Preface

This book concerns indeterminism as a local and modal concept. At its heart lies the notion that our world contains events or processes with alternative, really possible outcomes. We assume that our world is indeterministic in this sense, and we set ourselves the task of clarifying what this assumption involves. We address this task in two ways. First, we provide a mathematically rigorous theory of local and modal indeterminism. Second, we support that theory by spelling out the philosophically relevant consequences of this formulation and by showing its fruitful applications in metaphysics. To this end, we offer a formal analysis of causation, which is applicable in indeterministic and non-local contexts as well. We also propose a rigorous theory of objective single-case probabilities, intended to represent degrees of possibility. Third, we link our theory to current physics, investigating how local and modal indeterminism relates to some aspects of physics, in particular quantum non-locality and spatio-temporal relativity. We also venture into the philosophy of time, showing how our resources can be used to explicate the dynamic concept of the past, present, and future based on local indeterminism.

The theory that we put forward and develop here was launched by Nuel Belnap in 1992, and is called *Branching Space-Times* (BST). As stated in the founding paper, the aim is to answer the following question: "How can we combine relativity and indeterminism in a rigorous theory?" The combination of non-relativistic time and indeterminism was already well-known from Arthur Prior's ideas of so-called Branching Time (BT) and related semantic models; the challenge was to accommodate space-like related events, as known from the special theory of relativity. One aspect of space-like relatedness, the absence of causal connections, was also needed in another research program that Nuel Belnap was involved in with his collaborators in the 1980s. This was the so-called *stit* program in the theory of agency and action, where "*stit*" is an acronym for the agentive notion of "seeing to it that" (see, e.g., Belnap et al., 2001). A careful analysis of causal dependencies and independencies is very much needed in the theory of collaborative actions. Some insights from this project then became useful

for the formulation of BST. The central idea of BST, in agreement with BT, is to represent events as being partially ordered. A partial order leaves room for some events to be incomparable. BST shows that certain incomparable events can be understood to be space-like related, and these could, for example, represent the actions of independent agents. Thus, despite the present book's focus on applications to physics, it is worth keeping in mind that the initial inspiration for BST came from a problem in the theory of agency. Limitations of space means that we do not develop BST as a theory of agency in this work but there are, however, several promising ideas for combining the *stit* program with BST (see, e.g., Belnap, 2003a, 2005a, 2011).

Many of the formal results presented in this book, as well as the philosophical discussions that surround them, have been published in papers we have written (sometimes with collaborators) over the past twenty-five years. Although this book has been written entirely afresh, we acknowledge the particular papers that provided the basis for the content of several of our chapters.

Chapter 2 presents the results and discussion of the BST founding paper (Belnap, 1992), of which there is also a postprint providing additional information (Belnap, 2003b). A recent alternative formulation of BST is the topic of Chapter 3, which draws on the paper of Belnap et al. (2021). The BST theory of events and propositions was initially presented in Belnap (2002), sets of transitions were investigated in Müller (2010), topological issues in BST were studied in Placek and Belnap (2012), Müller (2013), and Placek et al. (2014)—these five papers are relevant for Chapter 4. Our investigation of non-local modal correlations in Chapter 5 builds on the earlier work reported in Belnap (2002, 2003c) and Müller et al. (2008). Chapter 6 extends Belnap's (2005b) theory of originating causes (*causae causantes*), making it applicable in non-local contexts as well. Chapter 7 gives a BST-based theory of objective single-case probabilities; our earlier publications relevant to this topic are Müller (2005), Weiner and Belnap (2006), and Belnap (2007). Chapter 8 then applies our accounts of non-local modal correlations and objective single-case probabilities to analyze non-local quantum correlations. Over the years, quite a number of papers have appeared on this topic, starting with Belnap and Szabó (1996) and including Placek (2000), Müller and Placek (2001), and Placek (2010). In Chapter 9, the sections on Minkowskian Branching Structures draw on Müller (2002), Wroński and Placek (2009), and Placek and Belnap (2012). Sections on the Hausdorff property and on bifurcating curves in General Relativity build

on Luc and Placek (2020), whereas for our discussion of determinism and indeterminism, the relevant papers are Müller and Placek (2018) and Placek (2019). Finally, Chapter 10 integrates material from Müller (2006, 2019) and from Placek (2021).

This book and its authors owe a debt of gratitude to a number of people. Over a long period of time, we have benefited from discussions with our students and collaborators and from the feedback of the numerous audiences to whom we presented our ideas. We especially acknowledge the contributions of our co-authors on BST papers, including Kohei Kishida, Joanna Luc, László Szabó, Matthew Weiner, and Leszek Wroński. Most importantly, for this book, Joanna Luc read and checked all the formal proofs, finding errors and infelicities, providing us with suggestions for how to correct them, and supplying her valuable insights about philosophical issues as well. She also compiled the index. A full list of Joanna's contributions would be far too long, so we offer her our sincere thanks for her invaluable help. The formal proofs in earlier versions of Chapters 2 and 3 were also checked by David O'Connell. Of course, any remaining errors are our own. Aeddan Shaw helped with language correction, Sahra Styger double-checked the index, Louis Pfander helped with the galley proofs, and Marta Bielińska labored long and hard over the preparation of the diagrams and figures. Saul Kripke, Robert Stalnaker, and Craig Callender allowed Tomasz Placek to participate in their seminars and provided feedback on some of the issues discussed in the book. Agnieszka Barszcz, Antje Rumberg, Jacek Wawer, and Leszek Wroński also provided various important suggestions over the course of the creation of this book.

We gratefully acknowledge the generous financial support of the (Polish) National Science Centre research grant: Harmonia 8 number 2016/22/M/HS1/00160. We thank Peter Ohlin and his team at OUP for the smooth handling of the whole book production process. Last, but not least, we thank our families and especially our loved ones, Eva and Kasia, for bearing with us during the times of absences and stress that finishing a book implies.

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March 2020