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Civil engineering challenges of the Einstein Telescope project: An underground observatory for gravitational wave detection

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ABSTRACT: The Einstein Telescope (ET) is a proposed underground facility designed to enhance gravitational wave detection by coupling low and high frequency interferometers in an arm length up to 10–15 km. This increase in sensitivity is mainly driven by increasing the interferometer arm lengths, compared to the current generation of 3–4 km arm length. Additionally, by situating the facility deep underground it will benefit from the enhanced seismic and environmental noise isolation that subsurface conditions could provide. The complexity of such a scientific ambition introduces unique challenges for the design of civil engineering works required, particu-larly given that different sites are proposed. As part of a collaboration agreement with the research funding institutions, Civil Engineering experts at the European Laboratory for Particle Physics (CERN) have been invited to provide technical advice services on key aspects such as civil engineering design strategies and cost estimation methodologies that will contribute to the definition of the Technical Design Report (TDR). This paper, authored from CERN's independent perspective in collaboration with the Engineering Department of ETO (Einstein Telescope Organisation), presents a structured analysis of the key challenges and opportunities involved in specifying a large-scale underground infrastructure project. The driving requirements of scientific complexity coupled with the analysis of local site conditions make the evaluation of civil engineering design performance particularly challenging. Through comparative analysis of previous large-scale case studies and CERN's internal design approaches, the study highlights critical aspects that may require specific construction solutions to be developed. To address the complexity of comparing design options, the paper also examines the integration of parametric design and automation tools, specifically through the use of Grasshopper, a visual programming tool. The paper also reflects on strategic implications for a broader project, including site selection parameters, cost profiling and risk management strategies in early design stages.

1 INTRODUCTION AND SCOPE

The Einstein Telescope (ET) is a proposed next-generation underground observatory for gravitational wave detection, conceived to extend the arm length of interferometers to 10–15 km, significantly longer than the 3–4 km facilities currently in operation (Abbott et al. 2016, Abac et al. 2025). By locating the infrastructure deep underground, ET aims to benefit from the enhanced seismic and environmental noise isolation that subsurface conditions can provide, thereby opening

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the low-frequency regime down to 3 Hz (Amann et al. 2020). This scientific ambition introduces a series of unique challenges for civil engineering design, requiring solutions that are beyond the scope of conventional tunnelling projects. The complexity of ET's civil works arises not only from the scale which is estimated to be more than 30 km of underground tunnels and multiple large caverns, but also from the highly stringent operational tolerances of a physics-driven facility (Sorrentino et al. 2025). Structural stability, hydrogeological control, and ventilation must be reconciled with sub-millimetre alignment requirements, thermal stability, and ISO standard cleanliness in experimental caverns (Sorrentino et al. 2025). The evaluation of design feasibility is further complicated by the consideration of multiple candidate sites, each with distinct geological and hydrogeological characteristics (Amann et al 2020). In recognition of these challenges, CERN's Civil Engineers, drawing on their experience with large-scale underground scientific facilities, have been invited to provide independent technical advice to the Einstein Telescope Organisation (ETO). This collaboration focuses on defining design strategies, cost estimation methodologies, and risk profiling approaches that will feed into the Technical Design Report (TDR). This paper, authored jointly from CERN's independent perspective and ETO's engineering expertise, examines the civil engineering challenges in a site-independent manner. It outlines the translation of scientific requirements into civil works design constraints, presents a reference baseline concept, and reflects on design optimization and cost estimation strategies that can support decision making in early project phases.

2 SCIENCE REQUIREMENTS AND CIVIL DESIGN DRIVERS

The driving scientific requirement of ET is to significantly extend interferometer arm length, thereby increasing sensitivity to gravitational waves at low frequencies (Abac et al. 2025). Realising 10–15 km long underground arms impose geometric constraints far beyond conventional tunnelling practice: beamline paths must remain straight and stable within millimetre tolerances over decades, thus requiring careful alignment strategies and long-term ground deformation monitoring/control (Sorrentino et al. 2025).

Noise reduction, particularly Newtonian noise from seismic and atmospheric perturbations, dictates placement of the facility at depths of 200–300 m. At these depths, Rayleigh wave amplitudes are attenuated, reducing coupling to test masses (Amann et al. 2020). This design choice translates into substantial civil engineering works, including deep access shafts or inclined tunnels, and has a direct impact on excavation methods, lining requirements, and technical infrastructure design.

Hydrogeological requirements also play a pivotal role. Fluctuations in groundwater flows not only increase operational risk but also induce mass redistributions that generate gravity gradient noise (Sorrentino et al. 2025). Consequently, drainage and waterproofing systems must be integrated into the lining design from the outset. Modelling indicates that drainage ducts near test masses must maintain separation distances of at least 100 m (for flows of up to 20 m/s), reducing to 20 m in caverns where flows are slower. This places direct constraints on tunnel invert design, shaft waterproofing, and pumping systems, which must also avoid introducing secondary vibrational noise.

Thermal stability and cleanliness requirements further impact design decisions. Cryogenic operation of test masses demands temperature stability within narrow tolerances, while particulate contamination must be controlled to cleanroom standards in experimental caverns. Ventilation and environmental control must therefore balance airflow for stability across 30 km of tunnels with isolated, vibration-free clean zones around the sensitive systems. These requirements, coupled with seismicity and surface activity constraints, mean that ET's underground works must be specified not only for structural safety but also as precision-engineered environments for physics.

3 SITE-INDEPENDENT BASELINE CONCEPT

A site independent baseline layout has been developed to serve as a reference for engineering studies and cost estimation ahead of site selection. There are currently two conceptual layouts for the Einstein Telescope; the Triangle layout and the 2L layout. In the Triangle layout each of the three vertices hosts a pair of interferometers, resulting in a total of six interferometers. In the 2L layout, consisting of two independent L-shaped detectors, each L-shaped detector houses a pair of interferometers, leading to a total of four interferometers. Focussing on the Triangle layout, the underground infrastructure consists of three 10–15 km arms, with large experimental caverns at each node to house the interferometer towers, cryogenic systems, and associated services.

The tunnels are envisaged to be TBM-excavated with circular cross-sections of 6.2 m (L layout) or 7.4 m (triangle layout) internal diameter, sufficient to house the vacuum beampipe, logistical needs, drainage, ventilation, and safety passage. Allowances are incorporated for TBM deviation, lining thickness, and annulus gaps. Shafts or inclined adits are currently planned to be positioned only at end the nodes for both construction logistics (TBM delivery and extraction, cryostat transport) and long-term personnel and equipment access.

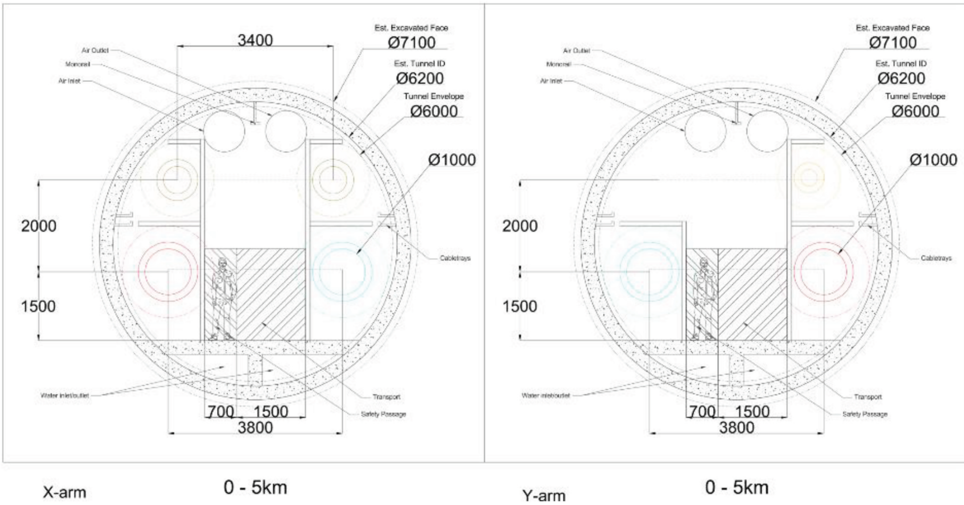

Figure 1. Tunnel cross section L-Layout.

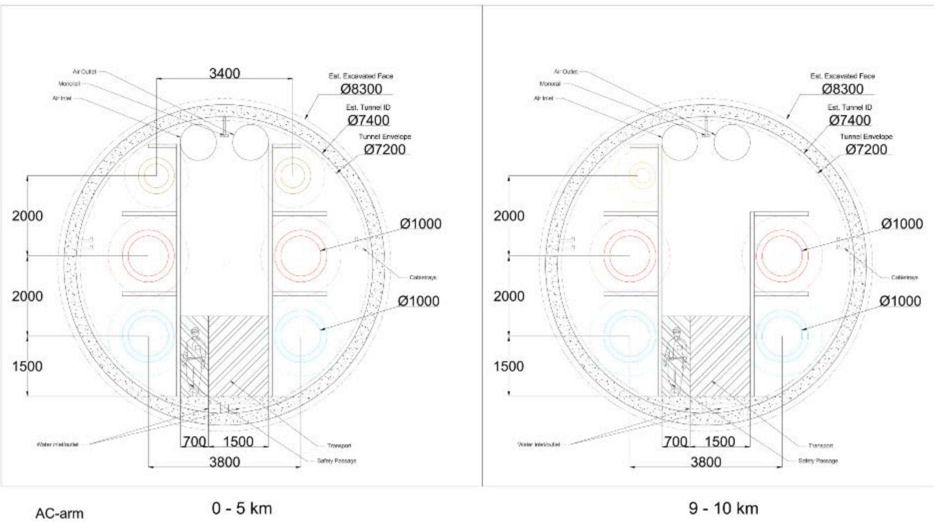

Figure 2. Tunnel cross-section Triangle Layout.

Cavern dimensions are preliminarily defined by rock engineering criteria and comparative analysis of similar facilities. Typical spans of up to 25 m and heights of up to 20-25 m are assumed, with width-to-height ratios between 0.5 and 1.0 depending on host rock quality. Cavern separations are scaled relative to cavern height (1.0×H minimum) to avoid excessive stress interaction. Linings are envisaged as cast in-situ reinforced concrete with waterproofing membranes in areas of high hydrogeological risk. These specifications are subject to refinement once geotechnical investigations at candidate sites are complete.

The baseline concept defines the scale and configuration of ET's underground civil works while providing a platform for initial cost and risk assessment. Its modular and parametric character ensures adaptability to local geological and hydrogeological conditions, while retaining fidelity to the scientific requirements that ultimately drive the facility's design.

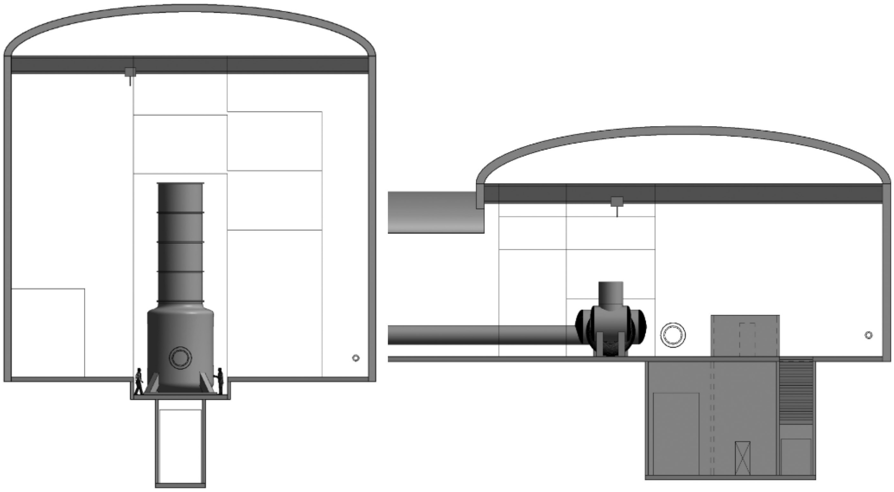

Figure 3. Cavern concept section views.

4 SITE-SPECIFIC CONSIDERATIONS

There are three possible candidate sites for Einstein Telescope as shown circled in Figure 4; Sardinia (Italy), Euregio Meuse-Rhine (EMR) Region (Netherlands/Belgium/Germany), Lusatia (Germany). From a tunnelling perspective, a key consideration to differentiate between these sites will be their relative geologies. The geology of the chosen site will influence design decisions such as accessways, excavation methodologies, and water management strategies among many others.

In Sardinia, the Sos Enattos site is the chosen location for the facility if the Italian proposal is successful. Firstly, seismic noise, which is a key consideration for the physics performance of the experiment, is very low in this location. Sardinia is a microplate meaning that it is a detached portion of the Eurasian plate and therefore not connected to active tectonic zones. Site investigations are underway in Sardinia, but already it is known that the geological conditions of the site will be hard rock.

In the EMR Region, similar qualities of low seismic noise are present, and site investigations are underway to determine the geological conditions of the potential siting.

The Lusatia, again, geological conditions are being investigated through ongoing ground investigations, though it is already known that the site sits on stable granite massif with low seismic activity.

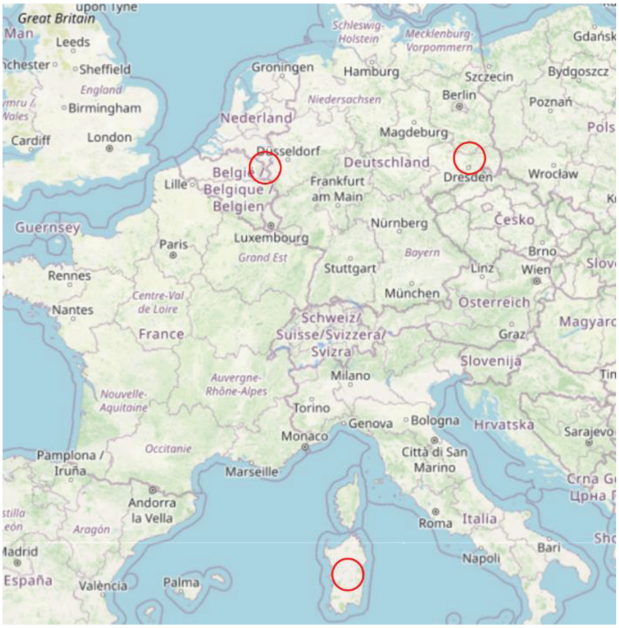

Figure 4. Map (credit: OpenStreetMap contributors) of central Europe showing three candidate sites circled in red.

5 PARAMETRIC DESIGN AND AUTOMATION WORKFLOW

The baseline design of ET's underground civil works provides a parametric framework for the site-specific designs of underground infrastructure. Parametric design is a method which involves specification of various design outcomes based on algorithms rather than direct manipulation of variables. An example of this, applied to ET would be as stated in section 3, cavern height is defined as:

$1.0 \times \text{Hminimum}$

where H minimum is a parameter that can be varied depending on the specific inputs which are passed into the design.

Given the site independent nature of the initial design phase for this project, a parametric approach is the only possible solution for delivering a concept design. For civil works design, Grasshopper software, developed by Robert McNeel & Associates offers highly flexible parametric modelling opportunities. Its place within the McNeel Associate's Rhino modelling tool makes it particularly versatile since Rhino allows designers a visual modelling environment which feels familiar to users of software such as Revit and AutoCAD. The Rhino suite of tools informs the suggested use case in this report, but other similar parametric scripting design tools would be equally viable.

Using a visual programming design software like Grasshopper for the design of ET would enable all uncertainties within the design to be mapped out alongside known parameters. The knowns and unknowns would be interlinked and could provide the users with a preliminary understanding of how the unknowns interact with the known quantities. This could then inform a pipeline, or hierarchy, of unknowns in need of determination. For example, if the geotechnical parameters have the highest number of dependent connections leading from their outputs compared with any other unknown variables, this could indicate to the designer that the geotechnical parameters are the variables in most urgent need of definition.

A concrete application in the current feasibility study and preliminary analysis phase—where ET is presently positioned—involves addressing several critical aspects, foremost among them the definition of the geometric envelope. This envelope follows the optical layout while incorporating parameterizable civil engineering constraints. At this stage, the optical layout is still undergoing continuous modifications and fine-tuning. Consequently, the geometric envelope, defined by the void volume of the underground caverns and tunnels, must be continuously updated to remain reliable for subsequent analyses and design activities.

Manual updates of this geometric model are highly time-consuming and require substantial interpretative effort and follow-up after each layout modification. Such a manual workflow not only slows down the overall design process but is also prone to human errors.

To overcome these limitations, a procedural modelling approach has been developed to automatically generate an approximate enclosing volume that adapts to the evolving optical layout. This approach accounts for the various technical elements defined so far—such as suspension towers of different types and heights—and integrates them into the geometric model.

The procedural modelling algorithm uses as input the two-dimensional plan view of the optical layout, as discussed and agreed upon with the scientific community, together with the surrounding spatial constraints defined on the basis of technical, functional, and safety considerations. These inputs are then converted into a three-dimensional representation through the developed algorithm, which takes into account both the 2D positioning and the geometric characteristics of the involved components.

Moreover, additional offset or clearing distance parameters can be defined in a fully parametric way to generate alternative models adapted to specific design scenarios.

This procedural approach has also been employed to produce multiple geometric variants corresponding to alternative versions of the interferometer's optical layout. These variants can then be compared both visually and analytically, enabling approximate estimations of excavation and construction volumes. Such estimates are crucial for supporting early-stage design decisions, evaluating technical feasibility, and producing preliminary cost assessments related to civil engineering and infrastructure development.

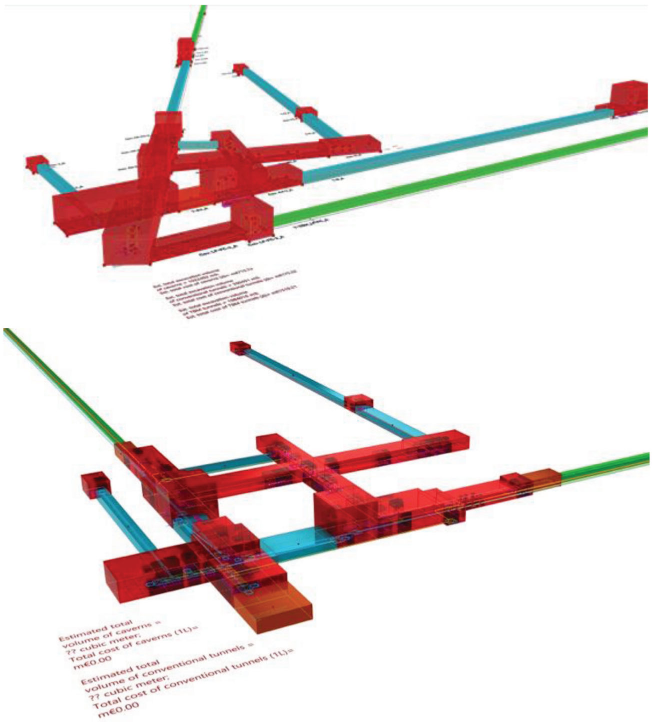

Figure 5. Models for two vertex variants (Triangle (top) and L (bottom)) generated automatically from 2D drawings and input metric parameters, and the result also contains text of relative volume (and cost) estimates.

Over the course of a project's development, the cost uncertainty reduces as various elements are defined. It is therefore necessary to identify a common methodology for attributing the maturity level of the civil engineering design and consequently associate it to a certain cost estimation class. Usually, costs are defined by relevant cost principles (reasonable or lower costs in a competitive marketplace, realistic estimates in function of the level of understanding of the requirements for the works contained in the technical proposal (performances, materials, detailed layouts, etc.).

Generally, proposed budgets must comply with the applicable national/regional regulations on cost estimates, as implemented in the local studies provided by the contracting process. For example, in the Netherlands the regulation for costing is provided by NEN2699:2017 while in Italy there are different Price Lists that can be applied to the estimate the works of the different design steps (Pre- Feasibility, Feasibility definitive, execution) identified in the Procurement Code issued by the Superior Council for Public Works (Ministry of infrastructure).

Despite local variations in costing strategy, an equivalence between the outcomes must be drawn to allow effective comparison between local proposals.

To achieve this, benchmarking standards are required that:

- Describe the expected cost estimating methodology, maturity, and, if applicable, accuracy range at each stage of the design (e.g. based on expert opinion, analogy, parametric, engineering build-up, historical data).
- Explain any ground rules, assumptions and exclusions that apply broadly to the estimate, allowances, and other sensitive or significant factors or considerations, including their rationale and any references.

The approach for estimating cost based on a certain degree of uncertainty is a practice that is already well established at CERN. Given the collaboration between the CERN and ET engineering departments, a similar costing strategy has been adopted by ET to enable cost benchmarking. The costing strategy adopted uses upper and lower bounds of cost estimations which vary depending on project maturity. At the end of the current phase of development for Einstein Telescope, the cost estimation upper bound uncertainty will be 20-50%. This means that the cost estimated at this stage could increase by up to 50% compared with the number quoted at that time.

The methodology for cost estimation at this stage of the project involves accounting for a high degree of uncertainty arising from the unknowns due to site independent design. The process follows a hybrid approach, combining bottom-up work breakdown structures (WBS) with parametric scaling factors to account for unknowns. Key drivers for a project of this type and scale will be excavation volume, methodology, diameter of tunnels, overburden depth and geological make-up, groundwater control, and access conditions. These factors are all site dependent so clearly, uncertainty ranges must be incorporated to inform early-phase decision-making and strategic budget allowances.

The experience of CERN in facilitating and actualising comparable projects to Einstein Telescope has enabled best practice to be shared. In addition to the incorporation of CERN's preferred cost classification systems, Einstein Telescope has been able to benefit from lessons learnt from past and future projects at CERN.

The International Linear Collider (ILC) is an ongoing proposal which was initially based, like Einstein Telescope, on a site independent study until the siting of ILC in Japan was selected. A key comparison between ILC and ET has been carried out in collaboration between the local site's teams. ILC is a highly collaborative project in which aspects such as costing methodology and civil engineering designs are shared between Japan and other global physics laboraties. This collaboration creates an environment of knowledge sharing which pushes the whole scheme, wherever it is located, forward.

Based on this, a key recommendation from CERN's experience to the Einstein Telescope project is to encourage collaboration across and between the different sites.

7 OPERATION AND LIFECYLE CONSIDERATIONS

With any large-scale underground infrastructure project, operation and maintenance must be a consideration in the planning stage right from the start of project conception. Tools such as digital twins for monitoring and introducing varied access options into design planning can be initiated in early-stage design. Again, CERN's experience with maintaining existing scientific experimental facilities is a helpful guide for Einstein Telescope. At CERN, Year End Technical Stops (YETS) are used for small-scale, frequent maintenance. Every few years, the physics experiments stop entirely to allow for Long Shutdowns (LS). These LS events allow the facilities at CERN to be signifincatly overhauled and upgraded since they typically span 2-3 years; generally this is sufficient time to also undertake medium-scale civil works.

In between these YETS and LS events, in-person maintenance is restricted to a minimum due to the potential radioactive conditions created by the experiments in certain areas. To combat this, various innovations in the space of automated inspections and digital twins have been trialled or proposed. Following this experience, Einstein Telescope could adopt similar strategies early on to ensure full-automated integration into the design of the facilities.

Another consideration relating to the lifecycle of the Einstein Telescope facility must include the integration of whole life carbon management into the design process. PAS2080 is the global standard for managing carbon in infrastructures and has been authored to meet World Trade Organization requirements. By adopting best practices as set out in PAS2080, Einstein Telescope could gain a structured process for carbon management across the value chain. Part of the challenge of undertaking a carbon assessment is the definition of civil works within the scheme. To enable a successful sustainability agenda for the project, collaboration between all teams involved in the scheme is essential to enable knowledge sharing for carbon assessment.

8 CONCLUSIONS

This paper has provided an overview of some of the key challenges and opportunities involved in specifying the large-scale underground infrastructure project that is Einstein Telescope. Despite challenging driving requirements of scientific complexity coupled with the analysis of local site conditions, civil engineering design performance can be enhanced and driven forward through the adoption of parametric workflows. Project maturity dependent costing strategies can provide the necessary benchmarking needed to evaluate early-stage design, whilst collaborative knowledge sharing can push the design forward. Putting in place the project frameworks discussed in this paper such as parametric procedure and costing strategy will enable Einstein Telescope to smoothly prepare the subsequent phases of development. At this stage, the project offers an opportunity to set an example for the industry in how to approach large-scale underground infrastructure, starting from the earliest stages of development and maintaining a consistent design approach through site selection, bidding, and construction.

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