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Novel Approaches for Scaling up Engineering-Based Inclusive Innovation

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Abstract. Given their obvious need, why is it so hard for new pro-poor, engineering-based inclusive innovation (EII) to become more mainstream? Can new trajectories emerge that are more inclusive and environmentally sustainable? Those interested in these questions have studied the role of science and engineering in development but have faced a range of constraints. These include the poverty of those who might benefit most but also institutional barriers to the inclusion of some actors with knowledge and experience of scaling innovations towards the mainstream. This paper presents new theories and a set of case studies of attempts to scale and mainstream innovations. We have gathered data from and analysed scaling up case studies from different sectors and geographies. The paper advocates for the advantages of evolutionary approaches to development engineering that take account of institutional variety over static, neo-classical and one-size-fits-all approaches. We show that one size fits all does not apply to scaling up for engineering-based inclusive innovations. We illustrate that engineering innovations not replicated on a large scale have not necessarily failed. We conclude by arguing that it is possible to go beyond market failure approaches towards a more agile framework for the delivery of innovations and suggest that our results resonate with broader changes in the greening of the global economy.

Keywords. Scaling up, Development engineering, Transdisciplinary engineering, Engineering-based inclusive innovation, Evolutionary approaches

Introduction

Engineering for Development (E4D) links global development and engineering by building solutions for societal challenges for people generally left out of the development process [1]. Previously, E4D was considered a marginal and ‘appropriate’ solution that failed to integrate into mainstream economy and society. Huge efforts by well-meaning, talented, and hard-working individuals and teams have designed and built prototypes aimed to solve poverty and inequality but failed to be widely taken up, remaining utopian and often forgotten. However, previous research analysing Research Excellence Framework (REF) 2014 cases of E4D shows signs of socially and institutionally aware engineering in complex and uncertain environments [2]. It also highlights the beginnings of scale-up and integration of networks and communities to solve pressing societal challenges [2]. Building on this work, in this paper, we conceptualise serious efforts applying science and engineering to address societal challenges and real-world impact as engineering-based inclusive innovations (EII), which are more than just technofixes.

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Given the increased focus on scaling up, our aim is to understand what scaling means and investigate the pathways to scale-up and mainstreaming of EII across sectors and geographies. Scaling up is generally associated with expanding interventions or innovations into new contexts to ensure the broader societal impact of innovation. Improving understanding of scaling involves assessing impact, typically transitioning from the pilot phase, where innovation is the key process, to scaling, where diffusion becomes paramount, and wider stakeholder involvement is critical [3]. Various research areas delve into these two aspects of scaling, including social innovation[4–6], pro-poor initiatives focusing on the bottom of the pyramid [3, 7] and more recently, development engineering [8] and inclusive innovation [9, 10]. The paper has three sections. Section 1 reviews extant literature to develop conceptual underpinnings of scaling EII, frameworks and their underlying assumptions. Section 2 follows up with case studies from previous work [2] alongside recent cases across sectors and geographies by reviewing extant literature. The case studies discussed are high-tech engineering solutions - not merely cheaper alternatives - designed with an understanding of institutional contexts, exhibiting signs of scalability by involving various actors, networks, and communities to address societal challenges in local settings. Our analysis showcases a variety of scaling-up strategies that go beyond replication and wider adoption. Section 3 concludes by highlighting insights to develop more agile frameworks to theorise scale in EII across sectors and geographies rather than market failure-based and standard economic approaches.

1. Conceptual underpinnings of scaling up EII

1.1. Dominant frameworks to scale in development engineering

In this section, we critique a framework for scaling EII based on theories and methods of standard development economics and social sciences in engineering practice [8]. The framework offers to develop scalable development engineering solutions with iterative activities - innovation, implementation, evaluation, and adaptation – to enable researchers to anticipate and design solutions for common challenges associated with technology for development. It defines development engineering as 'process of discovering and characterizing a problem and then developing a generalizable technological solution—one that can address the challenge at scale' [9, pp70]. It is based on the premise that development engineering is closely linked to recent use of randomised controlled trials in public policy to address poverty, focusing on technological innovation as a tool for achieving sustainable development. Scaling up here is defined as taking an innovation that has positively impacted a limited number of users during the evaluation stage, modifying it to reach a larger number of users, and expanding its reach to users in new geographic locations [8].To operationalise this framework, the authors describe 'hypothesised constraints', 'common' for many 'developing countries and low-resource communities':

(i) Market constraints, e.g. lack of insurance markets, capital constraints, missing information, high transport costs and shallow markets, labour market failures, etc.
(ii) Institutional constraints, e.g. intermediaries, weak contracting environment, high transaction costs, principal-agent problems within government and citizens, asymmetric information.
(iii) Behavioural/ social norms, e.g. cognitive bias, intra-household bargaining, social norms, etc.

Further, the authors describe the means to overcome these constraints as 'diagnostic and design tools' to understand the user base and explain why technologies that work in developed settings may fail when applied to a new setting [8]. However, despite stating innovation efforts as 'iterative' and 'non-linear', our argument is that this is not enough. We argue that approaches need to go beyond heavy reliance on microeconomic depictions of developmental issues and market failure-based framings, a neoclassical perspective on scaling up.

1.2. Dangers of using microeconomic lens to theorise scaling up of EII

Frameworks based on static and neoclassical assumptions are impractical for real-world innovation efforts. We discuss some of the reasons:

(i) Representation of constraints faced by developing countries or low-resource communities as uniform and common is misleading given diversities within and among them. Moreover, market constraints overlook that availability and accessibility of technologies are affected by factors beyond pricing and income, which the framework states are the main factors of uncertainty for poor people. For instance, it is important to focus on vertical inequalities (taking population as a whole) and horizontal inequalities (within sub-groups, like gender, ethnicities, etc.) [11]. Although the authors acknowledge the wider context and challenges of adopting a top-down approach for innovation, the hypothesised constraints lack nuance and present a siloed discussion, which is difficult to apply to complex developmental challenges.

(ii) The framework posits 'design requirements' with a manual for 'development engineers', who are assumed to be the principal actors responsible for innovation in low-income countries. The framework undermines the plurality of actors and institutional variety that enables knowledge exchange, technological learning, and adoption. The innovation process is an evolutionary approach involving various actors, knowledge and technologies, and institutions [12] and assuming a 'development engineer' can observe market constraints and user behaviour to develop a suitable solution fails to acknowledge the complexities of the innovation process. While microeconomic principles have been widely used to study firm-level or industry-level dynamics, they cannot capture the complex dynamics through which engineering innovations evolve. They require identification, involvement, and communication of actors specific to each sector to operationalise the scaling and diffusion process as exemplified by a study on effective delivery platforms from field practices of sanitation entrepreneurs in India [7]:

> '...'market-oriented or 'market delivered' innovation does not mean that the end-user effectuates all transactions associated with the diffusion through markets. Behind a market delivery, there is a complex network of actors comprising financiers, facilitators, service providers and field staff, the last interacting most closely with the target community'

To some extent, frameworks like that proposed [8] discuss the need to evaluate and implement scaling-up efforts to achieve success, e.g. using business models for the long-term sustainability of scale-ups that rely on market processes; navigating the political economy of institutions, government regulations, legal challenges, and the role of civil society with partners. A broader discussion is required focusing on delivery platforms as it helps identify different actors and the significant role of low- and middle-income countries (LMICs) as consumers and producers of innovation. This approach is necessary to recognise that LMICs are more than just an end market in global value chains [13].

1.3. Going beyond the static framings of scaling EII

Given the above challenges, while scaling up EII to address societal challenges has gained prominence in policy discourse, strategies and initiatives based on static framings tend to focus on quantity rather than quality, overlooking important points of contention around the direction and nature of innovation [9]. Existing frameworks to achieve scaling seldom take into consideration the complexity or unpredictability of the broader system [14]. The lens of scale may vary in these different framings [9] and recent work has provided a wider range of frameworks. For instance, a recent review highlighted the importance of a more dynamic and systematic approach to scaling that considers marginalised groups and anticipates, addresses, and assesses the extent to which scaling is inclusive [10]. They identified three key aspects of socially inclusive scaling: phases, directions, and inclusions [10]. First, the generic pathways of the five scaling phases comprise identifying, planning, implementing, learning, and adapting. Second, there are four directions of scaling: up (changes in laws, policies, institutions, or norms), down (resource allocation to support implementation), in (ensuring organisations can deliver good practices required) and out (geographically replicating or broadening the range or scope of good practices). Third, multiple inclusive actions across the phases and all directions to take inclusive actions ensure that marginalised groups are not left behind. Using these three aspects, scaling inclusive innovations occurs within the context of complex adaptive systems (CAS). The CAS approach can help understand scaling in complex systems by examining interactions among agents inside and outside the system to identify and address the root causes of exclusion or discrimination in the scaling process [14].

To conceptualise scale in EII, there is a need to delve deeper into appreciating scale as a more complex and diverse process than simply focusing on the wider 'diffusion' of the product [4, 15]. Engineering is a complex field that cannot be reduced to simply applying scientific principles led by research and development. Static 'market failure' approaches are ineffective as the diversity of engineering knowledge and practices makes it impossible to have a single concept of E4D. Some learning can be taken from evolutionary frameworks, which provide a realistic and dynamic way of understanding the innovation process compared to neoclassical models that treat technology as exogenous [16]. For instance, a study highlights that scaling up research and development (R&D)-intensive technologies and promoting local development is not just about replicating a product but creating a comprehensive system to build a socio-technical adequacy [17]. The study used heuristic tools from constructivist approaches to the Sociology of Technology [18], learning conceptualisations from the economics of technological change [12], and a 'backwards mapping' approach to policy analysis [19]. Using such heuristic enables a systemic problem-solving strategy instead of relying on a technology-fix public aid approach by involving active users who contribute to product shaping and public policy [17]. Another study highlights the merit of framing scaling within a wider sociotechnical context. It does so by combining the multi-level perspectives (MLP) from the sustainability transitions literature and the Ladder of Inclusivity (LII) from the inclusive innovation literature to explain rapid transformations in the financial services sector in Kenya [20]. Combining these frameworks, researchers identify key aspects that drive rapid transition in a socio-technical system and how it necessitates strong landscape pressures that motivate regime actors to act towards a common goal of M-Pesa's success [20]. Over time, multiple pressures from different levels, oriented towards social inclusion, were exerted on the incumbent system.

2. Case studies of different scaling-up strategies across sectors and geographies

We explore scaling-up strategies using case studies of EII in different sectors and geographies. Table 1 frames the developmental problem, the role of engineering and its impact, and insights towards a broader understanding of how engineering innovations can be scaled up by different actors in different sectors and geographical contexts.

Table 1. Engineering-based inclusive innovations across sectors and geographies.

Case Study	Problem / Challenge	Role of Engineering	Insights on scalability
Technology to filter arsenic from groundwater	Arsenic contamination in water sources poses health risks	Chemical engineering innovation to filter arsenic from groundwater in 2004-06 developed by Indian and European engineers led by Bhaskar Sen Gupta (Queen's University, Belfast, now at Heriot-Watt University)	• Provides chemical-free water treatment, scalable with solar/wind power • No viable business model for private providers • Prof Sen Gupta formed an NGO • Needs funding and institutional support for financial sustainability • Potential role of state/ intermediaries in creating markets
Disaster Monitoring Satellite spin-out company	Limitation of single satellite systems for global monitoring	Paradigm-shift engineering by Surrey Satellite Technology Limited (SSTL), Surrey University spin-out using off the shelf technology to develop constellation of low-cost satellites for 24-hour global monitoring	• Constellation of low-cost satellites for 24-hour global monitoring • Replaced big and high technology with small and flexible technology for commercial and non-commercial applications of space engineering • International cooperation frameworks and network building through capacity building in space engineering
Sustainable water engineering services in Uganda	Challenges of providing piped water to poor urban settlements	Evaluation of water delivery solutions. Collaboration between Water Engineering and Development Centre, Loughborough University and National Water and Sewerage Corporation	• Improved water provision for over a million people, including urban settlements • Institutional partnerships between the WEDC and NWSC for capacity building and new models for service delivery
Low-energy strategies for healthcare buildings	Lack of sustainable heating/cooling strategies for buildings	Passive Downdraught Cooling as alternative to high tech cooling systems and closed buildings	• Adoption of low-energy ventilation and cooling techniques • Applications in the UK NHS, India (Ministry of Health and Family Welfare), and China (construction companies)
Unified Payments Interface (UPI), a state-led innovation	Access to digital finance, duplicity of payment applications	Open-source technology and commodity hardware for flexible architecture	• Open-source technology, interoperable platform supporting multiple banks and third-party apps • Accessibility across all mobile devices, including those without mobile data connections for widespread adoption • Commodity hardware for interoperability • Potential for international partnerships
OralScan by Indian Medtech start-up	Availability of affordable and objective oral cancer screening	Non-invasive, point of care, handheld device with mach. learning sw by interdisciplinary team	• Engineering innovations using start-up formations to access government schemes on funding, incubation, etc. • Diff. delivery models for affordable access

Source: Authors' analysis

These cases involve identifying and framing problems and challenges, the role of engineering, and the desired societal impact. We identified how key indicators and metrics influencing their conceptions and adoption differ in different sectors and geographies, offering scenario building and exploring the meaning of scales in EII.

2.1 Chemical engineering innovation to filter arsenic from groundwater

A team of Indian and European engineers led by Sen Gupta developed the process of filtering arsenic from groundwater [21]. Their work involved utilising chemical engineering knowledge for arsenic remediation, which is crucial in addressing the toxicity of non-piped water. One key breakthrough has been the successful implementation of pilot plants successfully in three countries, bringing learning to improve the technology. The success of this approach hinges upon financial sustainability for scaling up [2]. The engineers are trying to fund investment by having users of decontaminated water pay an affordable fee for the service, albeit also acknowledging that water should be provided free to poor users. There is no incentive or business model to attract private service delivery institutions because once the plant has been built and installed, there is nothing to sell. The approach to scale provides insights into the challenges of scaling public goods (drinking water) and presents the potential role of state/intermediaries in demand generation, capacity building, and creating new markets.

2.2 Water engineering improves water service delivery in underserved areas

Providing piped water to poor, informal, urban settlements in developing countries is challenging due to financial and budgetary constraints and quality issues. National Water and Sewerage Corporation (NWSC), Uganda's largest water authority, provides potable water and sewerage services in urban towns on a financially viable basis. The Water Engineering and Development Centre (WEDC) and NWSC collaborate to provide sustainable engineering services. They have conducted surveys, interviews, and focus groups to understand user needs and evaluate delivery solutions for water through pipes [2]. In terms of scaling:

(i) the WEDC and NWSC's strong ties began in 1988 and they have developed new models to extend and improve water service delivery to underserved areas.

(ii) NWSC signed a Memorandum of Understanding (MoU) with the WEDC, under which NWSC sponsors their staff to pursue MSc degrees in Water & Waste Engineering, Water and Environmental Management, and Sanitation. These programs offer in-person training in the UK and Uganda and self-study distance learning, which adds to the capacity development of employees and organisation sustainability. Many NWSC employees, including PhD, masters, and those on short courses, were taught by WEDC academics. Over time, they have built a shared discourse of water engineering networks.

(iii) NWSC's corporate plan for 2021-2024 aligns with Uganda's national development plan (2021-2025), which identifies NWSC as one of the key actors ensuring improved urban safe water and waste management services and associated infrastructure in Uganda [22].

2.3 Space and electrical engineering to improve global disaster monitoring:

Surrey Satellite Technology Limited (SSTL), Surrey University's spin-out company, designed and built earth observation (EO) microsatellites, low-cost yet highly capable small satellites and imaging sensors using the latest `commercial-off-the-shelf' technologies and devices to create the international Disaster Monitoring Constellation (DMC). DMC presents a new set of knowledge by reconfiguring existing products based on constellation building and miniaturisation in electrical engineering with strong socio-economic components to fit satellite technology for developing countries [2]. The case presents a more evolutionary style of engineering practice with room for error as opposed to the risk-averse military model of satellite development. DMC International Imaging (DMCii), a commercial imaging company and a SSTL subsidiary, was formed to coordinate first-generation microsatellites and stimulate EO applications. It is the only company in the world that finances its own EO satellites without government subsidies. The project strongly emphasises three key aspects for scaling up activities:

(i) replacing big and high technology with small and flexible technology,
(ii) network building through capacity building in space engineering for China, Algeria, Nigeria, Turkey, Spain, and the UK
(iii) affordable access to space technology for developing countries to improve disaster monitoring worldwide.
(iv) These engagements are also influenced by factors external to the technology deployment, e.g., national security, regulations for space technologies, etc.

2.4 Paradigm-changing building engineering for sustainable buildings:

In this case, the innovation involves incorporating passive cooling (or heating) of hospital designs as a substitute for high-tech air conditioning systems and closed buildings. It builds on existing knowledge with new practices and strong networks of research, development, and use. Two networks worked towards it: modelling of air flows in buildings and analysis of water and air usage by Alan Short's team in Cambridge, Andy Woods and colleagues from the BP Institute; data collection and modelling of temperature, humidity, and airflow behaviour over extended periods by co-investigators at Loughborough University. This approach has resulted in viable retrofit adaptation schemes for recurring building types, showing potential for significant energy and carbon emission savings. Using this research, environmental design proposals are developed for various clinical and non-clinical spaces. The ventilation and energy performance of these components are modelled and scaled in the UK, India and China [2, 23]:

(i) 200-bed hospital conducive to service delivery policies of the National Health Service (UK)
(ii) a prototype of a 200-300-bed hospital being developed by the Indian Ministry of Health and Family Welfare led by its Chief Architect, Professor Chandrashekhar.
(iii) Healthcare organisations and stakeholders in China's Hot Summer-Cold Winter region responding to government carbon reduction policy –interdisciplinary research from the UK and China focus on addressing challenges in building the existing stock's resilience – it has garnered interest from the Chinese construction companies.
(iv) new forms of scaling and impact in form of a film that showcases adapting China's existing building stock, comprising over 9 billion square meters, without constructing new buildings.

2.5 State-led system-wide engineering innovation to enhance access to digital finance:

The UPI platform, developed by the National Payments Corporation of India (NPCI), standardises payment platforms in India, allowing real-time fund transfers between bank accounts through a single mobile application [24] . It merges various banking features, fund routing, and payments into one platform. UPI ID (a virtual payment address) enables cashless payments across applications and wallets. NPCI launched a pilot in Apr

2016 with 21 member banks, subsequently expanding to more banks and third-party payment service provider apps. These apps pay NPCI a platform fee to utilise the UPI infrastructure. As of Feb 2024, the UPI ecosystem supports over 550 partner banks and third-party payment service provider apps, making it an attractive model for other countries [24]. This state-led innovation is widely adopted due to the following scaling strategies:

(i) Utilising open-source software like Java, TDB, and Cassandra, for flexible APIs, enabling easy customisation and integration with mobile devices, and convenient user interface.
(ii) Opting for commodity hardware, not a private cloud, allowed for enhanced scalability through interoperability and reduced both cost and dependency on specific vendors.
(iii) Collaboration with banks ensured seamless functionality across multiple mobile banking apps and third-party UPI-compliant apps, increasing user accessibility.
(iv) Accessibility across all mobile devices, including those without mobile data connections, ensured widespread adoption, particularly in remote and rural areas.
(v) Regulated by the Reserve Bank of India, ensuring compliance, promoting safe banking practices and tech diplomacy efforts by exporting UPI architecture.

2.6 AI-based MedTech innovation for early detection of oral cancer:

Oral cancer is a leading cause of death in India. The present screening technique, visual inspection, is subjective and often misses detecting oral potentially malignant lesions (OPMLs) in the early stages. Conventional oral examination often leads to multiple biopsies, increased expense, and false-negative reports, causing delays in diagnosis and treatment. Dr Subhash Narayanan, a physicist, applied physics principles to biomedical engineering to find screening modalities for oral and cervical cancer screening. This technology was a culmination of 20-25 years of knowledge exchange and multidisciplinary collaborations of Dr Narayanan with researchers, dentists, and biomedical engineers [25]. These efforts resulted in scientific and instrumentation breakthroughs to screen and detect oral cancer by miniaturising instrument design. The research efforts were institutionalised to build technologies for early cancer detection by incubating OralScan, under the start-up Sascan Meditech Private Limited, using early-stage support from government programmes. OralScan is a handheld device with proprietary ML-based software to assist in screening and guiding the surgeon in taking a biopsy from the most appropriate site. After multicentric clinical trials in Indian hospitals, it received approvals from Indian regulators, got an Indian patent, filed for a patent in the USA, and obtained a CE mark. The objective of scaling this innovation case has been to reach as many people as possible. While government funding is available for early-stage innovation, it has been challenging to secure subsequent stages. Since cancer screening is an underserved area, both from private and public provider perspectives, Sascan is leveraging technology to disrupt delivery models by lowering capex to disrupt healthcare delivery creation:

(i) direct sale model, as a one-time investment (around INR 5.9 Lakhs or USD 7120) for hospitals and laboratories without additional consumables costs.
(ii) pay-per-use model for diagnostic chains, small clinics
(iii) large screening camps and demand creation efforts by engaging key stakeholders.

In summary, the scenarios underscore nuances of scaling strategies that cannot be understood using a standard neo-classical economics framework. Case studies demonstrate that scaling is not always widespread use or replication but rather a co-evolutionary trajectory of networks, communities, and institutions in sectors that lead to broader developments and the adoption of technologies for societal impact. Introducing an engineering innovation for developmental challenges substantially differs from a standard product launch. This point is pivotal for engineering innovations with no visible markets, e.g., arsenic removal technologies. The arsenic removal plant has not been replicated on a large scale, which does not mean it has failed. In the Indian cases, engineering innovations supported by universities are not taking the standard and traditional pathways of starting with 'pilot' and scaling up by fitting into value chains. The innovators opt for start-up formation, reacting, and evolving with the larger systemic change of evolving institutional support for 'start-ups', for instance, through Start-up India and Make in India policies. The start-up formation helped institutionalise access to funding, incubators and accelerators, government programmes and schemes, and eventually, policy recognition. Since cancer screening is an underserved area in India case, both in terms of public and private interventions, this case also presented insights on demand generation and the creation of new markets by innovative approaches in delivery. Such forward and backward linkages help in coming out of the 'round peg in a square hole' challenge faced by a range of well-intentioned development interventions.

3. Conclusion

The paper presents different framings and meanings of 'scaling up' EIIs and the implications for mainstreaming these innovations in society. Instead of adopting a generic approach to scale, we draw attention to the multiplicities of framings and how they influence scale and its impact. We also argue that the current foci of scale-up in development engineering studies are based on frameworks that use economic assumptions with a restricted perspective on actors, factors, and knowledge. We emphasise the significance of diverse frameworks. We highlight the need for an agile framework to study the scaling up of EII with variables, including network building, socio-economic and political influences, institutional support, capacity creation and demand-generating mechanisms, which have a strong role in scaling up.

We use case scenarios of the UK case studies and Indian startups to demonstrate that one-size-fits-all does not apply to scaling-up strategies for EII in different sectors and geographies. Scaling is not always widespread use or replication but a co-evolutionary trajectory of networks, communities, and institutions in sectors that have led to broader developments and the adoption of technologies for societal impact. Innovations in different sectors highlight the importance of identifying the different aspects of sectoral systems of innovations, including knowledge and technologies, actors and networks, and institutional scale-up. This approach allows us to map the coevolution of technologies with actors, knowledge, networks, and institutional paradigms, e.g., by creating a matrix. To better understand scaling, it is also important to consider variables that explain effective demand, value, and political economy of innovation. Further bifurcation of diffusion must include scaling up, alongside discussing the delivery mechanism, for a deeper exploration of efficiency, effectiveness, sustainability, and social equity measures. These insights will likely inform better delivery models, value chain advances, and the de-colonisation of development engineering by breaking off from 'cookie-cutter' models.

Our conclusions resonate beyond discussions concerning the role of E4D and conceptions of EIIs. At a broader level, they posit the recent growth in debates about industrialisation and the global economy. Although large-scale, capital-intensive mega projects still proliferate, there has perhaps been a shift to a less 'productionist' industrialisation. Service-led and consumer-led industrialisation is on the rise. The old debates on green vs growth, tomorrow's technology vs today's consumption, and so on are changing so that arguments are emerging strongly that green does not contradict growth and investment-led belt-tightening is not the only way to grow an industrial economy. The work that links health to industrial systems, fossil fuels to renewables, and local and shorter supply chains during COVID and post-COVID crises may be in their early days. However, the changes we have studied and the institutional variety they illuminate seem to fit close to these potential changes in the global economy and society.

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