Preface

Reasoning by analogies is a natural inclination of the human brain that operates by associating new and unknown situations to a series of known and previously encountered situations. On the basis of these analogies, judgements and decisions are made: associations are the building blocks for predictive thought. It is therefore natural that analogue models are also a constant presence in the world of physics and an invaluable instrument in the progress of our knowledge of the world that surrounds us. It would be impossible to give a comprehensive list of these analogue models but a few recent and relevant examples are optical waveguide analogues of the relativistic Dirac equation (linking optics with quantum mechanics), photonic crystals (linking optical wave propagation in periodic lattices with electron propagation in metals) or, at a more profound level, the Anti-de Sitter/Conformal Field Theory correspondence (linking quantum systems in D dimensions to gravitational systems in $D+1$ dimensions). The purpose of this book is to give a general overview and introduction to the world of analogue gravity: the simulation or recreation of certain phenomena that are usually attributed to the effects of gravity but that can be shown to naturally emerge in a variety of systems ranging from flowing liquids to nonlinear optics.

Questions often arises regarding the implications of analogue models, particularly in the context of analogue gravity. So this appears to possibly be a good starting point for a Preface. The analogue models treated here can all be reconnected to some form of flowing medium. This flowing medium, under appropriate conditions is expected to reproduce or mimic the flow of space generated by a gravitational field. However, it is important to bear in mind that analogue models are always “analogies” and never, or hardly ever, “identities”, meaning that we should not confuse the two systems under comparison. In the specific case of analogue gravity, the analogies do not usually attempt to reproduce the *dynamics* of a gravitational system, for example a black hole. The dynamics rely on Einstein’s equations and require the presence of a gravitational source term. On the other hand, the analogies can reproduce to a large extent the *kinematics* of a black hole. The kinematics refer for example to photon or particle trajectories and these are determined by the system’s spacetime metric. Whether the curved spacetime metric is the result of a gravitational field or of a flowing medium becomes irrelevant when the analysis is restricted to the description of wave propagation and evolution in this flowing medium: the kinematics are identical and the analogy is robust. The absence of a link between the dynamics of the analogue and gravitational systems may seem to be an inherent and even disappointing weakness of the ideas presented here. Questions often arise regarding the usefulness of analogue models for gravity if we cannot produce predictions regarding the evolution of, for example, binary black hole systems, the quantum or the purely geometrical nature of gravity or whatever may be the hot topic at the moment you are reading this book. These objections are certainly valid: unless things take an unexpected twist in the future, it seems rather unlikely that analogue gravity will provide us with answers to these questions. This is mainly because analogue gravity simply does not address these problems. Re-iterating once more, analogue gravity builds upon our knowledge in general relativity and condensed matter physics in order to build a deeper understanding of certain physical effects that rely solely on the kinematics of the two systems. This declaration contains within it a series of fundamental and outstanding problems in modern physics that fully justify the interest in the field. Moreover, the search for a deeper understanding of the laws that govern the universe is only one aspect of analogue gravity. We hope that in reading this book, you will appreciate how the strive to develop and understand both old and new analogue models is leading to innovation, technical advancement and new discoveries in a remarkable range of physical systems ranging from acoustics and gravity waves to optics, all linked by the common denominator that lies within the geometrical description of spacetime, as first introduced in the context of gravity.

So what are these “kinematical” effects addressed by analogue gravity? The most important and obvious member of this list is without doubt Hawking radiation. Hawking radiation is the spontaneous emission of blackbody radiation due to the distortion of the quantum vacuum in the vicinity of a black hole event horizon. This effect was first described in detail by Stephen Hawking in 1974 although the first hints that black holes should have non-zero equilibrium temperatures came from Bekenstein, a year earlier based on the analogy between the laws of thermodynamics and those of black hole mechanics (yet another fruitful analogy!). Hawking radiation has since attracted the imagination and efforts of countless scientists, all looking for a deeper understanding of why this radiation is emitted, how it is emitted and the implications of this emission with big questions concerning information loss and even the final fate of our universe. A remarkable point that needs to be remembered is that Hawking radiation in realistic gravitational systems such as stellar and galactic black holes, is remarkably weak—so weak that we have very little hope of directly observing it in a gravitational context. This is somewhat of a set-back for what is without doubt one of the most fascinating and prolific ideas of modern physics. Analogue gravity will probably not be able to claim that this unfortunate glitch will be overcome, simply because analogue gravity experiments do not deal with gravitational black holes, yet it certainly does give us the opportunity to study Hawking radiation from a fresh and rather unexpected perspective.

Bill Unruh first proposed an analogue for gravity in 1981 in the context of sound waves propagating in a flowing medium. The underlying idea is very simple: if we imagine a sound wave propagating against a counter-flowing medium it is easy to appreciate that if the medium flow velocity is smaller than the wave velocity, then the wave will be allowed to propagate upstream. If the wave then encounters a velocity gradient such that the flow accelerates up to supersonic speeds, then the wave will inevitably slow down until it is completely blocked by the counter-propagating medium. The sound wave cannot propagate upstream against a supersonic flow. The wave-blocking point lies at the transition from sub to super-sonic flow and, as such, represents the analogue of a gravitational wave-blocking horizon. This is just a pictorial description of the situation. The mathematics reveals a far more unexpected and revolutionary aspect: the sound wave propagation and trajectory is fully described by a spacetime metric that is distorted by the flowing medium close to the velocity gradient. This distortion can be formally identical to the metric close to the event horizon of a gravitational black hole and, taking one step further, Hawking radiation, now in the form of sound waves is predicted to be emitted from the "sonic" horizon. Most interestingly, the sonic horizon emits Hawking radiation that depends on the gradient of the medium velocity across the horizon and therefore can in principle be engineered and optimised in the laboratory. For several years these predictions were not fully appreciated and it was only later on that Bill re-proposed his idea and today, under the thrust of continuous technological improvements there is a thriving and expanding community dedicated to the search of new settings in which a flowing medium of some sort can be generated and controlled in a such a way as to recreate curved spacetime metrics with various applications.

The resulting theoretical models are becoming ever more sophisticated, spurred by and in turn spurring new laboratory tests and experimental success stories. Hawking-like radiation mechanisms have now been analysed in wide range of systems well beyond the original acoustical analogue, e.g. superfluids, flowing Bose-Einstein Condensates, ion-rings, electromagnetic waveguides, soliton-like pulses in optical media just to name a few. The last few years in particular have seen a sudden surge of experimental tests that are paving the way for greater things to come: horizons have been generated and observed with gravity waves in flowing water, phonon oscillations in flowing Bose-Einstein-Condensates and light scattering from laser pulse-induced flowing optical media. Negative frequency waves have been observed in water-wave and optical analogues and direct evidence of Hawking-like behaviour in a classically stimulated context has been observed using water-waves. The first evidence of spontaneous emission from an optically generated perturbation has also been observed. These are all remarkably important in light of the evident advancement of the whole field from a rather sidetrack idea to a fully fledged research area that is leading to innovation and important discoveries at both the theoretical and experimental level.

Clearly there still remain many challenges and hurdles. Notwithstanding the remarkable experimental progress in the last years, a clear and undisputed experimental indication of spontaneous Hawking emission is still lacking. This may come from one of the analogue models mentioned above or possibly from one of the many and new models that are currently emerging. An additional point that is requiring significant effort and is one of the main complications with respect to the original

Hawking description, is the presence of dispersion. On the one hand, dispersion provides a simple solution to the so-called transplanckian problem as it curbs any frequency divergence at the horizon. But on the other hand, it may significantly complicate the analogy or even modify the nature of the emission. This difficulty is certainly relevant in the optical analogues but plays a role also in other settings. Moreover, although Hawking radiation is certainly the most prominent and desired effect one would want to observe in these analogues, other effects are also equally noteworthy and are gradually gaining attention, such as the emission from analogues of a cosmological expansion, from superluminal flows, rapidly changing media or from rotating media in analogy with so-called superradiance from rotating black holes.

The scope of this book is to present an overview of the ideas underlying analogue gravity together with a description of some of the most promising and interesting systems in which analogues may be built. The aim is to provide scientists, independently of their background in any of the topics approached by analogue gravity, with a general understanding of the field. A full and deeper understanding will probably require some extra work beyond the reading of this book. However, it is our hope that these pages will encourage you to ponder the beauty of how wave propagation in flowing media is intricately connected to the geometry of space and time and to thus stimulate new ideas and new questions.

This book is divided into a number of chapters that start from a general overview of analogue gravity, providing also some background knowledge to black hole physics before moving on to consider in detail some specific analogue gravity models.

Chapter 1 gives an overview of black hole geometry and Hawking emission from gravitational and analogue black holes.

Chapter 2 delivers an overview of the field of analogue gravity as a whole with a brief description of the foundation pillars applied to a few specific examples.

Chapter 3 gives a broader description of some possibilities for observing diverse fundamental quantum effects in the laboratory, therefore going beyond Hawking radiation.

Motivated by recent experimental success, Chap. 4 gives a theoretical and general description of surface waves in fluids.

Chapters 4 to 8 give an in-depth description of surface waves on flowing media in terms of the analogue gravity perspective, rounding up with a description of recent experimental results in this area.

Chapter 9 treats the Bose-Einstein-Condensate analogue model and Chaps. 8 and 9 treat in detail the optical analogue first from a purely theoretical perspective and then introducing some recent experimental results with these analogues.

Chapters 10 and 11 deal with the so-called optical analogue model including an overview of some recent experimental results.

Chapter 12 also deals with a particular application of nonlinear optics in which light flows as if it were a fluid ("luminous liquid") and represents a promising experimental avenue.

Chapter 13 gives an overview of Lorentz-invariance breaking and possible observational tests in the context of analogue gravity.

Chapter 14 extends the concepts of analogue gravity to studies involving the topology of the vacuum—the topological constraints on the quantum vacuum structure determine some universal properties of our universe and these can be mimicked and studied in analogue systems.

Chapter 15 describes a further extension of analogue gravity, here in the realm of Einstein diffusion modified by a curved, or analogue curved spacetime background.

Finally, Chap. 16 is a return to the origins and provides the reader with an overview of the current observational evidence of event horizons in gravitational black holes.

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