Over the past decade, robotic fabrication in architecture has succeeded where early digital architecture failed: in the synthesis of the immaterial logic of computers and the material reality of architecture where the direct reciprocity of digital designs and full-scale architectural production is enabled. With robots, it is now possible to radically enrich the physical nature of architecture, to ‘inform’ material processes and to amalgamate computational design and constructive realisation as a hallmark feature of architecture in the digital age, leading to the emergence of a phenomenon we described a few years ago as ‘digital materiality’.1 As a consequence, a uniform technological basis for architecture has been established, which from the onset of building industrialisation in the early 20th century was more vision than reality. We are no longer witnessing the delayed modernisation of an industry, but rather a historical departure: the modern division between intellectual work and manual production, between design and realisation, is being rendered obsolete.2

At the same time, a wide range of inherently architectural topics are finding their way back on to the agenda, not least among which are crafts and the art of construction, and, in particular, methods of architectural design. As robotics becomes increasingly commonplace in architecture, the subject of debate can no longer be its ‘dematerialisation into pure form’, as raised by digital architecture during the 1990s. Instead, what we are observing today is the comprehensive digitalisation of architecture, which entails a radical paradigm shift in its production conditions. The employment of robotics in architecture is opening up the prospect of entirely new aesthetic and functional potentials that could fundamentally alter architectural design and the building culture at large.3
Robots

Employing digital technologies solely for the purpose of generating complex geometries and renderings warrants some scepticism, and there are plenty of cases in point. However, the question is whether digital technologies can impact and therefore change architectural material practice. Our research work with robots at ETH Zurich and the Future Cities Laboratory (FCL) at the Singapore ETH-Centre for Global Environmental Sustainability (SEC), is heavily anchored in this voyage of discovery, and this issue of  explores what happens if architecture absorbs the proposed connection – enabled by robots – between computational logic and material realisation as a new basis for the discipline’s practices.

The industrial robot, because of its ability to perform an unlimited variety of non-repetitive tasks, is considered as the enabler for this deep transformation. However, rather than focusing on the technological development of robots itself, no matter how fascinating this might be, we are interested in establishing an architectural perspective by exploring the potential of robot-induced design and materialisation processes. To this end, we have reverted to using articulated-arm robots as established, cost-efficient fabrication machines that are at once both reliable and flexible, and whose potential in conventional industrial applications has been thoroughly proven. It is essential that architecture and the conditions specific to its production inform our approach to robotic fabrication, and not vice versa. Only in this way can we significantly expand the range of architectural design and production options, enabling a new material differentiation and complexity to emerge and find expression.
Start, Crash, Reboot

For various reasons, the initial introduction of robotic systems to the building construction industry was anything but a success. Most of all, the development of robot-based construction processes in the 1990s frequently led to either highly specialised, extremely expensive construction robots with extremely limited flexibility, or to robot-based construction factories yielding the same constraints. Robots in building construction up to this point were used exclusively to further optimise (standardised) building processes, as a means of achieving only greater productivity (see the article on ‘Changing Building Sites’ by Thomas Bock and Silke Langenberg on pp 88–99 of this issue). Ultimately, no real lasting added architectural value, let alone any new (digital) building culture took hold during these initial attempts at integrating robotics into the building industry.

All of this radically changed at the turn of the millennium. Digital technologies became more commonplace among the architectural discipline and began having a greater impact on the understanding of architectural design and practice. In addition, with the rapid spread of computer-controlled production machinery borrowed from other industries, such as milling and laser cutters or 3D printers, the ‘digital project’ attained considerable material value. In 2005, in order to examine the resulting new production conditions for architecture, a multi-purpose fabrication laboratory employing an industrial robot – the first such laboratory in the field of architecture – was installed at ETH Zurich.

Industrial robots are distinguished by their versatility. Like computers, they are suitable for a wide variety of tasks because they are ‘generic’ and therefore not tailored to any particular application. Instead of being restricted in their operations to a prescribed range of applications, the ‘manual dexterity’ of robots can be freely designed and programmed. Their material manipulation skills can be customised to suit a specific constructive intention, both at the material and conceptual levels. It is precisely this quality – unleashing a previously unimaginable range of freedom in the interplay between the machine and the object – that distinguishes the operational applicability of industrial robots from all other specialised digital fabrication machines. In order to exploit this potential, which massively expands the concept of architectural design, not only a technical grasp of the robot’s construction capabilities, but also an in-depth understanding of the materials to be processed, is necessary.
Challenging Scale

Only once digital architecture has assumed a more radical, substantial role in the aesthetic and material realisation of architecture will the discipline finally arrive in the digital age. The Gantenbein vineyard facade (Fläsch, Switzerland, 2006) represents the first of our projects to demonstrate this immanent architectural potential. It is remarkable because it anticipated the central principle of an additive robotic fabrication of architecture at full scale by demonstrating the non-standardised assembly of the extraordinarily large number of single (brick) elements.

We have since further intensified our explorations and sharpened our focus through a number of research projects. As such, the range of robotic processes is gradually expanding, from prefabrication towards direct use of robots on the construction site (see Volker Helm’s ‘In-Situ Fabrication’ article on pp 100–107). Flight Assembled Architecture (FRAC Centre, Orléans, 2011) ultimately demonstrates, five years after the Gantenbein vineyard facade, that future robotically facilitated construction processes are capable of vastly surpassing previous scales of digital (pre-) fabrication. In this architectural installation, several autonomously flying quadrocopters were employed to collaboratively assemble over 1,500 building modules to form a porous, vertical (urban) aggregation. In contrast to conventional building processes, here the flying robots were able to operate freely in airspace and amalgamate temporarily with the building materials they ultimately deposit.

All of our projects are driven by a curiosity to explore the capabilities of robotic fabrication in relation to real building construction, with all its requirements and challenges. Rather than simply producing a novel aesthetic effect, they seek to create a fundamentally new construction method, capable of achieving previously unattainable scales and levels of complexity.

Gramazio & Kohler in cooperation with Bearth & Deplazes, Gantenbein vineyard facade, Fläsch, Switzerland, 2006
below top: The plasticity and hue of the rotated fields of bricks changes depending on the position of the sun, while from close up the three-dimensional depth dissolves and disappears in the detail of the individual bricks.

below bottom: The 400-square-metre (4,300-square-foot) facade of the Gantenbein Winery was robotically fabricated from 20,000 individually rotated bricks.
than a mere theoretical exercise, we regard this empirical attitude as crucial to unlocking the full potential of robotic practices in architecture. This materialist approach proceeds from an understanding of design that is directly informed by the material’s constructive capacities in conjunction with well-attuned fabrication principles (see Norman Hack and Willi Viktor Lauer’s research on Mesh-Mould structures on pp 44–53). In turn, rather than merely ‘illustrate’ a predetermined design idea, architectural design should be informed by novel fabrication processes directly derived from the logic of the given material. As architecture embodies pure physical substance, the concrete task is to figure out creatively – together with robots – the relevant material processes at hand. Here, robotic fabrication brings novel design concepts and performative capacities of materials to the foreground (see Neri Oxman’s investigation into ‘robotic swarm printing’ on pp. 108–15).

This issue of 3 looks at new digital fabrication paradigms and provides a basis for contextualising and examining the scope of this focal point in detail. It presents selected contributions that not only challenge the reputedly clear division between theory, research and practice, but also serve as an instrument for sounding out the application of robotics at full architectural scale. As the title of the issue suggests, the driving force behind these explorations is the desire to seek lasting future strategies for ‘making’ innovative architecture with robots.

**Venturing Out of Bounds**

Our core contribution to the issue, the Design of Robotic Fabricated High Rises design research studio at the Future Cities Laboratory illustrates a pioneering attempt to place digital fabrication in the context of architectural production, and to explore the potential of robotic construction processes in the context of large-scale residential tower developments. In order to overcome the prevailing paradigm of repetition and mono-functionality in such urban developments, as well as the resulting monotony, the central concern of the project is the tectonic inquiry into high-rise typologies through digital design and fabrication processes. The design research studio in Singapore is geared towards 1:50 models of mixed-use high-rises, which are computationally designed and robotically fabricated (see Michael Budig, Jason Lim and Raffael Petrovic’s contribution ‘Integrating Robotic Fabrication in the Design Process’ on pp 22–43).

Hereby, robotic fabrication overcomes the repetitive build-up of standard building elements in favour of a differentiated assembly of bespoke elements, and links computational design to the fabrication of physical study models. Our thesis is that through such hybrid digital-physical methods, the physical model – even in the age of computation – again gains central significance.11

**Robotics Pioneers**

Is the robot also a new El Dorado for startups? In addition to academic research and teaching projects, Made by Robots presents important pioneers in this field: a selection of startups devoted entirely to architectural robotic fabrication processes (see pp 60–75). They are distinguished by their nonchalance as well as their savvy and innovative application of novel production technologies. At Odico Formwork Robotics, RoboFold, Machineous or ROB Technologies and GREYSHED, the usual coveted symbols of status, brand identity and recognition are being trumped by the advantage
Even if today’s very specific implementation of robotic fabrication processes – in comparison to the lack of material substance in the early days of architecture’s digitalisation – is practically forcing architecture’s arrival in the digital age, what still remain vague are the ties to architectural history, its theoretical implications and future prospects.

in being curious, adaptable and versatile. An entrepreneurial spirit that favours cooperation over authorship pervades these enterprises, in the sense of empowering oneself and others. Each is striving to remove the stigma associated with the mechanical-age mentality of standardised thinking and serial production. Here, robots offer a reliable and cost-effective technology that is globally accessible and extremely flexible in its application (see particularly the text by Machineous on pp 70–71).

It is this understanding that underlies the focus of the startups featured in this issue, not only on the programming and application of robotic fabrication processes – the assembly of non-standardised building elements (ROB Technologies, pp 72–3), the cutting of individual formwork (Odico Formwork Robotics, pp 66–7) or the folding of sheet metal (RoboFold, pp 68–9) – but also on the development of novel interfaces, software or design processes. Academic research in this area is giving rise to new enterprises and innovative business ideas, and comparable to the 3D printing sector their dynamism is increasingly taking hold and permeating the entire field of architectural activity to the hum of ‘how to make almost anything’. Should robotic fabrication processes actually become commonplace in the construction industry over the next decades, these ‘pioneers’ could be credited with having dauntlessly transformed the building industry bottom-up (see GREYSHED, pp 74–5 and facilitated the breakthrough of the digital architectural production of the future.

Theory of Change – Change of Theory
Even if today’s very specific implementation of robotic fabrication processes – in comparison to the lack of material substance in the early days of architecture’s digitalisation – is practically forcing architecture’s arrival in the digital age, what still remain vague are the ties to architectural history, its theoretical implications and future prospects. Rather than run the risk of getting caught up in the latest robotic technologies, a reflexive awareness is called for that asks: How do we define architectural production in today’s world, if the current dichotomies of code and material, type and variation, author and artefact, human and machine, are increasingly losing ground and being replaced by new categories that render them outdated? (See, for example, the work of François Roche/New-Territories on pp 116–25).

What is the point of architectural discourse today if the dominant narrative finds itself increasingly clutching at straws rather than contributing to greater clarity? Neither the pledge to overcome the Modernist legacy nor the sole focus on a (post-) digital future is of much use in this case. Explorations into our current digital age must broaden to include both practical and theoretical perspectives. This would require that the robot be regarded not only as a medium of production, but also as an epistemological approach (see Antoine Picon’s encounter with the theoretical implications of architectural robotics on pp 54–9). Only then would it be possible to stimulate relevant and rigorous exploration, discussion, principles and prospective applications for robotics in architecture.

Architecture in the Second Digital Age
This issue of D ventures to take a look forward because we believe robotic potential in architecture is inextricably future-oriented. The robotic fabrication of tomorrow, surprisingly,
will no longer be bound to constricting standards, constraints or ideologies, but will allow each architectural experiment with robots the freedom to follow its own agenda. We now have access to enormous knowhow and different forms of knowledge – anyone can become an expert in digital fabrication these days. The present moment is thus ripe for revolutionising architectural production; robots are now connecting technology and knowhow, as well as imagination and materialisation, like never before, and have the potential to reveal a radically new way of thinking about and materialising architecture. This takes away the abstract and forced artificial character of the digital in architecture and imbues it with a totally distinct material significance and identity. One could even speak of the dawn of a ‘second digital age’. This issue hereby signals a seminal shift. Or, in other words, architecture is at long last beginning to develop an adequate material practice for the cultural logic of the information age.

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Notes
4. The Future Cities Laboratory (FCL) is a transdisciplinary research centre for urban design and sustainability at a global scale, under the direction of the Singapore-ETH Centre for Global Environmental Sustainability (SEC). See: www.futurecities.ethz.ch.

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