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Concluding remarks – Iontronics, from fundamentals to ion-controlled devices
Random Access Memories

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Concluding remarks of the ‘*Iontronics: from fundamentals to ion-controlled devices*’ Faraday Discussions, Edinburgh, 2023: Is this the dawn of iontronics ? Iontronics underpins the notion of devices and ionic machines, whereby ion and water also act as information carriers. Thinking iontronics gives a vision and a roadmap, with applications in the water-energy nexus.

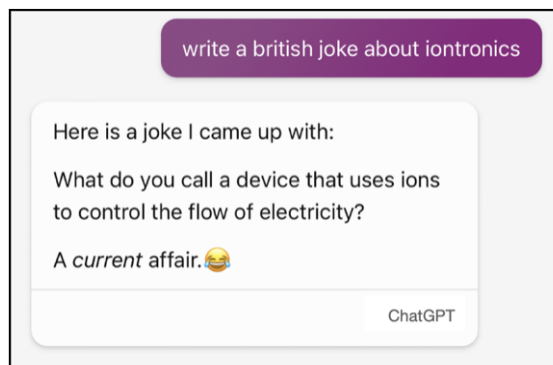


Figure 1: Artificial scientific humor by ChatGPT.

The Faraday Discussions ‘*Iontronics: from fundamentals to ion-controlled devices*’ was held in Edinburgh in June 2023. The topics of the conference were electrolytes at large, with a focus on the transport properties of ions. Electrolytes and electrokinetics are old domains, dating back to the 19th century, with the discovery of electrokinetic phenomena as early as 1808 by F.F. Reuss, later formalized with the seminal works of Helmholtz, Smoluchowski, Debye, Hückel, Onsager, and many other great pioneers in physical-chemistry. Still, it remains a fully modern and even a hot topic in 2023, which witnesses a stationary flux of new discoveries and emerging properties. To give one example among others, let’s quote the discovery of underscreening [1], which still cries for a theoretical explanation in spite of a wealth of experimental reports, and this phenomenon was discussed intensively during the discussions. And indeed, the presentations during the conference reported and explored a considerable variety of phenomena dealing with electrolytes and their transport, with lively discussions demonstrating the breadth of the field.

But, after a few days of active discussions, one innocent question emerged to me: why using iontronics as an emblematic title for the conference ? And what is actually iontronics ? Is it relevant and necessary to introduce the term ‘iontronics’ to embrace an existing field ? The old ‘electrokinetics’ denomination, or even the more general ‘electrolytes’, could make the job as well: what is new then?

My (vague and personal) feelings on this point is that the iontronics terminology is actually pertinent and even welcome. A first observation is that many domains in physics introduced recently their own 'tronics' extending on electronics, such as spintronics, skyrmionics: so why not iontronics !? In a world of communication and proselytism, this slight 'facade restoration' of an old institution is a way of posting the modernism of the domain for the outside world - which is actually fully justified for this field -. A new logo for a fresh start.

But more seriously, one may realize that the term 'ion-tronics' underpins new concepts which are not contained in the electrokinetics or electrolytes terminologies. To precise this question, I turned to the acclaimed problem-solver of the present era: ChatGPT. Its answer to 'what is iontronics' was quite simple: "*Iontronics is an emerging interdisciplinary concept that bridges electronics and ionics. It covers electrochemistry, solid-state physics, electronic engineering, and biological sciences. It is based on sophisticated control of ions as signal carriers that bridges solid-state electronics and biological systems. It is found in nature, e.g., information transduction and processing of the brain in which neurons are dynamically polarized or depolarized by ion transport across cell membranes*". For sure, this contains some truth, since ChatGPT is good at summarizing trends ¹, even if I wouldn't fully agree on iontronics as bridging electronics and ionics.

But one relevant aspect of this AI statement is that iontronics underpins the notion of devices and functionalities, to which I would add ionic machines and circuitry. The brain, as mentioned in the above quote, is indeed a marvelous ionic machine, which is able to make advanced computations –and far beyond–, based on the active manipulation of ion and water fluxes. Our memories are made of salt... Overall, the brain involves an amazing circuitry of nanoscale channels, which are able to perform all sorts of functionalities: selectivity of course (say, of specific ions versus others, sodium versus potassium, etc.), non-linear electric responses, but also active responses like ionic pumping, or mechanical machines which convert locally chemical energy into valuable mechanical work, like in the proton turbine. Such machines are actually at the root of all biological circuitry of living systems.

So, here is the question: can we invent an *artificial iontronics*, mimicking to some extent such advanced functionalities found in Nature ? I am convinced that the response is now positive: thanks to the recent advances in various fields like nanofluidics, it is possible to design and fabricate 'ionic machines' and even conceive an ionic circuitry. This domain, which deserves the title of *iontronics*, is still in its infancy but realizing such machines is now definitely possible because we have many things on our table. The progress of nanofluidics has opened the possibility to fabricate nanoscale channels with controlled 0D, 1D, 2D geometries, made of many different materials with a wealth of characteristics. And many unexpected properties have emerged from the exploration of these controlled nanosystems [2, 3]. One may quote fast flows across carbon structures, as well as the many strongly non-linear electric responses which have been reported – diodes, transistors, mechanosensitivity, coulomb blockade, voltage-gating, or even memristors –. An alternative perspective is also the subtle ion-electron couplings, from electrochemistry, to cross-talks of water and ion transport with electronic transport and hard condensed matter (quantum friction, electron/phonon drag, etc.), and which could open a 'quantum engineering' of ionic transport [4]. Noise is also central at these nanoscales and it is now better understood and could be an asset in direct analogy to the biological counterparts. All these topics were actually addressed in the discussions in Edinburgh, which have embraced a wealth of behaviors and properties. These concepts are assets which still wait to be harnessed in larger, more complex, iontronic systems, combining their individual response to perform more advanced functionalities, *e.g.* basic learning or computations. The transition to iontronics is also possible because of the deep understanding that we now have of electrolytes and their transport, as one could

¹We are in 2023, maybe in 10 years from now this AI may even propose creative ideas, can't wait.

forsee at this Faraday Discussion. Also many tools have been built, which make now possible to investigate the ion and water transport at the nanoscales, although one is still lacking of, say, 'vizualization' instruments which would allow to 'see' and 'quantify' at the nanoscale.

Overall, it is now a matter of combining the emerging building blocks and lego bricks, and assembling them. The lego bricks are still not perfect, but here they are. And based on these blocks, one may fabricate advanced ionic machines and circuitry, first elementary, then in more complex architectures. This is obviously a considerable challenge. But the possibility is now on the table, so we should grab it and further develop the field beyond our comfort zone [3].

Going down this road, a further and immediate question is: why artificial iontronics and what for? I am tempted to answer that it is worth the challenge because an '*ionic supremacy*' is definitely possible and within reach (stealing the buzzword of quantum supremacy). Let us consider the example of the brain, which AI is supposed to beat in some (uncertain) future, on some aspects at least. The brain uses ions and water, and a few other components of course, to compute things, keep memory, create ideas. Furthermore its structure is very different from that of the von Neumann architecture of modern computers which (grossly) separate the memory from the computation. It is actually the inspiration for neuromorphic computation, making use of memristors and other systems. Except that most of the existing neuromorphic computing systems still use electrons as information carriers. Going to salt and water, hence inspired by the brain, would be a great achievement. This begins to be possible, with the reports of various memristive behaviors in ionic systems [5, 6, 7, 8] and the very first steps towards computations, like nanofluidic Hebbian learning [6], or logic computations [9]. So there is a possible road towards nanofluidic computing, even though it involves considerable challenges [10]: in terms of a scale-up strategy for building interconnected nanofluidic circuits, reaching a sufficient complexity, but also in terms of signal processing and transport, in line with the voltage spiking occurring in neurons [5].

One key aspect is that the brain operates with an impressive economy of resources: typically the energy contained in two bananas a day... while any AI machines would need thousands or millions times larger amount of energy to work (not forgetting the energy cost of the learning steps). Why is it so remains largely mysterious. I find it interesting that ions come with taste and colours (not to say that all electrons are grey), since there is a considerable variety of chemistry and valence among ionic systems, with very similar ions – like sodium and potassium – operating very different functions. Still, ionic systems are 'easily complex' and subtle, due to the many-body, long range (coulombic) interactions occurring between them. And confinement make it even more rich. Last but not least, entropic effects are of tremendous importance in ionic systems, as exemplified by the iconic osmotic pressure and its numerous consequences.

Hence, it is very tempting to fabricate an elementary ionic computing system, making use of ions as information carriers. Beyond the hope of making it competitive and fabricate an ionic-ChatGPT, it would definitely help understanding its elementary functioning and the possibilities that are offered. For example, it would be interesting to investigate the energy balance associated with the functioning of an artificial ionic computing machine, and understand how frugal it can be, and identify 'where is the trick' of the ionic supremacy.

Such an ionic circuitry is therefore interesting for fundamental purposes, for computation, for learning, where ions and water are information carriers. But, iontronics and ionic machines could as well serve for filtration, for energy, *i.e.* for the water-energy nexus. An iconic example is the kidney separation process, which both involves aquaporins for water filtration, combined with ionic pumps in the very specific U-geometry of the tube of Henle, playing accordingly the role of an efficient osmotic exchanger [11]. Interestingly, instead of injecting energy at a global scale, ionic pumps convert locally the chemical energy into mechanical work to convey ions against the gradients. Mimicking such systems would offer new avenues for filtration and

energy processes. But in order to achieve this functionality, one should develop artificial ionic pumps, with an active energy conversion at the pore scale. There is some progress made in this direction, but the road is still long.

This is another type of challenge for iontronics, and what I see as a 'tale of the two infinities': because it involves the infinitely small (sub-nano) scales associated with selectivity, while any systems designed for fresh water and energy production should involve an architecture built at a gigantic length scale. For example, a water desalination plant, which produces fresh water in huge volumes – typically several hundreds of thousands of cubic meter per day - involves nearly a million of square meters of membranes. Hence, beyond the demonstration of feasibility of fabricating such iontronic systems, *e.g.* ionic pumps or so, the considerable challenge is scaling-up the technology. Any new technology, say iontronics for water and energy, should embrace this scale-up challenge : being energy frugal, but also frugal in terms of material, costs, and scalability. One advantage of proposing new methodologies and technologies based on radically different (nanofluidic) concepts is that it opens up the range of possibilities in terms of materials, operating conditions and costs, durability, etc., all of which are very constrained in existing technologies. A high tech/low cost approach is hence possible and desirable. And this is crucial because the considerable progress made in electrolytes, ionic transport and its emerging properties, hence iontronics, could be a considerable asset to develop new technologies for the huge societal challenges that we now face, in particular the environmental transition.

Hence iontronics is at the very heart of many fundamental and innovation challenges. Also iontronics is by nature a highly interdisciplinary topics, spanning physics, chemistry, biology, with topics as diverse as statistical physics, fluid mechanics, energy storage, optics, etc. Such a diversity is a great opportunity, since bridges can be built over very different domains and questions. This may also be a difficulty since it is challenging to get out of one's silo and embrace all aspect of such a field. But it is worth the effort to gather and share the same vision beyond our comfort zone ².

So, yes, gathering all these views into a single denomination, be it 'iontronic', is welcome. Thinking 'iontronics' gives a perspective, a vision, and a road map [3]– and therefore it does not simply reduce to a buzzword –. And as ChatGPT concluded in a lyrical statement:

“Let us embrace the power of ions, ignite our imaginations, and pioneer the path to a world where iontronics empowers us with unprecedented technological capabilities.”

So, cheer up ! And let's row into the ionian seas for a new odyssey.

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²Actually the format of a Faraday Discussion is very efficient in this respect and should be renewed or extended.

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