Chapter 3: A Practical Framework for Research

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1 Introduction

This chapter will outline a practical framework for designing scalable technology solutions for disadvantaged communities. We begin with an overview of the common constraints to sustainable development that are encountered in the context of poverty. These constraints are based on a large body of research in development economics, political economy, psychology, and other social sciences; and they help to explain why engineering innovations so frequently fail to achieve outcomes when implemented in the real world. In the second part of this chapter we provide a framework for implementing development engineering projects, consisting of four key activities: innovation, implementation, evaluation, and adaptation. Combining these activities in an iterative (and usually non-linear) path allows the researcher to anticipate and design around the most common pitfalls associated with "technology for development."

2 Innovation under Constraints

To find solutions to thorny development challenges, all researchers need to first build a deep understanding of context and environment. To some extent, this can come from direct observation—from researchers embedding themselves within representative communities, observing the cadence of daily life, learning how it is to walk in the

shoes of the potential users of a future innovation. This approach is central to the success of product design firms like IDEO (Kelley, 2005).

Until recently, direct observation (and other elements of human-centered design) have remained relatively uncommon in the technocentric approaches to "engineering for development" found in many elite universities. Yet development economists, political scientists, and others in the social sciences have invested decades in such work; and it has resulted in generalizable findings about the market systems, institutions, behaviors, and social norms governing life in many low-resource settings. Learning to systematically apply these insights to the design of a novel technology is an essential thrust of development engineering.

This section provides an overview of the common constraints encountered in many developing countries—and to some extent in low-resource communities throughout the world. Without judgement, these constraints are actually just alternatives to the "ideal" market systems and institutions imagined to exist in wealthy countries. In some cases, they have emerged as critical adaptations to local conditions (such as resource scarcity, conflict, colonization, and ethnic diversity). In the engineer's mindset, we can think of these conditions as design requirements, because they can affect the adoption, performance, impact, and scaling of a technological solution. We can also think of these constraints, themselves, as targets for intervention (Soss et al 2011). For example predatory policing, which may be observed as a constraint to economic development, could be directly targeted through the design of mobile applications and political reforms that empower citizens to monitor and report police activity.

In a sense, the most basic constraint faced by people living in poverty is income uncertainty. For survival, humans require continuous access to food, water, heating, cooling, and shelter. Yet poor households, by definition, experience scarcity—not just lack of income, but also income that is lumpy across time. This makes it difficult to invest in basic needs, let alone new technologies. In urban settings, this lumpiness may take the form of irregular income from small family-owned enterprises. These businesses are often constrained by a lack of access to capital (in the form of savings or credit). As a result, they cannot invest in the inventory, marketing, supply chain tools, and other inputs needed to build more reliable profits.

It is a more complex story for households reliant on farming for survival. Agriculture employs the majority of the world's poor, typically on small family-owned farms. Income from agriculture is seasonal by nature: profits are generated largely at harvest time. This cyclic pattern of production creates lumpiness in household consumption. In addition, productivity is dependent on weather and climate conditions, which are highly unpredictable and can vary substantially from season to season, or from year to year. This uncertainty makes it difficult for households to purchase goods or services on a regular basis, and it can also deter households from

large up-front investments in new technologies (even when the longer-term economic benefits of a technology are well understood).

Beyond lumpy consumption, households face a lack of access to savings, credit, and insurance products, all of which are useful for managing risk and smoothing household consumption. This unmet need for financial services—combined with unpredictable "shocks" like climate change, illness, and death—means that many poor households are risk averse when it comes to spending on new products and services.

There are a host of other constraints encountered by low-income households in developing countries (and in many developed countries). In this chapter, we will outline three classes of constraints that the development engineer should consider: 1) market constraints; 2) institutional constraints; and 3) behavioral and social constraints. You may not encounter all of these constraints in a given project, and those encountered may not be binding (meaning that they may not be the bottleneck we need to target). However, these are useful as diagnostic and design tools, and they can help explain why technologies that have worked in "developed" settings may fail when transplanted to a new setting.

These constraints are also ripe targets for technological innovation. Where markets fail to meet the needs of poor households, there may be a technology—say, the capture of real-time information on prices—that can level the playing field for disadvantaged households. When institutions have been captured by elites (creating conditions for inequality), there may be innovations that decentralize ownership of assets, or force transactions to be more transparent to citizens.

2.1 Market Constraints

Markets are the mechanisms through which goods and services are produced, distributed, and consumed; and well-functioning markets can generate clear signals of supply and demand, transmitted in the form of prices. In reality, all markets operate imperfectly, and every country suffers from market distortions (or "failures") that result in the inefficient allocation of resources. Yet the developing world is particularly complex.

In most developing countries, the economy is dominated by the informal sector, which consists of market activity that is not organized, monitored, or regulated by government. This informality, combined with challenges like weak infrastructure and high transport costs, inhibits the development of modern, market-based economies. Informality also reduces government tax revenue and the state's ability to redistribute resources through public benefits programs. As a result, markets in developing countries often fail to efficiently allocate the supply of goods and services to those with greatest demand.

Informality may enhance resilience in some communities and contexts; however, it also intensifies the uncertainty that poor households already deal with. Understanding

informal and imperfect markets—and anticipating their effect on the performance and sustainability of a technology—is key to designing a product or service that will scale. A brief summary of common market constraints is outlined in Table 3.1.

Table 3.1. Examples of market constraints

Lack of insurance (risk) markets: People living in poverty face a diversity of risks, made worse by a lack of formal insurance products. This naturally reduces the appetite for risk-taking. Even innovations that demonstrably improve welfare may seem too risky for upfront investment by households, which is why money-back guarantees, free trials, and warranties can be useful (#ref). Unmitigated risk is a particularly important issue for agricultural businesses, because actuarially-priced crop insurance is still too expensive for most small-scale farmers (Cole and Xiong 2017). Without insurance, the investment in a yield-enhancing technology can be lost to unexpected floods or drought.
Capital constraints and weak credit markets: Firms and households in low-income communities often lack access to the upfront capital needed to invest in a new technology. They may lack savings, or they may face high interest rates for credit. In part this is because lenders incur fixed costs when servicing loans, and partly it is because of asymmetric information and high default rates: people who are unbanked (or underserved by formal financial services) lack conventional credit histories, which makes it difficult for lenders to assess creditworthiness. When developing a solution that requires upfront costs, researchers may need to design smart subsidies, cost-sharing arrangements, or innovative financing to be deployed alongside the solution.
Missing information: Buyers in low-income settings may lack access to information about the products available in markets, particularly if they have limited literacy or live in remote areas. This missing information reduces agency and can prevent households from adopting affordable technologies that could improve their welfare outcomes (#ref). Sellers in these settings may also lack access to information, including demand signals, as a result of missing market data. While digital receipts are the norm in developed countries, these enabling technologies have not yet penetrated the majority of small merchants in developing countries. As a result, sellers may not have the consumer insights needed to stock the right inventories. Finally, SMEs often have weak knowledge of management practices; where such practices are widely adopted, they can increase the efficiency of production and trade (McKenzie 2020). An example is the adoption of improved

agricultural practices by small-holder farmers; farmers may lack information about how to optimally weed or manage pests, and simply providing information provision can increase yields (Fabregas et al 2019). Of course it matters how the information is presented, and many have observed that conventional trainings for farmers or SMEs fail to improve outcomes (Bridle et al 2020, McKenzie 2020).
High transaction costs: For remote households, the travel to markets to buy a product can be prohibitively costly, even where subsidized public transportation is available. In addition to transport costs, households may face high opportunity costs when accessing certain products; losing a day's income on travel to a distant market can have serious implications for daily earners. In addition, there are the costs of searching for the right product to meet needs; it can be difficult to gather information about product quality and prices, since they are often opaque or negotiable in informal markets. Collectively, these transaction costs can put welfare-enhancing technologies outside the reach of low-income communities.
High transport costs & shallow markets: Lack of physical infrastructure (like warehousing and roads) increases the cost of transporting goods. This can make it prohibitively expensive to transport goods to market, particularly those requiring refrigeration. These high transport costs make it difficult for buyers and sellers to enter into transactions. As a result, small rural markets are particularly isolated from larger markets, leading to price variation and spikes in supply and demand. Middlemen with access to transport often exploit price variations as arbitrage opportunities; this undermines more inclusive development by pushing profits for agricultural production toward traders, rather than producers.
Labor market failures: Inefficiencies in the labor markets of the developing world are driven in part by the high costs of job search for would-be workers, as well as asymmetric information between employers and job seekers. It is difficult for job candidates to signal their skills and training, in part because of unregulated training firms and counterfeit certificates. There are also lumpy labor supply cycles in agricultural settings, due to harvest cycles: for parts of the year there is too much labor, and at other times there is too little. Seasonal migration from rural to urban centers can overcome some of this, but there are high upfront costs for laborers looking to migrate. These frictions in labor markets make it difficult for businesses to grow, consolidate, and achieve economies of scale. For the developer of a new technology, labor market failures can also introduce difficulties in establishing the technical workforce needed to operate, support, and maintain a solution.

Input and output market inefficiencies: To maintain profitability, firms must sustain business operations (or other productive activities) over time. However, interruptions and inefficiencies in business operations are often introduced by upstream and downstream failures. For example in agriculture, a lack of reliable access to fertilizer can reduce crop yields, while lack of access to markets reduces farmers' bargaining power over the prices they receive. Traffic congestion can introduce uncertainty into the delivery times for key inputs and outputs, resulting in wastage and other inefficiencies. Also an issue is the seasonality (or temporal variation) of input and output markets, particularly in agriculture and related businesses. Seasonality introduces time-sensitivity, by requiring that inputs or outputs be available at specific points in time.

Market-distorting policies: As we all know, well-intentioned government policies can create distortions in how markets function. In many cases, government subsidies for food (which are intended to improve people's welfare) can make it difficult for market-based innovations to succeed. For example, governments often procure staple crops from farmers at a minimum support price. This can limit the development impact of technologies that improve farm-to-market supply chains, since higher input costs are not recovered from market prices (#ref). Government subsidies, taxes, and mandated commodity pricing can all introduce inefficiencies in markets and need to be accounted for by researchers developing technologies that leverage market-based processes for successful implementation.

Lack of Quality Grading: The lack of standards and certifications in informal and less developed markets—for example, the lack of technology to grade the quality of agricultural produce—can affect the price received for goods and services (#ref). When quality information is not signaled, the market does not return the expected premium to producers of higher quality goods. As a result, the incentive to provide higher quality goods is eliminated.

Missing Human Capital: A common challenge in low-resource communities is under-investment in "human capital" or human potential, which begins at primary school and carries through to higher education. For product developers, this can mean a lack of access to trained workers to produce, distribute, or support a product. It may also mean that you need to invest more in onboarding users and building their confidence in using a new product. Ultimately, missing skills and expertise can limit the ability of new technologies to achieve impact, and can affect the efficiency of firms, particularly in areas of management (McKenzie 2020).

2.2 Institutional Failures

Organizations, in particular government bureaucracies and non-governmental organizations (NGOs), play a critical role in delivering basic services to people in developing countries—from water, sanitation and education, to pensions and social protection schemes. Many low-income households rely on these formal institutions, whose operations are guided by written rules and laws, for their welfare. At the same time, people in resource constrained settings also rely on informal arrangements[1], like social networks, based on kinship or caste for accessing services. For example, it is common for villagers in rural settings to finance loans or emergency support from family members or money lenders within the village.

Both formal and informal institutions can introduce inefficiencies and distortions in implementation of new technologies or policies (Helmke and Levitsky, 2006). For example, ethnic or provincial community leaders may hold socially important positions in communities and may limit the power of members appointed by governments to manage local governance. In the absence of effective community oversight, these local leaders control the functioning of the state apparatus, and divert government resources aimed at creating public goods for private benefits (a process known as "elite capture"; see Bardhan and Mookherjee, 2012). Thus, governments often find that their policies fail to achieve outcomes for disadvantaged communities, or that outcomes differ from a policy's stated objectives. For example, states in resource constrained settings tend to generate less tax revenue than targeted, due to weak collections and audit capacity as well as missing infrastructure.

Therefore, in large parts of the world where formal institutions are inefficient or weak, informal institutions remain relevant and effective at meeting the needs of citizens. Indeed informal institutions, like their more codified counterparts, can establish and enforce rules, negotiate disputes, distribute shared resources, and constrain social behavior. However, informality is also challenging for the scale-up of a technology: informal institutions often follow tacit rules, known only to "insiders". By their very nature, informal norms and institutions (particularly those without written record) require context-specific understanding. Researchers who want to successfully implement and scale up new technologies need to invest time and resources in trying to understand how informal institutions behave in resource poor settings. A few examples of commonly encountered constraints are given in Table 3.2.

Table 3.2 Examples of institutional constraints

[1] See Helmke and Levitsky, 2006 for understanding the role of informal arrangement. They describe informal institutions as "created, communicated, and enforced out- side of officially sanctioned channels".

Elite Capture: A pervasive challenge in developing countries is the capture of formal (and informal) institutions by elites. Elites capture resources for private benefit rather than for (intended) public use (Bardhan and Mookherjee, 2000). Elite capture is also linked to political patronage networks where resources are used to monitor and control how citizens and communities elect political representation (Stokes et al, 2013, Kitschelt and Wilkinson,2007). Thus officials may often be unable to adhere to rules and guidelines while implementing public policies.
Intermediaries: Intermediaries are pervasive lower-level actors that use private information or networks to impose "rents" on individuals seeking their rightful access to public services (Bertrand, 2007). This takes the form of bribes or speed-money paid by citizens to get their requests processed by an institution or bureaucracy. Intermediaries rely on social norms and strong social networks to help citizens get access to government services (Wisoe,2007). The presence of intermediaries is also linked to the inability of citizens to directly hold the bureaucracy accountable.
Weak contracting environments: In resource constrained contexts, the ability to enforce contracts is often weak or absent due to limited resources available to governments. Thus the process of seeking judicial redress for lack of adherence to contracts can take years if not decades. Even contracts with governments may not be implemented properly due to lack of transparency, red tape, or corruption (Gupta, 2012). This introduces uncertainty into business transactions and can reduce trust in formal institutional processes.
High transaction costs: There are often heavy user costs for "free" services provided by government agencies. Because formal institutions in developing countries are often inefficient, they often impose costs on those seeking access (in the form of high transport costs to reach a government agent, long delays in the administration of benefits, or expensive documentation required to qualify for benefits). Thus many citizens avoid these high transaction costs by seeking the help of intermediaries to get government approvals.
Principal-agent problems: Principal agent problems arise when the goals of the "principal" (a person or group with authority) are misaligned with the incentives of the "agent" performing a service on the principal's behalf. Governments regularly face this challenge, for example when programs formulated by political leaders need to be implemented by local officials. Ensuring that the local official

implements the program appropriately (rather than shirking duties, skimming resources, or altering protocols) requires sophisticated monitoring systems. Without these, the principal cannot ensure that agents are performing. In low-income countries, governments are resource constrained and underfunded. As a result, higher levels of government are often unable to monitor the actions of local officials authorized to act and interface with citizens on a day to day basis. This leads to poor performance in the delivery of public services, as the government fails to enforce performance contracts. The lack of monitoring results in absenteeism among officials and increases the corruption and leakage from public programs by agents of the government.

Principal-agent problems also exist between politicians and citizens. Voters are the principal (they are the ultimate source of authority). Yet they can only hold politicians (the agents) accountable at the ballot box, which gives just one opportunity for accountability every 4-5 years. In the interim, communities should have access to effective grievance redressal systems-- channels through which citizens can voice their dissatisfaction with government. Yet these are often unavailable to disadvantaged communities. The same is true of civil society. A well-funded civil society (including watchdog groups, advocacy organizations, universities, and religious institutions) is required to hold the government accountable. In wealthier countries, this is funded by a combination of philanthropists, government grants, and individual citizens -- as in the case of news subscriptions supporting independent journalism and independent news media. There is limited capacity for civil society oversight in developing countries and in many disadvantaged communities.

Asymmetric information (and disinformation): Lack of literacy and education limits the extent to which written information can be expected to spread across different segments of a community or society. Of course the advent of smartphones and greater internet penetration is rapidly changing how information is disseminated. Still, individuals may lack the ability to seek out credible information sources, due to limited social networks or lack of connection to government decision-makers. This can result in rapid spread of misinformation. There is also asymmetric information between citizens and politicians, which makes it difficult to hold government agents accountable.

Collective action failures: Cooperative arrangements (across individuals, households, and firms) are essential to capture economies of scale, for example through bulk purchasing, industry-wide standardization, and collective marketing. Coordination is also important to increase bargaining power (e.g. labor unions

among workers, farmer cooperatives for smallholders), invest in public goods (e.g., infrastructure and education), and manage shared resources (e.g., water for irrigation). Disadvantaged or marginalized groups often find it difficult to bargain collectively for their rights; they may also struggle with cooperation due to cultural factors (Ostrom 2010). Part of the challenge is due to limited social capital. Societies with limited social capital (i.e reduced trust and sense of reciprocity among individuals) find it difficult to leverage collective action. Ethnic diversity also contributes towards the challenge of collective action, with more homogeneous societies being able to overcome collective action challenges (Habiyaramana et al, 2007).

Weak social capital: In communities that have experienced colonialism, civil war, and other forms of violence, there is often a lack of trust among individuals. This loss of social capital leads to lack of trust in institutions. Individuals may not view institutions as fair, or impartial, and working in the common public interest. Limited social capital can reduce the ability to act collectively.

2.3 Social Norms and Behaviors that Constrain Development

Communities and individuals living in poverty face unique behavioral and cognitive constraints that affect their decision-making about technology. There are also social norms that—while not clearly related to poverty or development—appear consistently in certain contexts. Some of these are outlined in Table 2.3.

Table 3.3. Examples of norms and behavioral constraints

Cognitive Biases: While lack of information impacts how individuals in resource-constrained settings make economic decisions (about their jobs, investment in children's education, household expenses, savings, etc), this alone does not predict a household's decisions. A large body of research from psychology and behavioral economics demonstrates how decision making is influenced by cognitive biases that are exacerbated when decisions are being made under the pressure of resource constraints (Mullainathan, 2013;Banerjee and Duflo, 2011). These biases are often due to cognitive scarcity, or to reduced attention available to allocate to tasks (given high levels of uncertainty and routine income shocks that poor people must weather). Cognitive biases can prevent or slow adoption of promising technologies, and researchers implementing new technologies should take the biased nature of decision-making into account (Mani et al 2013).

Intra-household bargaining: While products or technological innovations are targeted towards individuals, the decision to adopt the product is taken at the level of the household. Resource constrained settings are characterized by households where members need approval or consent before taking individual decisions. The nature of intra-household bargaining has a large and adverse impact on women for whom new products and technologies are often being introduced, but who lack the economic and social agency to make the decision to adopt new technologies without the consent of other household members (elders like mother-in-law, or husband). For example, while mobile phones have rapidly spread across developing countries access to them is often gendered with men being able to access them more easily (Joshi et al, 2020; Women, G. C. (2018)). Intra-household bargaining, and women's limited control over resources needs to be accounted for when designing new technologies
Social norms: Individual decisions are heavily constrained by societal norms and rules, especially in rural communities where individuals have limited anonymity and interact with other members on a regular basis. In such settings the decision to adopt a new product can both be sanctioned or influenced by community norms. For example, in poor villages people with limited resources take loans to organize a lavish wedding in order to meet expectations from the community. Similarly, in Brazilian favelas social norms related to family size were induced by telenovellas, which depicted the lives of female characters (single in their 30s - poor economics).
Social learning: Learning and gathering information is often a social process. Women's self help groups have often been used to disseminate products (for example microfinance interventions or sanitary products are often introduced through SHGs), since they facilitate social learning.
Aspirations: Aspirations are affected by societal expectations, peer pressure and sanction within communities. These mental constructs can influence individuals' decisions, including about investments of effort, attention, and other limited resources.
Mental Models: There are assumptions about what researchers know, and what power they have, derived from people's experiences with colonialism, inequality, and poverty. These experiences are internalized and can deprive individuals of agency and a sense of self-efficacy, instead endowing outsiders with authority. (#ref)

Mood disorders (depression): Mounting evidence suggests that poverty is a driver of depression, which has disabling effects on people's well-being, productivity, and ability to provide care for others (Ridley et al 2020). In some cases, it may be useful to design a new solution with the expectation that end-users are suffering from depression, which can affect decisions and behaviors.

Box: Reviews of market, institutional, and behavioral constraints

Below is a collection of practical white papers outlining the constraints faced by households, institutions, and markets in developing economies. These are organized by sector, making them a useful resource for engineers and development practitioners. Additional reviews of the evidence from international development research can be found at the *International Initiative for Impact Evaluation* (http://3ieimpact.org).

Agriculture

https://www.atai-research.org/wp-content/uploads/2019/03/Experimental-Insights-on-the-Constraints-to-Agricultural-Technology-Adoption_March2019.WorkingPaper_FINAL.pdf

https://escholarship.org/content/qt6m25r19c/qt6m25r19c.pdf

Governance

https://www.povertyactionlab.org/sites/default/files/documents/Introduction%20v%20October%202013.pdf

Digital Identities and Finance

https://www.povertyactionlab.org/sites/default/files/2020-03/DigiFI_framing-paper_june-2019.pdf

Post-Primary Education

https://www.povertyactionlab.org/sites/default/files/2020-03/PPE_review-paper_executive-summary_2013.05.07.pdf

Cash Transfers and Child Health

https://www.povertyactionlab.org/sites/default/files/2020-03/CaTCH_review-paper_cash-transfers_2018.10.09.pdf

Gender and Women's Agency
https://www.povertyactionlab.org/page/what-works-enhance-womens-agency

Labor Markets
https://www.povertyactionlab.org/sites/default/files/files/2020/03/JOI_Full-and-Pilot-Proposal-Application_Spring%202020.docx
https://doi.org/10.31485/pi.2234.2018

Urban Services
https://www.povertyactionlab.org/sites/default/files/2020-03/USI_review-paper.pdf

Youth and Employment
https://www.povertyactionlab.org/sites/default/files/documents/YouthReviewPaper_March_2013_0.pdf
https://www.povertyactionlab.org/sites/default/files/2020-03/SYP_review-paper_2017.pdf

3 Framework for Research

As the previous section outlines, the success of any innovation requires deep understanding of the constraints - market, institutional, and behavioral - that can prevent adoption of the solution and its impact at scale. These constraints inform the design of technology, and they can also affect our ability to implement high quality research. Years of field work have resulted in a set of best practices that we present here, as a **practical framework** for advancing promising technologies from the lab to the field. The most important guiding principle behind this framework is its emphasis on feedback and iteration, and the avoidance of a linear implementation process.

The practice of development engineering focuses on the entire arc of innovation -- from problem discovery and technological invention, to prototyping and pilot testing, to impact evaluation and finally adaptation for scale-up. These stages are part of a continuum, and they are not necessarily carried out in sequence. In some cases, the real-world evaluation of an existing product will lead to the design of an entirely new technology, based on iterative feedback from users. The chlorine water dispensers developed by Miguel, Kremer and colleagues is one example (Null et al, 2012). In other cases, a novel technology will enable measurement of development outcomes at higher frequency or resolution, leading to the discovery of new problems and opportunities (ref Blumenstock et al, 2015, also see Chapter 15 in this textbook by Wilson).

Each of the following chapters in this textbook will describe a unique research workflow, but they will all be placed within the framework of four activities: innovation; implementation; impact evaluation; and adaptation for scale (see Figure 1).

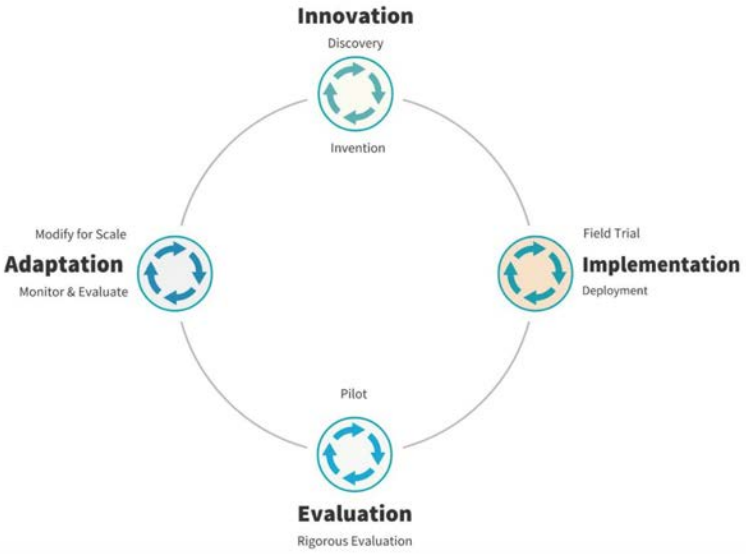


Figure 3.1: Iterative Framework for Development Engineering

Innovation

Innovation is at the heart of every development engineering intervention or solution. It is the process of discovering and characterizing a problem, and then developing a generalizable technological solution -- one that can address the challenge at scale. The innovation can lie in adapting an existing technology to solve a new problem (for example, by bundling a well-known technology with a novel economic, political, or behavioral intervention); or it might lie in designing an entirely new technology around any of the constraints outlined earlier in this chapter. The innovation may even lie in creating new ways to measure development outcomes, either through instrument design (like a wireless cookstove sensor) or the design of new analytic techniques (like the use of remotely sensed imagery to predict household asset wealth).

However, the discovery of a suitable problem, and the development of the design requirements for a solution, is never linear; it requires a critical and evolving understanding of local context. As an example, we consider the design of a treatment system for removal of arsenic from drinking water. First, we investigate the

experiences and environment of households affected by arsenic contamination (mostly people living in rural Bangladesh and Eastern India). In this context, tubewells are the main source of drinking water, household asset wealth and consumption are low, and willingness to pay for safe water is almost zero (#ref). Perhaps there are collective action failures in the maintenance of existing water infrastructure, and community trust of outside organizations is limited (#ref).

The engineer's goal is to solve the problem of access to clean water, using a combination of technological and social innovations to overcome these hypothesized constraints. The solution must address market failures, institutional challenges, and the preferences and behaviors of people facing arsenic poisoning -- in addition to their public health needs. These constraints can be shaped into the solution's design space, in the form of performance parameters (e.g. failure tolerance, reliability, salience, desirability, cost, accessibility). It is also important to anticipate any negative externalities created by the innovation, such as wastewater production and environmental contamination.

Once the problem has been defined, the constraints characterized, and a solution prototyped (often just on paper), the researcher can begin to articulate a theory of change: a set of hypotheses about how the proposed solution overcomes observed constraints. This is the key output of the innovation activity: a prototype, and a set of hypotheses that are to be tested. But how do we get here?

To develop basic insights about a community's development challenges, researchers often use qualitative approaches like ethnographic observation and human-centered design (HCD).[2] Much has been written about these methods, and we refer readers to useful resources in Box 1. In addition to these methods, development engineers often consult existing data and survey research to understand their targeted communities. Well-designed surveys can offer a nuanced and representative view of users' perceptions and preferences. Examples include nationally representative datasets like the Living Standards Measurement Surveys (Grosh and Glewwe 1995) and the Demographic and Health Surveys (Corsi et al 2012), as well as large-scale survey research projects published in journals of development economics and political economy. In addition, national statistical offices in most countries publish census data

[2] Human-centered design (HCD) is a pervasive new approach that offers detailed toolkits for implementation (ref IDEO). It often encourages practitioners to set aside knowledge of existing solutions, instead entering the design process with as few assumptions as possible. It focuses on listening and responding to users and building empathy for their lived experiences. However, users can provide incomplete, biased, or irrelevant information, and there is growing concern that these newer approaches lack evidence of effectiveness, despite their popularity (Robertson and Salehi, 2020;Sloan et al, 2020, Thomas et al, 2017).

at intervals, and they may release other de-identified administrative datasets. Large non-governmental organizations (NGOs) often publish their own datasets, in areas like education (Banerji et al 2013; Mugo et al 2015), health (Murray et al 2020), and politics (Afrobarometer Data). Resources like these are described and referenced in many of the chapters in this book.

Of course there are many challenges in collecting reliable survey data in low-resource settings (Iarossi 2006), and these have been deeply documented across a range of domains—from health, nutrition and gender to welfare and politics (Caeyers et al 2012, Glennerster et al 2018, Lupu and Michelitch 2018). Issues with survey data include sampling errors, respondent biases, and small sample sizes (because budgets for survey research are always limited). There are other sources of unexplained variation in survey data, as well—artifacts that are introduced throughout the surveying process. These range from the selection of interviewers (West et al 2017) and the nuances in the wording or in the order of presentation of survey questions (Blair et al 2020), to the length of a survey and how you compensate study participants (de Weert et al 2020).

To improve the reliability and reproducibility of survey results, some researchers carry out intensive qualitative research with random samples of individuals surveyed in quantitative surveys, particularly in cases where survey questions address sensitive issues like corruption, crime, or other risky behaviors (Blattman et al. 2016). Some researchers now publish their survey protocols, or use published questionnaires that have been validated against more reliable methods of data collection. Still, there are few repositories that allow you to browse and search for questionnaires by geography, population, or topic. You will often need to sift through the supplementary materials published as part of academic journal articles (in fields as diverse as sociology, anthropology, economics, political science, and public health) to discover existing survey instruments.

To supplement survey datasets, researchers are also turning to digital technologies that capture complementary and (in some cases) less subjective information about context within their communities of interest. For example, financial transactions using mobile phones or debit cards can offer a view into consumer behavior including purchasing patterns (Bachas et al 2017), loan repayments (Björkegren and Grissen 2018), and social insurance mechanisms (Blumenstock et al 2016). Remotely sensed data—like satellite imagery or drone video footage—allow us to directly observe agricultural yields and management practices from the sky (Lobell et al, 2019). Data extracted from social media platforms can expose relative poverty (Fatehkiah et al 2020) as well as popular sentiment and prevailing social norms, using natural language processing to automate analysis (Calderon et al 2015). Technology companies like Facebook have begun leveraging internal, georeferenced transaction logs to produce a range of datasets, from human population density to international firm surveys

(Stevens et al 2019, Schneider 2020). Anonymized call detail records and geolocation data from mobile phones can also reveal household outcomes—from consumption patterns and asset wealth, to migration decisions and response to violence (Aiken et al 2020, Blumenstock 2015, Chi et al 2020, Blumenstock et al 2018).

Insights obtained using these large-scale datasets can be useful to understand context, and also to measure development outcomes. However, few of these methods have been extensively validated against "ground truth". In addition, these digital data sets carry their own biases, for example based on who has access to mobile technology, or on which communities have been surveyed enough to train a machine learning algorithm based on satellite imagery.

Ultimately, the data take us only so far. It takes decades to build deep knowledge of the development constraints facing any country or community. It requires knowledge of domestic and regional politics and economic history; it requires familiarity with local views about colonialism and its legacies. It also requires understanding a nation's struggles with ethnic and gender identity. Perhaps this creates a natural imperative to collaborate with researchers, policy-makers, and civil society organizations based in the communities you wish to empower. Inclusive, respectful partnerships with local actors are key to many successful development engineering projects, and this success relies on the alignment of incentives for all participants.

Box: ***Leveraging Data to Define Your Problem Set***

- Qualitative research reported in academic publications, using a variety of methods (#ref):
    - key informant interviews
    - focus groups
    - direct observation
    - ethnography
- Quantitative survey research:
    - Academic research surveys of specific populations, including in-person enumerated surveys or mobile surveys (administered via call centers, Interactive Voice Response, or Short Message Services)
    - Nationally representative government surveys and census data
    - International surveys like the Demographic and Health Surveys (DHS) and Living Standards Measurement Surveys (LSMS).
- Administrative data:

- Transactions records generated in the delivery of services by health systems, schools, government agencies, cooperatives, and other public organizations.
- Customer transactions records generated by retailers and other private sector firms.

- 'Big' data:
  - Social media traffic scraped from public sources or accessed through agreements with technology firms.
  - Satellite imagery, including public and private assets.
  - Anonymized call detail records accessed through agreements with mobile network operators.
  - Geolocation data captured through consumer smartphone applications.
  - Networked sensors (e.g. personal activity monitors, grid electricity sensors, and precision agriculture devices) that capture large volumes of environmental or behavioral data.

Implementation

Implementation is the process of piloting a new innovation, monitoring its technical performance in the field, and understanding the factors that influence "effective" implementation. This is in sharp contrast with the linear (and often idealized) model of the engineer moving directly from invention to impact. An iterative approach is required -- a multistage progression from invention, to pilot, to full deployment -- with feedback loops. We must frequently return to earlier stages of our research to update our hypotheses and theories of change. Each assumption is revisited in light of the data and insights gained from the previous iteration. This iteration -- the process of advancing, updating, and retrialing -- can start within the lab. But it is also part of the move from the lab to field trials, or the expansion from one market to another.

In industrialized countries, such iterative loops are relatively commonplace in product development. Technology firms have specialized teams focused on product marketing, user interaction, design, product management, engineering, quality control, sales and growth, and financing. Because these activities are well-resourced and have been well-studied, they result in relatively reliable processes of iteration. In the context of development engineering, often the same team is blessed with the burden of taking a technological invention from the lab, all the way to product development, evaluation, and distribution. There are plenty of stumbles and failures along the way. This framework therefore focuses on training the practitioner to cultivate a learning

mindset, treating each iteration as a valuable learning opportunity, and remaining ready to investigate and pivot when outcomes diverge from expectation.

The implementation stage does not focus on technological prototypes alone. It also involves the design, testing, and refinement of different business models (or delivery models) for a technological solution. At this stage, it is useful to test hypotheses about users' willingness to pay, or about how they access information. This is a good time for using experimental methods that reveal the demand for a new product or service, including pricing experiments as well as behavioral games (like take-it-or-leave-it studies) that can reveal people's preferences (Dupas et al 2013).

At this stage, the development of sound partnerships also becomes paramount. Innovating in a resource-constrained setting can be challenging because it often requires coordination across multiple partners, each with differing standards, norms, and incentives. One partner may support small-scale manufacturing, while another carries out field testing. Still other partners may be needed to collect user feedback, or implement rigorous evaluations. The researcher is often reliant on local partners to understand the local context and effectively implement studies, deployments, and experiments. These partners may deprioritize the project, or deviate from agreed plans, because of internal challenges or as a response to the external environment.

The weakness of government or community institutions can also constrain the ability to implement a project effectively. Piloting of new technologies may be regulated by governments, and research involving humans is always overseen by local review boards. Yet a lack of transparency can make it challenging to obtain the necessary permissions for experimentation. Researchers must learn local processes and find ways to overcome institutional challenges. Iterative implementation allows the researcher to discover the optimal implementation strategy over time, learning how the solution will ultimately perform in the targeted setting.

Evaluation

The evaluation component of the development engineering framework focuses on using scientific approaches (i.e. randomized controlled trials and quasi-experimental methods) to isolate the causal impacts of an innovation. We are interested in understanding the effects of a new solution on human and economic development; we also want to accumulate knowledge that can generalize to new contexts. Evaluation plays a central role in development engineering, in part because the field is in strong need of better evidence. If we fail to learn from our work, we will perpetuate the "valley of death" between tech-for-good innovations and their successful scale-up.

In this framework, we emphasize evaluations that test hypotheses and rigorously investigate how a technology affects health, economic, and other outcomes in the "real world." We are also interested in exposing barriers to technology adoption, and testing our theoretical models about the optimal delivery of a technology. In some cases, we

may want to measure spillovers (or unintended consequences) of an innovation, or to assess long-term effects. While a short-term evaluation might show strong initial take-up, later follow-ups often expose disuse, environmental costs, and other failures that dampen benefits.

We may use surveys to collect self-reported outcomes, or we may use sensors and other networked devices to automate the monitoring of outcomes. We may choose to instrument our solution, so that ongoing evaluation is incorporated into operations. Regardless, by designing your evaluation carefully, you can investigate whether the failure of a technological solution stems from technology design itself, or from the delivery model. If the failure is due to a flawed business model, evaluation results can be used to modify pricing or design a new financing scheme. If the failure has to do with technology design -- for example, if the volume of human waste collected from a community is too limited to support continuous urea extraction -- the results of evaluation can be used to refine design parameters and develop a more appropriate solution. A good evaluation allows for design iteration -- with researchers incorporating the feedback into redesign -- and also yields generalizable knowledge that can be applied in new contexts.

While many researchers will evaluate their solution at pilot scale, with careful control over implementation, there can also be value in deploying and evaluating a technology at large-scale (e.g. nationwide). This teaches us something about the effectiveness of a solution at scale, when it is implemented under less controlled conditions (see Chapter xx, on evaluation of *Aadhaar,* India's national digital authentication program). There is also value in evaluating a solution deployed across multiple contexts, in tandem, through portfolios of field experiments that test a shared hypothesis. This teaches us about the variations in effectiveness across conditions, and can also reveal the sorts of adaptations that are required for an innovation to succeed at large scale (ref meta-keta, WSH eval).

Adaptation

Scaling up involves taking an innovation from the evaluation stage (with evidence of positive impact, albeit on a limited number of users) and adapting it to reach a larger number of users, and to reach users in new geographies. The process of maintaining a technological solution at scale comes up with its own unique challenges. For example, for scale-ups that rely on market processes, the business model becomes a critical factor determining long-term sustainability. There will be challenges in managing deep supply chains, which requires strategies for mitigating risks from the market frictions commonly found in developing countries. Operations and maintenance, along with monitoring for quality assurance, will require critical attention. In addition, customer "success" may require not only technical support, but also costly investments in user training or onboarding, particularly for communities that have not interacted

extensively with your class of technologies. Some innovations will require intellectual property (IP) protections to ensure broader use and scale-up. However, IP regimes in resource poor countries may be poorly designed or weakly implemented, making IP protection a risky choice for researchers.

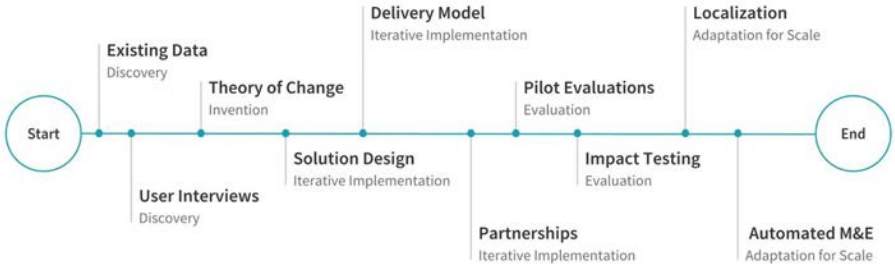
For scale-ups implemented in partnership with governments, it is key to navigate the political economy of institutions (and the incentives of those with vested interests) as well government regulation, legal challenges, and the role of civil society in oversight. Further, public institutions responsible for implementing or disseminating services may fail to adhere to the researcher's well-defined standards, which can compromise the fidelity of implementation. This is an issue in many under-resourced communities, where there are high rates of absenteeism among frontline workers who are also overburdened with administrative tasks and responsibilities (Finan et al, 2017). The prevalence of corruption, along with weak monitoring of government workers, can also make implementation of projects a challenge.

The success of scale up efforts is closely linked to the concepts of evaluation and iterative implementation. Evaluations conducted as part of small-scale field pilots allow the researcher to understand the challenges of implementation and gather evidence of a solution's impact. Ideally these evaluations also reveal the mechanisms through which a product acts, and expose any required or enabling conditions. This generalizable knowledge enables scale. As we move from the pilot context to a larger scale, or from one country to another, we can then test whether the conditions for intervention success are found in new target environments, and target scaling efforts where the innovation is most likely to achieve impact (Bates and Glennerster 2017).

Several successful examples of scale-up, from chlorine dispensers to provide clean water to deworming tablets were first piloted at a smaller scale. There are also examples where attempted scale-up without evaluation led to failure. For example, the Embrace infant warmer developed to work in poor countries with limited health care facilities (Pg 71, Jugaad), proved effective in pilots but failed to find traction after initial adoption.

The case studies that follow are written to tie these processes -- innovation, iterative implementation, evaluation, and adaptation -- together. They demonstrate how feedback from one stage informs the next. The framework (and this textbook) will also undergo iteration, as new ideas are incorporated over time.

Figure 3.2 The Path of Development Engineering



4 Additional Resources

In addition to this textbook, there is an expanding pool of resources available to researchers in Dev Eng. These include the open access peer-reviewed journal *Development Engineering: the Journal of Engineering in Economic Development*. This journal publishes original research across multiple areas of DevEng, including:

- Engineering research and innovations that respond to the unique constraints imposed by poverty.
- Assessment of pro-poor technology solutions, including field performance, consumer adoption, and end-user impacts.
- Novel technologies or tools for measuring behavioral, economic, and social outcomes in low- resource settings.
- Lessons from the field, especially null results from field trials and technical failure analyses.
- Rigorous analysis of existing development "solutions" through an engineering or economic lens.

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