<1>Introduction

<2>Knowing where to mark the "X"

In the early 20th Century, a bearded gnome was sighted by the children of Schenectady, New York. The gnome, the children claimed, would row along Schenectady's waterways in a canoe. The gnome was often cited smoking a panatela cigar, while leaning over a tiny desk positioned in the bottom of the canoe, on which he scribbled intently. The gnome's young followers sometimes collected papers that flew out of the boat and into the water—as evidence to present to their disbelieving parents.

Outside the city, the gnome had become well-known to scientists—including Thomas Edison, Albert Einstein, and Nicola Tesla—who referred to him as "The Little Giant of Schenectady". Among the scientific community, the four-foot-tall man, Charles Steinmetz, was amongst the world's most talented electrical engineers. He suffered from short stature due to a genetic disease known as kyphosis, but—despite skepticism from the city's children—had obtained a position amongst the elite engineering team at the General Electric company of Schenectady.

Steinmetz was not only known for deriving differential equations while drifting on his canoe, but also for collecting Gila monsters, alligators, and rattlesnakes, which he tended to in a customized mansion that sat atop one of the city's popular avenues. Though eccentric, Steinmetz secured his role in the history of American innovation, by carefully dissecting the period's toughest engineering problems and delivering solutions critical to the future of industry. He had, for instance, devised a mathematical law known as the Law of Hysterisis (or Steinmetz's Law), which explained how energy dissipates through heat—paving the way for more efficient electrical power generators.

But Steinmetz's image as an innovator in the American popular parlance did not solidify until an edition of *Life Magazine* in 1965 revealed his interactions with the industrial magnate Henry Ford, who operated a large automobile factory in Dearborn, Michigan. Steinmetz was invited by Ford to his factory, which was experiencing a perplexing problem with a massive electrical power generator. Steinmetz had been told that Ford's engineering team could not decipher how to fix the generator, despite multiple attempts to modify it. Apparently the Ford team disagreed about what to do. Some engineers on the Ford team wanting to replace expensive parts of the machine's backbone. Others wanted to continue adding patches as bandages to the generator's periphery, in a desperate trial-and-error attempt to get the machine working as soon as possible.

According to legend, Steinmetz arrived in Dearborn and dismissed all of Ford's engineers, ignoring their theories and proposals. He demanded a notebook and a pencil. In isolation, he mentally diagnosed the machine's ailments without opening a single panel of the massive metal structure. He listened to its wounded whirring, slept next to the machine in a cot, and jotted down notes for two days and two nights. He carefully diagrammed the machine and its parts, tracing every component of its infrastructure and every step required to operate it. At the end of the second night, he reportedly left the factory to purchase a piece of chalk, and returned to request a ladder, which he used to climb aboard the generator and mark a large chalk "X" on one of the machine's main panels. He instructed Ford's engineering team to remove the panel at the location of the "X" and replace 16 turns of copper wire from a coil underneath. Steinmetz's instructions were followed by the Ford engineering team incredulously, but the generator restarted in perfect working order.

Steinmetz had relieved Henry Ford from a major dilemma. He was asked by Ford to mail a bill for his consulting services. Steinmetz sent Ford a request for $10,000—approximately $208 per hour for two days' work. In disbelief, Steinmetz was asked by the accountants at Ford's company for an itemized invoice to justify the expense, to which Steinmetz replied:

Making chalk mark on generator: $1
Knowing where to make mark: $9,999

Steinmetz was paid in full.

Steinmetz was paid in full.

<2>What do we mean by "modeling" public health and healthcare systems?

The legend of Charles Steinmetz offers a lesson for those of us concerned with modern public health and healthcare systems. Many of the daily challenges faced in the public health and healthcare sectors are complex "operational" problems—dilemmas that involve systems that are at least as convoluted as Henry Ford's generator, if not more so. People working in the public health and healthcare fields commonly face problems with ineffective or "broken" operational environments. These environments lead to questions such as: "Why are patients waiting so long in the emergency department before being seen by a doctor?", "Why are we still seeing cases of an infectious disease in our community, despite a massive vaccination program that was supposed to have eradicated it?", or "Why are we paying so much for this new laboratory test instead of using a cheaper alternative?"

When faced with public health or healthcare delivery problems, many people respond with the same desperation as Ford's engineers: either wanting to replace expensive, fundamental parts of a complex system ("Fire the current doctor and hire a new one, and hopefully the waiting times in the emergency department will be reduced"). Others simply add patches as superficial bandages that are unlikely to fix the underlying dilemma ("Start an education program to inform patients about when the emergency department is busiest, so they'll come at another time" …a suggestion the author of this book received, when consulting for a local hospital).

As an alternative to using a desperate trial-and-error approach, we can learn from Steinmetz's strategy: to carefully diagram the key components of the complex problem we are attempting to solve. We can analyze each element of the diagram systematically until we identify the root cause of the problem. The method of carefully diagramming a problem is what we now call "modeling". Modeling involves creating an abstract model of a real-world problem, to help us diagnose and treat the problem in a thoughtful, systematic, and meticulous way. Unlike Steinmetz, we have the luxury of not simply using a notebook and pencil (though these tools are often adequate for many problems), but also using modern high-performance computers to assist us in creating and analyzing our models.

Our goal in this book is to teach students "where to put the X" on major healthcare and public health problems that involve breakdowns and failures in our systems. These breakdowns and failures produce long waiting lines, poorly-distributed human or material resources, and poorly-conceived plans for how to diagnose the neediest patients or provide them with the best treatment. Many of these problems have been extensively studied through Steinmetz's approach of modeling a problem. The modeling field has identified several effective strategies for solving common problems in public health and healthcare delivery. In this book, we present these common strategies through a case-based approach, to sequentially build students' skills for "knowing where to mark the X".

<2>How to use this book

This text is organized into three major sections and their associated chapters. The sections and even individual chapters may be read in isolation, but have been intentionally organized to flow naturally from one another and provide a comprehensive overview of the current state of essential knowledge and the common tools employed by experts in modeling public health and healthcare systems. Hence, we would suggest that students and their instructors maintain the order of operations in the book.

The book's three parts include: (1) foundations for modeling public health and healthcare systems, which includes key concepts, associated terminology, and fundamental methods of cost-benefit and cost-effectiveness analysis, decision tree analysis, and Markov modeling; (2) simulation techniques including ways to model both infectious and non-communicable diseases using compartmental (Kermack-McKendrick) models and microsimulation techniques including agent-based modeling; and (3) novel mixed methods incorporating statistical learning techniques commonly known as machine learning, and econometric methods that use data from natural experiments to improve the derivation and validation of models.

Throughout each chapter, key concepts and modeling techniques are taught through a case-based approach in which problems are drawn from real-world settings, then solved in a manner that can derive a generalizable equation, method or principle for broader application. The real-world problems are taken from healthcare organizations (e.g., the Stanford University hospital), non-governmental organizations (e.g., Oxfam International), public health departments (e.g., San Francisco County Department of Public Health), and international agencies (e.g., the World Health Organization) to motivate each section of each chapter. Each chapter uses a discovery-based learning approach in which one to three problems are solved to provide demonstration and derivation of a key method, followed by application of the method to solidify key concepts.

To ensure that the key concepts and methods are understood and solidified, each chapter is accompanied by code that can be run in the free statistical program *R*, which we discuss further below. These auxiliary materials are posted online at a permanent repository accessible at the URL: https://github.com/sanjaybasu/modelinghealthsystems.

<2>How to be prepared for this book

This book is intended to be used by advanced undergraduate students (typically in their junior or senior years of college) and students enrolled in Master's degree programs in public health, epidemiology, healthcare administration, health policy, or related fields. The mathematics background necessary for this course is limited to knowledge of basic calculus including ordinary differential equations. For example, if we write the following differential equation:

[Equation 0.10] ,

readers should be able to interpret the equation as indicating that the rate of change in variable *X* for a change in variable *t* is a function of the constant *c* times the value of *X* at time *t*. In all cases, we have strived to ensure that any equations used throughout the text are explained thoroughly, with examples to maximize interpretability. In addition to having knowledge of basic calculus, readers should have taken an introductory-level course in probability and statistics, which would cover topics such as probability distributions (e.g., what is a Gaussian or normal distribution, versus a skewed distribution), the Central Limit Theorem, and basic principles of statistical sampling and regression.

In addition to a basic background in probability and calculus, readers should be prepared to use the free statistical program *R*, which can be downloaded from https://www.r-project.org/. Those students who have not previously used *R* are recommended to take the free introduction to *R* available at https://www.datacamp.com/, although this book will include a detailed introduction to the program.

We stress that we do not expect students using this book to have any prior experience in computer programming. We will introduce coding strategies as they are needed in the course, and at this point students should simply download *R* to have available when they are introduced in later chapters of this book.