Chapter 1
Introduction to Development Engineering

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1 What is Development Engineering?

Technological change has always played a role in shaping human progress. From the power loom to the mobile phone, new technologies have continuously influenced how social and economic activities are organized—sometimes for better and sometimes for worse. Agricultural technologies, for example, have increased the efficiency of agricultural production and catalyzed the restructuring of economies (Bustos et al., 2016). At the same time, these innovations have degraded the environment and, in some cases, fueled inequality (Foster and Rosenzweig, 2008; Pingali, 2012). Information technology has played a catalytic role in social development, enabling collective action and inclusive political movements (Enikolopov et al., 2020; Manacorda & Tesei, 2020); yet it has also fueled political violence and perhaps even genocide (Pierskalla & Hollenbach, 2013; Fink, 2018).

Nevertheless, the United Nations (UN) has recognized technology as key to achieving the Sustainable Development Goals (SDGs), a set of global policy targets adopted by 193 national governments for implementation by 2030.[1] An outstanding question is how to *systematically* harness technology for sustainable development?

[1] United Nations Sustainable Development Goals at https://sdgs.un.org/goals

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Fortunately, the research community has begun to offer paths forward. In this textbook, we introduce the nascent field of *development engineering*, an area of research focused on discovering generalizable technological solutions that can improve development outcomes in poverty-constrained settings. It integrates the theory and methods of development economics (and other social sciences) with the practice of *engineering*, promoting the co-design of engineering advances alongside the social and economic innovations required for impact in the "real world." The resulting solutions—whether they focus on intensifying agricultural production, enhancing early child development, or expanding access to sanitation—are well positioned to succeed at scale, and within planetary boundaries.

As a field, development engineering is closely aligned with the recent movement to scientifically validate different approaches to poverty reduction, exemplified in the 2019 Nobel Prize in Economic Sciences (awarded to development economists Abhijit Banerjee, Esther Duflo, and Michael Kremer)[2]. These researchers and their co-authors have helped pioneer the use of randomized controlled trials in public policy, bringing a precise and incremental approach to solving the problems of poverty. Development engineering follows in this tradition, yet is distinct in its focus on technological innovation as a tool for achieving sustainable development.

For all the promise of technology to accelerate sustainable development, we must also recognize the potential for new tools to harm people and the environment. Indeed the motivation in launching this new field has been, in part, the long string of failures in the area of "technology for good." There is a rich history of engineering projects that have been technically sophisticated but have failed to achieve social impact in the real world—or worse, have rolled back the frontiers of human development. Examples include costly but ineffective attempts to improve educational outcomes through low-cost laptops (Cristia et al., 2017; Kraemer et al., 2009); water rollers[3] that were intended to facilitate water transport but failed to gain adoption within targeted communities (Borland, 2014; Crabbe, 2012; Stellar, 2010); and large-scale irrigation systems that failed to deliver promised benefits (Higginbottom et al., 2021).

These failures have a number of elements in common. First, it is not obvious, *ex ante*, that such projects should fail, and the causes of failure are not always clear. They are often well intentioned efforts, employing human-centered design to better meet the needs of individual users. Yet they often overlook the top-down view of development: the politics, institutions, and social norms that surround any user. These conditions can doom the most well-intentioned efforts to fail.

Second, engineers operating in the context of poverty often lack information about users' habits. Take this as a thought experiment: as a consumer in a well-functioning market, you benefit from a vast infrastructure for data collection that reveals the economic behavior of you and people like you. The firms that service your needs have access to your web traffic logs, digital payments, utility meters, and mobile location data—not to mention household economic surveys, government economic indicators, and industry analyst reports. But what about the homeless

[2] See https://www.nobelprize.org/uploads/2019/10/advanced-economicsciencesprize2019.pdf

[3] See https://www.hipporoller.org

consumer who lives in urban poverty, subsisting on free meals and donations? Or the rural subsistence farmer who uses cash to operate in informal markets?

The most disadvantaged households are rarely reached by business analysts and government enumerators. Just 10 percent of households in rural India have access to formal sources of credit; the vast majority leave no trace in the credit market (Demirguc-Kunt et al., 2018). Fewer than half of all nations in sub-Saharan Africa have conducted a nationally representative household economic survey in the last decade (Yeh et al., 2020). People living in poverty, by definition, are excluded from participating actively in formal markets. As a result, their preferences are rarely captured in market price signals or routine consumer data. They may provide feedback to researchers in the form of self-reported preferences (e.g., through focus groups or interviews), but these inputs may be biased and unreliable. Without reliable insights to guide technology design, it is unsurprising that so many engineers have failed to achieve impact.

In recent years, we have developed better techniques to observe the preferences and behaviors of underserved communities. These include low-cost sensors for monitoring product use, automated digitization of administrative records, and even behavioral experiments conducted outside the lab, in "the field." Some of these tools will be discussed in future chapters; they are increasingly being used by engineers to design for people excluded from conventional markets.

A third challenge is the paucity of research identifying the long-term economic and social impacts of new technologies (largely for a lack of investment in rigorous evaluation). Rarely have the developers of "pro-poor" technologies had the resources to evaluate the downstream social and economic impacts of their inventions. We are all familiar with the use of randomized, controlled trials (RCTs) in medicine; these methods are used to rigorously measure the effects of a novel medical treatment or prophylactic, across large populations of patients. More recently, software developers have adopted this approach to test the effects of different product features, using rapid experimentation to generate user feedback in a process known as A/B testing. Yet the tools of rigorous evaluation have only slowly diffused into the broader engineering community. This is despite the fact that engineers are interventionists at heart, seeking to make changes to markets, the environment, and people's lives.

Through collaboration with economists, political scientists, and public health researchers, engineers are now investigating the impacts of their inventions. Adapting the experimental methods used in medical trials (and more recently in public policy), we can now ask: How does the use of tablets in classrooms affect learning outcomes, both for the highest-performing students and those in the bottom quantile (Chap. 11)? How does the introduction of improved cookstove technology affect household consumption and nutrition (Chap. 15)? What is the impact of mobile telephony on local economies (Chap. 11), and what is the development impact of access to grid electricity (Chap. 5)?

Rigorous evaluation can help explain the causal relationships between a technology and its downstream impacts, including impacts on the climate and the environment (Alpízar & Ferraro, 2020). It allows us to learn how technologies effect change, and it teaches us about the economic and social constraints that any successful solution must address. Experiments in real-world settings have also led to a better understanding of how technologies get adopted in disadvantaged communities. These insights can be used to weave novel behavioral, economic, and social interventions into the design of technological solutions.

What does a "development engineering" innovation look like? One of the earliest examples is a community-scale water chlorination technology for rural households, designed by a team of engineers and economists. For user convenience and perceptual salience, it is a brightly colored device placed at high-traffic points of water collection, like springs. It dispenses just the right amount of chlorine to fill the typical household's container, and it is provided free of charge. Its design is based on rigorous studies of users' willingness to pay, their consumption habits, and an understanding of how social pressure influences hygiene practices (Kremer et al., 2011; Null et al., 2012). The system is now being scaled to millions of households across sub-Saharan Africa, with appropriate adaptations; and it is widely viewed as one of the most sustainable modern solutions for providing clean water to rural communities (Ahuja et al., 2015).

Technologies like these leverage important recent insights from economics—for example, the finding that poverty-constrained households do not use preventive health technologies (like insecticide treated bednets) when pricing is non-zero[4] (Dupas, 2014). They are built for specific social, behavioral, environmental, and economic contexts. This means that when markets cannot deliver the desired development impact, the public sector (or civil society) is leveraged as the channel for delivery.

In some sense, development engineering is similar to other problem-focused fields, like environmental engineering and bioengineering, in that it combines two or more disparate disciplines to holistically address a defined set of problems. By definition it is highly interdisciplinary, combining insights from development economics and political science as well as computer science, environmental science, and of course engineering. Similarly, it is applied: there is a limited focus on basic research and an emphasis on identifying innovations that solve problems reliably (and at scale) within complex "real-world" environments. It is unique in its emphasis on the challenges faced by individuals and communities subjected to poverty and marginalization.

Defining Terms: Technology, Invention, Intervention

In this textbook, we refer to a "technological solution" as a technology integrated with the social and economic interventions required to achieve impact at scale. When brought together, these two elements solve a development problem that neither could have achieved independently. In some cases, we will use the word "innovation" in place of the word "solution." To help

(continued)

[4] See https://www.povertyactionlab.org/case-study/free-bednets-fight-malaria.

navigate the jargon-rich world of development engineering, here we define a set of common terms that you will find throughout the textbook.

Technology is the body of scientific and engineering knowledge *and* its application to improve the production of goods, the delivery of services, and the accomplishment of societal objectives. Technology can take the form of novel systems, practices, or processes.

An **invention** is a unique device, method, process, or composition that is technically novel, nonobvious, and often patentable. An invention is the result of a creative process that involves the discovery of something new. It may not require new technology. For example, invention of the lightbulb brought together multiple existing technologies in a new arrangement, yielding a useful and novel product.

An **intervention** is an action taken to effect or modify the outcomes of individuals, populations, and systems. In the context of development engineering, an intervention may be a social or economic strategy designed to change the behaviors of markets, institutions, and households. Interventions can be innovative, and they may involve technologies or inventions, but these are not required.

Development engineering is a practice, but it is also a field of research, with a research agenda that explores how technological solutions (and their design) can be optimized and applied for sustainable development. While the design of technology has been well studied in developed markets, it is less clear how innovations should be designed to solve development challenges. The field aims to generate technological solutions that can be rigorously evaluated, can perform reliably at scale, and can improve millions of lives.

The authors of the various case studies in this textbook speak from experience. They have engaged in research and collaboration across disciplines and over many years. Electrical engineers studying power grids have learned in the field alongside development economists exploring the demand for electricity in rural communities. Political scientists interested in post-conflict state capacity have collaborated with computer scientists on the design of digital governance technologies. They have also advanced the measurement of social and economic outcomes, leveraging tools like remote sensing, mobile data, and networked sensors to observe and understand the process of sustainable development. By learning each other's languages—and defining this new discipline—we are able to form a more coherent, systematic approach to global development challenges.

While we attempt to define development engineering in the opening chapters of this book, the research community has offered several diverse definitions of the field (Nilsson et al., 2014; Agogino & Levine, 2016). Taken together, these perspectives are beginning to shape an important dialogue about technology and its role in sustainable development. We value these contributions, and we aim for this textbook to offer a comprehensible (if not comprehensive) synthesis of research to date.

2 Intellectual History of the Field

The concepts of “engineering for development” and “technology for development” have taken many forms over the last few decades. This section sketches an intellectual history of the field, tracing the different paradigms that have dominated our thinking about technology in resource-constrained settings. We start with research on the broad relationship between technological change and human development and then review the various movements employing technology as a solution for societal challenges. We conclude by explaining how this new field differs from earlier paradigms.

It is well established that technological innovation is central to economic growth. Technological advances, with an enduring consistency, have led to increases in the productive capacity of societies, allowing them to move from scarcity to surplus (Landes, 2003; Nelson & Nelson, 2005). Economic historians have studied this process in great detail, starting with the industrial revolution (Mokyr, 2018; Landes, 2003; Polanyi & Maclver, 1944; Piketty, 2014). Propelled by technological innovation, the industrial revolution had a profound impact on the thinking of philosophers and economists. It introduced the idea that technological transformations can make persistent improvements in economic conditions; it also established the centrality of markets in shaping the economic life of individuals and societies. It introduced the notion that human intervention can actually shift the course of our development (Smith, 2010).[5]

However, the idea that human development could be achieved through policy intervention did not take root until the end of the second World War and the so-called Marshall Plan. Postwar policy initiatives focused on economic growth across war-torn Europe, with the underlying assumption that technological progress would increase productivity and create economic surplus (Landes, 2003, Keynes, 2018). Such progress was “engineered” through large-scale industrialization that was managed by corporations and guided by governments through economic policy. The success in spurring postwar economic growth led to a Western concept of *development* that had well-defined stages of growth, with all societies passing through distinct phases and eventually converging through the diffusion of technology (Rostow, 1960).

In the postwar era, Europe’s success in using large-scale industrial technology to solve the challenges of production led to the transfer of these technologies to less developed countries, with the aim of rapidly transforming their economies. However, this effort to transplant technology was riddled with failures. Not only did many of these technologies (like synthetic fertilizers and large-scale dams) create

[5] Prior to the industrial revolution, economic growth was seen as cyclical. Scholars embraced the notion of a Malthusian trap, an argument that views technical progress as linear and population growth as exponential. Malthus (in his famous essay published in 1798) argued that for a fixed technical growth in resources, small populations will experience greater per capita income, resulting in population growth that overshoots the available resource base. This, in turn, will reduce per capita income, inevitably driving a contraction of the population.

unforeseen environmental harm; they also failed to be widely adopted or fell into disuse (e.g., handpumps to access groundwater).

2.1 Appropriate Technology Movement

The movement for appropriate technology emerged, in part, as a reaction to the frustrations stemming from attempts to rapidly replicate "Western" models of technology-driven growth in lower-income settings. The Western model often excluded community input, treating people as recipients of intervention rather than participants in development.

Peaking in the 1970s and 1980s, the appropriate technology movement argued for small-scale technological solutions that were based on local needs and "appropriate" for the nature of local endowments, rather than implemented by central authorities (Schumacher, 2011, Dunn, 1979). The movement borrowed heavily from the Gandhian ideal of self-reliant village communities. It also viewed the adoption of technology, and its consequences, through the lens of equality, by focusing on *who* adopts a technology, and how the gains from a technology are distributed. As a consequence, the approach has focused on local and indigenous production of (appropriate) technology, so that communities benefit from wider-scale adoption in multiple ways.

Impact on the environment is also a central tenet of the movement, with a strong emphasis on sustainability and the use of renewable sources. An example of a widely adopted appropriate technology is the treadle-pump for irrigation, which is easily constructed at the village level and sustainably enables the farmer to provide water to his or her fields (Adeoti et al., 2007). In reality, this innovation has been delivered through a centralized nongovernmental organization (NGO) to enable product quality certification ("KrishiBandhu"), signaling some of the shortcomings of this approach.

The appropriate technology movement has had a deep impact on how the development community thinks about the role of technology in shaping lives of people in poor communities. It has highlighted the need to pay closer attention to the negative environmental externalities of industrial technology. However, appropriate technologies have not seen widespread and sustained adoption over the medium to the long run. Critiques have suggested that the lack of attention to the role of markets and scalability has limited the success of "appropriate" technologies (Rybczynski, 1980; Willoughby, 1990).

2.2 Market-Oriented Approaches

In parallel to the appropriate technology movement is a long history of leveraging market-based incentives to stimulate innovation for resource-poor settings. The idea of profit at the "bottom of the pyramid," popularized by CK Prahalad, asserts that there are large, untapped market opportunities in low-resource communities that can be exposed by making technologies more affordable for the poor (Prahalad, 2009). Rather than viewing people who live under $2 a day as passive recipients of development aid, this approach views them as consumers of profitable goods and services. Given the very large number of people living in resource-poor environments, even a small profit margin can yield substantial profits at scale. While the poorest households cannot afford a bottle of shampoo or a box of tea, they do desire, and can afford, a small sachet that is cheaply priced. This approach has encouraged corporations to pursue profit while ensuring that people with limited resources can access the products they need. This approach too has its limitations, since it focuses exclusively on needs that can be addressed through market expansion. Large "public goods" requirements—like education and health—are not always effectively met by this approach.

A different market-oriented approach has focused on the productive and creative capacity of people living in resource-poor settings. Challenging the often held assumptions that associate technological innovation with high levels of formal education, this approach emphasizes the entrepreneurial and generative capabilities of the poor as "frugal innovators." The idea is that within resource-constrained settings, local innovators can develop technologies with unique forms and functionalities, tailored to local problems and environments. Anil Gupta's Honey Bee network leverages the traditional knowledge created by grassroot innovators to identify and screen new technologies for scale up (Gupta, 2006). An example of this is the biosand filter, an adaptation of centuries-old indigenous technology that was refined for scale-up in 1990. It is now estimated to serve more than 4 million people in 55 countries.

Like Prahalad's market-oriented approach, the view of people in resource-poor environments as technology creators leads to technologies that are adapted to local contexts and preferences. This can have spillover benefits for wealthier consumers, when products optimized for low-income communities move into developed markets. Indeed the unique nature of innovations from resource-constrained settings has led to a so-called "boomerang" effect, with products designed for scarcity benefiting users in more prosperous economies (Immelt et al., 2009; Winter & Govindarajan, 2015). For example, the leveraged freedom chair which provided users navigating uneven terrain in rural India with added control and flexibility was also successfully marketed in the United States as GRIT Freedom Chair, at a higher cost (Judge et al., 2015). Thus, market-oriented approaches have focused on people in under-resourced conditions as both consumers and producers of technological innovation for solving development problems.

2.3 Humanitarian Engineering

Humanitarian engineering is a paradigm that explores how engineering solutions can be used to provide access to basic human needs—like water, sanitation, energy, and shelter—in response to disasters, emergencies, and other resource-challenged environments. Unlike market-oriented approaches, humanitarian engineering takes a rights-based view, placing the needs of communities as the central motivation behind intervening. It often relies on researchers and innovators contributing their time to develop a technological solution that solves a well-identified problem within a community.

While the field of humanitarian engineering has begun to embrace market-based solutions, for example, through the distribution of cash transfers to households recovering from economic shocks, it is unclear whether private sector approaches actually work, particularly when it comes to provision of goods like water and sanitation (Martin-Simpson et al., 2018). Alongside recent exploration of market-based programming, there has been an emphasis on the design of "dual-use" solutions that operate in an emergency and also enhance community resilience by building preparedness for future emergencies. For example, a project to provide clean drinking water within a refugee tent camp might be taken up by a voluntary organization like engineers without borders but designed to support sustained use as the camp evolves into a longer-term settlement.

Humanitarian engineering has been especially effective when applied to disaster mitigation, a process that prepares disaster-prone communities to rebuild using resilient technologies. For example, the Berkeley-Darfur Stove, developed initially for Darfur refugees, now serves more than 60,000 families in different settings across Africa (see PotentialEnergy.org). UVWaterworks, a water purification technology initially developed in response to a cholera epidemic in India, now serves 26 million customers across 5 different countries (see WaterHealth.com).

2.4 ICTD

The proliferation of information and communication technology (ICT) across the world has fundamentally altered how individuals access and receive information, search for jobs, obtain government services, engage with financial institutions, and communicate with others. With more than 3 billion Internet users worldwide, ICT plays a central role in how under-resourced communities experience social and economic development (WDR, 2016). Gains from access to ICT can be significant for people who previously lacked access to the technology: for example, fish markets in Kerala saw dramatic reduction in spatial price variation after the introduction of cell phones, which allowed fishermen and wholesalers to more easily exchange information (Jensen, 2007). Similarly, M-pesa, a mobile-based money transfer application introduced in Kenya, has allowed millions of people to easily access remittance flows (Mbiti & Weil, 2015). However, the adoption and benefits of ICTs depend heavily on social and economic factors. For example, more educated people living in urban areas are more likely to have access to smartphones (World Development Report, 2016, Pg 167).

The field of ICT for Development (ICTD or ICT4D) has focused on understanding how this digital divide can be bridged, by making access to ICTs more equitable. One thrust of the field is how to reduce information asymmetries, so that remote and disconnected populations can connect to markets. For example, modifications to communication services like interactive voice response (IVR) enable those with low literacy to access relevant digital information (Chu et al., 2009; Mudliar et al., 2012).

ICTD researchers have also partnered with governments to change how states deliver services to their citizens. The most common innovation is the deployment of "helplines" that enable citizens to register their grievances through web-based or IVR platforms. Thoughtful design of these systems can empower marginalized citizens, providing new channels for reporting their grievances (Chakraborty et al., 2017). This approach has also been adopted by civil society, enabling individuals and communities to act collectively and voice their grievances (World Development Report, 2016, Chap. 3). For example, IVR platforms are being used to help smallholder farmers to raise concerns and grievances with local authorities (Patel et al., 2010).

A corrective critical perspective for the field of ICTD explores the inability of technology, by itself, to improve welfare and the need for institutional arrangements that support technological solutions and their effective adoption (Toyama, 2015; Johri and Pal, 2012). Indeed in the private sector, deployment of ICTs often focuses on the end-user and the product, without close attention to institutional arrangements, power dynamics, and the cultural environment of targeted users. For example, the one-laptop per child (OLPC) program aimed to transform learning by providing every child with an affordable laptop. However, it failed to achieve the impact at scale by failing to account for local cultures and preferences within the educational system (Kraemer et al., 2009).

2.5 Human-Centered and Participatory Design

A persistent challenge in "technology for development" is that products are designed by people who are far removed from the end-user's context. Human-centered design (HCD) advocates for a product design strategy that explicitly centers around the daily experiences of people in their native environments. The hypothesis of HCD is that failing to understand and empathize with the user's needs and requirements can lead to failure in adoption when the technology finally arrives at the user's doorstep. As discussed earlier, the water-roller was designed to help women in rural low-income settings access large quantities of water. Yet it fell into disuse as a result of severe design flaws, including failures on uneven terrain and the size of the product, which failed to meet women's needs (Crabbe, 2012). HCD emphasizes the perspective of the user and her environment, focusing on the complete product cycle from interface to manufacturing, distribution, and repair (Donaldson, 2009). A successful example of HCD is the wheelchair by the Gear Lab at MIT, which serves people with disabilities. The specific needs of disabled people living in low-income settings were incorporated into a redesign of the traditional wheelchair model, allowing users to traverse more rugged terrain with greater maneuverability (Winter and Govindarajan, 2015).

A related effort has been that of participatory design (or co-design), which actively involves end-users and other stakeholders in the design process (Spinuzzi, 2005; Steen, 2013). Thus, the consumers of the new technology provide their inputs from initial ideation to finalization and production. The active involvement of the end user ensures that the design of a new product does not leave out needs of the consumers. However, the deep involvement of a small number of end-users can limit the effort taken to get feedback from a larger, more representative sample of customers. It remains unclear whether human-centered design and co-design result in innovations that achieve superior development outcomes at scale. However, they are a promising complement to approaches that focus on market constraints, institutional failures, and social and behavioral norms.

2.6 Development Engineering

Development engineering borrows from many of the intellectual paradigms mentioned above but also differentiates itself in key ways. Like appropriate technology and frugal innovation, it pursues the well-being of people living in resource-constrained environments (as opposed to targeting rapid industrialization, or macroeconomic growth). Yet unlike these movements, development engineering brings attention to the importance of markets and political institutions in shaping human development. As with humanitarian engineering, we focus on sustainability and resilience, yet we also seek to discover the causal mechanisms through which technology shapes sustainable development over the long term. By studying the *mechanisms* of development, development engineering aims for generalizable lessons that extend beyond any one context, population, or environment.

In many ways, this new field follows in the tradition of ICTD, particularly its emphasis on interdisciplinary collaboration. It seeks to bring insights from the rapid adoption and positive impact of ICTs to other important areas of engineering, including some with great economic promise (like off-grid energy and precision agriculture) and some with importance for health (such as wastewater treatment and sanitation). As such, development engineering extends beyond ICTD's focus on information and computing to include civil and environmental engineering, mechanical engineering, electrical and power systems engineering, materials science, chemical engineering, and related disciplines. And unlike market-oriented approaches, development engineering does not rely on one particular strategy for the implementation of a technological innovation: if markets are the appropriate channel, they are leveraged—while not ruling out the option of delivering a technology through government agencies, nongovernmental organizations (NGOs), or communities.

Indeed development engineering has emerged in the absence of a profit motive, driven by university researchers focused on efficiently meeting the unmet demands of disadvantaged people. These university actors have worked alongside international development agencies, governments, social enterprises, and for-profit ventures to create "testbeds" for innovations that can advance progress toward the SDGs. This team-based architecture has allowed for the accumulation of knowledge and the discovery of generalizable solutions, while also facilitating the transition to scale of effective solutions.

On that note, we should point out that development engineering focuses explicitly on the *scalability* of technological solutions. It does not emphasize "boutique" or bespoke solutions to niche problems nor does it rely exclusively on the participatory approaches that some technical groups (e.g., MIT D-Lab) have developed. The scalability and generalizability of research findings are viewed as critically essential and important features of development engineering, while recognizing that scale-up of any innovation will require localization, customization, and adaptation to local conditions.

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