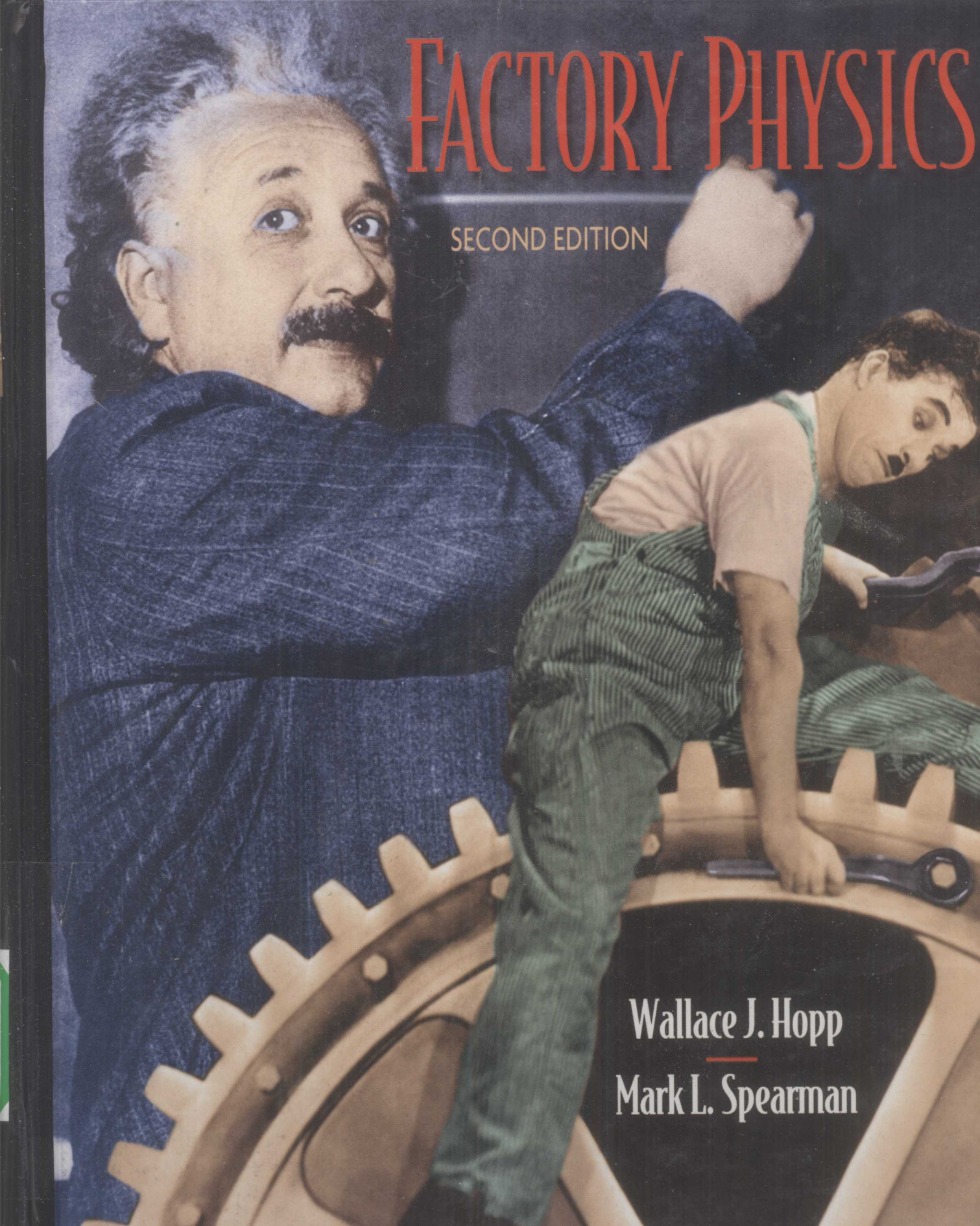


# FACTORY PHYSICS

The book cover features a composite image of Albert Einstein and Charlie Chaplin. Einstein, on the left, is shown from the chest up, wearing a dark blue textured sweater, looking back over his shoulder with a curious expression. Charlie Chaplin, on the right, is dressed as the Tramp character in green striped overalls over a light pink shirt, leaning forward and working on a large, golden-brown mechanical gear. The background is dark and industrial.

SECOND EDITION

Wallace J. Hopp  

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Mark L. Spearman

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# FACTORY PHYSICS

Foundations of Manufacturing Management

SECOND EDITION

**Wallace J. Hopp**

*Northwestern University*

**Mark L. Spearman**

*Georgia Institute of Technology*



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To Melanie, Elliott, and Clara  
W.J.H.

To Blair, my best friend and spiritual companion who has always been there to lift me  
up when I have fallen,  
to Jacob, who has taught me to trust in the Lord and in whom I have seen a mighty  
work,  
to William, who has a tender heart for God,  
to Rebekah in whom God has graciously blessed me, and  
*To him who is able to keep you from falling and to present you before his glorious  
presence without fault and with great joy  
to the only God our Savior be glory, majesty, power and authority, through Jesus  
Christ our Lord, before all ages, now and forevermore! Amen.*

—Jude 24–25

M.L.S.

## Origins of Factory Physics

In 1988 we were working as consultants at the IBM raw card plant in Austin, Texas, helping to devise more effective production control procedures. Each time we suggested a particular course of action, our clients would, quite reasonably, ask us to explain *why* such a thing would work. Being professors, we responded by immediately launching into theoretical lectures, replete with outlandish metaphors and impromptu graphs. After several semicoherent presentations, our sponsor, Jack Fisher, suggested we organize the essentials of what we were saying into a formal one-day course.

We did our best to put together a structured description of basic plant behavior. While doing this, we realized that certain very fundamental relations—for example, the relation between throughput and WIP, and several other basic results of Part II of this book—were not well known and were not covered in any standard operations management text. Our six offerings of the course at IBM were well received by audiences ranging from machine operators to mid-level managers. During one class, a participant observed, “Why, this is like physics of the factory!” Since both of us have bachelor’s degrees in physics and keep a soft spot in our hearts for the subject, the name stuck. Factory physics was born.

Buoyed by the success of the IBM course, we developed a two-day industry course on short-cycle manufacturing, using factory physics as the organizing framework. Our focus on cycle time reduction forced us to strengthen the link between fundamental relations and practical improvement policies. Teaching to managers and engineers from a variety of industries helped us extend our coverage to more general production environments.

In 1990, Northwestern University launched the Master of Management in Manufacturing (MMM) program, for which we were asked to design and teach courses in management science and operations management. By this time we had enough confidence in factory physics to forgo traditional problem-based and anecdote-based approaches to these subjects. Instead, we concentrated on building intuition about basic manufacturing behavior as a means for identifying areas of leverage and comparing alternate control policies. For completeness and historical perspective, we added coverage of conventional topics, which became the basis for Part I of this book. We received enthusiastic support from the MMM students for the factory physics approach. Also, because they had substantial and varied industry experience, they constructively challenged our ideas and helped us sharpen our presentation.

In 1993, after having taught the MMM courses and the industry short course several times, we began writing out our approach in book form. This proved to be a slow process because it revealed a number of gaps between our presentation of concepts and their



implementation in practice. Several times we had to step back and draw upon our own research and that of many others, to develop practical discussions of key manufacturing management problem areas. This became Part III of this book.

Factory physics has grown a great deal since the days of our terse tutorials at IBM and will undoubtedly continue to expand and mature. Indeed, this second edition contains several new developments and changes of presentation from the first edition. But while details will change, we are confident that the fundamental insight behind factory physics—that there are principles governing the behavior of manufacturing systems, and understanding them can improve management practice—will remain the same.

---

## Intended Audience

*Factory Physics* is intended for three principal academic audiences:

1. *Manufacturing management students* in a core manufacturing operations course.
2. *MBA students* in a second operations management course following a general survey course.
3. *BS and MS industrial engineering students* in a production control course.

We also hope that practicing manufacturing managers will find this book a useful training reference and source of practical ideas.

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## How to Use this Book

After a brief introductory chapter, the book is organized into three parts: Part I, The Lessons of History; Part II, Factory Physics; and Part III, Principles in Practice. In our own teaching, we generally cover Parts I, II, and III in order, but vary the selection of specific topics depending on the course. Regardless of the audience, we try to cover Part II completely, as it represents the core of the factory physics approach. Because it makes extensive use of pull production systems, we make sure to cover Chapter 4 on “The JIT Revolution” prior to beginning Part II. Finally, to provide an integrated framework for carrying the factory physics concepts into the real world, we regard Chapter 13, “A Pull Planning Framework,” as extremely important. Beyond this, the individual instructor can select historical topics from Part I, applied topics from Part III, or additional topics from supplementary readings to meet the needs of a specific audience.

The instructor is also faced with the choice of how much mathematical depth to use. To assist readers who want general concepts with minimal mathematics, we have set off certain sections as *Technical Notes*. These sections, which are labeled and indented in the text, present justification, examples, or methodologies that rely on mathematics (although nothing higher than simple calculus). These sections can be skipped completely without loss of continuity.

In teaching this material to both engineering and management students, we have found, not surprisingly, that management students are less interested in the mathematical aspects of factory physics than are engineering students. However, we have not found management students to be averse to mathematics; it is math without a concrete purpose to which they object. When faced with quantitative developments of core manufacturing ideas, these students not only are capable of grasping the math, but also are able to appreciate the practical consequences of the theory.

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## New to the Second Edition

The basic structure of the second edition is the same as that of the first. Aside from moving Chapter 12 on Total Quality Manufacturing from Part III to Part II, where it has been adapted to highlight the importance of quality to the science of factory physics, the basic content and placement of the chapters are unchanged. However, a number of enhancements have been made, including the following:

- *More problems.* The number of exercises at the end of each chapter has been increased to offer the reader a wider range of practice problems.
- *More examples.* Almost all models are motivated with a practical application before the development of any mathematics. Frequently, these applications are then used as examples to illustrate how the model is used.
- *Web support.* Powerpoint presentations, case materials, spreadsheets, derivations, and a solutions manual are now available on the Web. These are constantly being updated as more material becomes available. Go to <http://www.mhhe.com/pom> under Text Support for our web site.
- *Inventory management.* The development of inventory models in Chapter 2 has been enhanced to frame historical results in terms of modern theory and to provide the reader with the most sophisticated tools available. Excel spreadsheets and inventory function add-ins are available over the Web to facilitate the more complex inventory calculations.
- *Enterprise resources planning.* Chapters 3 and 5 describe how materials requirements planning (MRP) has evolved into enterprise resources planning (ERP) and gives an outline of a typical ERP structure. We also describe why ERP is not the final solution to the production planning problem.
- *People in production systems.* Chapter 7 now includes some laws concerning the behavior of production lines in which personnel capacity is an important constraint along with equipment capacity.
- *Variability pooling.* Chapter 8 introduces the fundamental idea that variability from independent sources can be reduced by combining the sources. This basic idea is used throughout the book to understand disparate practices, such as how safety stock can be reduced by stocking generic parts, how finished goods inventories can be reduced by “assembling to order,” and how elements of push and pull can be combined in the same system.
- *Systems with blocking.* Chapter 8 now includes analytic models for evaluating performance of lines with finite, as well as infinite, buffers between stations. Such models can be used to represent kanban systems or systems with physical limitations of interstation inventory. A spreadsheet for examining the tradeoffs of additional WIP buffers, decreasing variability, and increasing capacity is available on the Web.
- *Sharper variability results.* Several of the laws in Chapter 9, The Corrupting Influence of Variability, have been restated in clearer terms; and some important new laws, corollaries, and definitions have been introduced. The result is a more complete science of how variability degrades performance in a production system.
- *Optimal batch sizes.* Chapters 9 and 15 extend the factory physics analysis of the effects of batching to a normative method for setting batch sizes to minimize cycle times in multiproduct systems with setups and discuss implications for production scheduling.

- *General CONWIP line models.* Chapter 10 now includes an analytic procedure for computing the throughput of a CONWIP line with general processing times. Previously, only the case with balanced exponential stations (the practical worst case) was analyzed explicitly. These new models are easy to implement in a spreadsheet (available on the Web) and are useful for examining inventory, capacity, and variability tradeoffs in CONWIP lines.
- *Quality control charts.* The quality discussion of Chapter 12 now includes an overview of statistical process control (SPC).
- *Forecasting.* The section on forecasting has been expanded into a separate section of Chapter 13. The treatment of time series models has been moved into this section from an appendix and now includes discussion of forecasting under conditions of seasonal demand.
- *Capacitated material requirements planning.* The MRP-C methodology for scheduling production releases with explicit consideration of capacity constraints has been extended to consider material availability constraints as well.
- *Supply chain management.* The treatment of inventory management is extended to the contemporary subject of supply chain management. Chapter 17 now deals with this important subject from the perspective of multiechelon inventory systems. It also discusses the “bullwhip effect” as a means for understanding some of the complexities involved in managing and designing supply chains.

W.J.H.  
M.L.S.



Since our thinking has been influenced by too many people to allow us to mention them all by name, we offer our gratitude (and apologies) to all those with whom we have discussed factory physics over the years. In addition, we acknowledge the following specific contributions.

We thank the key people who helped us shape our ideas on factory physics: Jack Fisher of IBM, who originated this project by first suggesting that we organize our thoughts on the laws of plant behavior into a consistent format; Joe Foster, former adviser who got us started at IBM; Dave Woodruff, former student and lunch companion extraordinaire, who played a key role in the original IBM study and the early discussions (arguments) in which we developed the core concepts of factory physics; Souvik Banerjee, Sergio Chayet, Karen Donohue, Izak Duenyas, Silke Kröckel, Melanie Roof, Esma Senturk-Gel, Valerie Tardif, and Rachel Zhang, former students and valued friends who collaborated on our industry projects and upon whose research portions of this book are based; Yehuda Bassok, John Buzacott, Eric Denardo, Bryan Deuermeyer, Steve Graves, Uday Karmarkar, Steve Mitchell, George Shantikumar, Rajan Suri, Joe Thomas, Michael Zazanis, and Paul Zipkin, colleagues whose wise counsel and stimulating conversation produced important insights in this book. We also acknowledge the National Science Foundation, whose consistent support made much of our own research possible.

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In addition to those who helped us produce the first edition, many of whom also helped us on the second edition, we are grateful to individuals who had particular influence on the revision. We acknowledge the people whose ideas and suggestions helped us deepen our understanding of factory physics: Jeff Alden (General Motors), John Bartholdi (Georgia Tech), Corey Billington (Hewlett-Packard), Dennis E. Blumenfeld (General Motors), Sunil Chopra (Northwestern University), Mark Daskin (Northwestern University), Greg Diehl (Network Dynamics), John Fowler (Arizona State University), Rob Herman (Alcoa), Jonathan M. Heuberger (DuPont Pharmaceuticals), Sayed Iravani (Northwestern University), Tom Knight (Alcoa), Hau Lee (Stanford University), Leon McGinnis (Georgia Tech), John Mittenenthal (University of Alabama), Lee Schwarz (Purdue University), Alexander Shapiro (Georgia Tech), Kalyan Singhal (University of Baltimore), Tom Tirpak (Motorola), Mark Van Oyen (Loyola University), Jan Van Mieghem (Northwestern University), Joe Velez (Alcoa), William White (Bell & Howell), Eitan Zemel (New York University), and Paul Zipkin (Duke University).

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