Human Agency in a Digital World

/ Understand technology and make it work for you

< MARCUS FONTOURA

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To my family, especially my daughters,
Ayesha and Shanti, whose curiosity about
technology and productivity inspired me
to write this book.

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Endorsements

"As someone responsible for building some of the largest cloud systems on the planet, I've seen firsthand how technology can feel like it's racing ahead of us all. *Human Agency in a Digital World* is the antidote: Marcus Fontoura doesn't just explain AI, quantum and cloud with clarity and wit—he hands you the keys and shows you how to drive. This book is a practical, empowering guide for anyone who wants to use technology as a tool (not a magic trick), and a timely reminder that it's our human agency—our choices, curiosity, and values—that truly shape the future. In an age where AI headlines can make even the experts pause, Marcus gives everyone—from engineers to executives—the confidence and practical know-how to steer, not just spectate. Read it, enjoy it, and get ready to take the wheel."

Girish Bablani, President at Microsoft Azure

"With the rising importance of software and artificial intelligence in our world, it's increasingly important for everybody to understand how this new technology works, to demystify algorithms, and to democratize understanding of computer systems. Marcus Fontoura's *Human Agency in a Digital World* does a fantastic job of explaining complex concepts in simple terms, to make computer science topics approachable for anybody who would otherwise be intimidated to learn."

Hadi Partovi, Founder and CEO at Code.org

"Marcus wrote a witty and creative book about how information systems and AI works. The use of examples and tales that people can easily relate to will help readers quickly build intuition in a broad sense, from what is possible and real with AI to its energy efficiency! This kind of intuition gives people agency in a world where information systems and AI affect every aspect of our lives. This book is a delight to read, and can only be written by someone like Marcus who actually deeply understands the space, makes factual claims, and doesn't get people lost in noise and hyperbole going around about AI."

Prof. Luis Ceze, Lazowska Endowed Professor, Paul G. Allen School of Computer Science & Engineering, University of Washington

"As someone who has built real-world systems, from large-scale search engines to AI-driven healthcare platforms, I found *Human Agency in a Digital World* to be both timely and refreshingly grounded. The book argues that understanding technology is no longer a niche technical skill but a form of modern literacy, essential for navigating everything from algorithms to social infrastructure.

What distinguishes this book is its lens: it frames computing not as magic, but as a vehicle for efficiency and human agency. It sidesteps both techno-optimism and fear-mongering, focusing instead on how digital systems, search, cloud, AI, even quantum computing, can augment human capabilities, but only if guided by intentional, values-driven choices. The taxonomy of physical systems, physically-backed myths, and digital-only myths is especially insightful, and is a mental model I now find myself using when evaluating both technologies and organizations.

The writing is accessible, often witty, and never talks down. From the cautionary tale of NASA's Mars Climate Orbiter to the absurdity of bogosort, the book distills technical depth into vivid, memorable stories. If anything, the breadth occasionally comes at the expense of depth in later chapters, but that tradeoff is purposeful. This isn't a technical manual, it's a call to understand enough to steer.

For technologists, educators, policymakers, and curious citizens alike, *Human Agency in a Digital World* is not just a guide to the systems shaping our lives, it's a reminder that those systems remain ours to shape."

Kira Radinsky, Cofounder and CTO at Diagnostic Robotics

"Imagine a book where you learn how complex things work through stories, movie characters, books, and memories drawn from your own imaginary world. That book exists. *Human Agency in a Digital World,* by Marcus Fontoura, invites you on a journey where imagination meets insight, making the digital age feel personal, accessible, and alive.

Tracing the evolution of digital technologies—from the earliest concepts of computing to the rise of artificial intelligence—this book helps readers understand that technology isn't magic, but the product of human ingenuity. Behind every digital artifact are scientists, engineers, and creators whose work drives progress and shapes the world we live in.

At a time when digital technologies and algorithms deeply influence our lives, Marcus Fontoura's book offers timely insight into their dilemmas, complexities, and promises. I commend the author for his inclusive and engaging approach to unveiling the intricacies of technology for the lay reader. This

book sits at the heart of today's most pressing debates about the digital world."

Prof. Virgilio Almeida, Faculty Associate at Berkman Klein Center for Internet and Society, Harvard University. Author of *Algorithmic Institutionalism*

"Human Agency in a Digital World is an authoritative and engaging exploration of our digital world—from algorithmic efficiency and digital transformation to the interplay of physical systems and digital myths. Marcus Fontoura masterfully bridges deep technical insight with remarkable clarity, even making the quantum computing sections accessible and compelling. It stands as a significant contribution to the public's understanding of these complex systems."

Prof. Matthias Troyer, Technical Fellow at Microsoft

"Information technology is having both a positive and negative impact on everyone on this planet. This book provides a fascinating overview of this effect by making knowledge of computer technology and its impact on society accessible to a broad segment of society."

Prof. Donald Cowan, Distinguished Professor Emeritus of Computer Science, University of Waterloo, Canada

"What Marcus Fontoura has done with *Human Agency in a Digital World* is an intellectual tour-de-force illuminating both the origins of our digital transformation, the patterns behind these changes, and the way our lives might evolve to embrace what might initially be a more complicated future, but ultimately becomes a simpler form of abundance. The way Marcus draws analogies between diverse topics such as Daniel

Kahneman's work, computer programming, and neural networks exposes something rare: it shows us how the greatest systems thinkers who have been powering the transformation to the internet, mobile, the cloud, search, and now AI, have been actively fusing concepts from everywhere.

In the same way large language models have slurped up all the information on the web, deep thinking distinguished engineers at the top technology companies have used the power of the web to explore concepts far and broad, fusing them back into products and technologies to benefit our lives. No where is that on better display than in this book. You will find yourself coming back over and over again to sections and chapters as the web of intellectual connections unveils itself."

Brad Porter, Founder and CEO of Cobot.
Formerly Distinguished Engineer for Amazon
leading robotics and CTO for Scale AI.

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Foreword

There are many good books written by visionaries, business leaders and academics that bravely and sometimes brilliantly speculate about techno utopias and anti-utopias. My favorite by far is Mustafa Suleyman's *The Coming Wave*. Compared to those books, *Human Agency in a Digital World* stands out in several ways. Its author, Marcus Fontoura, is an engineer to the core of his being. At his day job Marcus works on the most technically complicated layer of Microsoft's infrastructure. Prior to that, he was building web search infrastructure at Google. His team of over a thousand engineers creates technologies at the foundation of Microsoft's public cloud, Azure, which powers not only Microsoft services, ranging from Outlook to Bing search, but also most Fortune 500 companies.

Some executives are engineers and some engineers are executives. Marcus belongs to the second category. He is one of the most prominent technical experts at Microsoft. Being an engineer is not just a job, it is a mindset and a culture. Marcus explains how complex algorithms and systems work, sometimes adding insightful and humorous pop culture references. A lot of writing about technology is sugar syrup brewed by influencers—engaging and easy to digest but only marginally

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nutritious. This book is different. It is written by an engineer with a capital E, and it shows. It is a more complex read than almost anything one could find on a bookshelf of an airport newsstand. However, per unit of mental effort, reading *Human Agency in a Digital World* has exceptionally high ROI (return on investment) in terms of developing the reader's mind and understanding of the world of technology. It is an excellent read for anybody considering careers in engineering or business. Anybody who is intellectually curious and not afraid to strain their mind would benefit from this book. Someone with an algebra phobia can skip more technical parts and still get a lot out of the book and someone with graduate training in computer science might skip the "obvious" parts and benefit from the rest. There is only one prerequisite for reading this book: willingness to stretch the mind and desire to do so. Although the book is intended for a general audience, it is a great reading for a college level course about technology and society. It is particularly suitable for business thought leaders because it contains a wealth of examples from the world of business.

We tend to marvel at newly invented technologies, and we are keenly aware of their potential to transform society. Yet, we take for granted technologies that have been around for decades, noticing them only in the rare moments when they fail to work as expected. It is easy to forget how technologies from the very recent past transformed not just the economy, but our

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lives. This book does not dwell on the future – it is grounded at the present. Most people neither understand nor appreciate the complexity of multilayered technical infrastructure required for making a simple phone call or saving a file "in the cloud," and very few of us have keen awareness how different we would be without these technologies. The author does a great job helping the reader appreciate the technological marvels that we tend to take for granted providing accessible yet substantive explanations about how algorithms and technologies ranging from search and AI to public cloud actually work.

For instance, most of us never ask ourselves why video streaming and email fail so infrequently. Medieval cathedrals do not fail even after centuries of neglect because the walls are massive. One might naively, and erroneously, assume that email is reliable for somewhat similar reasons. Internet services running on components that frequently fail – yet, the service continues to work smoothly because the system is cleverly engineered to be robust to failure – there is an interesting analogy here not with an old building that are reliable because the walls are so strong but with organizations: when some employees get sick or resign unexpectedly, a well-functioning organization continues to deliver the service or product without interruptions.

Only in the digital age engineers learned to build systems that have the kind of robustness that life forms and well-functioning organizations exhibit. Why do new

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digital technologies tend to be unreliable, gaining reliability over time, and what are the tricks that engineers discovered to improve the reliability of complex systems over time? One will find the answer to this and many other fascinating questions in this book.

Michael Schwarz, Microsoft Chief Economist
August 2025

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Introduction

While putting the finishing touches on my previous book, *A Platform Mindset*, I began to take a step back and think less about the power of digital platforms, and more about the power that we hold as individual users of these technologies, as people. This human power, which exists at both a personal and organizational level, is apparent whether looking at AI use today or quantum computing capabilities in the future.

Increasingly, the content we consume is focused on what technology is doing for us or to us, as if we are just passive bystanders. But each and everyone of us, regardless of our technical background or understanding of technology, has **human agency**. What does that mean? While there are many definitions, each makes it clear that we humans are autonomous beings, meaning that we act independently. As human agents, don't we owe it to ourselves to understand the strengths and weaknesses of AI and technology we use in our daily lives? My answer is "yes, absolutely."

I am a computer scientist, but I am a human first. A human who has daughters, to whom I've dedicated this book, and who wants to build a better world for them and for future generations. I care deeply about both technology and people, and as a result, how they intersect and

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impact one another. That's the first big idea of this book: human agency, which is our greatest tool to shape the impact of technology in our lives. Humans should understand technology. Evaluate it. Use it, if it is empowering, and not use it, if it is harmful. This concept is based on the definition of machine usefulness (MU) from MIT economists and Nobel laureates Daron Acemoglu and Simon Johnson's insightful book *Power and Progress*.[1] More important than being intelligent, efficient, or anything else, computer systems should above all enhance the human experience.

The second big theme of this book is something we often take for granted: how to use gains in **efficiency** to land a positive impact in society. The term "efficiency" today often rings like a 1950s corporate term for things running smoothly and economically. That is true, in part, but this term is woefully in need of modernization for today's day and age, especially as it is used in the context of today's technologies. Computers were first developed to improve the efficiency of numerical computations, and eventually evolved to create efficiencies in virtually all aspects of human life. Essentially, over time, we have been able to do more with less. It is my contention that the problems we face as a society, such as global climate change, hunger, healthcare, growth and productivity, at their core, are problems of efficiency. These complex

1. *Power and Progress: Our Thousand-Year Struggle Over Technology and Prosperity,* D. Acemoglu and S. Johnson, PublicAffairs, 2023.

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problems yearn for efficiency-oriented solutions such as more efficient manufacturing, agriculture, pharmacology, and industries.

This book is the meditation of a computer scientist. I've set out to write a self-help book for this and future digital generations. How do we develop our human agency even as we become increasingly more technologically efficient? I'm a big believer that human agency and technological efficiency must coevolve if we want to create a better world. Everyone should understand intelligent technologies and develop their unique human abilities and capacities. This is more important than ever before. I hope this book will provide some of the foundations needed to have these discussions, and that it will inspire a new generation of leaders and technologists to understand the intersectionality of technology and society.

* * *

> "If you can't explain something to a first-year student, then you really haven't understood."
>
> Richard Feynman

It's no news to anyone that our lives are becoming ever more dependent on technology. We are in the middle of the AI revolution and on the verge of the quantum computing revolution. The better we understand the technologies shaping our lives today, the better positioned we will be to guide future technology use. This book was

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born out of my intent to explain the key concepts behind computer systems, with the hope of demystifying our fear of algorithms and helping us understand how they can be instrumental in creating a brighter future, with a more equitable and prosperous society.

It may be difficult for many of us to realize how much of our daily activities are simplified, amplified, or sometimes degraded, by computer systems. When we listen to music while driving to work, how many systems are we interacting with? If somehow the system is glitchy, and we cannot play our Spotify playlists, what is really happening? I wanted to give people the tools to understand what is going on under the covers. A Caltech faculty once asked physicist and Nobel laureate, Richard Feynman, to explain a difficult concept in theoretical physics. After thinking about the problem for a few days, he came up with the opening quote for this book.[2] Of course he also said that if you think you understand quantum mechanics, you don't understand quantum mechanics! Given our current dependency on computer systems, and the expectation that such dependency will only increase, I want to explain the foundational elements to enable people to understand technologies such as social media, web search, cloud computing, AI, and quantum computing.

Computer technology was primarily born to enable efficiency. The Manhattan project employed human

2. https://magazine.caltech.edu/post/feynman-at-100 (Last accessed in March 2025).

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computers, which were ordinary women and men, to do calculations. Before the first computers were operational, this was common practice. The Electronic Numerical Integrator and Computer (ENIAC), which was the first programmable digital computer, was ten thousand times faster than the human computers employed by the Manhattan Project. The efficiency in computation brought by the ENIAC played a crucial role in the Cold War, where it was used for various projects, including development of the hydrogen bomb. Since then, the continued development of computer technologies has widened the gap between human and digital computers. The efficiencies produced by computer systems have allowed us to achieve more in faster and more accessible ways. We have better and faster news access. We shop online. We have cybersecurity systems. The current AI revolution, for instance, has only been possible due to the abundance of computational resources enabled by cloud computing and due to the large amounts of data generated or captured by computer systems. As I will argue in this book, computers are merely capable of making computations more efficient. Computers alone are not able to increase efficiency in society. We need human creativity and agency to transform computational efficiencies into real-world positive impacts on humankind.

Important questions about the future of humanity hinge on efficiency tradeoffs. Are we going to push for a society that focuses on doing more with less above all else, or will we consider how technology can be used

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to augment our humanity? South Korea exemplifies a high-efficiency society shaped by post-war urgency, Confucian values, and a tech-driven economy. The country boasts world-class infrastructure, ultra-fast internet, and a highly disciplined education and work culture that fuel innovation and global cultural influence. However, this relentless focus on speed and productivity comes at significant social costs, including long work hours, extreme academic pressure, mental health challenges, and the world's lowest birth rate. While South Korea's coordinated systems and national cohesion have enabled rapid progress, the country now faces a critical balancing act between maintaining its global edge and ensuring societal well-being and sustainability.[3]

We can automate boring, tedious tasks we don't like doing. Computers are great at those, and they also don't complain about doing the same tasks over and over. Computers can also make us smarter. The newer generations of chess players are likely better than those that couldn't play against computers, or any opponent for that matter, anytime they wished. Other uses of technology, unfortunately, can negatively impact society. The effect of social networks on teenagers' mental health may be the most evident example. The initial intent and excitement of being able to efficiently connect people across the globe ignored important tradeoffs. Of course, it may

3. https://www.ft.com/content/6e70f7bd-e311-41df-94fe-7a5575493ae6 (Last accessed in May 2025).

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not have been possible to anticipate the consequences of social networks before they were used, but it can be used as a lesson learned going forward. While I don't claim to resolve every issue here, I hope to offer a useful point of view, including historical perspectives. The more we understand about the underpinnings of technologies that power the computer systems that impact our lives, the more agency we gain to shape them in ways that serve us. This is the basis of human agency.

I have spent most of my career working on the infrastructure for search engines and cloud computing services. Many of the projects I worked on are related to efficiency, answering questions like: how to make search queries faster? How to design search engines to use fewer computational resources? How to democratize cloud computing use by lowering their costs? How to make cloud computing more sustainable by using energy more efficiently? And how to design an organization to execute these projects in a cost effective way? These efficiencies are enablers for us to tackle the world's most relevant problems. By managing computational resources better, cloud providers enabled fundamental advances in AI, which in turn allowed us to make progress on basic science at a faster rate. As an anecdotal example, the 2024 Nobel Prize in chemistry was awarded to researchers working on AI to advance our understanding of proteins and predicting their structures. Such capabilities can be utilized for research and development that are fundamental for

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understanding biological mechanisms and the treatment of complex diseases, such as Alzheimer's disease.

I tried to present the concepts and algorithms described in this book in simple terms, with the intent to reach a wider audience, including readers that don't have a computer science background but are interested in learning more about the topic. I hope this book will inspire people to try to understand computer systems at a deeper level. Since I could not cover every possible computer system in a single book, I chose to focus on a few technologies that have, or will likely have, a huge impact on our lives: social media, web search, cloud computing, AI, and quantum computing. I strived to present the technical concepts in an increasing order of difficulty. Starting with simple algorithms, our journey goes through the avenues of sorting, compression, distributed systems, and NP-hard problems. Chapter 1 starts by defining some basic concepts which are used throughout the book. After that, each chapter introduces a new technology, building on the concepts previously described.

A foundational way to understand technology begins with recognizing that all computer systems are ultimately about transforming data into useful output through efficient computation. First, we must understand the nature and structure of the data available, including its sources, limitations, and representations. Given that data is often massive and noisy, we normally have to use techniques like compression and abstraction to reduce complexity and highlight signal over noise. This prepares the data for

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algorithms, which are structured procedures, or recipes, for extracting meaning, solving problems, or generating responses to difficult questions. The efficiency of these algorithms matters deeply, as inefficient systems consume more energy and resources without improving outcomes. Once algorithms are selected, they are executed within systems, like cloud platforms, social networks, search engines, which must be engineered for scalability and robustness.

So, the theory goes like this. If there is a problem to solve:

- Understand the data and process it, for instance compressing it and creating appropriate abstractions;
- Apply efficient algorithms to the processed data;
- Finally, build systems that scale.

But above all, human agency is essential. Algorithms and systems don't carry intrinsic value. They only become useful when they empower people and enhance society. Technology is not inherently good or bad, it's how we choose to use it that defines its impact. In 2021, Meta developed smart glasses in partnership with Ray-Ban. The technology was very impressive. The glasses allowed users to take photos and videos, make calls, and listen to music without needing to pull out their phones. The pitch was "hands-free convenience" and seamless integration with your digital life. However, despite the technological advancement, people felt uncomfortable being around

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others wearing the glasses and some establishments even banned them outright. Rather than feeling empowered, users and bystanders felt vulnerable.[4] The opposite also happens. When the first AI models that power ChatGPT were developed, even the researchers working on them were astonished by their broad applicability to tasks they didn't have in mind to begin with. The technology proved to be very empowering in many scenarios, like answering complex questions about research publications, and it still amazes some of its early inventors. Through the book, I'll discuss several other examples of technologies that either positively or negatively impact society.

The reason I cover so much ground, starting from bits and moving all the way to complex systems such as AI and quantum, is to build our collective understanding of technologies and to develop our human agency. Let's consider sustainability. By covering how algorithms work, how they can be used in complex systems, and how cloud computing primitives support running these services at scale, we can have an informed discussion of how computational resources are used to run services we know and love, such as Google Search or Amazon.com. As we'll see in Chapter 4, efficient algorithms can lead to better resource utilization, minimizing the carbon footprint of services, and positively impacting sustainability. We'll

4. https://www.business-humanrights.org/en/latest-news/ray-ban-meta-glasses-raise-concerns-about-privacy-rights-consent-and-increased-surveillance (Last accessed in July 2025).

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understand how efficiency metrics such as resource utilization and power usage effectiveness (PUE) can help us have an informed discussion about sustainability and the impact of our power-hungry cloud computing industry in the world.

The last topics, AI and quantum computing, are the most complex, but by then we will have the tools to understand them more deeply. Technical readers will notice that I opted for clarity of presentation over completeness of some concepts. For instance, when talking about web search, I omit the use of caches, which are systems that store previously seen queries and their results to increase the overall efficiency by avoiding processing the same popular user queries over and over. I intentionally opted to go over more subjects at a shallower level, as opposed to conveying a smaller number of areas at a deeper level. Interested readers will find plenty of resources to dive deep into algorithms and systems they find interesting. I tried, as much as possible, to present technologies in chronological order, from the early days of the internet to today.

Chapter 5, on organizational efficiency, doesn't describe a new technology. In that chapter, instead of computer systems, I discuss how to run organizations to produce the most value, at the lowest possible cost, by building on and incorporating the concepts outlined in the rest of the book. My motivation to include this chapter was twofold. First, it provides a systematic approach for the organizational productive cycle. Innovations

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that generate efficiencies, positively impacting the bottom-line, allow us to reinvest our gains on innovations that produce value and increase the top-line, generating a virtuous cycle for organizations. Second, it gives us a good foundation to talk about the effects of AI in productivity. Perhaps one of the most foundational questions we need to answer as a society is how will the new AI systems affect the way we work. And given that, what changes should be done to the educational system to prepare for such a workforce. Chapter 5 provides a foundation for that discussion.

Writing this book has been one of the most interesting projects of my professional career. As Richard Feynman said, it is challenging to present complex concepts at the freshman level. And although I know that no one can become an expert in computer science by reading a book, hopefully people will find the topics presented here interesting regardless of their level of technical knowledge. Most importantly, I hope the book is fun and that it helps broaden our collective understanding about technology, and how it can have a positive effect in our lives.

In order to help understand some of the technical concepts presented here, I built an accompanying website, https://digitalagencybook.org, that provides extra material and shows visualizations for some of the algorithms I described throughout the book. Finally, all author proceeds from this book are donated through Microsoft Philanthropies to causes related to the democratization of computer science education.

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