Phase transitions and membrane-less organelles in biology

Physics of Life 1

Organelles with and without membrane enclosure

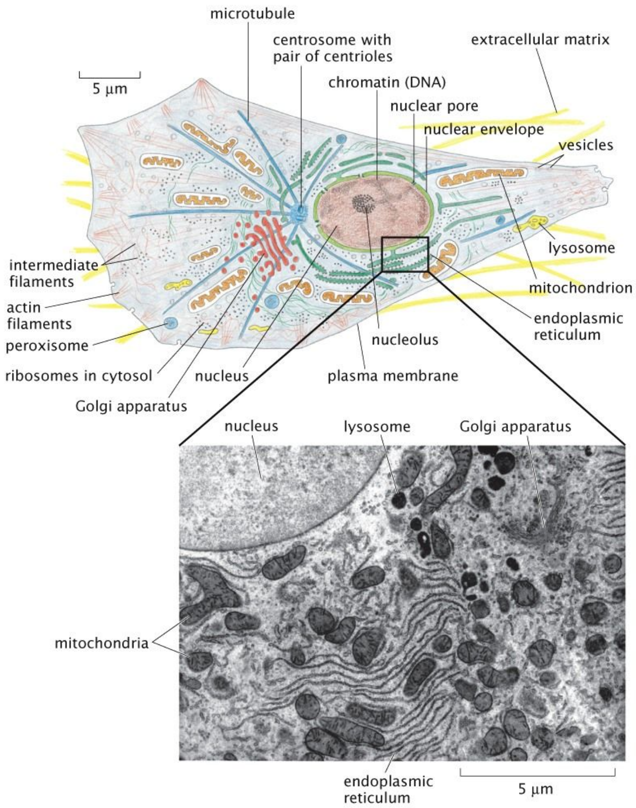
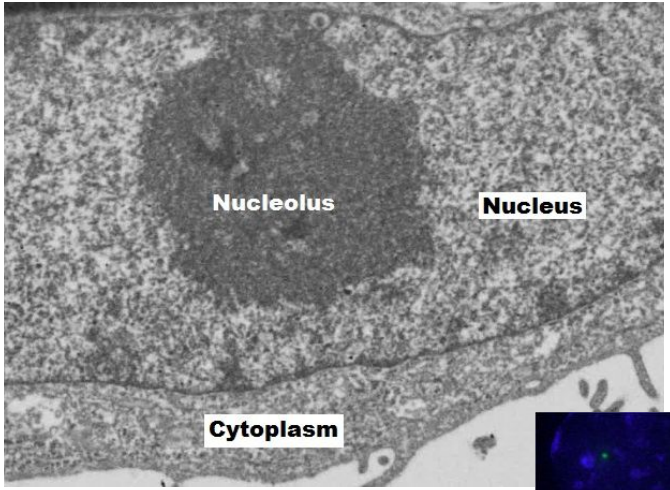
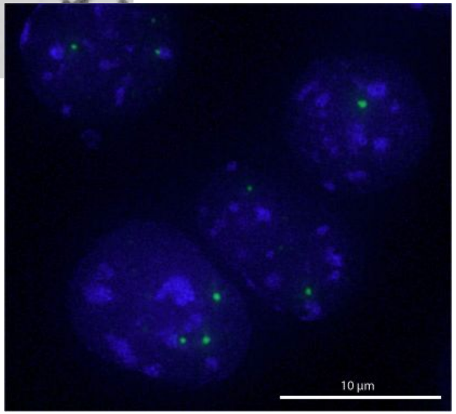


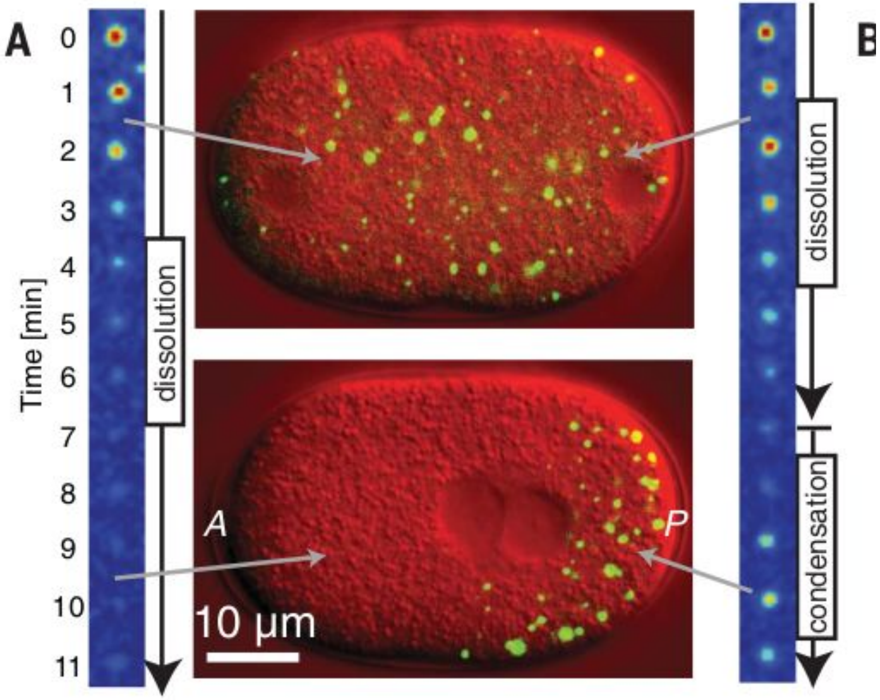
Figure 2.23 Physical Biology of the Cell, 2ed. (© Garland Science 2013)



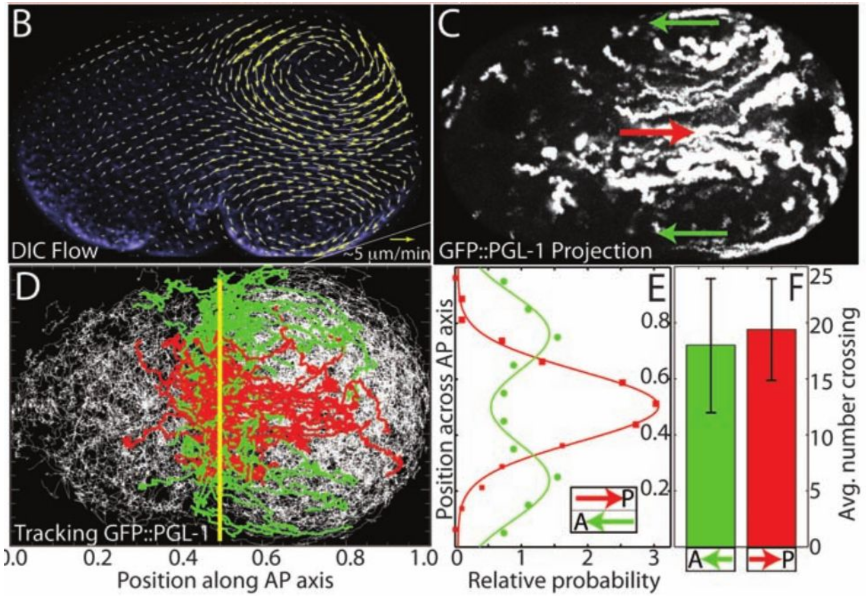


wikipedia.org

P-granules in C. elegans embryos

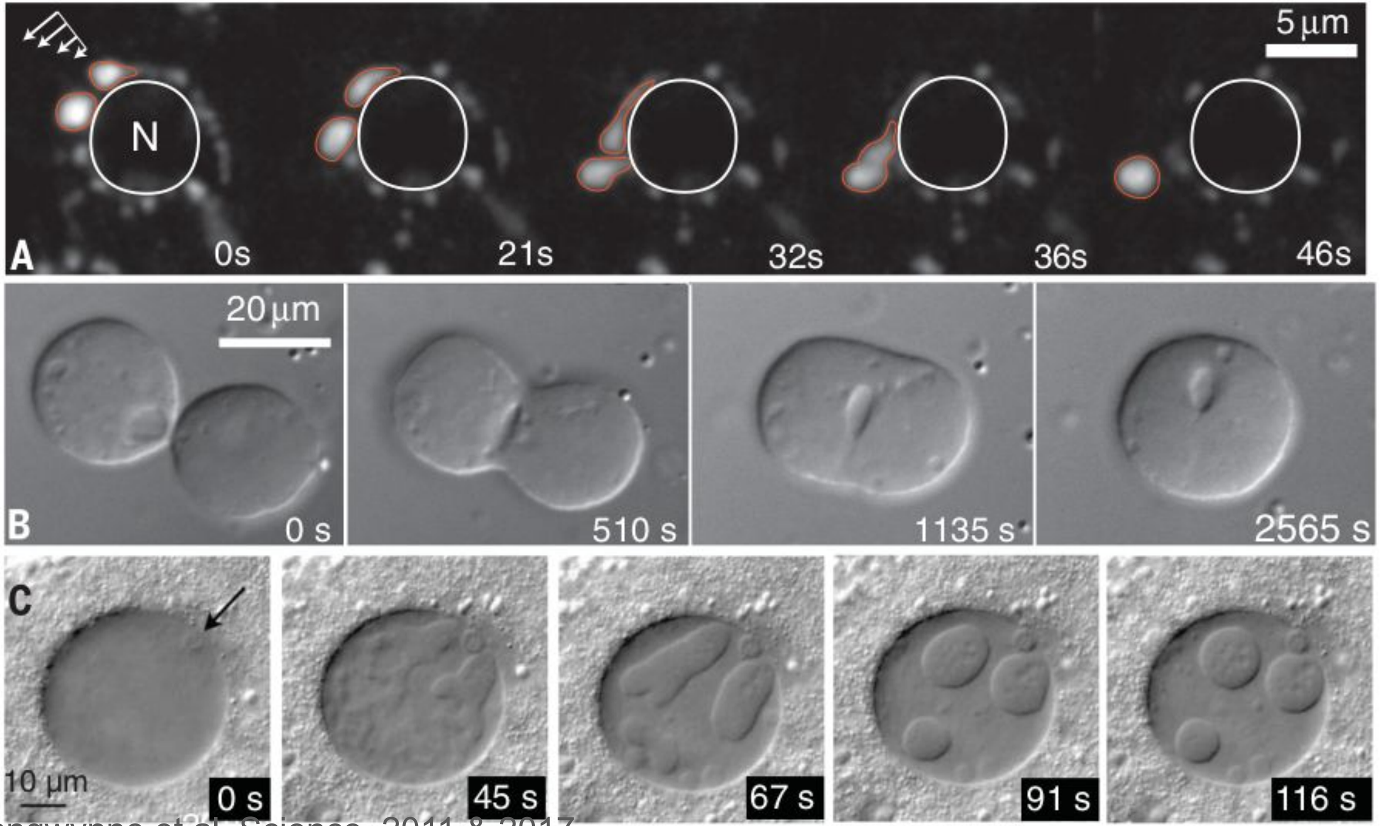


- Puncta that all end-up in the posterior cell (and ultimately the germ cells)
- Puncta disappear and appear
- Puncta move around, but there is no net flux



Brangwynne et al, Science, 2011 & 2017

P-granules have liquid-like properties



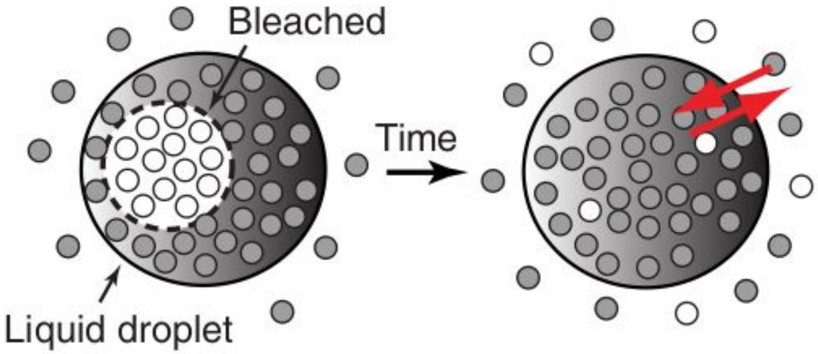
Brangwynne et al, Science, 2011 & 2017

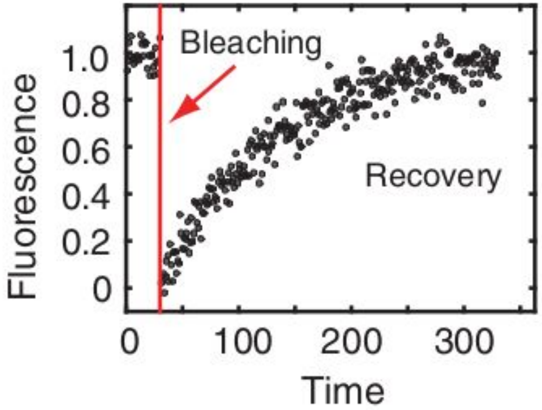
P-granules in C.elegans drip and flow

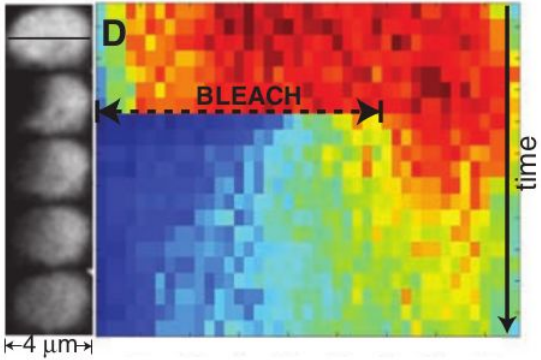
Fusion of nucleoli in Xenopus

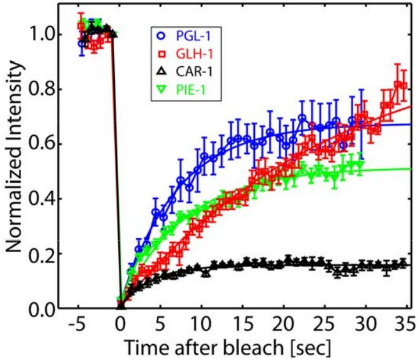
Liquid-like nuclear bodies in drosophila embryos

Diffusion within droplets and between cytosol and droplet









tions were made with GFP::GLH-1 embryos (movie S12). Using the length scale of these large granules, $L \sim 4$ μm, we obtained a diffusion coefficient on the order of $D \sim L^2/\tau \sim 1$ μm^2/s. By making the simplifying assump-

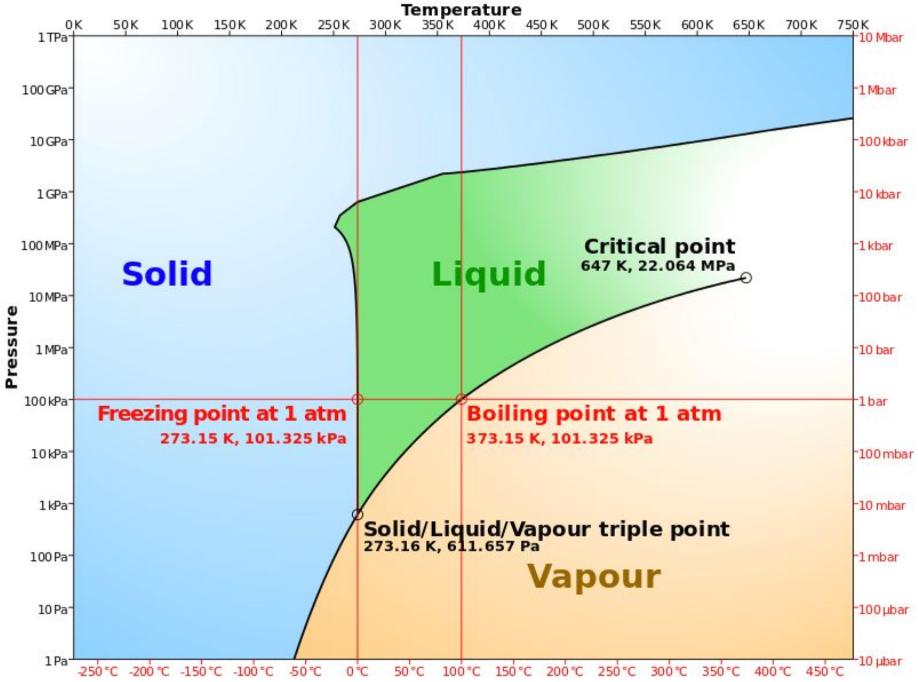
Brangwynne et al, Science, 2011

Hypothesis: These droplets form through phase separation

Background: https://www.youtube.com/watch?v=AP47mIkd-h0

Classical phases of water

- 3 phases (many phases of ice)
- Phase diagram:
  - State of the systems as function intensive variables (T, pressure)
- Different coexistence regimes
  - Single phases
  - Phase boundaries
  - Triple points
- Critical point
  - Point where ‘difference between liquid and gas’ disappears

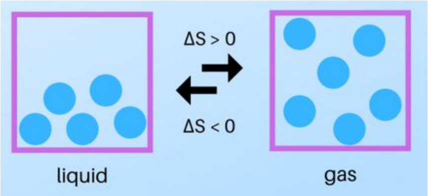


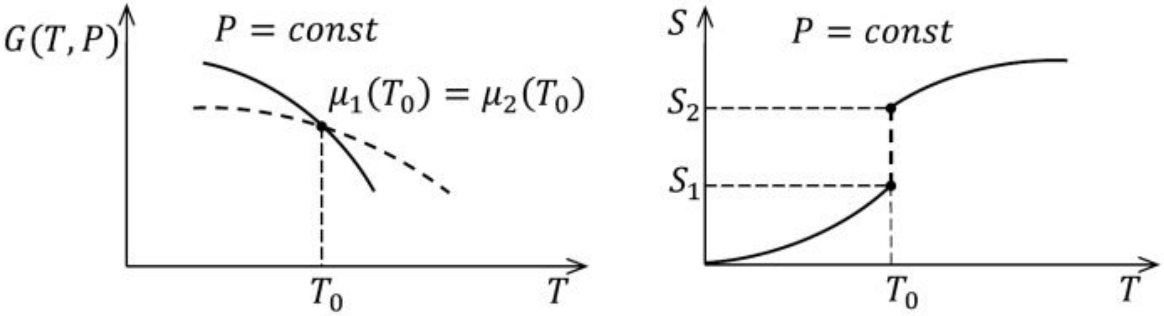
wikipedia

First order phase transitions

- Discontinuous first derivative of thermodynamic potential

  $\frac{\partial G}{\partial T} = -S$ jumps at the boiling point.





Latent heat: $\Delta Q = T(S_2 - S_1)$

From: https://itp.uni-frankfurt.de/~gros/Vorlesungen/TD/6_Phase_transitions.pdf

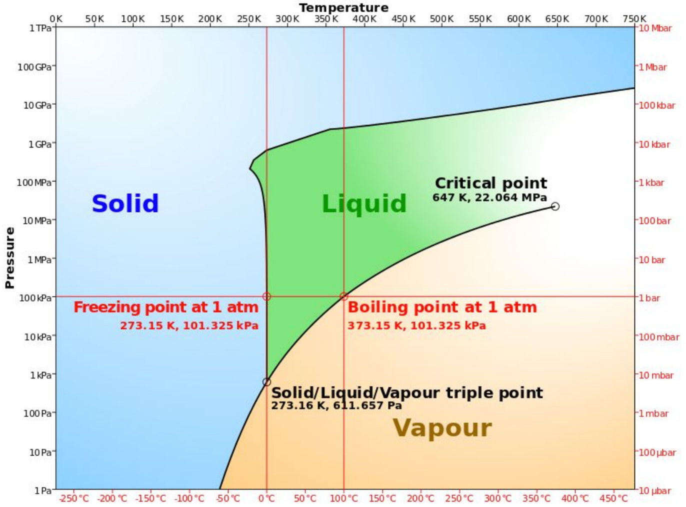
Phase coexistence

- At equilibrium, a multicomponent system minimizes the Gibbs Free energy:

$$G(T,P) = N_1 \frac{G_1}{N} + N_2 \frac{G_2}{N} = N_1 \mu_1(T,P) + N_2 \mu_2(T,P)$$

- If multiple phases co-exist, they share
  - Temperature T
  - Pressure p
  - Chemical potential of each component $\mu = \mu_1 = \mu_2$
    (it chemical potential differed, one phase would disappear)

- Equal chemical potential == constrains
  - Two phase coexistence → line in phase diagram
  - Tree phase coexistence → point



Gibbs' phase rule: the number of coexisting phases

Consider a system with *c* different molecular species and two intensive control parameters (e.g. temperature and pressure).

- If *p* co-exist, all *c* chemical potentials have to be equal in all phages
  → $c(p-1)$ constraints
- In each phase, the concentrations of each component is free to adjust
  → $(c-1)p$ free parameters

In a 2-d phase diagram, the remaining degrees of freedom with *p* phases is:

$f = 2 + (c-1)p - c(p-1) = 2 + c - p$

(in biology, we can have as many phases as we want)

What could drive phase transitions biology cases?

- Changing overall concentration of constituents
- Changing interaction strength (through modifications, changing abundance of ‘sticky molecules’ that mediate interactions)
- These are changes in intensive parameters