Lecture 1 - The Discovery of Cellular Membranes as Lipid Bilayers Embedded with Proteins

Janice L. Robertson

1 Origins of biology require compartmentalization

There are theories about the emergence of life from non-living materials into reproducible, sustainable biological units. One hypothesis is that this began in some extreme chemical environment, such as in deep sea hydrothermal vents. In these mineral rich and energetic regions, reagents are predicted to spontaneously synthesize and metabolize into organic molecules: RNA, DNA, amino acids and ATP. Yet, such an environment seriously limits the reaction efficiency and sustainability. Even if these important molecules were synthesized at low levels, they would eventually diffuse away, reducing concentrations to ineffective amounts. Alternatively, if these reactions were occurring in some sort of closed pocket within the vent structure, then the chemicals would be consumed and the reactions would eventually stop.

How then can the reaction environment change to enable sustainable chemistry over longer periods of time, and long enough for the system to reproduce? The solution that biology has adopted is compartmentalization of the reaction into a semi-closed system. In this way, chemicals are concentrated into a locally defined volume. Furthermore, the reaction can be "fed" by controlling what goes in, replenishing key molecules that have been consumed and removing waste products that build up. A barrier allows for chemical gradients to store information and potential energy, converting cells into batteries that fuel biological work. Important biological molecules - DNA, RNA, proteins and ATP are kept in close proximity, and salt and pH can be defined within optimal working ranges for proper biochemistry. A barrier also allows organisms to live in diverse environments, because the internal conditions can be precisely controlled. So, the benefits for barriers in biology is chemically rationalized, but the mechanism of forming a suitable barrier raises many questions. Do all cells have the same type of bounding mechanism, even for those existing in extreme environments? Is there a unique structure particular to each cell? What governs the particular passage of materials across these boundaries? What permits reproduction of these living compartments? Let's take a look at the journey that the field took in order to answer these questions.

1.1 Early evidence that life exists in compartmentalized units

A cell is the smallest structural and functional unit that supports biological life. In 1665, using a simple light microscope, Robert Hooke examined tissue from a cork tree and observed a collection of compartments he termed "cells". We know now that he was seeing the cell wall, a rigid layer that is dense in cellulose and polysaccharides, and is not the actual bounding structures that encapsulate cells. However, this would be the first observation that compartmentalization is prevalent in biology.

As it turns out, animal cells have boundaries too, but their structures are not resolvable by light microscopy. Shortly after, in 1677, Antonie van Leeuwenhoek reported his microscopic observations of bacteria and microbes. Following up on work of others, he provided detailed reports about imaging of erythrocytes, showing that the compartmentalization occurs in animal cells as well. He noted the important observation that animal cells and microbes did not have the distinct cell wall structures that he observed in plant cells. Later, imaging of mobile organisms like amoebas, revealed further information about the nature of the cellular boundary. Whatever it was that was encapsulating the cytoplasm was also flexible. Whatever the bounding mechanism may be, it must be flexible and ideally self-healing in order to sustain the complex requirements of biology. It was evident that animal cells were bounded by some mechanism, and that the cellular contents were somehow separated from the external solution, but now, the structure that was providing the barrier was not observable.

In 1836, C.H. Schultz used iodine to stain and visualize the erythrocyte plasma membrane. In 1839, Theodor Schwann, in collaboration with M.J. Schleiden, proposed "cell theory", tracing the development of animal tissues from embryonic to adult stages. In observing the division of the intracellular compartments, they deduced that there must exist a cellular "membrane" that limits the cellular volume in some way although the structure itself was invisible.

1.2 Requirements for cellular compartmentalization

Cellular membranes are:

- invisible
- malleable
- healable
- enable selective transport

2 The colloidal hypothesis of cellular segregation

Once cellular compartmentalization could be observed by eye, the prevailing theory was self-assembly by phase separation. In this model, there is no encapsulating structure, but the entirety of the cellular contents are somehow different enough from the extracellular milieu, that it formed condensed units. In 1857, Franz Leydig postulated that in most cells the cellular contents, or protoplasm, are colloidal in nature, acting more like a gel than a fluid. He proposed that the protoplasm self-assembles into a spherical-like shape that contains a central body called a kernel, i.e. the nucleus. In this model, the enclosing structure arises from a hardening of the protoplasm at the liquid interfaces. In hindsight, this may sound complex, but there is chemical precedence for such structures. For example, consider the process of "spherification" that is being used in molecular gastronomy today[1], where a flexible shell comprised of a calcium alginate aggregate forms when a sodium alginate solution is introduced to calcium chloride. Of course, this does not explain the movements and flexibility that were observed in organisms like amoebas, where appendages could be observed to extend and contract. In 1863, Max Schultze proposed a model to consolidate this discrepancy. He suggested that cells contain lumps of contractile protoplasm that are held together because of their inability to mix with the surrounding aqueous solution. This offered some rationalization for the flexibility that was observed in mobile organisms with the colloidal protoplasm model. As we go on, we will find out that the hardened droplet theories for cellular boundaries is not the solution that biology employs. However, it is interesting to consider that phase separated mechanisms are observed in biology in membrane-less organelles, such as P-bodies, stress granules and the nucleolus. Therefore, this is a phenomenon that may play an important role in biology, it just does not explain the behavior of the encapsulating structure for cells and organelles. To identify this, the field had to turn to quantitative biophysical studies.

3 Identifying the bounding mechanism requires physical models

How can one interrogate something that they cannot see? One can do this by interrogating the physical behavior of the system and build models based on that.

3.1 Cells shrink, swell and can burst

In 1748 Jean-Antoine Nollet first documented the observation of osmosis. He took a vial of alcohol that he carefully purged of air, sealed it tightly with a portion of pig's bladder and then submerged the entire vial into water. After 6 hours, he noticed that the pig's bladder was bulging. He then pricked the bladder and liquid from inside the vial shot up

[1] https://en.wikipedia.org/wiki/Spherification

through the air, about 1 foot in height. He had discovered that the water entered the vial, passing through the pig's bladder, by osmosis.

In 1773, William Hewson observed osmotic swelling and shrinking in red blood cell erythrocytes and proposed the existence of structure, analogous to the pig's bladder, must surround the cellular protoplasm. He did not actually use the term membrane, and this conclusion was largely ignored in the scientific community. However, the same type of osmotic study was revisited about 80 years later in plants, with the work of Karl von Nageli in 1855. This was easily observable using a microscope, as the inner boundary could be seen as pulling away from the cell wall. While still qualitative, it approached a quantitative level due to the outer boundary of the cell wall acting as a reference. Sugar and salt were used to control the osmotic conditions and von Nageli found that the process was reversible, as long as the cell did not become ruptured. Also, it was observed that isolated vacuoles from plant cells exhibited the same reversible behavior. One important thing to note, is that in all of the plasmolysis studies conducted during this time, is that the permeability characteristics varied quite a bit. Cells were generally permeable to water, but the rates varied amongst cell types and different organisms.

3.2 The cellular boundary is greasy

Over the course of seven years, from 1895-1902, Charles E. Overton returned to plasmolysis studies comparing over 500 substances used to control the osmotic pressure. Essentially, any compound that was available at the time in his laboratory, was tested. He quantified the results by visual measurements under a microscope, or by measuring changes in cell weight. He found that polar substances induced plasmolysis, while aliphatic alcohols and non-polar substances has little effect. Relating his results back to van 't Hoff's osmotic pressure law, he concluded that there is no cellular barrier for non-polar species. Therefore, whatever is enclosing the cell is by definition, a semi-permeable membrane. It provides no barrier to non-polar species, is somewhat permeable to water, and is generally impermeable to salts and polar species.

At approximately the same time, Hans Horst Meyer in 1899 and Overton in 1901, also tested the effect of non-polar substances that were known to act as general anesthetics in a clinical setting. They both found that the clinical efficacy of these molecules showed a strong correlation to their partitioning into olive oil. Putting all of these results together, Overton concluded that the cell barrier was lipoidal, and likely to be made of known biological lipoidal molecules like phospholipids and cholesterol.

3.3 A digression into the study of thin films

But, how are these lipoidal molecules structured to form a stable, flexible membrane barrier? For this, we must turn to the parallel physical studies of oil and the formation of thin films.

In 1623, Pliny the Elder was observed spilling oil on the sea, claiming that it had the ability to "still the waves". In 1774, Benjamin Franklin repeated this experiment, dropping a teaspoon of olive oil onto Clapham pond and observing it to spread out to the full size of the pond, about a half of an acre. He saw that the oil spread out to a very thin layer and demonstrated prismatic colors. We know that the oil is forming a lipid monolayer at the water air surface, and is one molecule thick. Back when Franklin conducted this experiment, he had all of the information he needed to calculate the molecule thickness of this lipid layer, but did not go as far as to quantify it.

Quantification would have to wait more than a century. In 1890, Lord Rayleigh repeated Benjamin Franklin's experiment, measuring the area to which a given volume of oil would expand. He reduced the experiment to a laboratory scale, 0.8 mg spread out to 5500 cm2, and measured the thickness of the layer to be approximately 1.6 nm. Further developments into the accuracy of the measurement of thin oil films would require the work of Agnes Pockels. She was a 19 year old homemaker, taking care of her elderly and sick parents while her brother, Friedrich Pockels, studied Physics at Gottingen University. She did not have a formal education, as was customary for women at that time, but she did have a passionate interest in science and particularly physics. She did however do much of the housework and this included cleaning the greasy kitchen pots and pans. During this, she regularly observed the thin films of oil and their prismatic colors on the surface of water. Curious about this, she developed a device, made out of her kitchen pans, that would measure the surface tension of the thin oil film. She showed her results to the physicists at Gottingen who showed no interest. Then in 1890, she learned of Lord Rayleigh's similar interest in this research and her brother advised her to write a letter to him. Rayleigh took note of her scientific advancements and helped to communicate Pockels' work [a]. In 1891, she published her first paper and this led to many more impactful discoveries that founded the field of thin layers[b]. With her device, a prototype for the Langmuir trough that is used today, she measured a thickness of the olive oil monolayer as 1.3 nm. When her brother died in 1913, she stopped publishing as she no longer had access to the University and scientific community.

[a] *"I SHALL be obliged if you can find space for the accompanying translation of an interesting letter which I have received from a German lady, who with very homely appliances has arrived at valuable results respecting the behaviour of contaminated water surfaces. The earlier part of Miss Pockels' letter covers nearly the same ground as some of my own recent work, and in the main harmonizes with it. The later sections seem to me very suggestive, raising, if they do not fully answer, many important questions. I hope soon to find opportunity for repeating some of Miss Pockels' experiments."*

[b] Pockels, A. Surface Tension. Nature 43, 437–439 (1891). https://doi.org/10.1038/043437c0.

In 1917, Irving Langmuir publishes on the molecular orientation of oil molecules on water, building a higher resolution "Langmuir trough" to measure surface tension based on Pockels' design. He is credited with bringing precise quantitative analysis of air-water interface studies. He was also one of the first people to understand that lipoidal molecules are asymmetry and have a dual personality – one region being hydrophobic and one region being hydrophilic:"Oleic acid on water forms a film one molecule deep, in which the hydrocarbon chains stand vertically on the water surface with the COOH groups in contact with water." He also, was the first to predict that hydrocarbon chains are flexible, and that a fatty acid with a double bond occupies a larger cross-sectional area and is more compressible than one without. With these realizations, he estimated that the oil layer at the air-water interface was formed by a single-molecule that was 1.3 nm in thickness. He is often recognized as the pioneer of surface chemistry because of this quantification and detail, although this 1917 paper was the only one he published on lipid monolayers.

4 Structural models of cellular membranes

These technical developments for measuring the properties of thin films was essential for the study of cellular encapsulation.

4.1 Purification of cell membranes supports a bilayer arrangement

In 1925, following these improvements in measuring surface tension, Gorter & Grendel carried out an experiment of extracting the membrane fraction from erythrocytes, and then depositing it into a Langmuir trough to measure the surface area[2]. The oil fraction spread out to a layer with a defined area. When considering the number of cells and the surface area of each cell, they then determined that the area on the trough was twice the surface area of the cells. With this, they proposed that the cell membrane was a lipid bilayer. In actuality, this was a serendipitous conclusion. Their paper contained several key errors that cancelled out. Furthermore, these findings appeared to be particular. When others repeated the study under different extraction conditions, they would get different conclusions. It was not a robust study, but it did put forth the idea that the cell membrane was comprised of a lipid bilayer.

4.2 Electrical recordings supports cell membrane thickness in line with a lipid bilayer

Another experiment was conducted at the same time, which quite robust but is often ignored. Also in 1925, Hugo Fricke carried out electrical impedance/resistance measurements

[2]Gorter, E. & Grendel, F. ON BIMOLECULAR LAYERS OF LIPOIDS ON THE CHROMOCYTES OF THE BLOOD. J. Exp. Med. 41, 439–443 (1925).

of erythrocyte suspensions[3]. Assuming that the membrane is made up of oil, as Overton proposed, he used a low dielectric constant of 3, and measured the hydrophobic thickness of the membrane as 3.3 nm thick, a value that stands to this day. However, he did not interpret this as a bilayer in his paper. In hindsight, given Rayleigh's, Pockel's and Langmuir's measurements of 1.3-1.6 nm for the olive oil monolayer, Fricke's data is also supportive a lipid bilayer structure.

4.3 The Davson &Danielli Paucimolecular model

In 1935, Davson and Danelli proposed a model that would consolidate the results from Fricke, Gorter & Grendel into a lipid bilayer, but one that could be potentially thicker due to a lipoid core. At the same time, Danielli & Harvey found that proteins are adsorbed onto the outer surface of egg cells, and that these proteins must protect and stabilize the lipoid molecules that are not stable when in contact with the aqueous solution. This begins to introduce the ideas of permeability in membranes. They proposed the formation of stable pores by these protein layers to allow for differential permeation.

4.4 Robertson's electron microscopy imaging of cell membranes reveals a trilaminar structure and the unit membrane hypothesis

In 1957 J.D. Robertson, an electron microscopist used potassium permanganate (KMnO4) fixation in his preparations of the myelin sheaths of Schwann cells. He observed the consistent appearance of trilaminar units, two dark bands with a light core, at all of the positions where cell membranes and barriers were expected to be. The KMnO4 was expected to have stained the protein layers that bound to the membrane surface, as was described in the Davson & Danielli model, and that these layers were separated by a lighter lipoidal core. Robertson's trilaminar model was similar to the Davson & Danielli model, with the exception that the membrane was formed as a true lipid bilayer.

Robertson observed the trilaminar structure in all preparations of cells, and for all of the organelles - anywhere where there was expected to be a cellular boundary. With this, he hypothesized that the membrane was continuous, in order to consolidate ideas of trafficking between the cellular compartments. While this is not the case, it does highlight the fact that the same membrane structure is shared across all of these regions, and that they are capable of exchanging under the right conditions.

5 Lipid bilayers are fluid

In 1970, Frye & Edidin conjugated mouse and human cells with fluorescein or tetramethylrhodamine labelled antibodies, then fused the cells together. When they examined the cells

[3]Fricke, H. THE ELECTRIC CAPACITY OF SUSPENSIONS WITH SPECIAL REFERENCE TO BLOOD. J Gen Physiology 9, 137–152 (1925).

5 minutes after fusion, they observed separated domains within the membranes. However, after the course of 40 minutes, they found that the entire membrane compartment had mixed completely. This indicated that the cell membrane, as formed by the lipid bilayer structure, exhibited fluid properties.

6 Cellular membranes also have proteins

Over the years, we can see that the concept of the cellular boundary changed from a hardened shell of colloid, to a lipoidal membrane to finally a lipid bilayer structure. Now, the missing part of the puzzle was what accounted for the differential permeability characteristics of cell membranes, and where were the proteins that were known to be associated? At this time, it was deemed unlikely for proteins to exist within the membrane itself because of the presumed instability of the polypeptide chain in a non-water environment. Not only would the protein be unstable, but the act of putting a protein in the membrane was expected to dissolve the membrane. This is why the Davson & Danielli model proposed that the membrane was lined by layers of protein, and that the permeability characteristics defined by extensions of these layers across the membrane.

However, in the 1960s, freeze-fracture electron microscopy would show key evidence that proteins could span the full lipid bilayer. In the first experiments by Moor & Mühlethaler, they found that they could fracture cells along the interface of the lipid bilayer, and imaged each separate leaflet. They noticed that the images showed defects in the membrane that provided positive and negative relief as if they fit together like a puzzle. Thus, they could show that a protein in one leaflet left a depression from where it was in the opposing leaflet, showing that it spans the full membrane.

7 The fluid-mosaic model

In 1972, Singer & Nicholson assembled the fluid mosaic model for cell membranes. In this model, they consolidate the facts from the many different models and propose that the membrane is a lipid bilayer, a thermodynamically stable structure comprised of phospholipids and membrane proteins. The lipid bilayer is a fluid solvent, constrained in 2-dimensions. Proteins are embedded within the membrane and responsible for selective permeability. They clarify that the lipid bilayer is the solvent for membrane protein reactions. The proteins and the membrane are thermodynamically connected, i.e. the reaction is driven by the free energy of the system as a whole. In 1976, Israelachvili and others bring a more complete physical understanding of the membrane in which the lipid bilayer can self-assemble around membrane proteins in a thermodynamic balance.

8 The first structural studies of membrane proteins

The final piece of evidence to solidify these theories were structural studies of membrane embedded proteins that would show directly that these proteins have the same dimensions as the lipid bilayer. The first of these studies relied on the observation that the halophile H. Halobium, which survives in highly concentrated salt solutions e.g., 4.3 M, had large, visible purple patches in its cell membranes. In 1967, Stoeckenius & Rowen isolated these membranes, and in 1970, Osterhelt & Stoekenius identified that these patches were comprised of a 26 kDa molecular weight species that we now know is bacteriorhodopsin, which is a light driven proton pump that obtains its purple color due to the binding of retinal. In 1975, Hendersen and Unwin determined the first membrane protein structure of bacteriorhodopsin by EM diffraction at 7 Å resolution, which clearly showed the alpha-helices that correspond to the dimension of thickness of the lipid bilayer. It was this discovery that led to the general acceptance of membrane embedded proteins within membranes.

It would take another 10 years before the first high-resolution structure of a membrane protein was determined, this time by x-ray crystallography. In 1985, Deisenhofer, Huber, Michel and others solved the structure of the photosynthetic reaction centre of Rhodopseudomonas viridis at 3 Å resolution. The critical step to the success of this experiment was the ability to solubilize membrane proteins stably with detergent. While this advancement now enabled structural studies of membrane proteins to take place, it must be stressed that this remains a serious challenge in the field, which can be seen by the limited numbers of membrane protein structures in the protein data bank compared to soluble proteins. Still, the experiments are possible and with recent advances in cryo-EM imaging, have become even more accessible within the field.

9 Summary

Our understanding of cellular boundaries have gone from hardened shells to self-assembled oily lipid bilayer membranes. We are now at a point where we are starting to understand this substructure and the physics associated with it. The lipid bilayer is a unified mechanism of bounding biological systems. It turns out nature goes for the robust common solution instead of one that is particular to each organism. This seems to be a common theme in biology. Throughout these lectures, we will learn more about the complex environment of the lipid bilayer membrane and the membrane proteins that are embedded within.