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Perspectives and challenges

Double-diffusion is a fun science. It is filled with unresolved dynamical problems and spiced up with controversial ideas. It challenges the imagination with counter-intuitive phenomena; it operates on vastly different scales and connects dissimilar disciplines. If this book conveys at least some of the beauty and depth of the subject, I am happy – the time invested in writing it was well spent.

As with any other extensive review, our discussion of the current state of double-diffusion inevitably leads to questions and speculations regarding its prospects. It was great for the last fifty years, how about the next fifty? Let us first state the obvious: the future of this field is secure. Interest in double-diffusion is on the rise, as reflected by the exponentially increasing frequency of publications, and there are no reasons to expect a slow-down. Many signs point towards much more rapid growth in years to come. Just by looking at the current playing field in fluid dynamics, one gets a sense of an impending change. Several classical disciplines are already beyond their prime; their central, most fundamental problems have been either resolved or abandoned, giving way to less exciting incremental developments. In this sense, double-diffusion is in excellent shape; we don't really understand a whole lot. The fall-out from aging sciences can only further invigorate double-diffusive research. The exploration of multicomponent phenomena is also the most natural evolutionary path for many established subjects (convective turbulence being the prime example), which is another reason to expect fluid dynamics to become progressively more double-diffusive. Regarding its real-world motivation, double-diffusion is involved in such a broad spectrum of applications that it is hard to imagine a more stable portfolio. In summary, we predict, as confidently as one can without a clairvoyant's crystal ball, that our field will continue to advance and its best days are yet to come. Perhaps it is more interesting and productive to consider whether some actions should be taken to accelerate double-diffusive research even more. Are there some artificial barriers that could be removed, applications emphasized or promising strategies explored? A serious conversation about the direction of double-diffusive research can benefit all parties involved and is long overdue. No firm prescriptions are given here, but as a starting point for the discussion I would like to offer a few observations and personal remarks.

13.1 Perceptions

Curious as it may be, double-diffusion does not exist in isolation. It is rooted in the traditionally defined sciences: oceanography, materials science and astrophysics, just to name a few. The strong connection with paternal disciplines is vital for its expansion and there is some room for improvement in this area. An important step involves raising the level of understanding and awareness of double-diffusion among non-experts. Most researchers in physical and environmental fields are familiar with the concept of double-diffusion, but important caveats tend to escape attention. Half-knowledge creates fertile ground for misconceptions that often distort the perception of our field. To illustrate the need for better communication with the outside world, let us review some evidently false notions that still occasionally surface in discussions with non-double-diffusers:

(i) *Double-diffusion is an esoteric science*. Any conceivable metric shows that double-diffusion has long graduated from oceanographic curiosity to a broad and vibrant field. For instance, the number of publications listing "salt finger" as a keyword exceeds that for "thermocline" or "meridional overturning circulation" – a couple of the most popular topics in oceanography. The significant and demonstrable impact of double-diffusion on climate and the biological productivity of the oceans is a reason in itself to invest more effort in its analysis. Double-diffusion is spread between several disciplines, which makes it difficult to fully grasp its overall importance, particularly for researchers reluctant to cross interdisciplinary boundaries. However, it should be realized that the cumulative influence of double-diffusion greatly exceeds its contribution to each subject. All the information required to dispel the "esoteric" myth is readily available; it only remains to make it widely known.

(ii) *Double-diffusion is similar to other mixing processes in the ocean*. Double-diffusion is unique in many ways. Unlike mechanically generated turbulence, it is highly interactive: double-diffusive fluxes are sensitive to the background stratification and the fluxes, in turn, affect stratification. The resulting feedback mechanisms trigger a series of secondary finescale instabilities (intrusions, collective and layering modes), which impart life and spontaneity into the ocean. Another essential double-diffusive characteristic is the counter-gradient density flux: double-diffusion makes light water lighter and dense water denser.

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Its ability to "unmix" density leads to sharpening, rather than diffusing, of vertical gradients. In the absence of double-diffusion, density patterns in the ocean would be as smooth, predictable and hopelessly boring as a bald man's scalp. Combining double-diffusion with turbulence under the general heading of small-scale mixing trivializes and masks very unusual dynamics and can ultimately lead to significant conceptual misinterpretations.

(iii) *Double-diffusion is a small-scale phenomenon*. Diffusive layers spread across the Beaufort Gyre, remaining laterally coherent from coast to coast and maintaining their identity for years. Thermohaline intrusions can reach vertical scales of hundreds of meters and laterally mix water masses over hundreds of kilometers. The fingering staircase in the Tyrrhenian Sea splits the water column into homogeneous layers half a kilometer thick. The ability of double-diffusion to directly affect such an enormous range of scales – from the salt dissipation scale ($\sim 10^{-3}$ m) to the basin size ($\sim 10^{6}$ m) – may be unmatched by any other physical phenomenon.

For many double-diffusers, concerns of this nature appear so unreasonable that no attempt is made to address them – well, isn't it obvious? However, in order for our field to completely break the shell of isolation, basic facts about double-diffusion have to be patiently and pervasively conveyed to as wide an audience as possible. The payoff for publicizing double-diffusion could be substantial: new workers, fresh ideas and productive interactions. Double-diffusion is addictive and the newly initiated tend to become loyal and active contributors to the subject.

13.2 Barriers

In addition to the challenges of addressing the general scientific audience, double-diffusers also have to cope with internal communication barriers, many of which are caused by the multidisciplinary nature of our field. While key questions and goals in various applications are similar, very often practitioners are unaware of parallel developments in other disciplines. As a result, the transfer of ideas and methods can be random and slow. The problem is exacerbated by the highly specialized structure of education in the natural sciences. Graduate programs are fine-grained; we produce molecular biophysicists, physical oceanographers and extractive metallurgists. An alternative approach (the Eastern European model) would be to offer broadly defined graduate degrees in "physical sciences", which assume some common background in math and the ability to speak the same scientific language. Of course, specialization has its advantages and I am sure that many subjects have benefitted immensely from narrowly focused education. However double-diffusion, I

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am afraid, may have gotten a raw deal in this system. For instance, oceanography still remains the largest consumer and motivator of double-diffusive research. Yet, oceanographic education lacks several components that help in the pursuit of such quintessentially physical subjects as double-diffusion. Exposure to classical fluid mechanics and analytical techniques is limited. Courses in nonlinear instability – the heart and soul of double-diffusion – are notably absent in most oceanographic curricula. To alleviate the problems caused by excessive specialization, an argument could be made for (i) embracing flexibility in the type of research expected from faculty members in applied departments, (ii) stronger support of interdisciplinary activities, and (iii) placing more emphasis on fundamentals in graduate coursework.

Of course, interdisciplinary barriers are natural and, to some extent, inevitable: we read different journals, attend different conferences and may not be personally familiar with colleagues in other departments. However, disconnect can be detected even within the boundaries of the same discipline. In most fields, double-diffusion is actively studied by theoreticians, observationalists, experimentalists and modelers. There is yet another, and much larger, group of researchers whose primary focus is not on double-diffusion per se but on various phenomena that could be affected by it. The urgent request from this group is the accurate parameterization of double-diffusion in the simplest user-friendly format. Such pragmatic interests should also be known and taken into account when developing double-diffusive products. Unfortunately, the exchange of information between all these types of researchers is not as fluid and swift as it could be. Needless to say, the intra-disciplinary barriers are counterproductive and preventable.

It is perhaps most fitting to mention at this point that a precedent for an open and unifying approach to double-diffusive research was set by the founder of the field, Melvin Stern. Being a hard-core theoretician by trade, throughout his career he maintained keen interest in all aspects of double-diffusion. For him, new observational, experimental and modeling developments were a constant source of theoretical ideas and deeper insight into double-diffusion. In an interview for the Florida State University newsletter, Melvin recalled his participation in early laboratory fingering experiments:

> An experiment and collaboration with Turner led to the happiest professional day of my career. The day we did an experiment on salt-finger convection . . . we had been using mixes of heat and salt, but heat diffuses into the atmosphere too readily, so we had the idea of replacing heat with sugar. We were not sure it would work because salt and sugar have such a slight difference of molecular diffusivity that, we did not think anything would happen. But, there it was on the first try! It was an eye opener – the effect was large and very beautiful. That experiment aided my professional development in particular because I began to think in a different way.

What a truly scientific attitude, uncompromisingly objective and inclusive. This all-embracing mindset has to be emulated by the community in order to finish what Melvin started and finally unravel the salt-finger dynamics.

I end this monograph with a plea for collaboration. For an astrophysicist, the task of understanding a double-diffusive study in the oceanographic context may seem daunting at first, but a second look usually reveals that the differences in the way we approach the problem are rather superficial. It is not unfeasible to monitor key developments in double-diffusive research across several subjects and this experience can be most instructive and stimulating. The opportunities for collaboration are ample and should be pursued without hesitation. And there is really no excuse for the lack of interaction between experimentalists, modelers and theorists in the same discipline. The time has come for all of us to get our hands dirty and take care of these fingers.