





Synergising Natural Material Complexity and Low-Impact Automation

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Abstract. The construction industry is considered one of the world's largest raw materials consumers. It is contributing towards global resource depletion which is exacerbated by increasing demographic demands thus making the industrialisation of innovative sustainable technology crucial. Digital fabrication offers solutions by enabling higher material efficiency as well as the use of renewable bio-based materials. It is not limited to complex processes employing robotic arms to create finely graded building components but can also include facile, cost-effective and low-impact approaches. These can involve unique features to deal with materials less prominent in the construction repertoire due to their inhomogeneity. Customised low-cost and low impact solutions may aid the democratisation of specialised digital fabrication workflows by enabling easier transportability and accessibility, in addition to bypassing the dependence on special skills for operation. To showcase the application potential of these perspectives, this paper focuses on the evolution of a tailored Cartesian coordinate robot that - within the context of a semi-automated fabrication process - enabled the development of a novel construction system made of willow-earth hybrid building components. The evolution of this willow processing machine followed principles of low environmental impact and cost efficiency as its unique features were iteratively developed to deal with the intricate variations inherent to the raw material. The feasibility of the fabrication process was validated through multiple projects along its evolution, most recently the project 'ReGrow Willow' where 63 willow-earth components were prefabricated and installed to be exhibited at the Bundesgartenschau (Federal Gardening Show) in Mannheim in 2023.

Keywords: Low impact automation · Additive manufacturing · Plant-based material · Sustainable Construction · Customised Fabrication

1 Introduction

1.1 Contextualisation

The construction sector stands as a major contributor to the global depletion of resources [1] due to its significant consumption of raw materials [2]. Further exacerbated by the growing demand for new buildings [3], this sector is in dire need of considering alternative materials and methods to diversify the existing construction repertoire in order

to mitigate the effects of climate change and global resource depletion. Digital design and fabrication methods enable the mapping of material characteristics to adjust the fabrication process to reach greater material efficiency [4]. Nevertheless, for a scalable solution, output consistency must be considered. Bio-based materials - that are derived from materials of renewable biological origin [5] often require the homogenisation of an intrinsically anisotropic material in order to reach the required uniformity in output. This may necessitate a multi-step pre-processing stage that involves cost- and energy-intensive, complex fabrication workflows [6]. However, digital fabrication is not limited to complex systems involving robotic arms, it also enables solutions that embrace low-complexity and cost-effective automation. By applying these principles to the development of fabrication processes for bio-based - especially plant-based - materials, the emerging technologies can enable a reduction of dependence on specialised craft while allowing production scalability and automation feasibly, leading to the re-industrialisation of more sustainable and circular construction materials [7, 8] thereby lessening the environmental impacts of climate change [9, 10]. As a result, custom fabrication solutions can become accessible for communities that are normally excluded due to barriers of cost, availability or specialised knowledge [11].

This paper focuses on the evolution of a tailored Cartesian coordinate robot that - within the context of a semi-automated fabrication process- enabled the development of a willow-earth hybrid construction system [12, 13].

1.2 State-of-the-Art

Combining and adjusting existing manufacturing principles with new materials can accelerate the industrialisation of more sustainable construction materials. 3D printing allowed plant-based material fibres to be reintroduced into construction via additive manufacturing. From wood fibre reinforced PLA [14] to ‘printing’ with willow [15]: a common consideration - key in the 2.5D additive manufacturing processes - is the adhesion between the layers. Pre-processing enables a more uniform filament and therefore more control over the adhesion while taking away from the inherent anisotropic behaviour of the raw material

Key factors affecting the production scalability of a digital fabrication process are feasibility, reproducibility and automation [16]. Prefabrication can reduce and control some variables by ensuring a standard external environment [17], however, this results in a disadvantage with transportation. Reproducibility can be enhanced through standardisation. However, in the case of plant-based materials, this is inherently difficult and process-intensive due to the high degree of non-uniformity [16]. In the context of homogenisation of willow, an additive manufacturing process - with each strip treated with adhesives to form a cohesive filament [15] - may be feasible. Industrial wood manufacturing however is preceded by the homogenisation of natural wood by the application of steam, heat, ammonia or cold rolling as well as densification [18].

Developing automated robotic fabrication workflows for plant-based materials without standardisation or pre-processing encompasses challenges. Dealing with uncharacterisable variations might involve the implementation of a communication strategy forming a closed-loop feedback system which is able to update the virtual model and the manufacturing process [19]. 3D scanning or statistical analysis might be used to

develop such a feedback system [20, 21]. Closed-loop systems could adapt to variations in pre-defined parameters without homogenising the material. There have been efforts to use reinforcement learning to characterise such variations and tackle challenges that bio-based materials pose from a fabrication perspective [22] however, the energy- and time-intensity may hinder the scalability potential.

Historical applications of plant-based materials in the vernacular building sector limited their pre-processing to soaking in the case of willow [23], which motivates the exploration of techniques that require minimal pre-processing. Such a technique is weaving - originally a characteristic of the textile industry - where a thin, bendable material is formed into a continuous woven 'sheet' of material either to be used as tension reinforcement for earth (historically) or concrete [24]. Since weaving techniques lend themselves to be used with long, slender materials, willow was proposed as a suitable plant-based material for the development of an automated weaving process.

1.3 Research Aim

The overarching research aim is to develop a digital fabrication system for a fast-regrowing plant-based material, willow (*Salix*). Starting from a material perspective, plant-based materials in their natural form are anisotropic with significant variance. By harnessing the construction potential of plant-based materials without introducing multiple levels of complexity in the pre-processing and fabrication stages a facile solution may emerge. The emergent fabrication system can be made more robust by incorporating readily available elements that can adapt to the variations of the material. Developing a process intended for efficient scalability - both in terms of building component scale as well as production rate - and automation could accelerate the reindustrialisation of sustainable materials. Furthermore, a fabrication system that consists of easily transportable and re-assemblable machinery, the application space - both geographically and socially - can be expanded as the fabrication process may utilise local materials, bypassing the need for specialised craftspeople. To drive the development of the envisioned custom fabrication system, the relationship between the required output quality - essential for structural requirements - and the principles of feasibility and low environmental impact have to be explored and compromises reached.

One of the main research lines at the Professorship of Digital Design and Fabrication at the Karlsruhe Institute of Technology has been focusing on reinterpreting vernacular practices of construction with bio-based, fast renewable materials through the digital perspective to explore their reintroduction into the current construction repertoire [8, 12, 13] by conceptualising and experimenting with low-impact, circular and localised solutions that could drive the industrialisation of more sustainable construction.

2 Methods

The overall fabrication process currently involves five steps as shown in Fig. 1 in order to produce the willow-earth hybrid components. The process utilises willow in its natural state with minimal pre-processing (watering or steaming). The weaving process is preceded by splicing and consists of willow extruded and laid weaving through a bed

of metal poles (Fig. 2). Earth is then introduced into the cells of the woven component lending it significantly more compression strength [13]. The earth-filling process lends itself to the adoption of existing automated robotic earth extrusion tending towards an increased degree of automation. The following sections introduce the evolution of the splicing and weaving stages highlighting the main features that were implemented to enable the fabrication of the willow rebar.

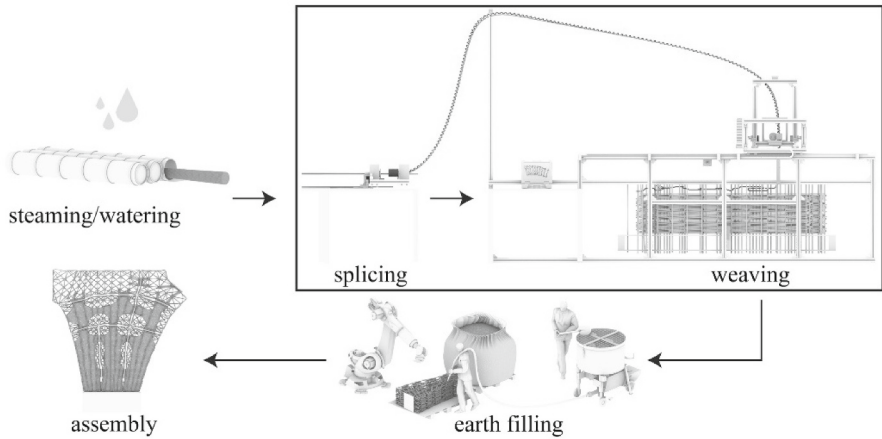


Fig. 1. Overview of the developed fabrication process.

2.1 Interdependent Process Designs for Custom Machinery and Architectural Components

Starting from a material perspective, manual material explorations were employed to gain familiarity with the raw material's inhomogeneities. Techniques traditionally used in vernacular architecture were also investigated to understand how such inherently slender and flexible materials can be made into building components by exploiting their features rather than necessitating homogenisation [8]. Taking inspiration from the textile industry [25], weaving and braiding logics were explored, for which the bending behaviour is key. Initial bending tests enabled an insight into this behaviour and a qualitative starting point for the design of the digital fabrication process could be established. This was an important step for the iterative development as - unlike for other bio-based materials, such as timber - there are no pre-existing standards that may be used to reliably estimate the variation in mechanical properties of willow. In addition to the bending radius, it was also verified that the bending location can seldom be predicted as it depends on the willow branches' internal structure in response to the external forces. Because of this unpredictability, established digital fabrication techniques - which rely on precise material behaviour and predetermined responses - are not applicable. Different strategies were explored for the manipulation of willow, for example, small-scale mobile robots and custom robot platforms on a rail guide. Both approaches offer scalability, allowing

more robots to expand both system size and braiding pattern options. Yet, practical tests revealed a constraint between strength and size, and the number of robots needed. Using too many large robots in proximity is impractical, while small robots lack the necessary strength for bending willow, leading to an alternative approach. Robotic arms possess the versatility required for the manipulation of plant-based materials; research into willow-based additive manufacturing methods shows promising results for 3D printing willow stems [26] by standardisation. Motion planning with Cartesian robots is simple, fast and unlikely to fail due to singularity, angle limits or self-collision [27]. These types of digital fabrication machines enable a range of applications and are highly customisable for specific requirements [27]. Therefore, adopting a low-complexity approach, a Cartesian coordinate robot was developed.

Component-level tests revealed how thin willow branches enable structurally stable components to be utilised as integrated formwork and tension reinforcement for earth construction [12, 13]. Digital design tools were employed to explore scaled-up versions of the test components allowing quick design iterations and an insight into the requirements for the Cartesian robot to fabricate the conceptualised components. The parallel development of the fabrication system and the building component design allowed the two processes to inform each other and iteratively move their evolution forward. Small, circular cells showed promising structural behaviour (Fig. 3 Left), however, the complex weaving parameters – exact bending location, length, weaving tightness – proved challenging for digital weaving. The initial Cartesian weaving machine prototype highlighted the main obstacles regarding digital willow weaving that required the most development. Pulling individual willow branches (weft direction) through a bed of poles (warp direction) created friction, that – though necessary for structural integrity – hindered the fabrication process. It also limited weaving patterns

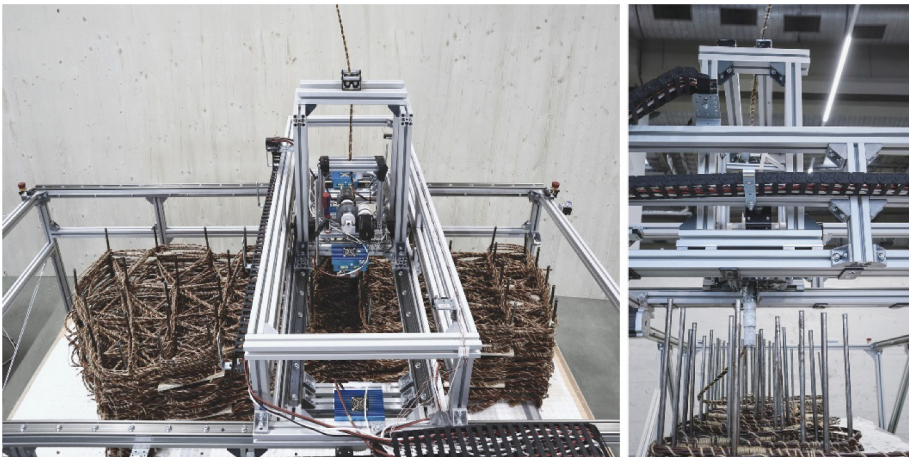


Fig. 2. Views of the Cartesian coordinate robot during the fabrication of willow components.

to straight lines (Fig. 3 Centre), which are less structurally favourable compared to interconnected patterns – as verified by structural simulations as well as by physical tests

[13]. Developing a continuous extrusion process that incorporates patterns developed and verified on the fabrication system means that an optimised cell distribution can be achieved (Fig. 3 Right) without friction hindering the fabrication and without the need to determine the length of each branch in the process.

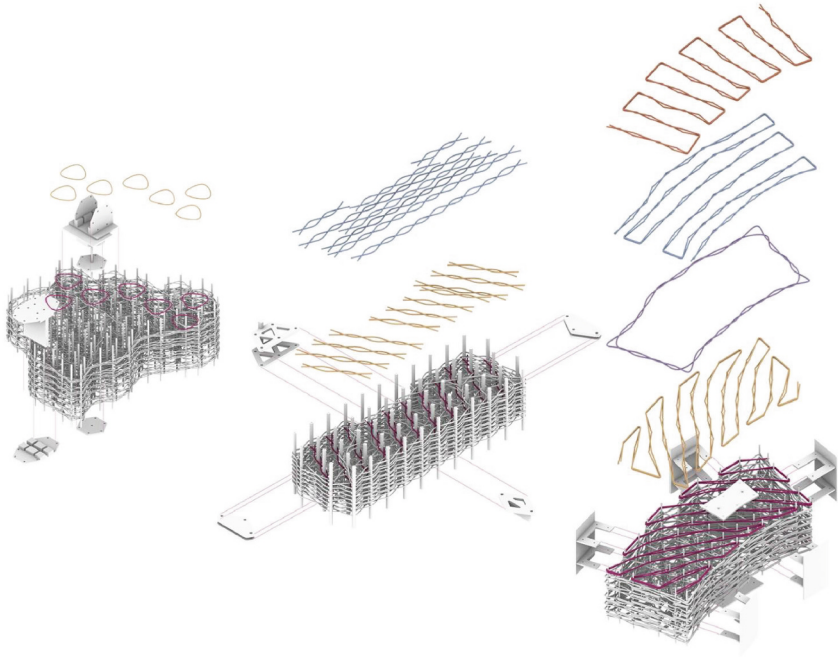


Fig. 3. Pattern evolution across different projects. Left: ‘InterTwig’, Centre: ‘RecodeWicker’, Right: ‘ReGrow Willow’.

2.2 Integrating Natural Material Behaviour

The fabrication process was optimised according to: inherent material features, building component evolution and industrialisation potential. Utilising willow branches necessitates a solution for encoding the length of each branch into the weaving process due to their variations. This requires either sensing the end of each branch or trimming it. Instead, a splicing solution can exploit varying lengths by creating a continuous willow macro-fibre. Preceding the weaving process, a splicer with a variable tension yarn feeder was thus devised (Fig. 4 Left), ensuring that the splicing thread held the branches sufficiently tight since the contact between the branches guaranteed the consistent quality of the macro-fibre. The resulting macro-fibre has a higher tensile strength compared to individual willow branches, lower deviation but a higher maximum in bending stiffness (as the willow branches are spliced superposed). Due to these variations, a standard extrusion process would not be suitable. An on-line measuring system could be adopted that detects

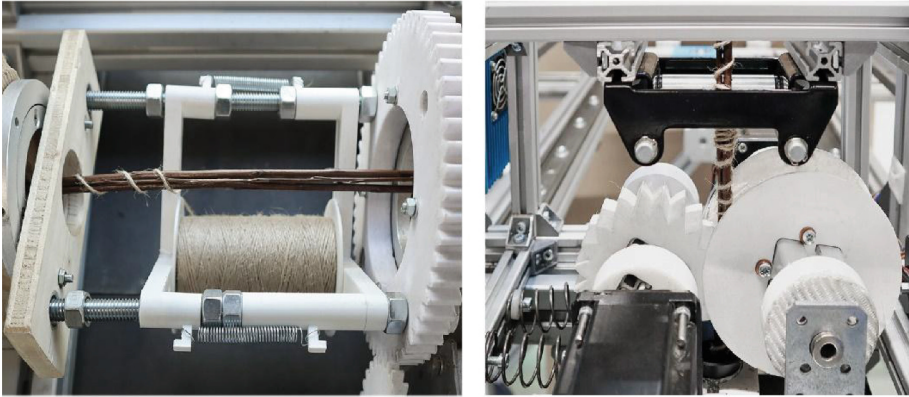


Fig. 4. Tailored fabrication features. Left: Willow macro-fibre splicer, Right: Custom extruder.

the instantaneous thickness variations and informs the extruder ahead to accommodate it. However, more robustly, spring-loaded, custom 3D-printed rollers were explored (Fig. 4 Right) as part of the extrusion mechanism as a hardware solution. The extruder followed a toolpath which was generated from the linear travel distance between the circular paths around the poles. This strategy minimised the travel distance while also maximising the distance from the obstacles (poles) thereby creating a safety margin to deal with the deflection of the poles which arise as the layers accumulate: the woven willow layers exert a force on the poles as tightness is essential for tension and friction within the willow rebar. Due to the non-standard nature of the willow macro-fibre, a straightforward coupling of the extruder speed with the machine translational speed is not suitable. Therefore, a synchronisation of the extruder speed with the XY motion is achieved by projecting each point on the toolpath curve onto a corresponding point on the intended willow path curve, thus dividing it into sub-curves which are then used to calculate the amount of extrusion necessary. Customising the script further enables the variation of the local tightness (such as the corners of the component), ensuring the willow macro-fibre is weaved tight thus lending structural stiffness to the components. Coupling these specialised features together resulted in a robust willow weaving Cartesian coordinate robot as depicted in Fig. 5 that enables the production of a range of differentiated building components with various adjustable parameters (e.g., rebar directionality, pole density, cell sizes, weaving tightness, macro-fibre thickness) thereby showcasing the feasibility of the iterative process that underpinned its development. Rapid prototyping techniques played a crucial role in expediting design iterations; especially in the context of the development of a custom fabrication solution, these techniques facilitate the quick testing of parts to optimise their interaction with existing elements and their sturdiness during the fabrication process.

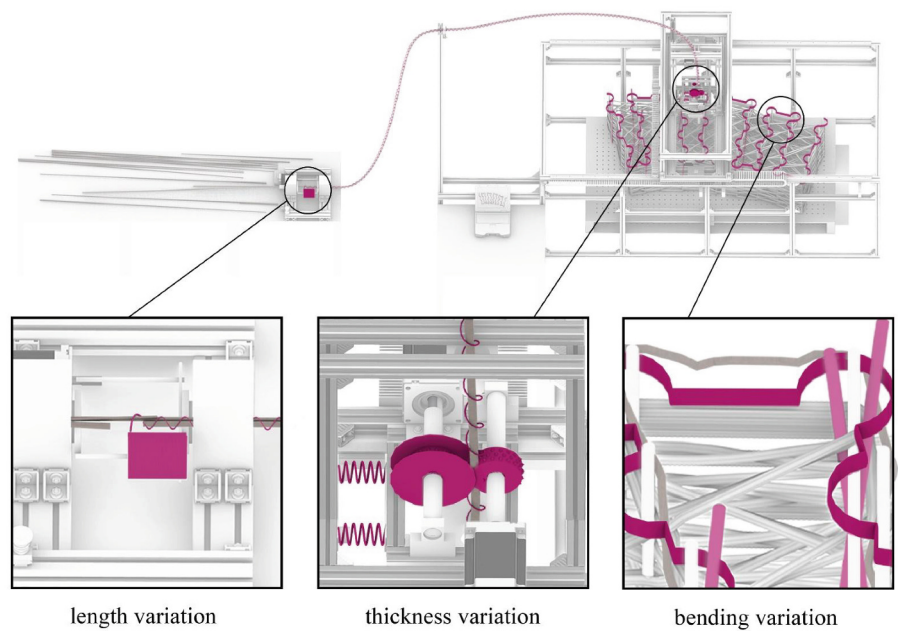


Fig. 5. Tailored solutions for dealing with natural material variations.



Fig. 6. Close-up details of the fabricated components for the project ‘ReGrow Willow’.

3 Results and Reflection

The implementation of the Cartesian coordinate robot in the context of the whole fabrication system, enabled the production of 63 woven willow-earth hybrid components for the project ‘ReGrow Willow’ in the Bundesgartenschau (Federal Gardening Show) in Mannheim in 2023 (Figs. 6 and 8). This was a significant milestone in its evolution over three full-scale research demonstrators (Figs. 7 and 8) showcasing the viability of the fabrication system and thus meeting the overarching research aim.

Inhomogeneities on the material level are dealt with by the implementation of tailored features in fabrication system that adjust to such ‘imperfections’ without necessitating the need to exactly model every intricacy of the variations in length, bending and thickness of the material. The fabrication system is able to deal with changes that arise during fabrication itself by employing an optimised workflow for a custom machine tool-path for every component, highlighting the advantages of embracing the unpredictable, non-perfect nature of reality using facile solutions. Employing an iterative development strategy, adopting rapid prototyping techniques to build custom parts where necessary and to couple them with readily available elements to accelerate each iteration - with the first iteration informed by empirical assessments - means that each sub-part can be quickly tested and improved for durability. This way the development of several conceptualised features could be parallelised and thus their interaction and role in the whole fabrication process could be explored from the initial stages. Developing a system through increasingly more automation in each iteration meant that the empirical knowledge of the material was used the most effectively.



Fig. 7. Left: Full-scale research demonstrator ‘InterTwig’, Right: Prototype ‘RecodeWicker’.

Without subjecting the input material to time- and energy-intensive or waste-generating standardising processes, the willow weaving robot showcased a cost-effective – it can be built from €5000 - and low-impact method for processing a plant-based material into formwork for earth filling. The efficacy of the fabrication process



Fig. 8. ReGrow Willow' demonstrator at the Bundesgartenschau (Federal Gardening Show) in Mannheim.

may be evaluated through physical labour and output quality. In the semi-automated proof-of-concept stage, one person was required to interact with the system to feed the 'splicer'. This is significantly lower in terms of physical labour input compared to manual weaving and splicing. Introduction for a new operator takes 10 min, thus making any machine operating expertise redundant. As the entire weaving path for a component is encoded into one file the operator does not need to understand weaving logic or follow the sequence. The output quality of the woven willow components has low variance as the range can be fine-tuned by different parameters in the process (spring tension, splicing speed, splicing yarn tension, weaving tension etc), this allows a greater control over the final product.

4 Conclusion and Outlook

Following the encompassing principles of minimising the embedded energy, cost and impact on the environment, a semi-automated fabrication system emerged. It demonstrates that material explorations as a starting point and an iterative development strategy catalysing process and fabrication integrated solutions - rather than complex simulation and modelling - can be an appropriate method for developing tailored fabrication processes. Taking the development further, a material feeding system has been conceptualised which instead of scanning and manipulating each branch, can robustly deal with a range of deviations through a material forwarding system. Employing off-the-shelf sensors around the extruder could set the willow tension automatically enabling a completely autonomous fabrication process. This is possible through the upgrade to a centralised, real-time controller (ROS) which can couple the currently decoupled splicing system with the Cartesian coordinate robot. Since the system was developed using widely available electrical and control components integrated with custom parts, deploying an increased level of automation is possible without large financial or time

investment. Due to inherent features of the Cartesian coordinate robot, scalability of components in dimension as well as production rate not only proves feasible as the relative cost-effectiveness of the system means that reaching industrial-scale output levels could be achieved by parallel machines - with one supervisor - thus validating its potential for technology transfer towards industrial production. As the fabrication system contains a range of adjustable parameters, it is not inherently standardised to one plant-based material. Similarly long and slender materials, such as reed, poplar - local to the point of construction - can all be used in such a digital fabrication workflow, reinforcing its application potential in a global context. The underlying versatility and the fact that it consists of easily transportable and expandable modules – depending on component dimension – mean that the application space may be expanded both geographically and demographically. Thus proving that with minimal complexity a fabrication system that utilises sustainable – potentially local – materials can emerge. As the next stage of the research, the willow-earth hybrid component logic will be applied to arched ceiling slab components as part of a construction demonstrator to be exhibited at the Landesgartenschau (State Gardening Show) in Wangen im Allgäu in 2024. The principles of minimising energy, impact and complexity that underpinned the evolution of the system make it applicable in a range of different contexts and to different materials, which can foster a new perspective on the industrialisation of more sustainable fabrication solutions. Such solutions may circumvent the traditionally complex processes and instead enable robust solutions that adjust to the ever-changing intricacies of the real world without standardising them.

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