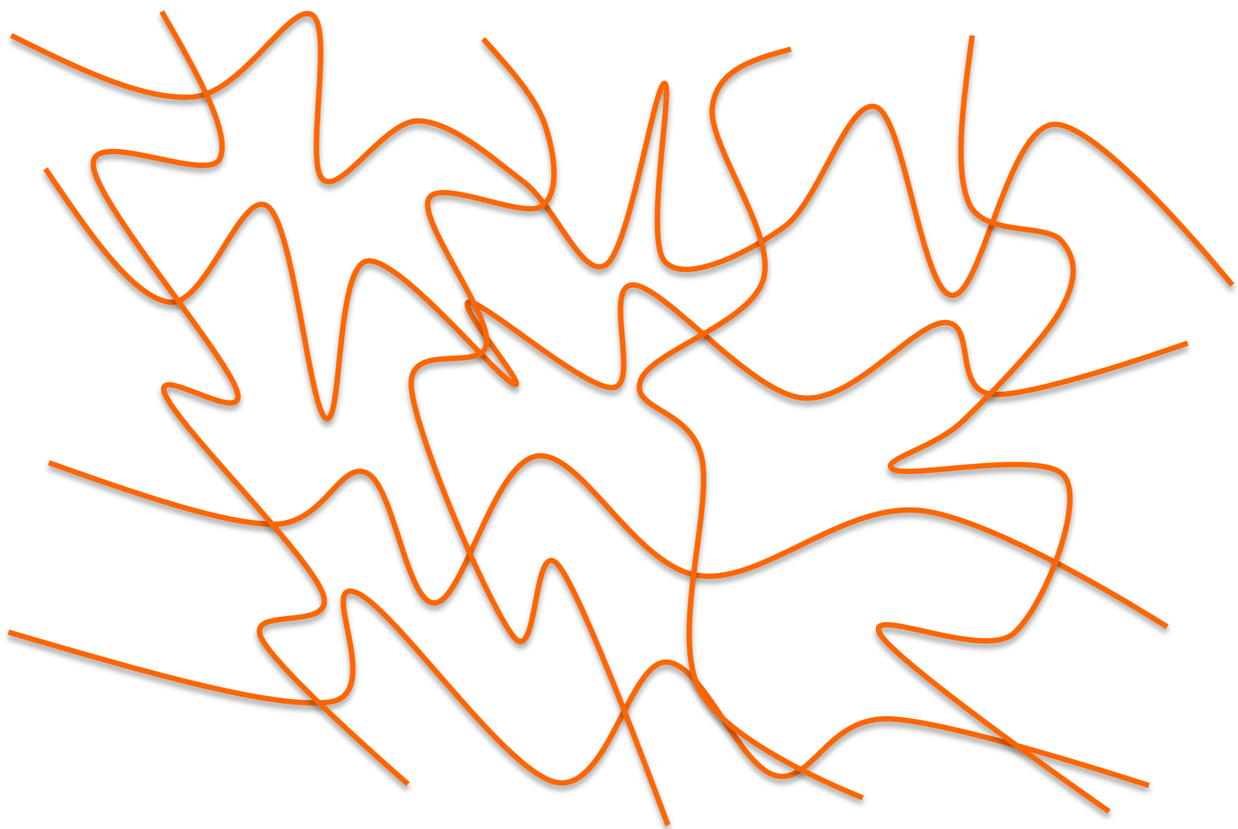
Entropy of polymers leads to elasticity

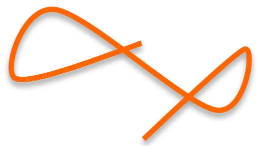
Stretching polymers reduces the number of states



Polymers chains form a network

Entangled chains

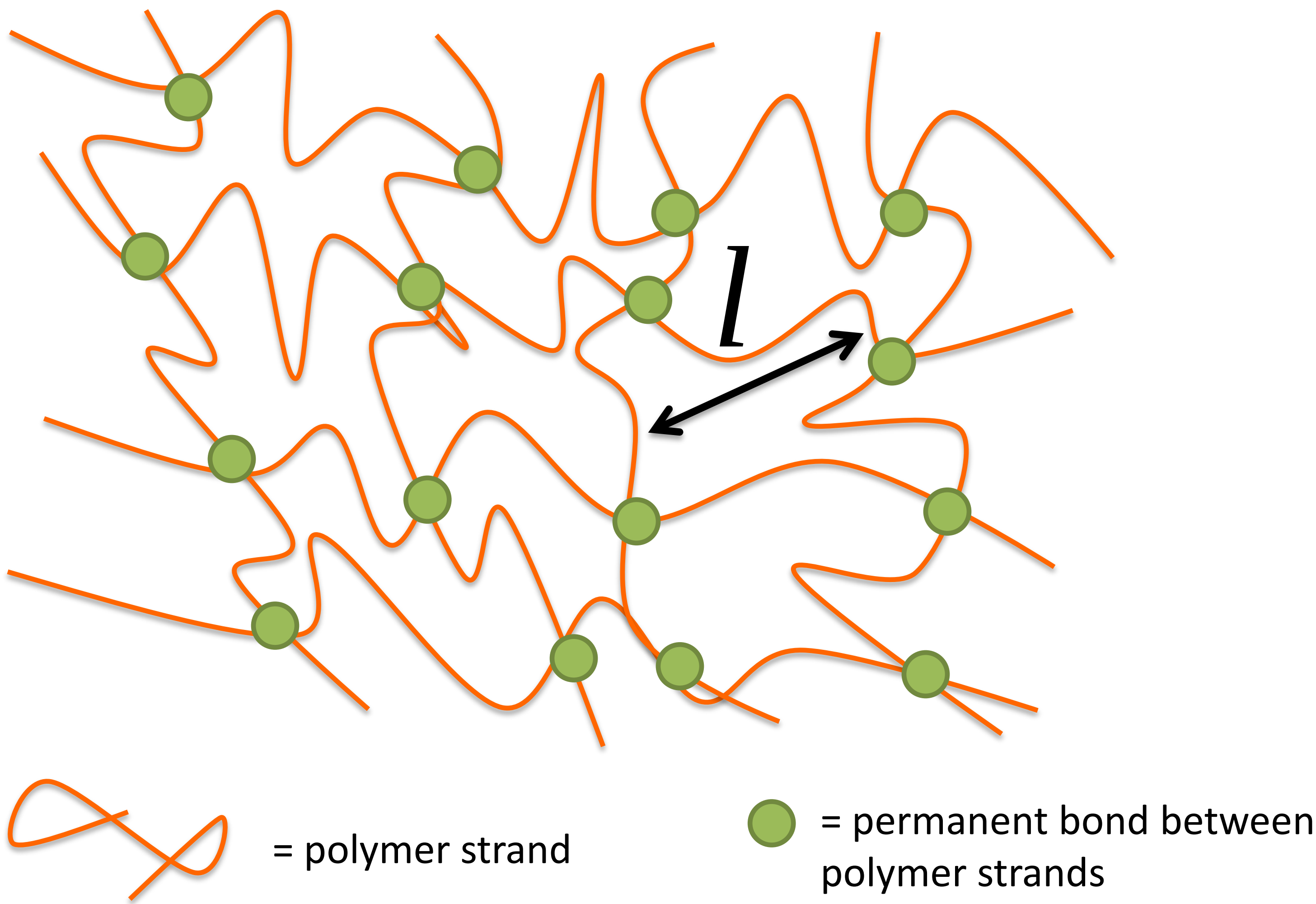




= polymer strand

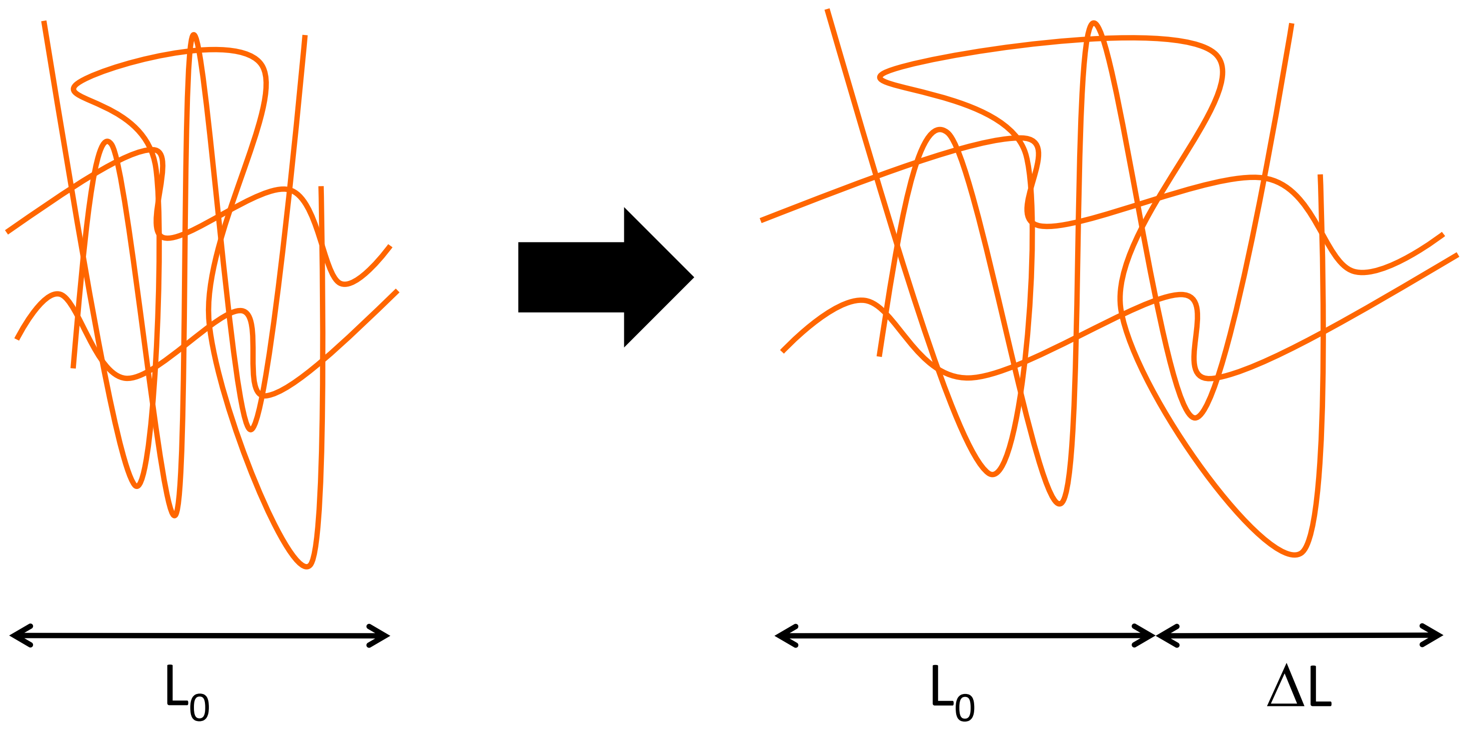
Polymers can cross-link to form a gel

Form chemical bond where polymers cross



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]

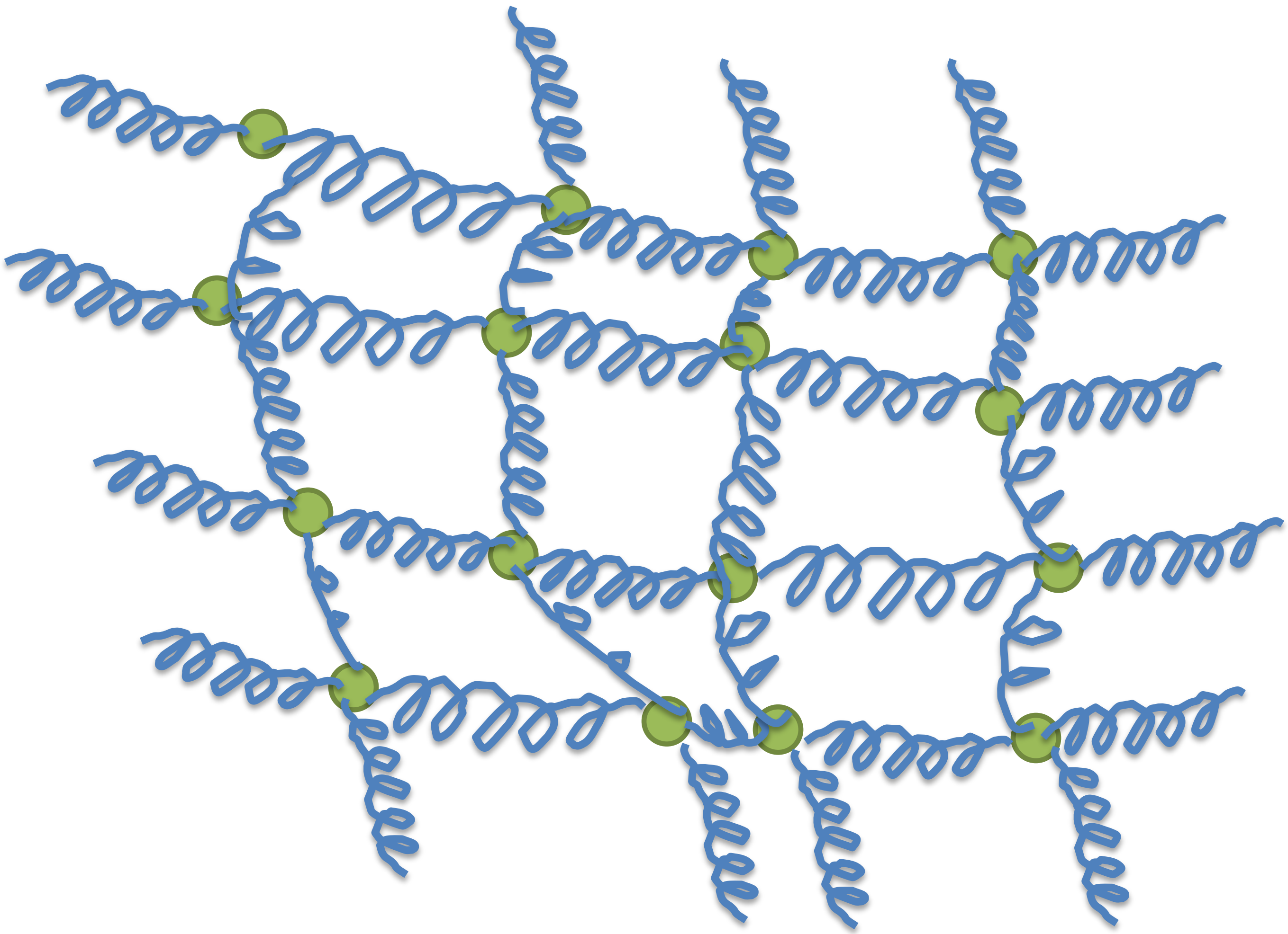
k_B = Boltzmann's constant [J/K]

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

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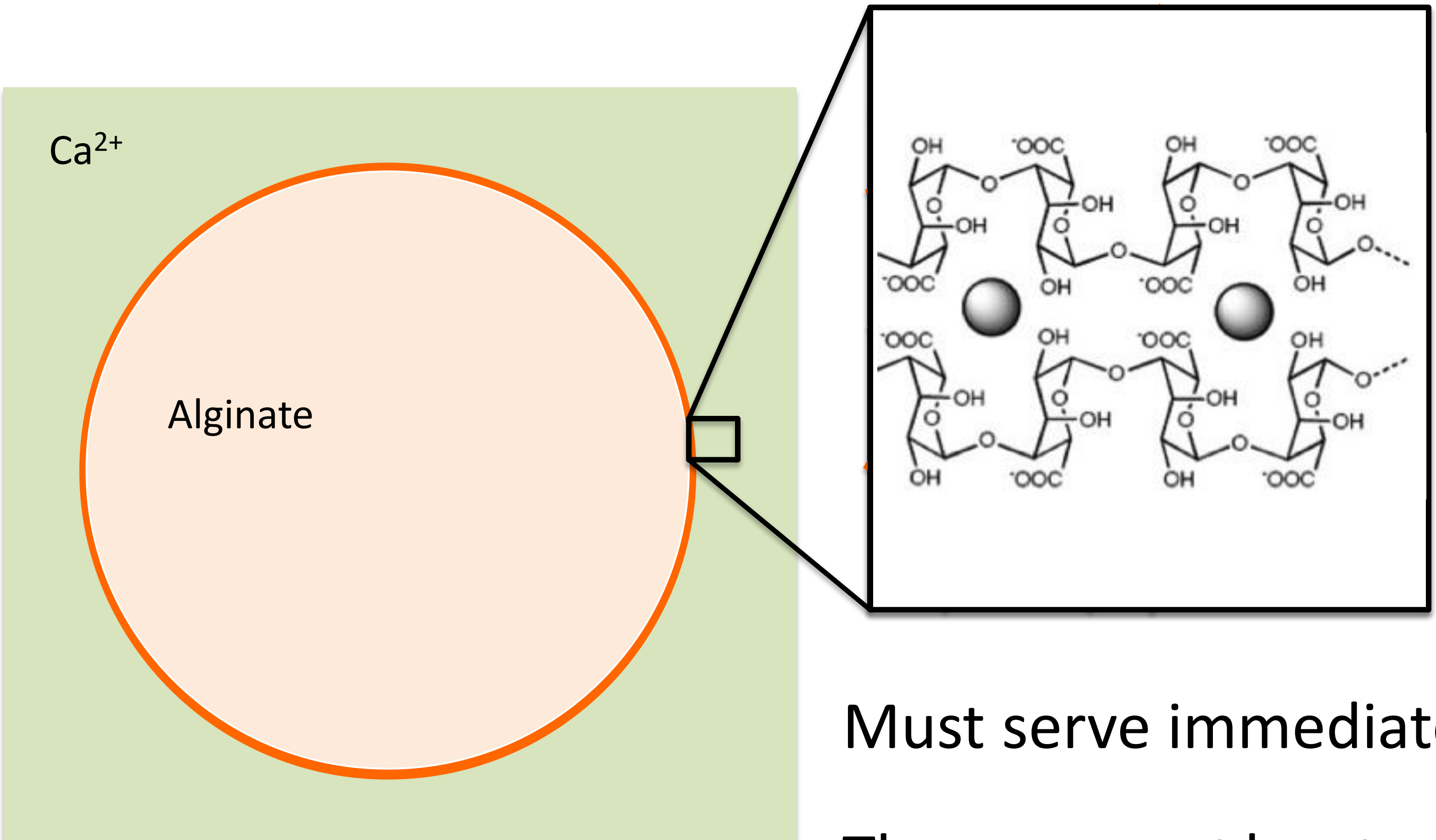
Spherification

Yogurt spheres

Spherification: Direct

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

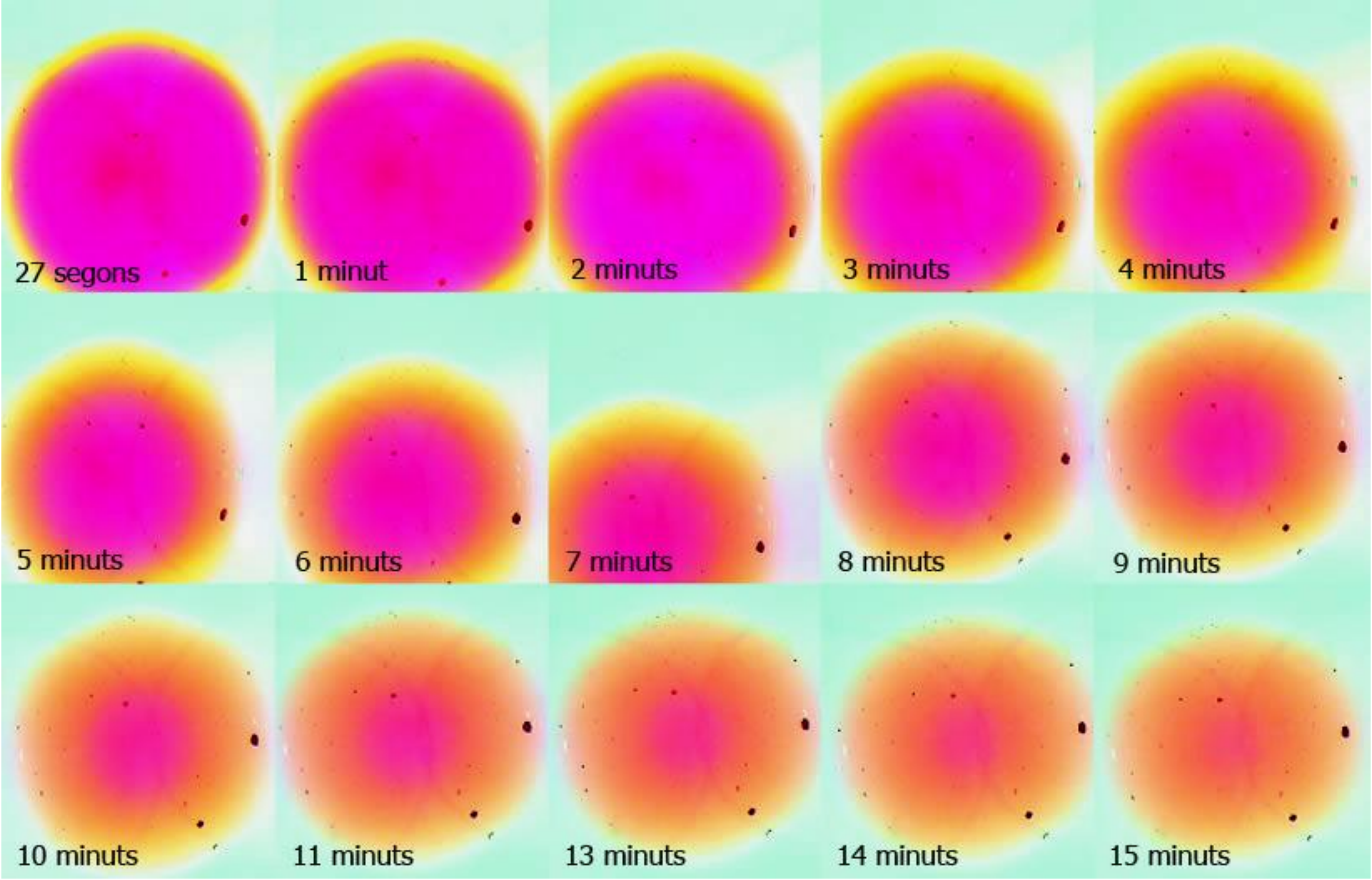


Must serve immediately

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)

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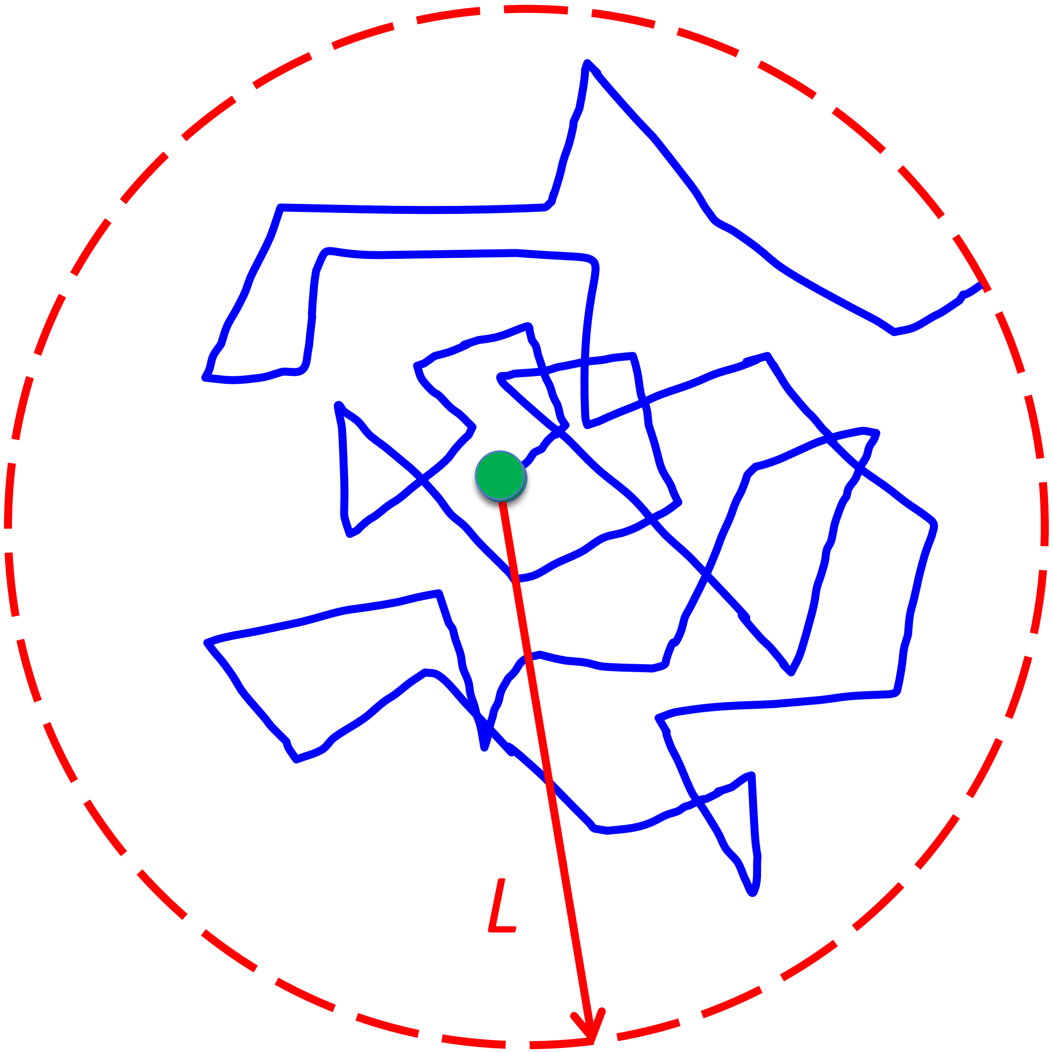
Random walk in two-dimenions

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]

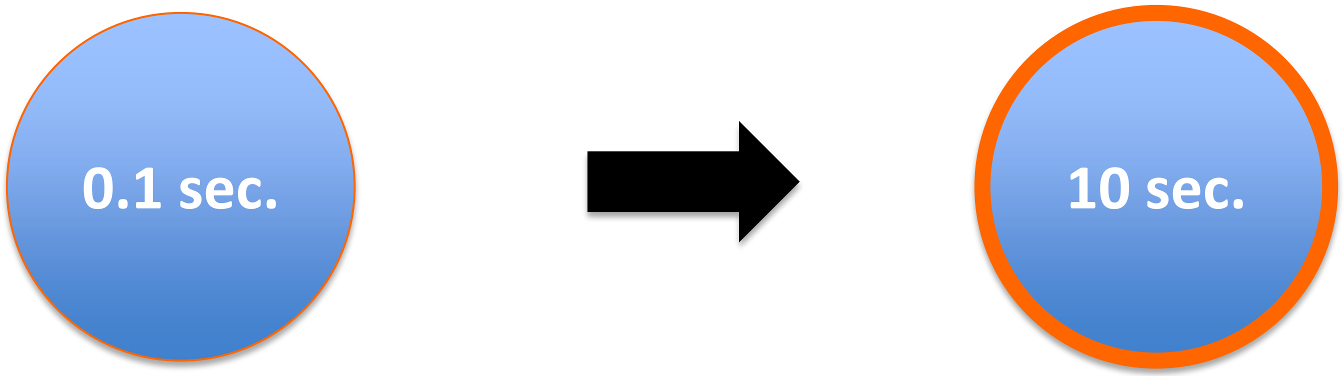
L = distance of diffusion [m]

D = diffusion coefficient [m^2/sec]

Time scale for spherification

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

10 micron shell **100 micron shell**



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

$$t = 0.1\,\mathrm{sec}$$

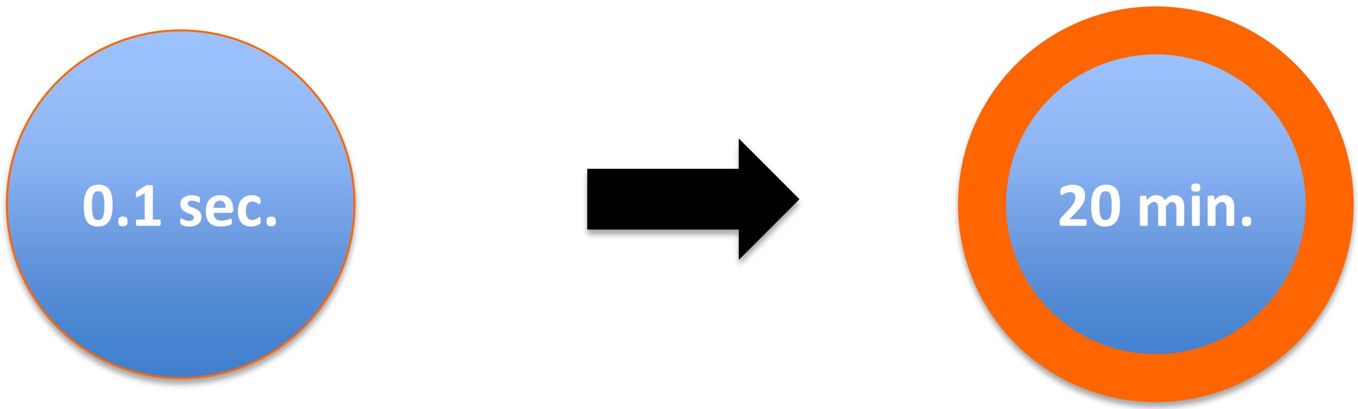
$$t = \frac{L^2}{D} = \frac{\left(100 \times 10^{-6}\,\mathrm{m}\right)^2}{7 \times 10^{-10}\,\mathrm{m}^2/\mathrm{s}}$$

$$t = 10\,\mathrm{sec}$$

Time scale for spherification

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

10 micron shell **1 mm shell**



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

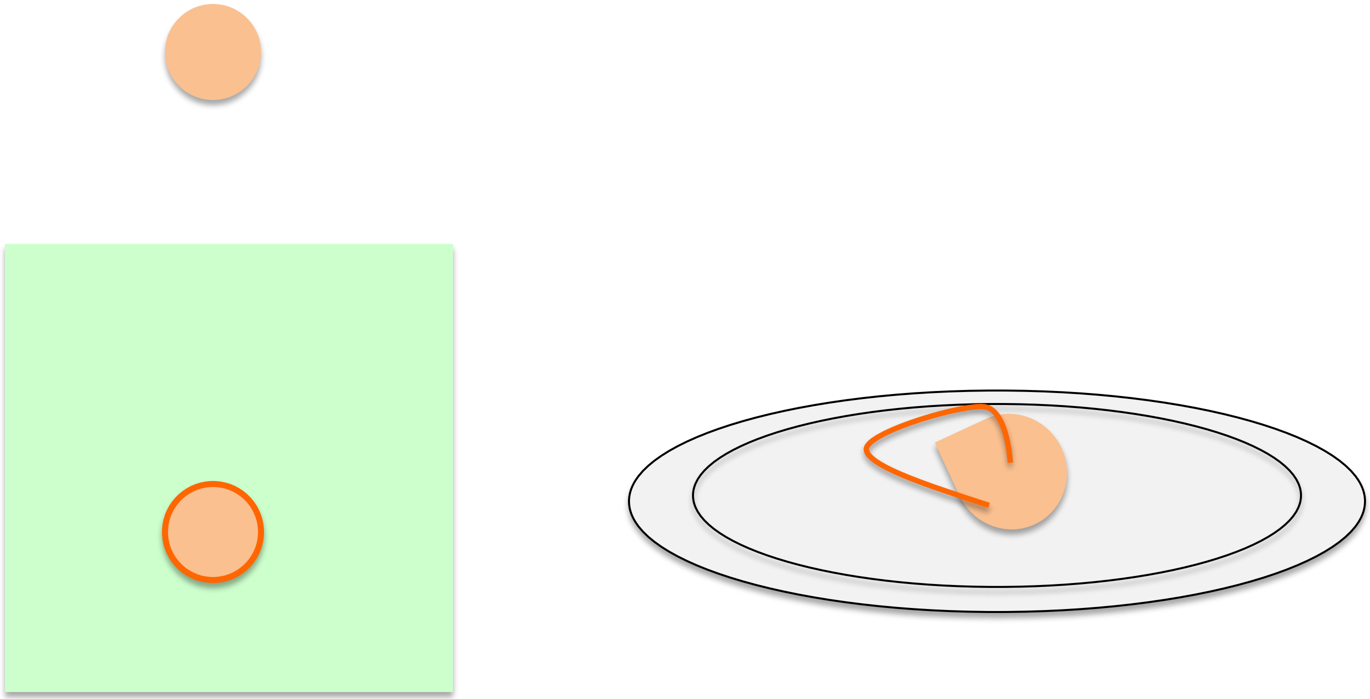
$$t = 0.1\,\mathrm{sec}$$

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

$$t = 1000\,\mathrm{sec} = 20\,\mathrm{min}$$

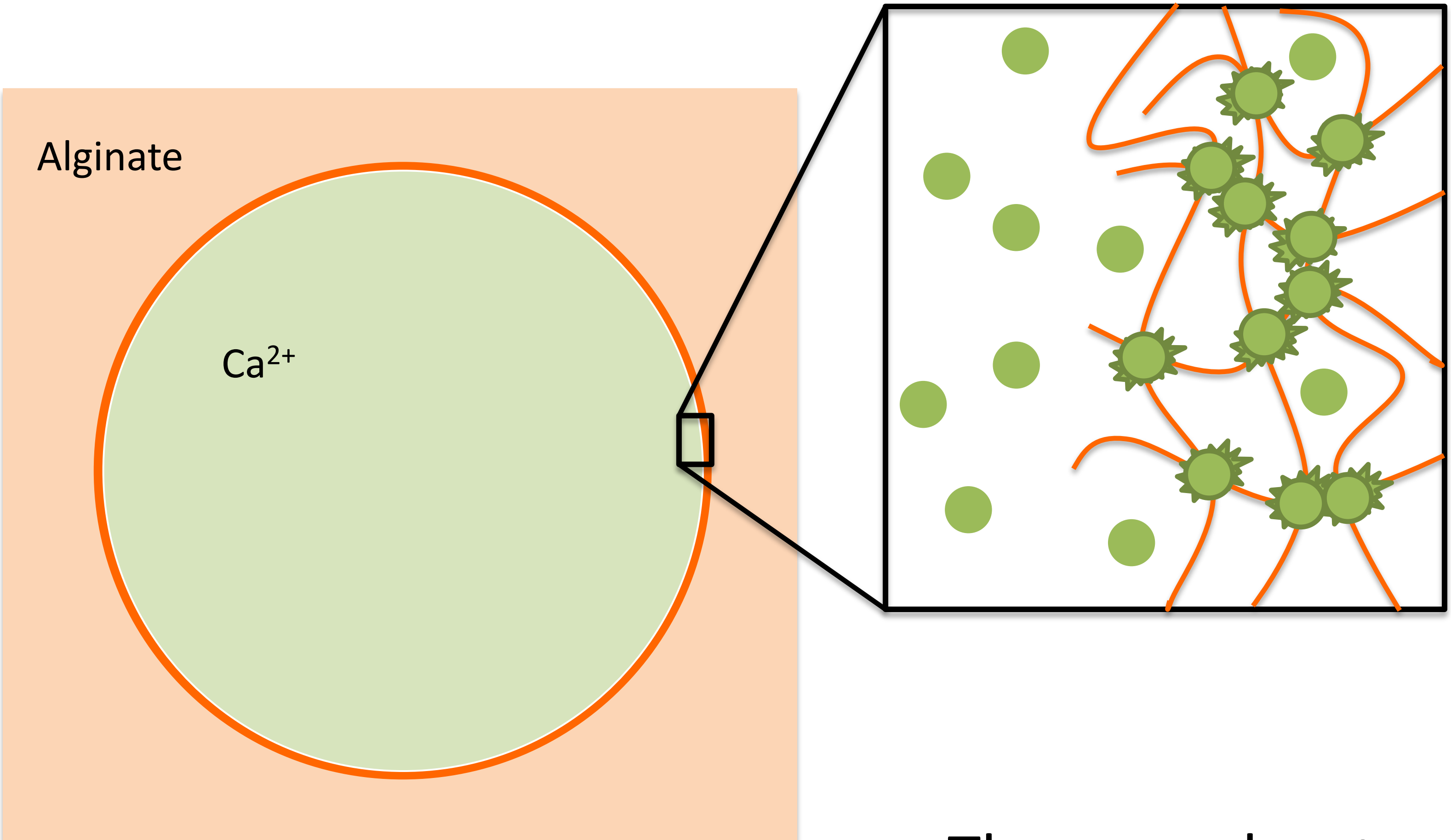
Inverse spherification

Form thin layer of gel around droplet



Inverse spherification

Ca^{2+} solution forms gels with aqueous alginate



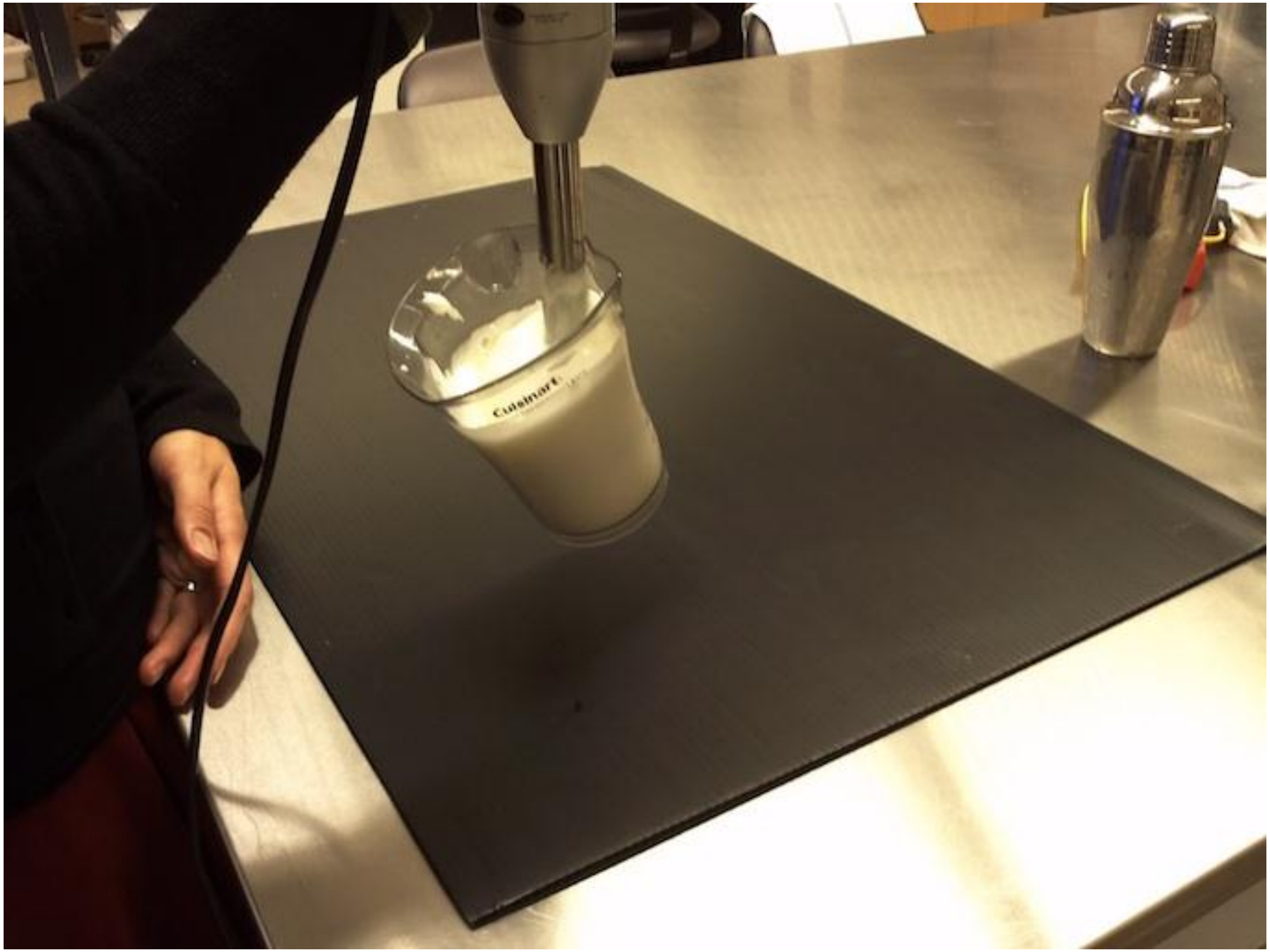
These *can* be stored

Emulsion:

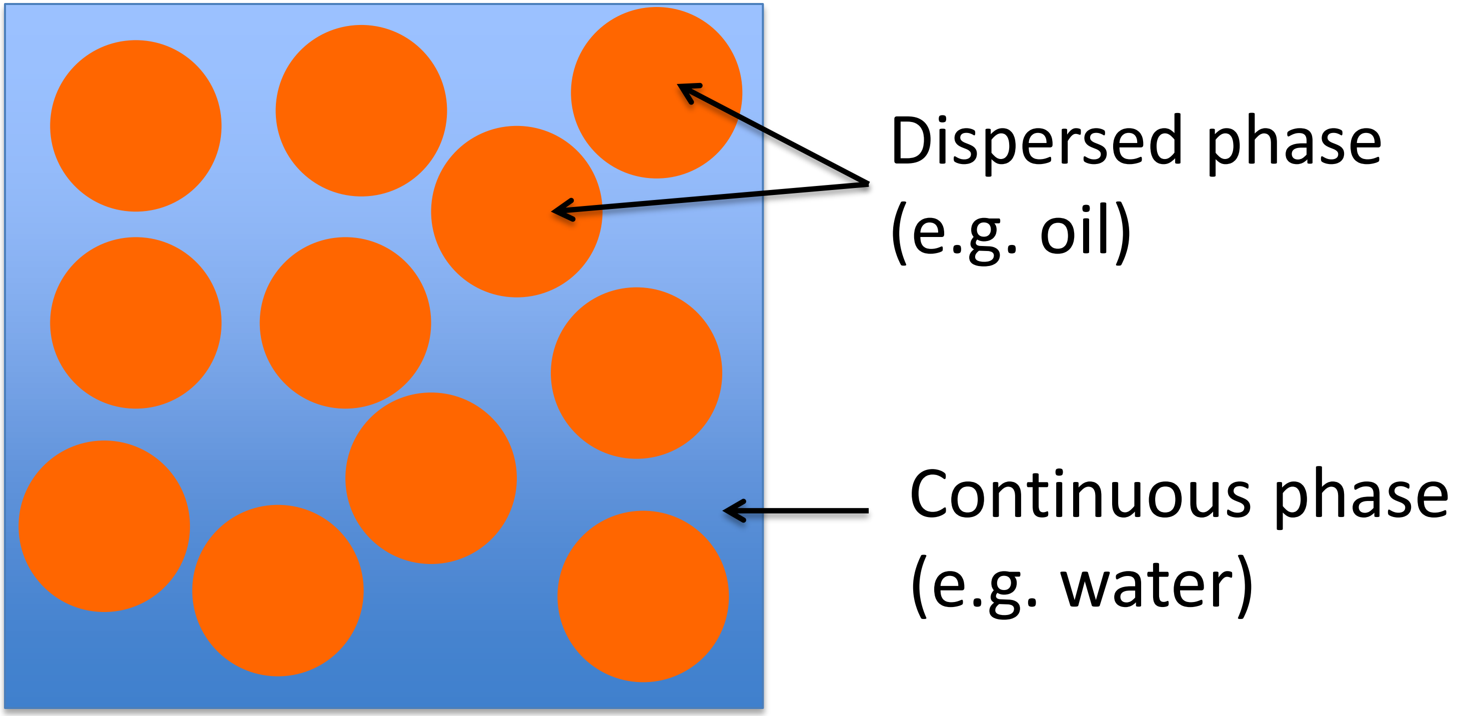
Mixing oil and water

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.

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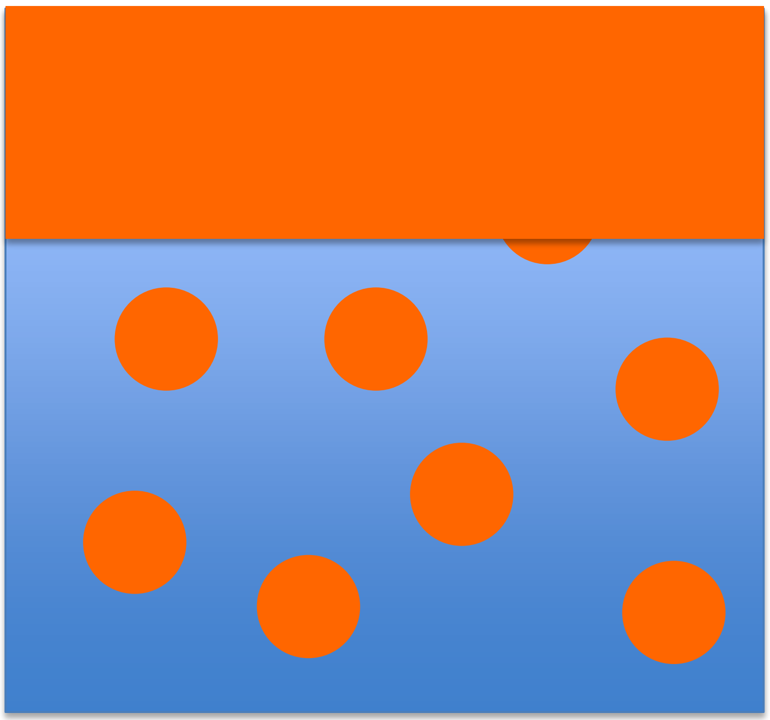
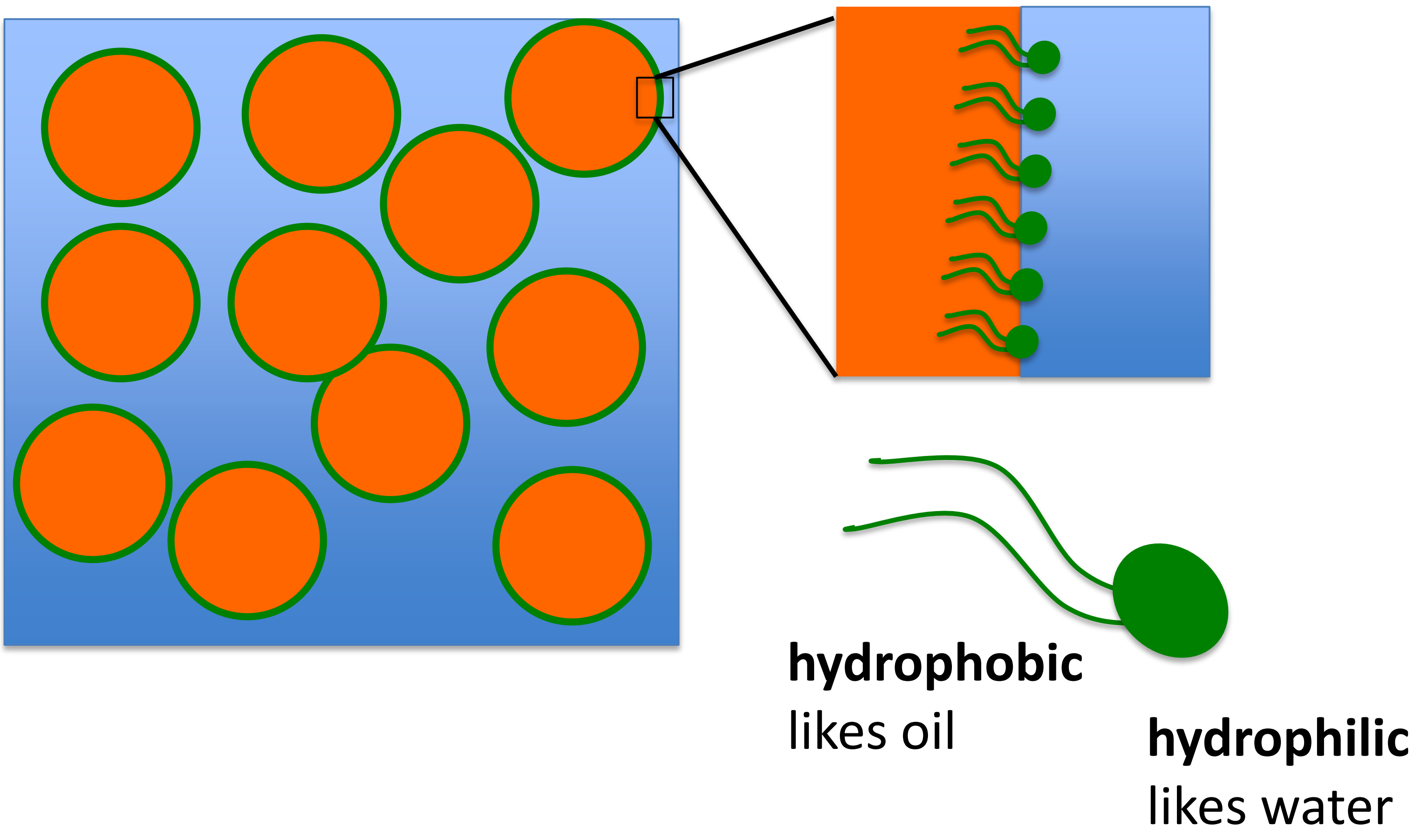


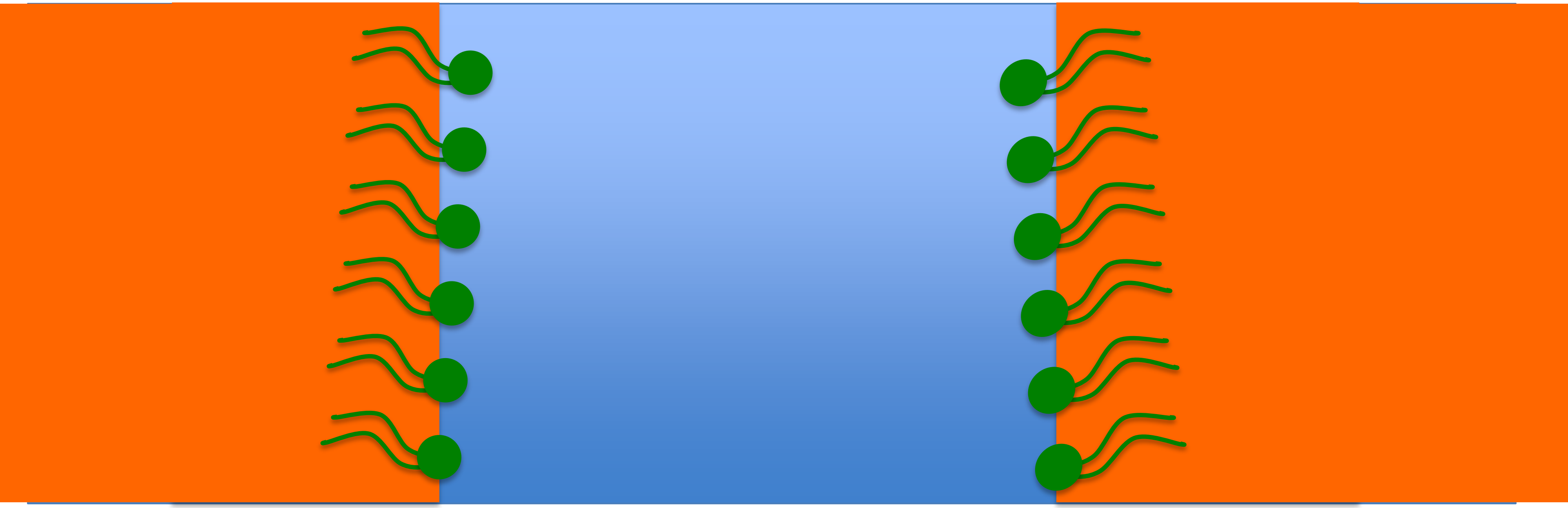
Surfactants stabilize emulsions

Surfactants: surface-active molecules



Surfactants stabilize emulsions.

Ampiphilic molecules attach to the interfaces.



Microscopic view of the interface between drops

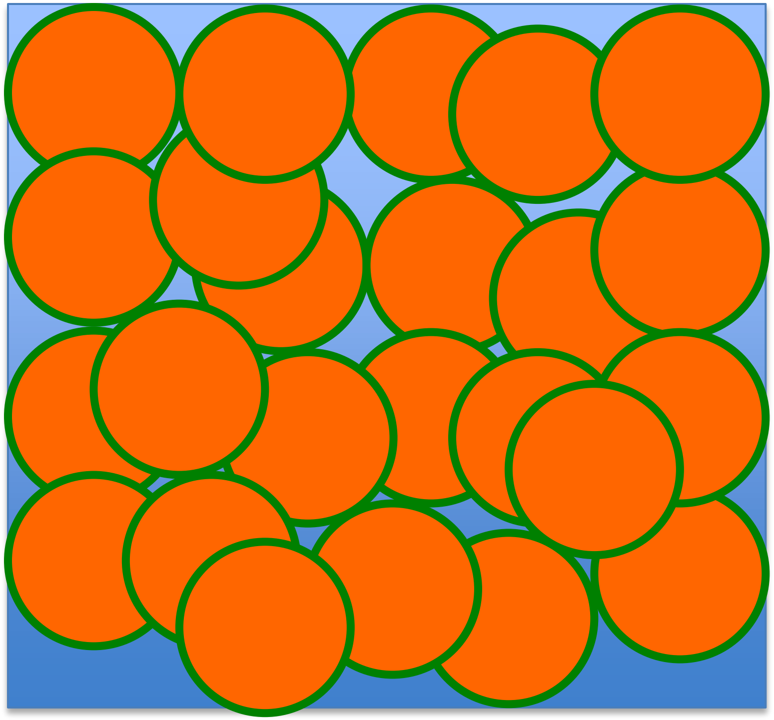
Concentrated emulsions are solids

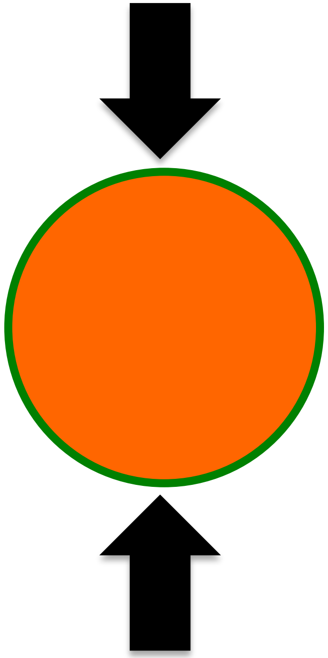
Two liquids mixed together become a solid!

Microscopic view of the interface between drops

Emulsions can be solids

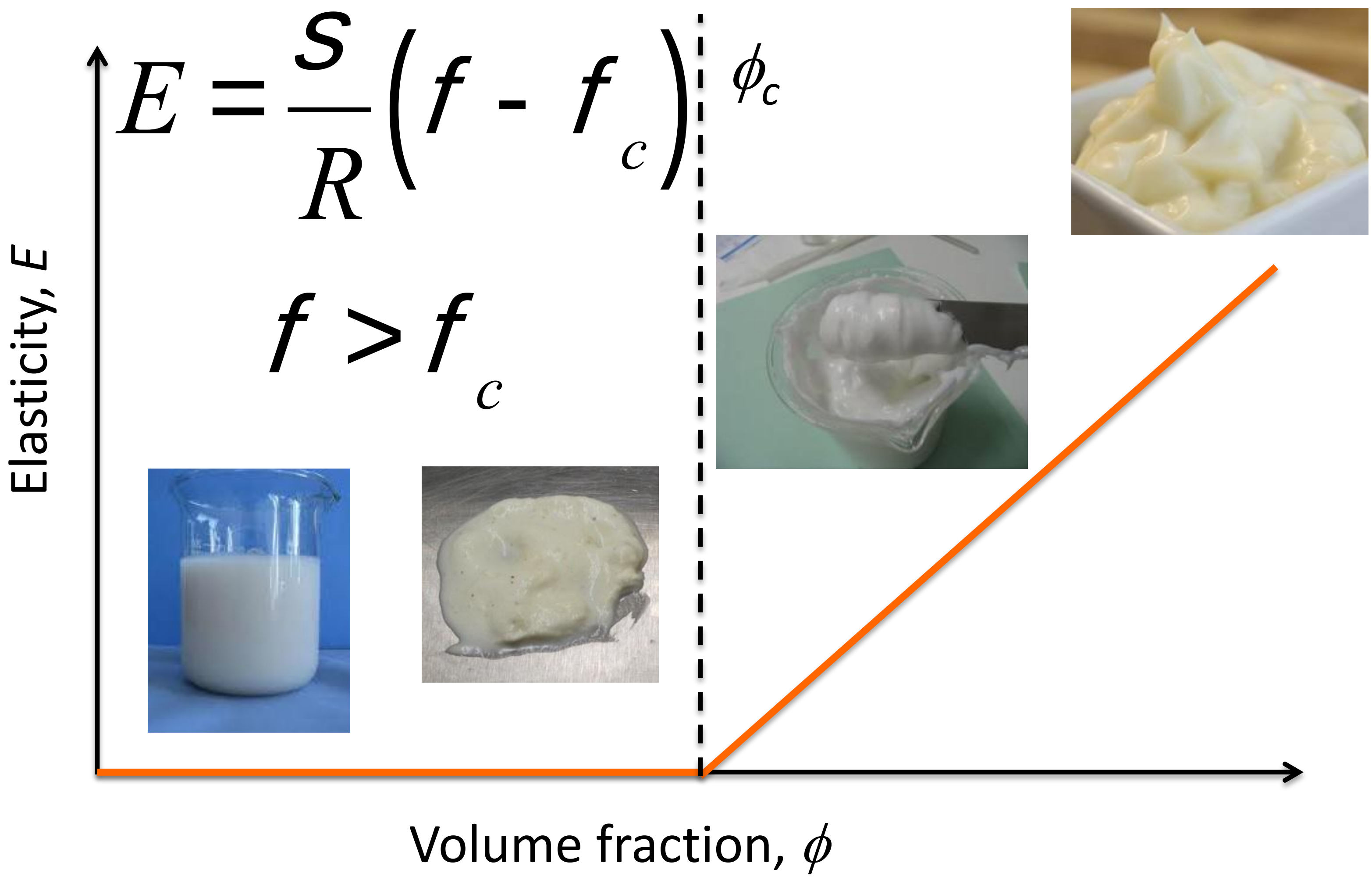
Compressed droplets resist deformation.





Elasticity as a function of ϕ

Emulsions are elastic above critical volume fraction.



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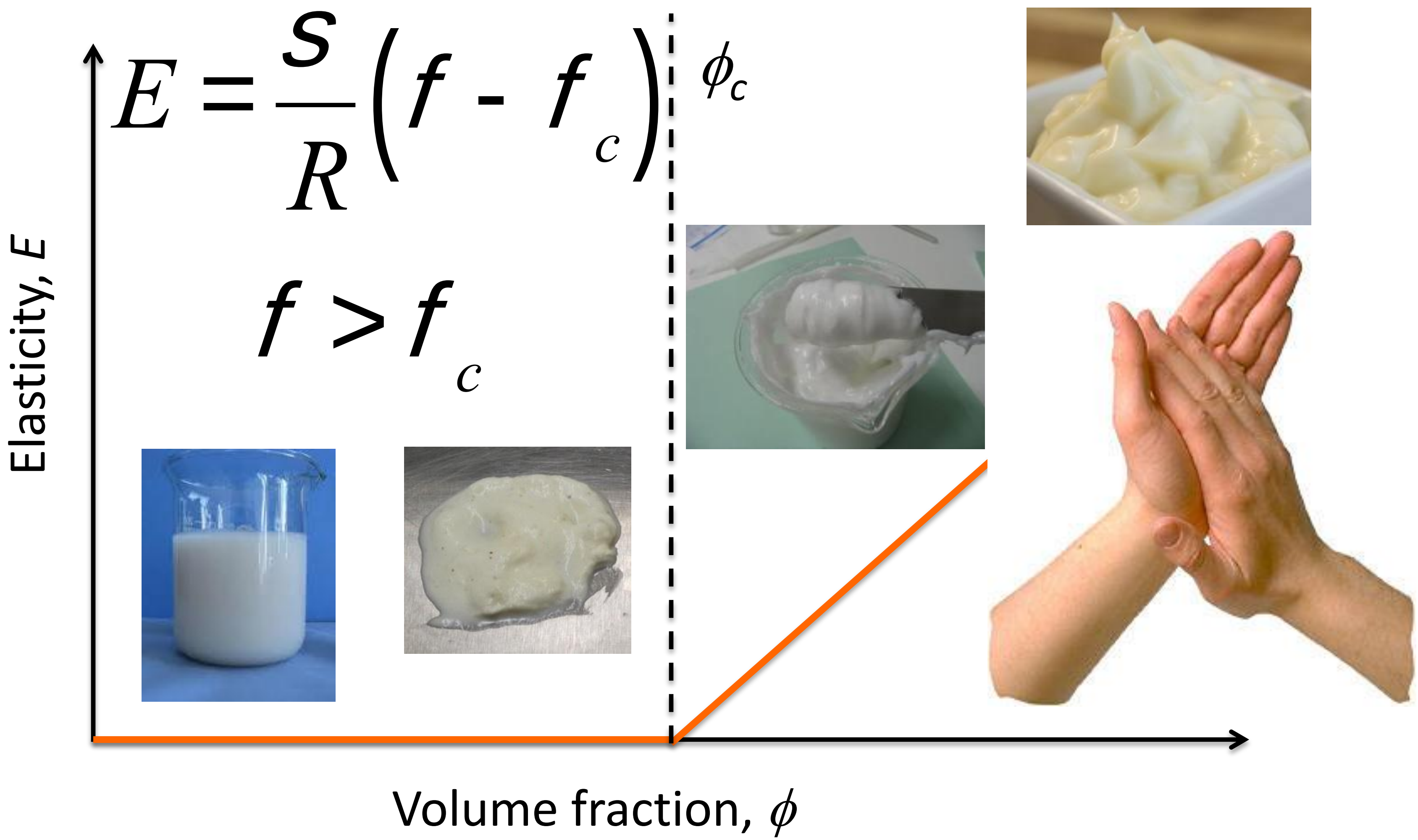


Foams:

Liquid + Gas = Solid

Example: beer foam

Gas becomes trapped by surfactants in the drink.

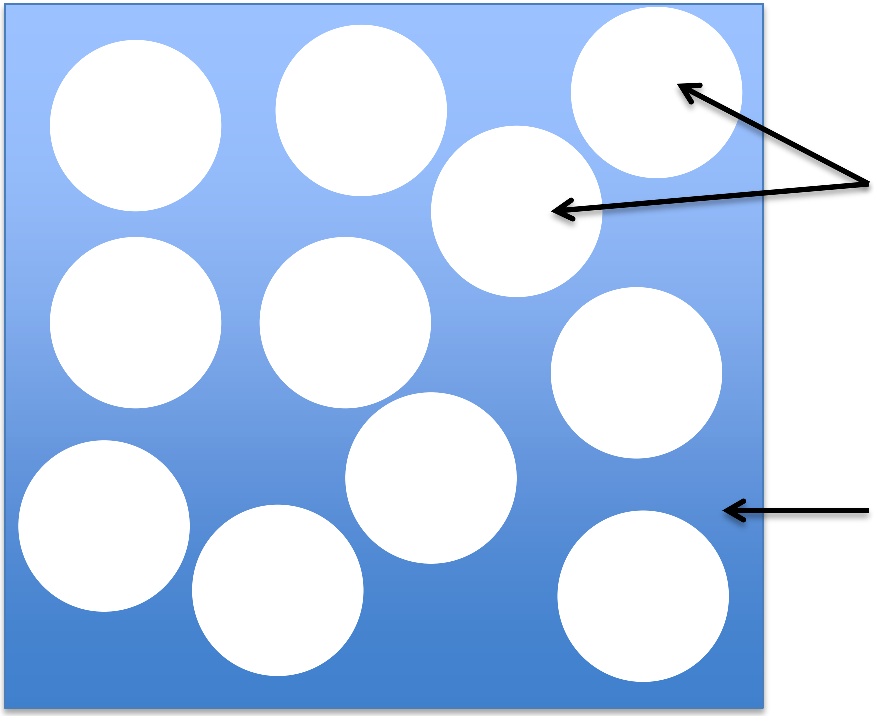
Foam production

Incorporate air into fluid

Mix

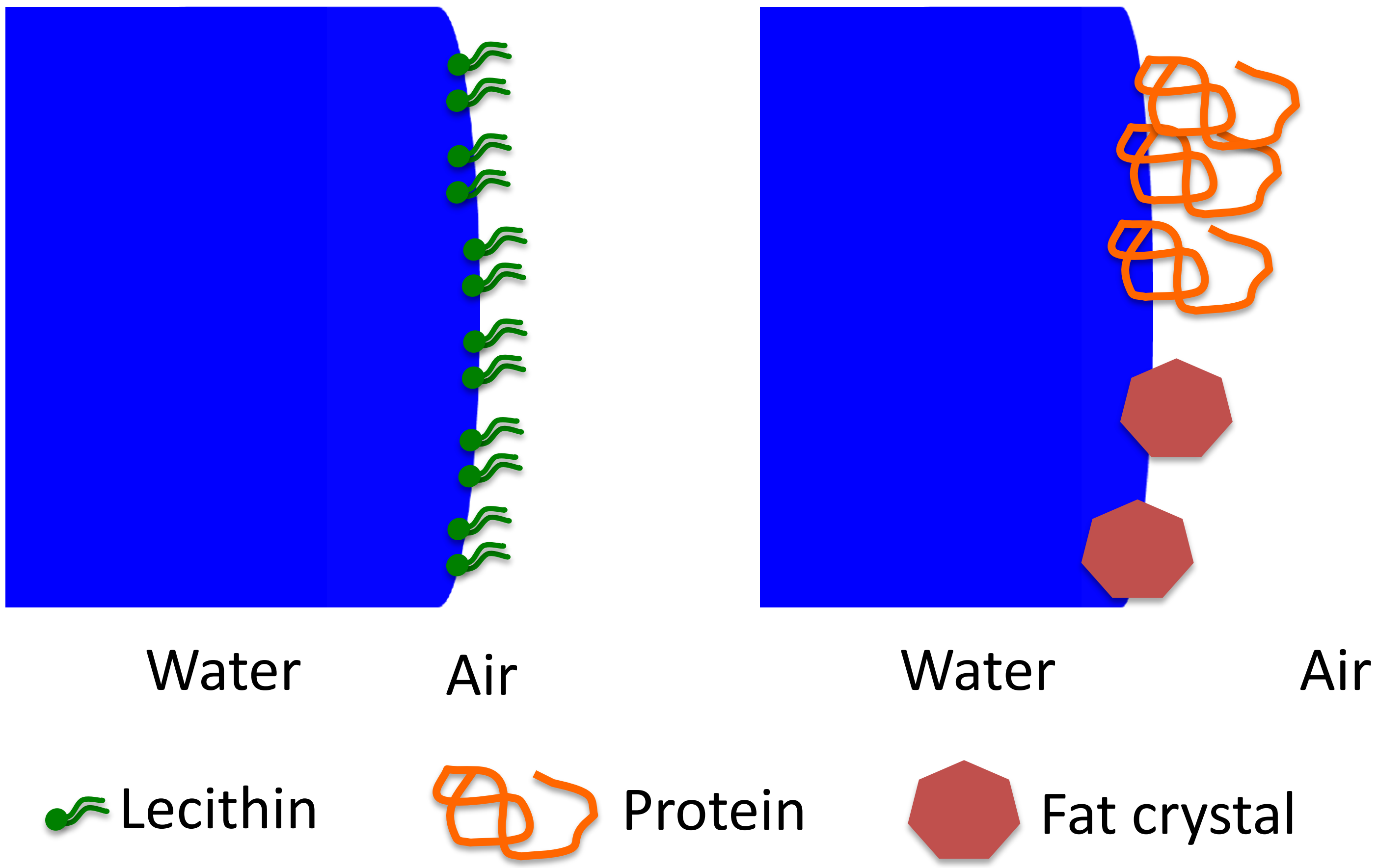
Foam: Bubbles of gas in a liquid

Emulsions with a dispersed phase of gas.



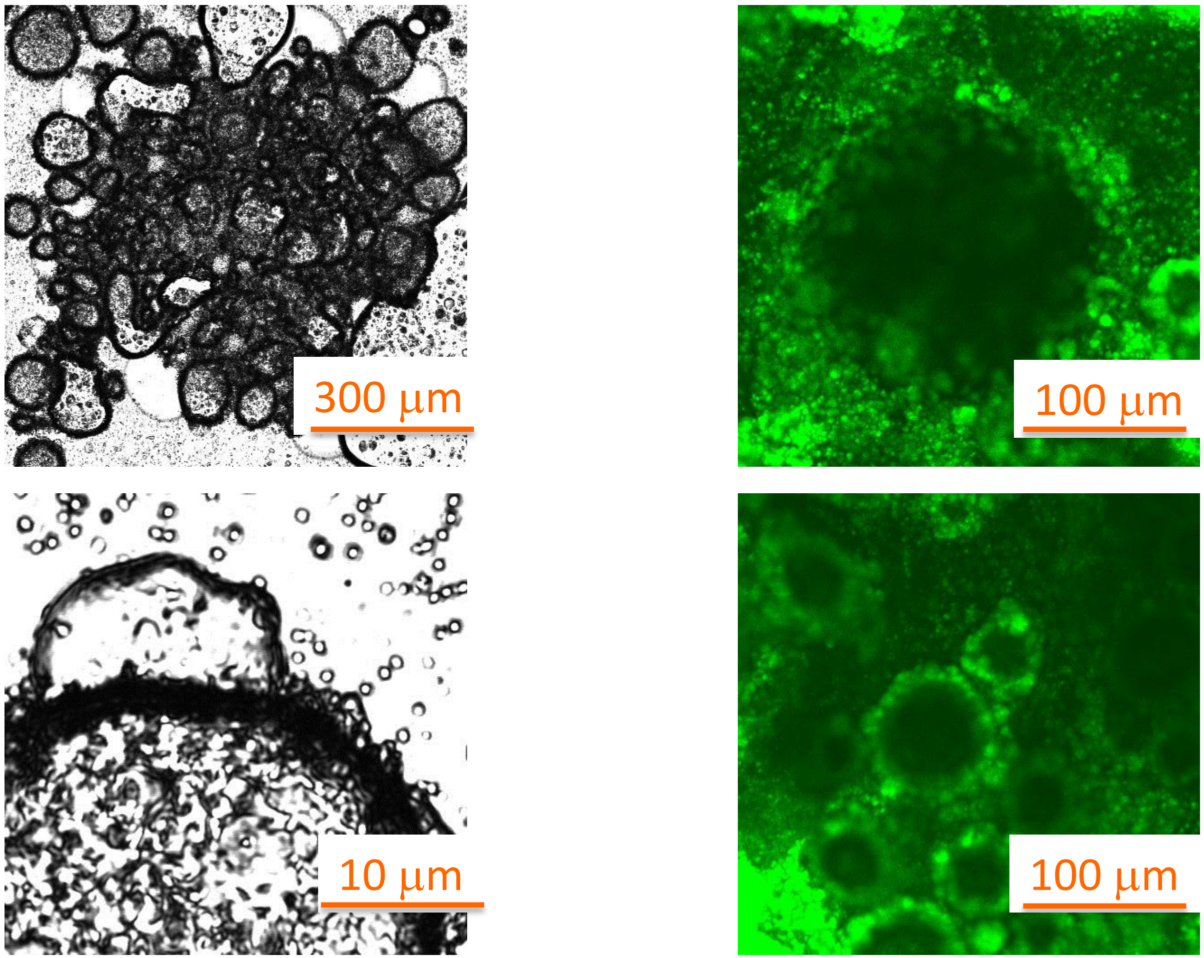
Role of surfactants

Proteins, starches, and fats can act as surfactants



Foam micro-structure

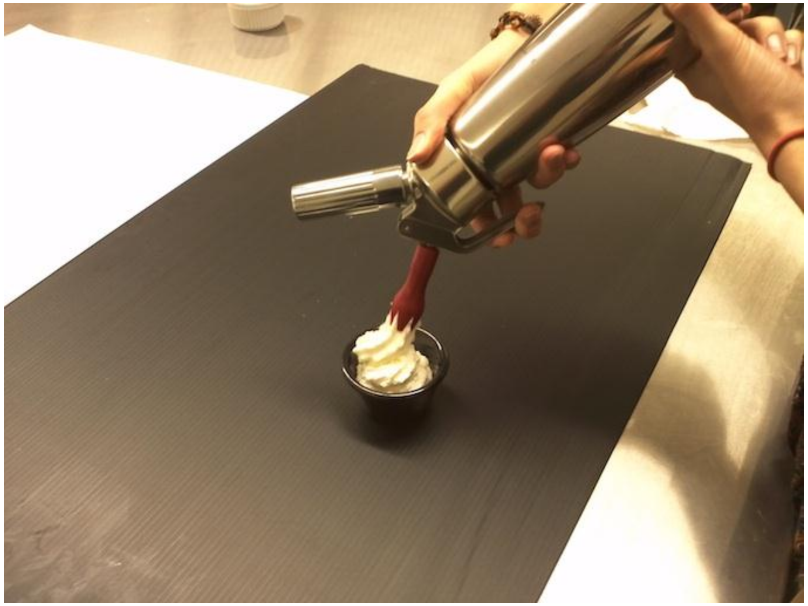
There are several methods for incorporating air.



Foam production

Incorporate air into fluid

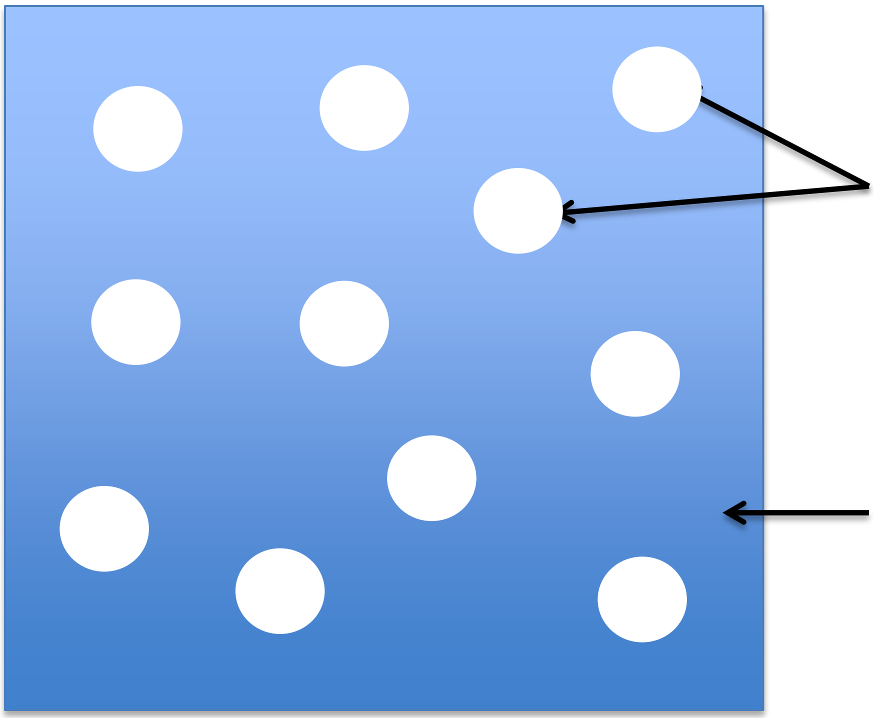
Mix



Add high-pressure gas

Foam: Mix compressed gas with fluid

Compressed gas is liquid – forms emulsion with fluid



Foam production

The resulting products differ in appearance.

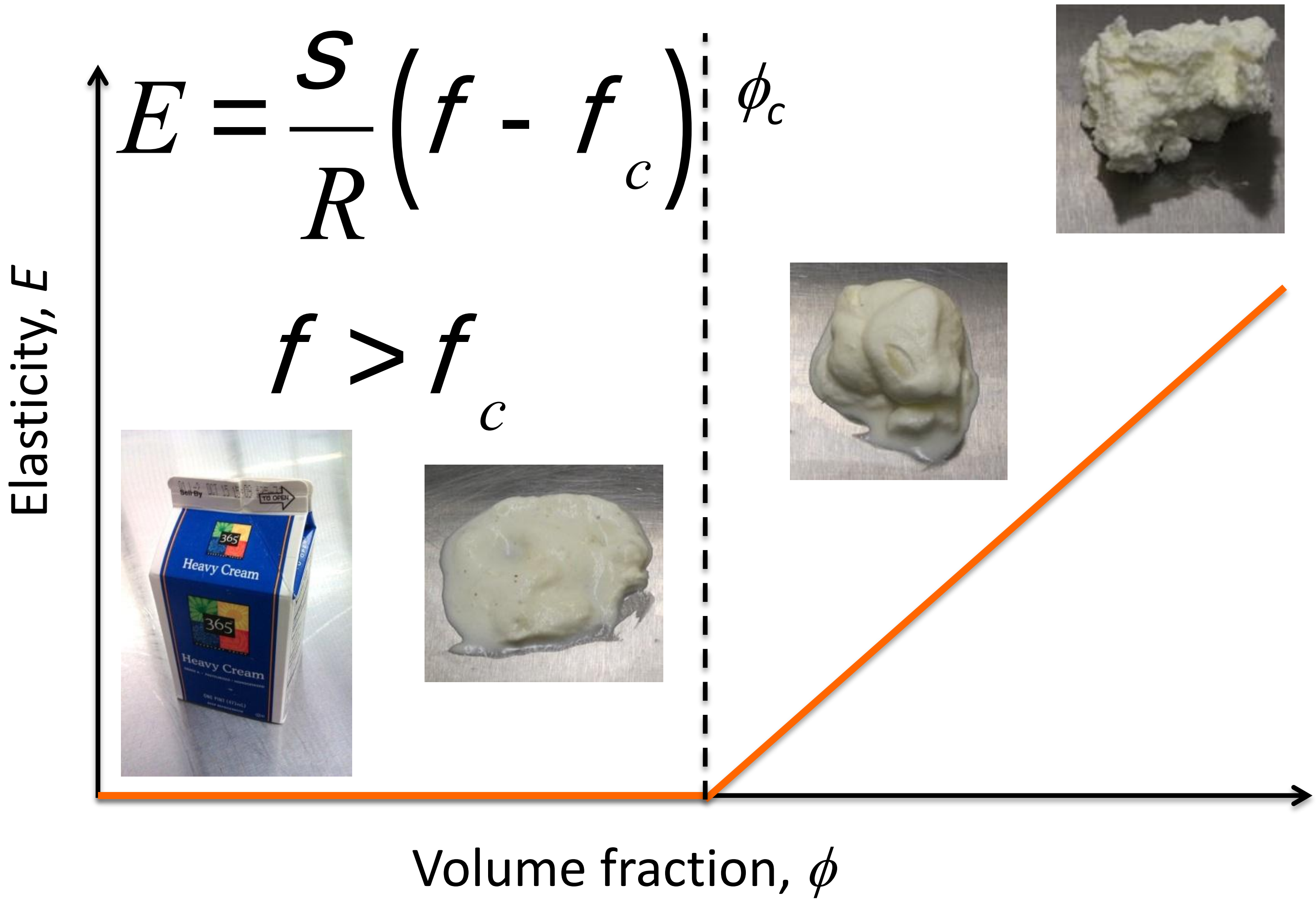
KitchenAid (short time)

iSi Whip

KitchenAid (long time)

Elasticity as a function of ϕ

Foams are elastic above critical volume fraction.

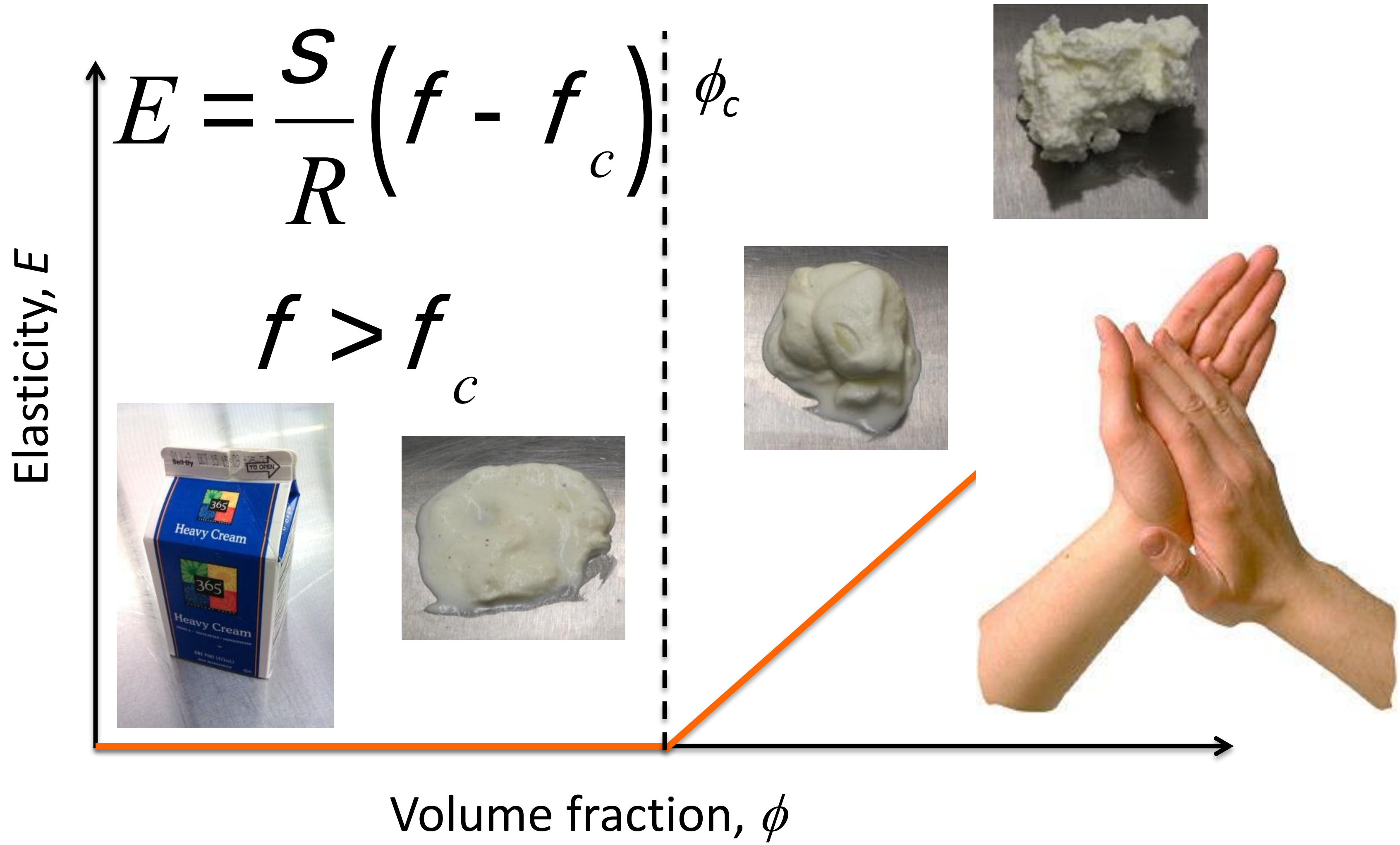


$$E = \frac{\sigma}{R}(\phi - \phi_c)$$

$$\phi > \phi_c$$

Elasticity as a function of ϕ

Foams are elastic above critical volume fraction.

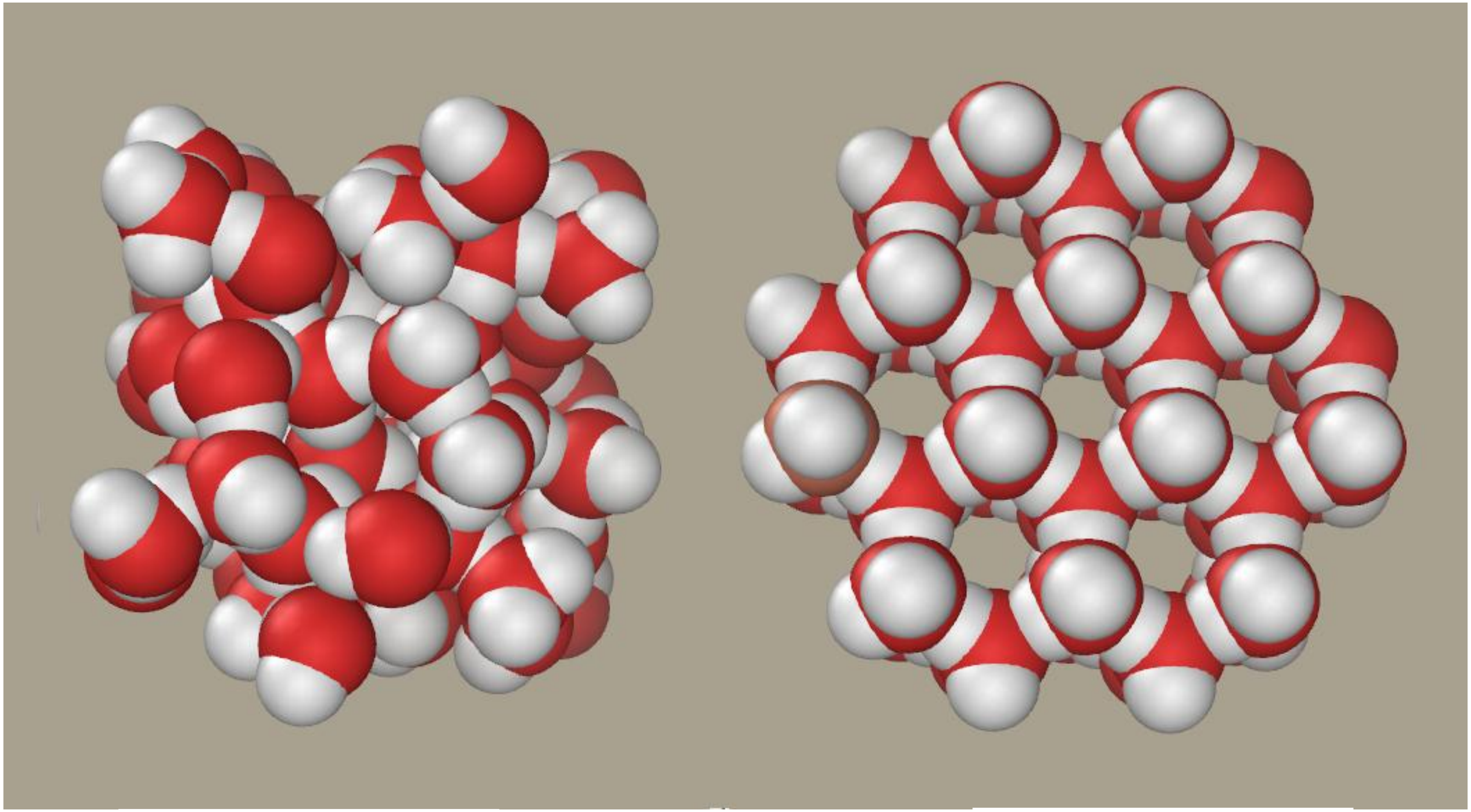


Cocktails:

Cooling and Dilution

Molecular viewpoint

Ice is in a lower entropy state than water.



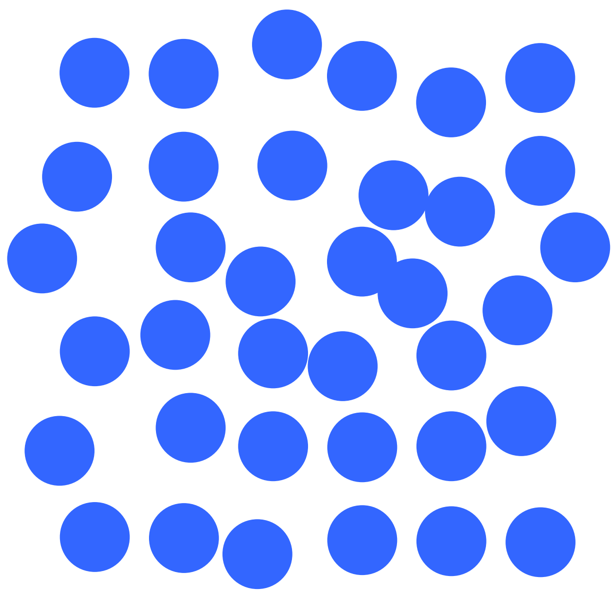
Liquid

Ice

Molecular viewpoint

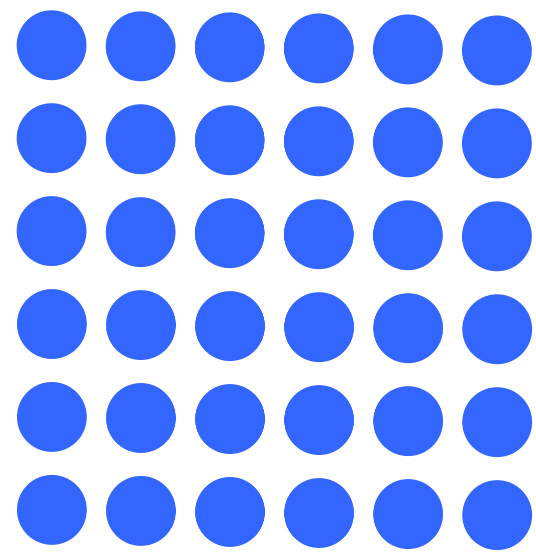
Ice is in a lower energy state than water

Higher energy



Liquid

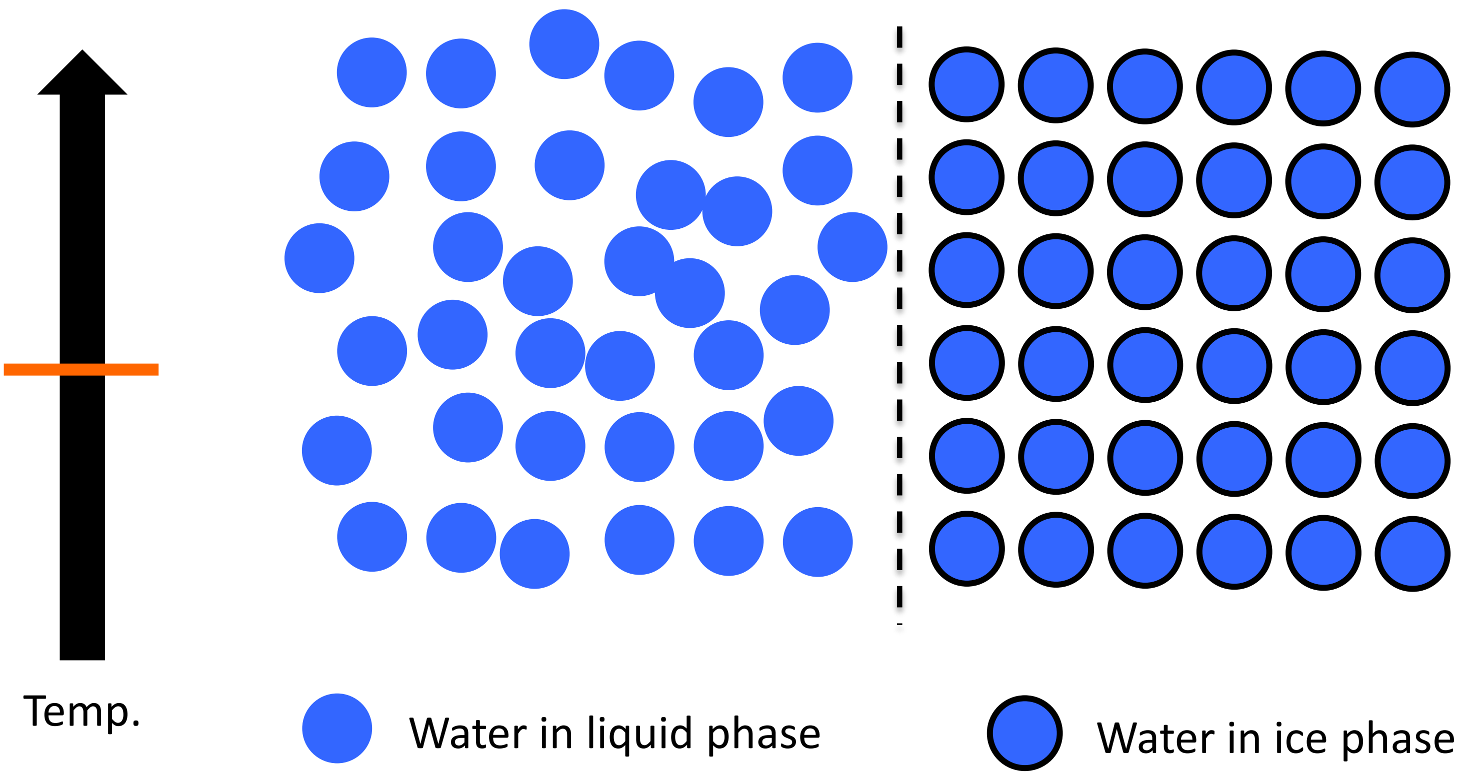
Lower energy



Ice

Molecular viewpoint

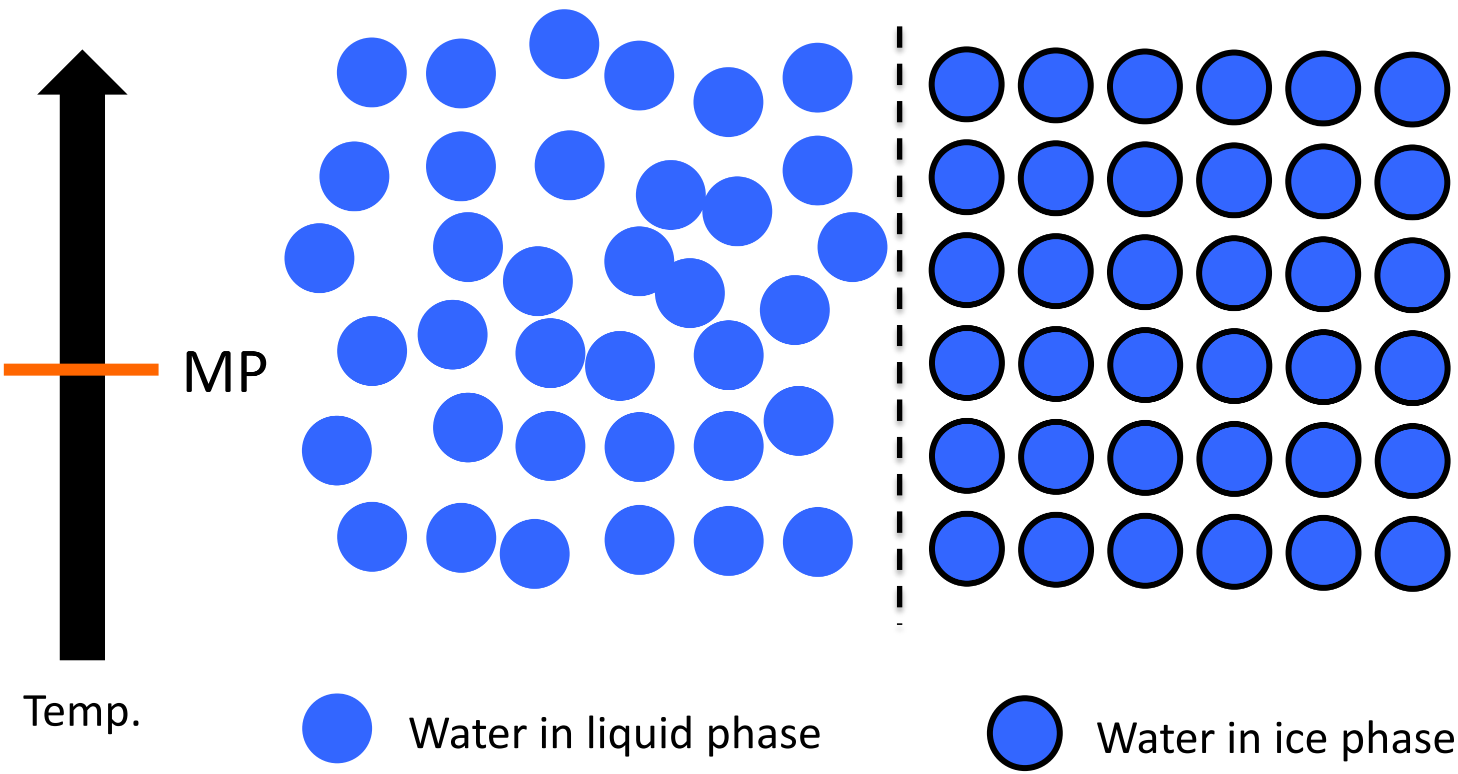
The interface continually exchanges molecules.



All the water molecules are chemically identical.

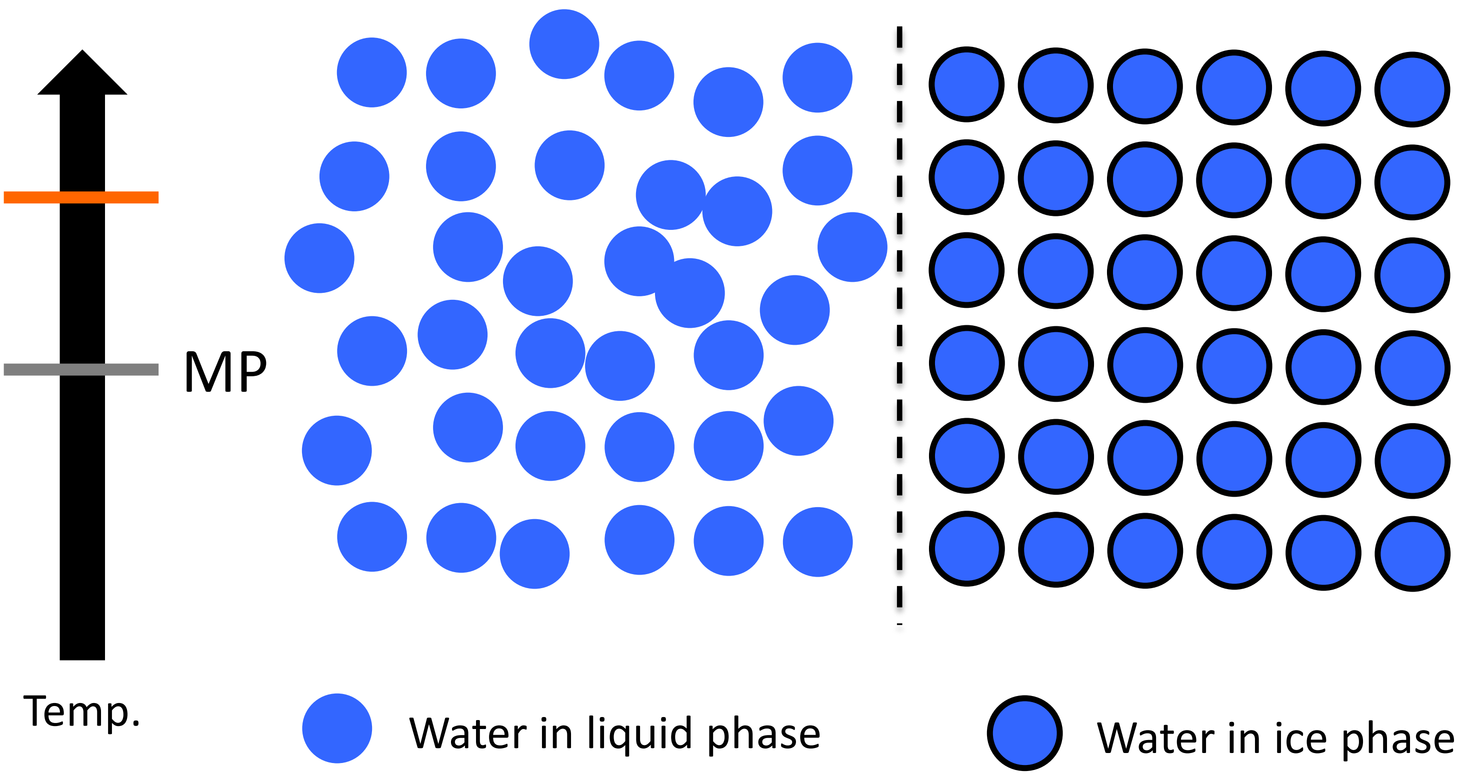
Equilibrium: at melting point

The same numbers leave and enter the ice.



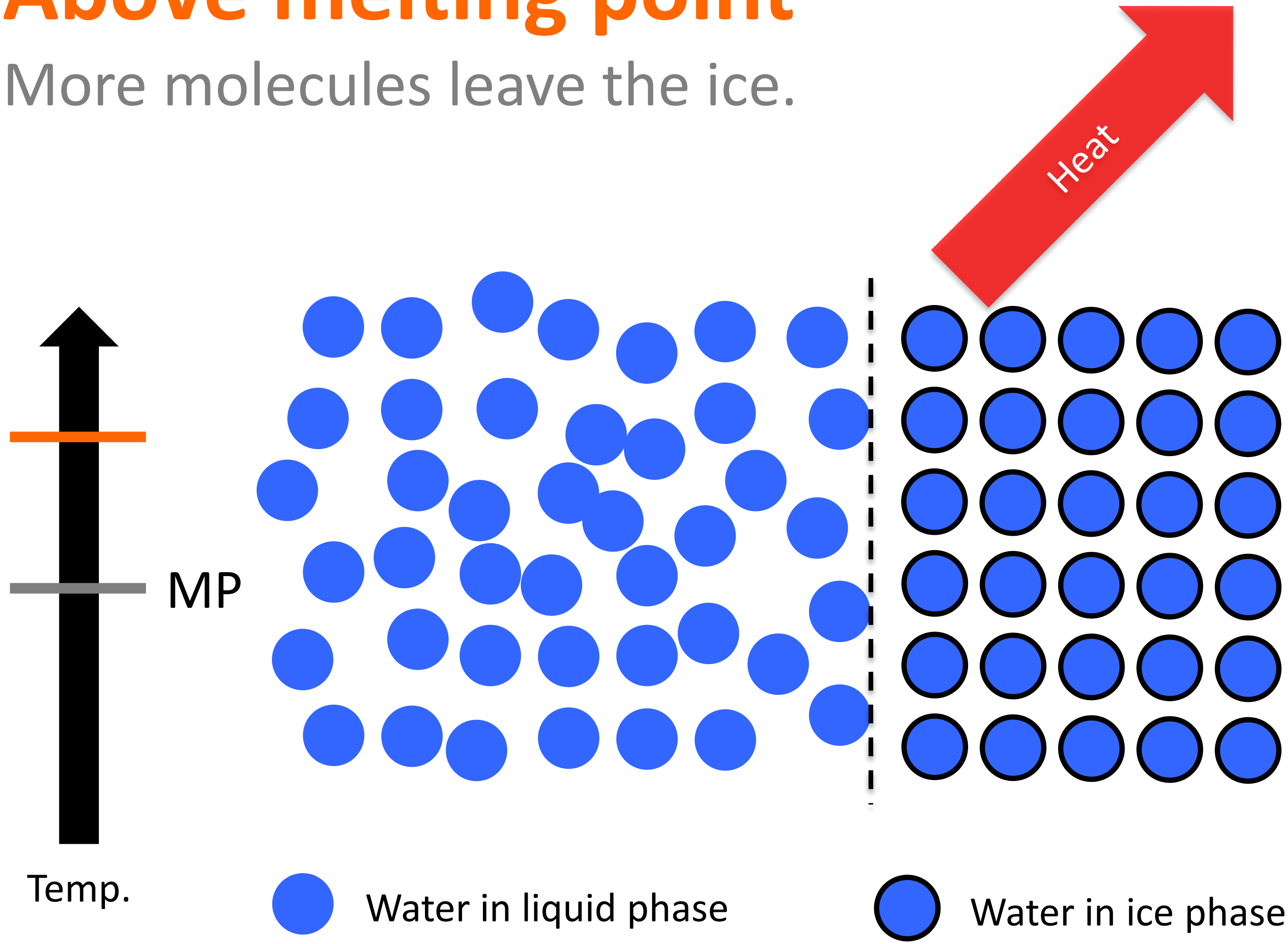
Above melting point

More molecules leave the ice.



Above melting point

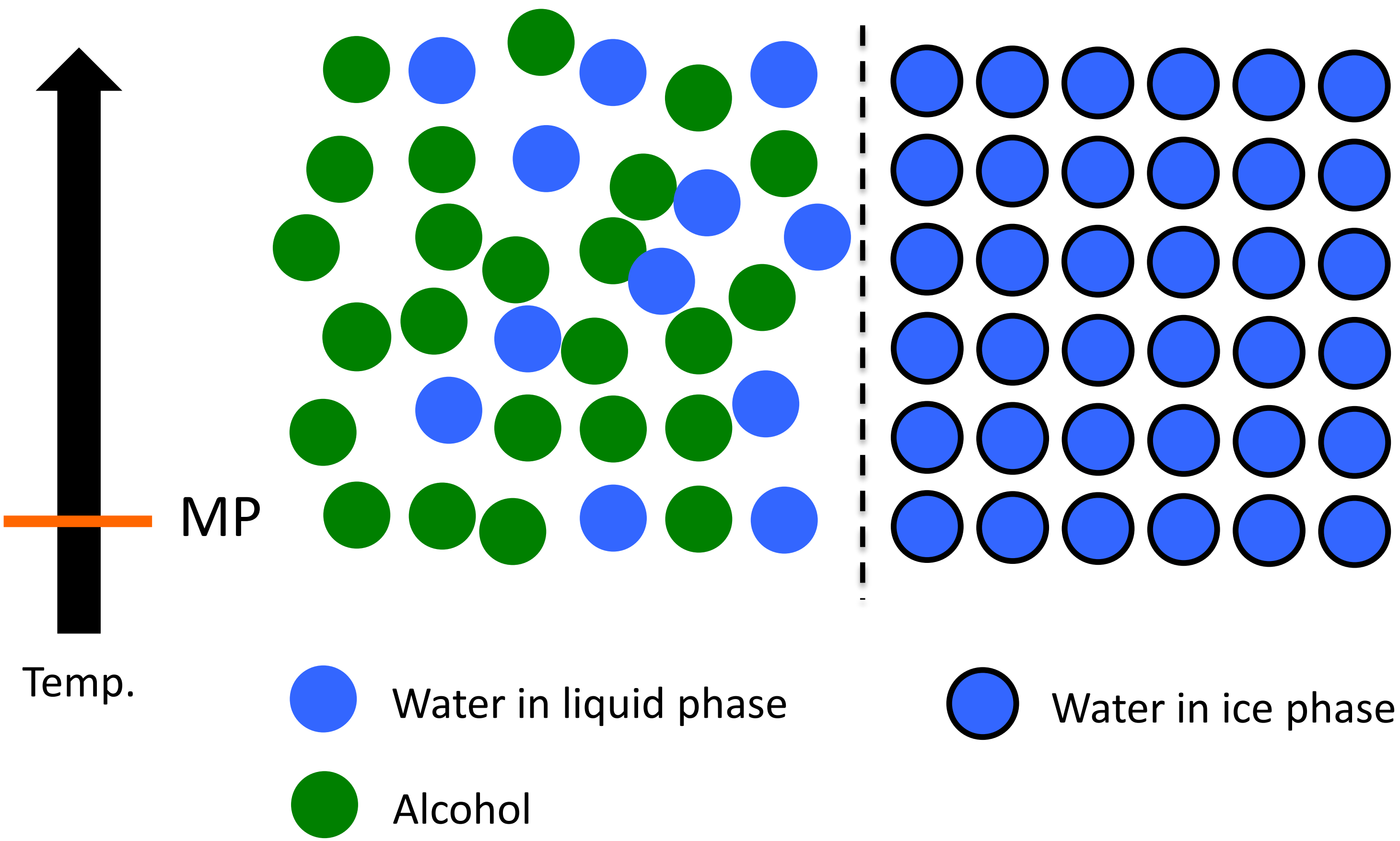
More molecules leave the ice.



Heat is required to melt the ice → fluid is cooled

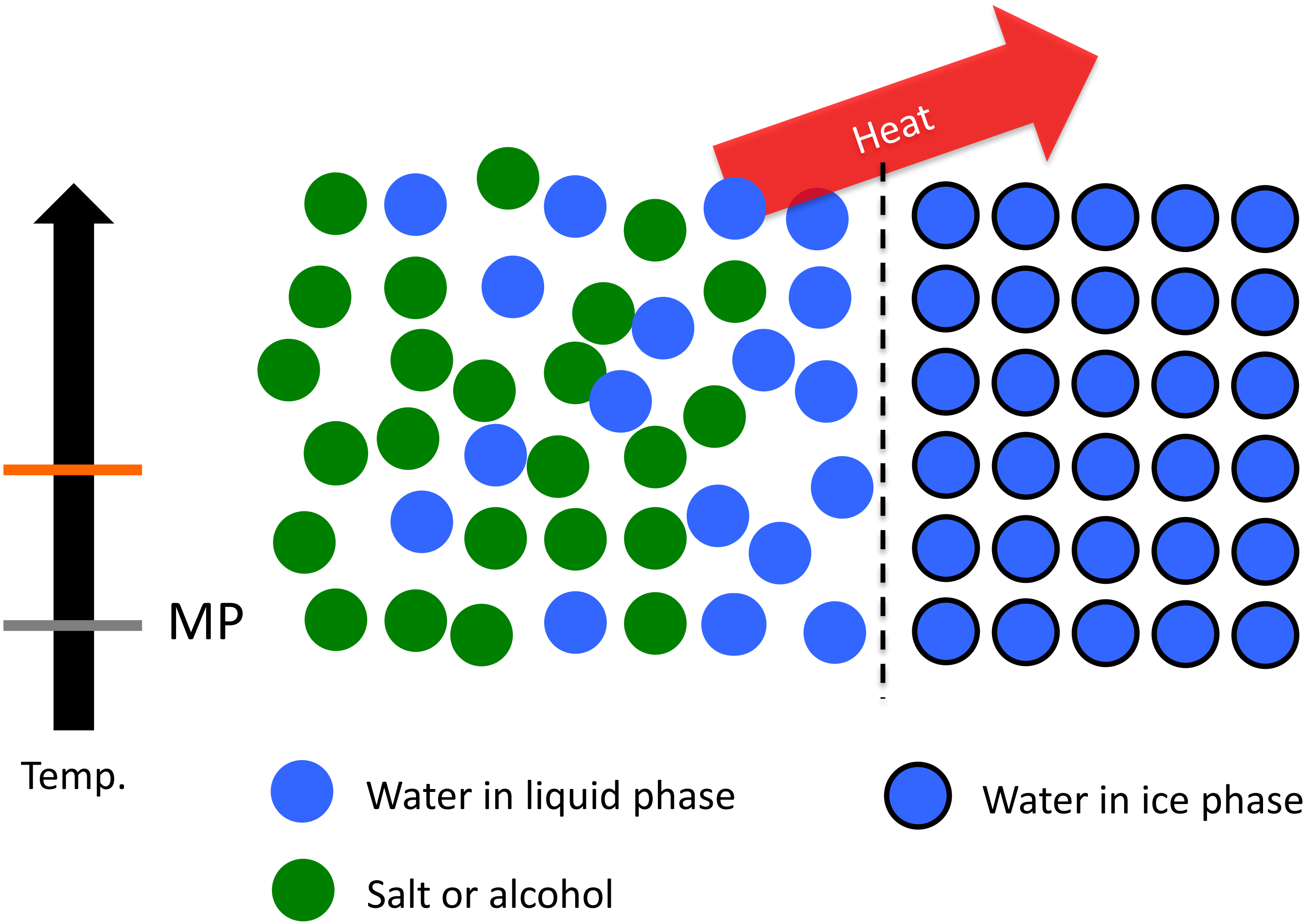
Solutes lower the melting point

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

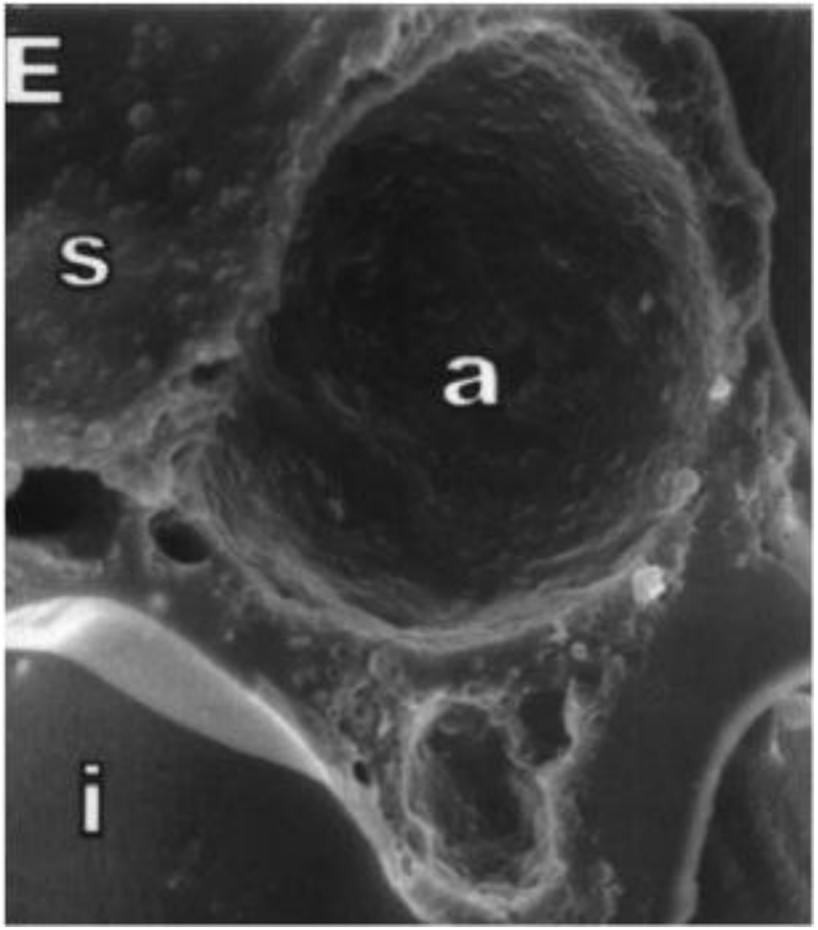
Food and Wine, 2007

Encore:
Ice cream

Foams, emulsions, and crystallization

Microscopic structure of ice cream

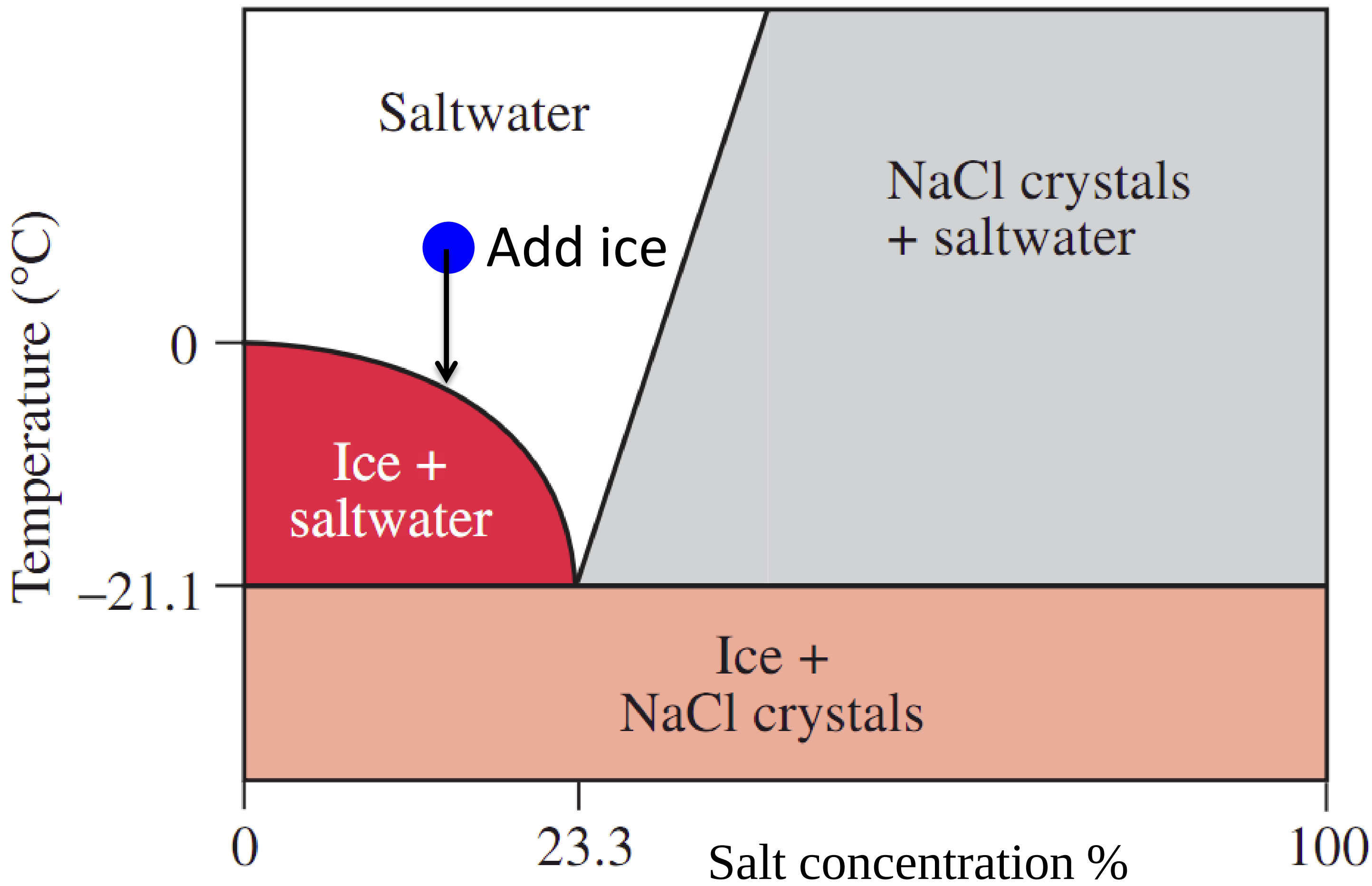
Fat globules are stabilized by proteins



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.



C Clarke, “Physics of Ice Cream” *Physics Educ.* 2003.