With the rising availability of digital capacities in smaller research-driven practices, the practice/research studio challenges the notion that academia is the best place for experimentation. It also begins to close that ever-troublesome gap for architects between representation (the things we draw and model) and realization (the things we build). Prototyping more than merely resembles the construct; it begins to essentially actualize it. This means that now practice is empowered to shape the industry rather than "shopping" for available parts, i.e. practice is at the driving end rather than the receiving end, shaping the purpose of available new technologies. We are at an incredibly dynamic point in our discipline where the vectors of sustainability, digital means, and aesthetics coincide, and are driving new forms and possibilities for architecture.

NOTES
1. Whereas in some respects, areas such as sustainability or structural engineering have progressed quickly in Europe, digital fabrication has been explored with much greater interest in North America.
2. For more information about the company, see www.truedoe.com.
3. Much of this research has been supported by collaboration with a roster of talented and resourceful European engineers, including Werner Sobek, Schlaich Bergermann, Arup, and Jürg Conzett.

FABIO GRAMAZIO AND MATTHIAS KOHLER
GRAMAZIO & KOHLER AND ETH ZURICH
9.1. The mTable designed using a mobile phone and digitally fabricated.

The digital revolution had an unquestionable impact on contemporary architecture; it has changed the ways in which architecture is conceived, built, mediated, and used. This evolution has only just begun, and it is still too early to predict the long-term consequences for the architectural discipline. Already, a whole spectrum of polemical views on digital technology—ranging from utopian enthusiasm to reactionary fear—has dominated the debate and divided the professional community. Due to its intangible nature, the digital realm is generally misconstrued as being antagonistic to the analogue or physical realm. Our intention is to unite these seemingly opposing realms.

Since its foundation in 2000, Gamazio & Koller has been exploring digital realities within architecture, working with the firm conviction that the digital paradigm will inevitably redefine the discipline. Human intelligence allows architects to take design decisions on complex issues using associative capacities and experience, yet unlike computers, humans are unable to process large amounts of discrete data. By understanding the fundamental concepts of digital logic and mastering its processing techniques, we expand our capacity to integrate information into the design process without losing control over it. The architect is engaged in selected relevant architectural parameters and the definition of subsequent rules and processes. The construct is created by a system that is entirely defined by the architect.

One of the most radical consequences of the digital revolution is the computer-controlled fabrication machine. As decades of artificial intelligence research and human activity have shown, a physical body is a precondition for every kind of intelligence. Architecture cannot be reduced to a conceptual, geometric, or mathematical phenomenon. Artificial "intelligence" in architecture can only manifest itself through a tectonic logic and a physical, material "body." The application of a fabrication machine in architecture allows a direct coupling between information and construction. In digital fabrication, the production of building parts is directly controlled by the design information. This seamless link between data and material, design and building, dissolves the apparent incompatibilities between digital and physical realities and allows a new constructive understanding of the discipline. Thus, these issues are the primary focus of our research in the Department of Architecture at the Swiss Institute of Technology (ETH) in Zurich.

**ROBOTIC ADDITIVE FABRICATION**

In order to investigate the consequences of incorporating digital logic with the physical material of a building, we created a research laboratory at ETH for the digital fabrication of full-scale prototypes and non-standard building parts (DFAB). For its first experiments, we chose a standard industrial robot. Its extreme flexibility, both in terms of the software that controls it and its physical capacities, allows us to program its movements and design the actual construction tools it selects for operations. For us, it is a veritable "personal computer" for construction. With this robot, we investigated the logic of additive fabrication, using the most elementary architectural building block—the brick.

The resultant projects, described below, confirm that digital logic, both in design and fabrication, will lead to profound changes in architecture, blurring and ultimately dissolving the boundaries between analogue and digital realities. We stand at the very threshold of an exciting development and believe that we should, as architects and authors of design information, actively lead this process towards a new, contemporary, and integral understanding of architecture that is relevant to our age.

**MTABLE**

The mTable table series project, completed in 2002, enabled us to examine the consequences of customer interaction when designing non-standard products. In the process, interesting questions emerged: how much responsibility is the customer able to assume? Who ultimately is the designer? To what extent does the co-designer identify with the product? What consequences does this development have on architecture?

With mTable, we created a table (figure 9.1) that customers can co-design. Modern communications and digital production technologies were used for its customized design and fabrication: we declared the mobile phone to be a personal design tool, and examined how it could be utilized to assist the individual to co-design his or her physical environment.

The design principle is simple. Customers choose the size, dimensions, material, and color of the table from their cell phone display (figure 9.2). Next, they place deformation points on the underside of the table and "press" them (figure 9.3); these points then "break through" the surface edges, turning the "landscapes" into specific designs.

Using a mobile phone to control the future display, customers are able to transmit the design to the designer, who can then verify the design via the phone. As soon as the user transmits the parameters, the design is created and delivered to the user. The following is the process:

1. The user selects the size, dimensions, material, and color of the table using the cell phone display.
2. The design is transmitted to the designer, who then verifies the design.
3. The design is created and delivered to the user.
had an unquestionable impact on architecture; it has changed the ways in which we conceive, build, meditate, and use. It is just begun, and it is still too early to evaluate its full consequences for the architectural world. A new polemic has emerged, ranging from the brash enthusiasm of the digital revolutionaries to the more moderate and measured views of the Digital Fabrication Workshop (DfLab). The digital world has divided the architectural community into two camps: those who embrace the new technology as a means to new possibilities and those who see it as an invasion of the realm of architecture.

Our intention is to unite these camps.

In 2001, Gramazio & Kohler set out to create a new field of digital fabrication within architecture. They believed that the digital paradigm could be the missing link between digital and physical realms and allow for new possibilities in design and construction. They designed and built a prototype building block—the building block of the future. The resulting projects, described in this book, confirm that digital design and fabrication are becoming the new normal in architecture.

Robotic Additive Fabrication

In order to investigate the consequences of inform digital fabrication with the logic of physical materials and vice versa, we opened a research laboratory at ETH Zurich's Digital Fabrication Laboratory (DfLab). The lab is engaged in the selection of relevant actors and the definition of subsequent projects. Our first experiments were conducted using an industrial robot that can perform tasks such as painting, welding, and other operations. For us, it is a valuable "computer" for construction. With this robot, we investigated the logic of additive fabrication, using the most elementary block as the building block. The resultant projects described below confirm that digital design, both in design and fabrication, is a powerful tool for new development in architecture, blurring and ultimately dissolving the boundaries between analogue and digital realities. We stand on the threshold of an exciting development and believe that we should be architects and designers of design information, actively leading this process towards a new, contemporary, and integrative understanding of architecture that is relevant to our age.

mTable

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With mTable, we created a table (figure 9.1) that customers can co-design. Modern communications and digital production technologies were used for its customization and fabrication: we declared the mobile phone to be a personal design tool, and examined how it can be utilized to assist the individual to co-design his or her physical environment.

The design principle is simple. Customers choose the size, dimensions, material, and color of the table from their cell phone display (figure 9.2). Next, they place deformation points on the underside of the table and "press" them (figure 9.3); these points then "break through" the surface, creating holes with extremely thin edges, turning the table's top and underside into two distinct "landscapes" (i.e., topographies). The phone on the cell phone then verifies that the table with holes is structurally feasible.

Using a mobile phone is an enjoyable and intuitive way to control the physical shape of the table. The phone displays low resolution and a deliberately simplified interface. The design is often a physical challenge for the customer, and the designer can test the design with the customer's own phone, comparing the design with the other customers' designs (figure 9.4). Following the placement of the order, the table is cut by a computer-controlled milling machine (figure 9.5).
driven by the data (parameters) transmitted from the mobile phone. The virtual three-dimensional model is transferred to the physical material.

The openings in the table top, the curved edges, and the spectrally undercuts (figure 9.6) lend every table a unique quality. Admittedly, different tables are only unique on the surface, as they all share a common formal and conceptual origin. Still, each table is a result of the customer's decisions and variations on a design pattern. Together, the tables form an entity—the mTable design family (figure 9.9).

The mTable project changes the task of designing from that of the 3D design system. The design concept and the formal consequences are carefully embedded in the software that provides a framework within which the customers can develop their own creative strategies, thus giving them control over the ultimate outcome of the design—the form. By deciding for themselves if and where the holes are placed, they assume partial responsibility for the aesthetic appearance, and functional efficiency of the tables. The designer, however, still retains control over which decisions are delegated to the customers and how freely they can intervene. This blurs the distinctions between designer and customer, as the customer becomes a co-designer.

**THE WORLD'S LARGEST TIMEPIECE**

The project for the Christmas lighting on Bahnhofstrasse in Zurich, Switzerland (2005), is based on a winning entry in a competition that called for a contemporary interpretation of the lighting installation designed over thirty years ago by Will Walter and Charlotte Schmid. Their project was described as "distinctive, generous, unique," and these were qualities the new design was naturally expected to incorporate.

We designed a continuous band of lights with a dynamically changing pattern (figure 9.7). The main premise behind the time-based light installation is that light is not static, but fundamentally dynamic in nature. Light can now be used as a highly flexible and interesting information medium, due to contemporary digital technology that can provide control over its intensity. By changing its appearance during the Advent season, "The World's Largest Timepiece," as the installation is called, accentuates the passing of time and creates a constantly changing "lightscape" on Bahnhofstrasse, and provides every visitor with a truly unique experience.

The installation is conceived as a single illuminated line running from the railway station to the lake, emphasizing the urban "boulevard" atmosphere of the Bahnhofstrasse and accentuating its two slight, yet distinct turns in direction as it negotiate its way. Its simple, linear form is a testscape of the street and points upward as a slick series of light-bedecking, changing curtains.

The install follows a high and place light tube has 32 pieces of equipment necessary for each bulb. There are a total of light. The intense light, using custom XMAS Generator of code were needed. Different light patterns illuminate the light tubes via an inner piece, a computer algorithm that changes the light artfully reflecting the passing street itself. In this way, the ambiences of light with a collective interaction, inner timepiece, and immaterial architecture.

Each of the 7 directions, which had to be done, involved tubes that allowed the inner light to be seen. Along the outer shell of the tube, there are several trials and errors manufacturing techniques involving insulation, manufacturing techniques were needed, and spun around each other, combining the additive logic of the stacking of the movements. A slide back and forth along inner light, an extremely stable number of tiers, and transformable stiff.
"THE WORLD'S LARGEST TIMEPIECE"

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The installation is conceived as a single illuminated line running from the railway station to the lake, emphasizing the urban "boulevard" atmosphere of the Bahnhofstrasse and accentuating its slight, yet distinct turns in direction as it negotiates the heart of downtown Zurich (figure 9.8). Its simple, linear course turns the band of light into a visual backbone of the city. The vertical shaft of light in the middle of the street contrasts with the surrounding building façades and points upward to the night sky. Depending on where the viewer is standing, the Christmas lighting can either look like a slick series of individually lit tubes or a glowing, constantly changing curtain of light.

The installation consists of 275 tubes of light, each 7 m high, and placed at 4 m intervals (figure 9.9a-b). Each light tube has 32 small LED bulbs and contains the electronic equipment necessary to regulate 256 brightness levels within each bulb. There are 8,000 LED bulbs in the 1 km-long band of light. The intensity of each bulb can be controlled in real time, using custom-made software written in C++ called XMAS Generator (figure 9.10). Approximately 26,000 lines of code were necessary for the creation of this software. Different light patterns were generated and transmitted to the light tubes via an optical database at the rate of 17 times per second.

The changing patterns of light are generated by an algorithm controlled by the dates associated with the holiday season and the street activities that were recorded using sensors. An increase or decrease in the number of visitors affects the character of the lighting patterns and the frequency of change. Hence, the light patterns not only reflect the passing of time but also the daily activities on the street itself. In this way, each passer-by can alter the street's ambience by influencing the lighting patterns. In a form of collective interaction the Christmas lighting becomes the city's inner timepiece, and creates an unpredictable, dynamic, and immaterial architecture, similar to clouds in the sky.

Each of the 7 m-long tubes had to illuminate in all directions, withstand wind and water, and be lightweight. We had to find a sufficiently rigid material for the shell of the tubes that allowed the transmission of light; a supporting aluminum core would have created unattractive shadows on the outer shell and thus compromised the effect. After several trial and error experiments, we stumbled upon the manufacturing technique for woven glass fibers used in high-tension insulation, in which glass fibers are soaked in resin and spun around a mandrel (figure 9.11). We were fascinated by the additive logic of this process. The winder controls the stacking of the fibers via two computer-coordinated movements. A sliding carriage drives the wound glass fibers back and forth along the spinning mandrel. This creates an extremely stable multi-layered shell. The stacking winder and the number of tiers and overlaps determine the flexural rigidity and torsional stiffness, as well as the transmission of light.
The bands of glass fibers are woven into a rhombus structure; the thick areas are responsible for the stability of the structure, and the slender necks create optical brilliance. In order to optimally join both light diffusion and rigidity, we developed software that simulates the fabrication process, enabling us to test weaving variations with different bandwidths, angles, and tiers. Using more than thirty physical prototypes, we tested effective optical qualities such as brilliance, light transfer, and surface structure for both night and day conditions. We also tested wind resistance. The final tube was 7 m long and 15 cm in diameter; its shell was only 2 mm thick. It weighed less than 2.3 kg, including lighting and control technology. An intense involvement with the computer operated production process allowed us to integrate two normally incongruent requirements into one single material, and thus implement for the first time wound glass fibers for lighting on this scale.

GANTENBEIN VINEYARD FACADE

The new service building for the Gantenbein Vineyard in Filisur, Switzerland (2006), was already under construction when Béard & Deplazes Architects invited us to design the façade (Figure 9.12). The building had three stories: a cellar for storing the wine barrels, a large fermentation room for processing grapes, and a terrace-like lounge for wine-tasting and receptions. The fermentation hall had to be windowless, because constant temperatures and subdued lighting are required to ferment the grapes properly. To provide natural lighting despite these preconditions, we designed a façade in which the bricks were laid with gaps between them to allow daylight to enter the fermentation hall (Figure 9.13). The façade itself has two layers outside; the masonry layer functions as sun protection, light filter, and temperature buffer; inside, polycarbonate panels protect against wind.

We decided to imitate the façade with a pattern that looks from afar like a basket filled with grapes (Figure 9.14). To create this effect, we designed an information generation process that produces an impression of a precisely controlled result by applying purely systematic chance. We interpreted the Béard & Deplazes concrete frame structure as a massive basket, and filled it with abstract balls (the “grapes”) that varied in diameter (Figure 9.14). The balls fell into a virtual container via digitally simulated gravity, until a specific density was reached (Figure 9.15). The elevation images of the digital “basket” were then used to create the “grape-like” brick wall patterns (with gaps), using an automated layout process (Figures 9.16a-b).

The brick wall pattern was rotated slightly, and a slightly different one. In this way, bricks with different image patterns on their faces form the vineyard. Unlike the vineyard, is a subtle interplay of three-dimensional material effects that the day (Figure 9.12) possesses a sense of movement.

On closer view, the wall resembles stone, round forms in actual hard bricks (Figure 9.12). The dynamic forms, which guide the viewer’s eye to the brick wall surface, is a mild, yet luminous (Figure 9.13); the subtle light modulation of the superimposed image in various ways.

A three-dimensional space is more effective than a two-dimensional, both visually and tactilely, in directions, with a sense of space. Each façade was implemented as much in
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The brick wall patterns are three-dimensional. Bricks are rotated slightly, and thus reflect light differently, resulting in slightly different tonal values on the surfaces (figure 9.17). In this way, bricks function like pixels that form the "grapes" image pattern on the façade, and thus brand the identity of the vineyard. Unlike a two-dimensional image, however, there is a subtle interplay between plasticity, depth, and color in a three-dimensional brick pattern, producing not one but many material effects that constantly shift during the course of the day (figure 9.18). The result is a dynamic surface that possesses a sensual, textile softness.

On closer view, the walls reveal a materiality that resembles stonework, and one is surprised that the soft, round form is actually composed of individual, orthogonal, hand bricks (figure 9.18). The façade appears as solidified dynamic forms, whose shallow three-dimensional depth invites the viewer's eye to wander. Once inside, the transparency of the brick wall surface becomes evident. The daylight creates a mild, yet luminous atmosphere in the fermentation hall (figure 9.13); the design intent becomes manifest through the subtle light modulation by the gaps between the bricks. The superimposed image of the landscape gleaners through in various ways.

A three-dimensional brick façade, therefore, is far more affective than a two-dimensional image. To create subtle visual and tactile effects, bricks were rotated in two counter-directed, with a maximum deflection of 17° (figure 9.19). Each façade was balanced, so bricks would progressively rotate as much in one direction, as in the other. Where there
is no visible "gape" (meaning where a gap is created in the virtual "basket"), bricks are in a neutral position and thus form a simple running bond.

The construction technology we developed at the ETH enabled us to lay each brick precisely using an industrial robot (figures 9.20a-b). Not only did the robot lay the bricks, it applied a special bonding agent onto each brick (figure 9.21) rather than traditional mortar. With this new digitally driven, additive production method, we were able to construct each wall differently, so that each wall possessed the desired light and air permeability, and thus create the overall pattern that covered the entire façade. We designed 72 different brick wall panels using a computer program created expressly for that purpose. The program generated the production data directly from the design data and calculated the exact rotation for each of the 24,000 bricks that comprise the 400 m² façade. The bricks were then laid out automatically by the robot according to programmed parameters, at prescribed angles and at exact intervals.

Because each brick is rotated differently, every single brick has a different and unique overlap with the brick underneath. We had to find a method of applying the bonding agent to such that it fits precisely every overlap (all of which were dimensionally unique) and, at the same time, distributes the adhesive evenly. Working closely with an engineer from the brick manufacturer, we devised a strategy whereby four parallel bonding agent paths could be applied at pre-defined intervals to the center axis of the wall panel. This strategy allowed us to attain consistent dimensions.

Load tests performed on the first manufactured prototypes revealed that the bonding agent was so structurally effective that the reinforcement normally required for conventional prefabricated walls could be completely eliminated.

Manufacturing 72 façade panels was a big challenge, both technically and in terms of deadlines. Due to the advanced stage of construction, we had only three months to complete the design and production before installation on-site. Because the robot could be directly driven by the design data, we were able to work up to the last minute on the façade design, while developing simultaneously the production method (figure 9.22). In the end, the façade panels were produced over just two weeks (with the robot working double shifts). They were then transported by truck to the construction site and installed by crane (figure 9.22). The procedure was developed in collaboration with a brick manufacturer who, as an industry partner, was subsequently able to take on the system guarantee on our manufactured panels.

PERFORATIONS
What is the spatial effect and architectural significance of a perforation in a wall, in the form of a diagonal, round hole? Openings regulate the amount of light and air that enters a building. Moreover, by allowing one to look into or out of the building, they also create visual relationships between the interior and exterior. Qualities such as dimension, position, depth of a reveal, and geometry determine their architectural expression. The complexity is heightened if an opening (i.e., a perforation) passes through a wall at a non-orthogonal angle; the reveal's visual presence is emphasized and the wall acquires more depth. Besides formal qualities, the number and arrangement of the voids also affect the architectural effect of a perforation.

Today, complex perforated architectural components can be created using digital design methods. In contrast to industrially manufactured elements, such as a punched perforated metal sheet, the digitally designed perforations do not need to be based on a repetitive, regular grid. The individual openings can be different in shape or diameter, and the material can be perforated not only orthogonally, but also at different angles through the surface. Moreover, given that each element can have a unique pattern of perforations, larger constructs made of different perforated components, such as façades, can be designed without repetition.

What is the best v opening? What we at a different angle at the ETH in Zurich spatial potential of the elements had to be which we encouraged aids to manage get students produced panels, concentrate of a self-devised p amounts of information process - required an integral element and expanded the based on the feedback process of design and production.

In the "oblique" had to allocate 2,400 potential of spatial large amount of digital form. The produce a robot hand; the use to the surface expanded distributing the holes in an algorithmic tools form as it was impracticable perforations with digital technology. The digital into production direct post-process. The consisted of its positional the tool's drilling path.

Surprisingly and the fact that design single hole (i.e., drilled thickness of the material two-dimensional 2d task, that revealed of Orienting fields of caused the physical, abstract, almost particular advantages and visual paths being independent of the moving about the use of perforations
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What is the best way to design using a large number of openings? What would it mean if each individual opening was at a different angle to the surface? In several elective courses at the ETH in Zurich, the students were asked to examine the spatial potential of highly perforated wall elements. These wall elements had to be developed using innovative digital tools, which we encouraged to be seen as more than simple technical aids to manage geometric complexities. In each course, students produced full-scale prototypes of perforated wall panels, concentrating on the materialization and development of a self-devised production technique. Designing with large amounts of information – and "informing" the material in the process – required the development of computational tools as an integral element of the design process. The students altered and expanded the digital tools in an agile, creative manner, based on the feedback attained through the iterative processes of design and production.

In the "oblique hole" course (Das scheife Loch), students had to allocate 2,000 holes over an irregular polygonal volume (figure 9.23). The objective was to examine the architectural potential of spatial perforations produced by distributing a large amount of circular openings in an irregularly shaped form. The production tool was a milling spindle mounted on a robot hand; the robot’s ability to drill holes at any angle to the surface expanded the design possibilities from merely distributing the holes to also defining their direction. Various algorithmic tools for distributing the holes had to be developed, as it was impractical to produce such a large number of perforations with conventional computer-aided design (CAD) technology. The digitally generated design data was translated into production data for the robot by a custom-developed post-processor. The production data for each individual hole consisted of its position in space and a vector that described the tool’s drilling path through the material (figure 9.24).

Surprising architectural artifacts were created despite the fact that design options were intentionally limited to a single hole (i.e., drill) size of 10 mm in diameter. It was the thickness of the material, which transformed a supposedly two-dimensional job into a complex three-dimensional design task, that revealed the project’s full architectural potential. Owing to the holes’ tendency towards a certain point in space caused the physical depth of the material to collapse into an abstract, almost immaterial surface when seen from a particular vantage point. The openings created new spatial and visual paths between the interior and exterior that were independent of the volume’s physical geometry. For the viewer moving about the room, the three-dimensional nature of the perforations changed the effects of the architectural volume.
The exploration of perforations continued in the "perforated wall" ("Die perforierte Wand") course. The students examined the potential of "informing" large Styrofoam panels (1 x 2 m in size) with a large number of round holes; the panels were considered full-scale components of a larger wall or facade design (figure 9.25). As in the previous project, the holes could be defined using five different parameters: the X and Y position on the wall, the "alpha" directional ("deflection") angle vector into the wall mass, the "beta" cut-out angle around the central axis of the hole, and the radius of the hole. The holes were distributed using dynamic force fields of attraction and repulsion, in which parameters defining the location and intensity of the forces could be interactively changed. The holes could produce different perforation patterns on two sides with the use of "target" points to define the "deflection" of the holes. We also used the custom-developed "color mapping" tool that translated the red, green, and blue (RGB) values associated with pixels in a chosen image into the "alpha" directional vector, the "beta" cut-out angle, and the radius of the hole, respectively. Working with images provided the students with an intuitive and direct way to "inform" the material.

With another group of students, we worked on developing a method to cast a large (3 x 2 m in size) perforated wall in concrete. We used a robot to cut the geometric extensions of the holes into the formwork boards (figure 9.26), in order to transfer the perforation information onto the concrete formwork. After assembling the formwork, standard plastic pipes were inserted into the holes as blockouts (figures 9.27a-b). The design information was thus indirectly transferred to the material via the formwork design.

Manufacturing the formwork presented a particular challenge, because, due to the irregularly distributed holes and the narrow breadth of the web, neither a conventional reinforcement, nor a mechanical re-densification of the concrete was possible. Also, we were unable to use the self-compacting steel-fiber concrete that had recently been developed by the Institute for Building Materials (Institut für Baustoffe) at the ETH Zurich. After a successful casting, we used various load tests (figure 9.28) to check the structural effectiveness of the wall element. We tested wall elements with different densities that even highly perforated walls in a building have the load-bearing capacity. The density of perforation prototypes revealed the perforated wall. By creating not only with some very interesting modulation (figures 9.29a-b), the load-bearing structural program was also realized.

THE PROGRAMME

A key assumption underlying digital technologies is that the architectural design is only the outcome of the research interests and the program of the architects. Examining the robotically produced panels, we asked ourselves about the implications of that approach. What does it mean to digitally fabricate a wall, for example, more than a person? A robot can create a pattern of holes that are impossible to manufacture with the same accuracy. The robot creates an identifiable pattern, which also allows complex repetition.

We chose to work with perhaps the most historical material of all: the brick. For over 90 years, the brick's dimensions and properties have been standardized. The sequencing, the arrangement, and the appearance of the brick have been well established in the traditional brick walls today aren't always the most modern or efficient. The brick is asymbols for the assembly of brick walls, automatic. A wall made with mathematics, meaning between the bricks, a wall made with mathematics and therefore, "program..."
The exploration of perforations continued in the “perforated wall” (Die perforierte Wand) course. The students examined the potential of “informing” (large Styrofoam panels (1 x 2 m in size)) with a large number of round holes; the panels were considered full-scale components of a larger wall or façade design (Figure 9.25). As in the previous project, the holes could be defined using five different parameters: the X and Y position on the wall, the “alpha” directional (“deflection”) angle vector into the wall mass, the “beta” cut-out angle around the central axis of the hole, and the radius of the hole. The holes were distributed using dynamic force fields of attraction and repulsion, in which parameters defining the location and intensity of the forces could be interactively changed. The holes could produce different perforation patterns on two sides with the use of “target” points to define the “deflection” of the holes. We also used the custom-developed “color mapping” tool that translated the red, green, and blue (RGB) values associated with pixels in a chosen image into the “alpha” directional vector, the “beta” cut-out angle, and the radius of the hole, respectively. Working with images provided the students with an intuitive and direct way to “inform” the material.

With another group of students, we worked on developing a method to cast a large (3 x 2 m in size) perforated wall in cement. We used a robot to cut the geometric extensions of the holes into the formwork boards (Figure 9.26), in order to transfer the perforation information onto the concrete formwork. After assembling the formwork, standard plastic pipes were inserted into the holes as block-outs (Figures 9.27a-b). The design information was thus indirectly transferred to the material via the formwork design.

Manufacturing the formwork presented a particular challenge; because, due to the irregularly distributed holes and the narrow breadth of the web, neither a conventional reinforcement nor a mechanical re-densification of the concrete was possible. Also, we were unable to use the self-compacting steel-fiber concrete that had recently been developed by the Institute for Building Materials (Institut für Baustoffe) at the ETH Zurich. After a successful casting, we used various load tests (Figure 9.28b) to check the structural effectiveness of the wall element. We tested wall elements with different densities of perforations and demonstrated that even highly perforated walls could be used as bearing walls in a building structure. We also demonstrated that the load-bearing capacity can be locally controlled with a density of perforations and the deflection of the holes. Our prototypes revealed the multiple architectural potentials of a perforated wall. By moving from Styrofoam to concrete, we created not only complexly “informed” concrete panels with some very interesting potential for light and sight modulation (Figures 9.27a-b), but also produced actual load-bearing, structural components.

THE PROGRAMMED WALL
A key assumption underpinning our work is that new digital technologies of design and production will influence the architectural definition of building components. Our research interests are not limited to the technology only. Examining the robotic additive fabrication of brick wall panels, we asked our students to explore social and cultural implications of that technological possibility. What does it mean to digitally fabricate a brick wall using a robot rather than a person? A robot is not only quicker, more precise, and more productive, but it also enables complex designs that are impossible for a human to build with that level of accuracy. The robot does not need an optical reference or an identifiable pattern in order to lay bricks precisely. It also allows complex walls to be built without relying on repetition.

We chose to work with bricks, because a brick is perhaps the most highly developed module in building history. For over 9,000 years, human hands have optimized the brick’s dimensions, proportions, weight, and material. The sequencing, the joint detail and the type of bonding agent used determined the specific structural qualities and appearance of the brick wall. Despite the long history and well-established traditions in the building industry, the brick walls today aren’t nearly as ubiquitous as they were not long ago; the brick is now mainly used as a single-layered facing on a building. Due to the high cost of labor, walls today are mostly made of large, industrially manufactured blocks or reinforced concrete.

If the brick walls are too expensive because of the high cost of labor, to continue working with this material, the assembly of brick walls could be programmed and automated. A wall made of brick is subject to the rules of mathematics, meaning the relationships (i.e., connections) between the bricks, and can be described by an algorithm and therefore, “programmed.” In turn, digital production
allows direct translation of computer programs into physical artifacts. A robot can build a wall: it can lay each brick in the exact prescribed position, at the exact angle, and at the exact interval, as described by the author of the program, i.e. the designer. The robot can also position each brick differently with no additional time and effort, which is not possible for humans (figures 9.30a-c).

New spatial and architectural possibilities open up with "programmed" brick walls. Continuous, procedurally controlled variations of the position and rotation of each brick could create flowing transitions between open and closed areas. Some walls can be formed three-dimensionally by bricks receding or projecting out of the surface plane of the wall; even if the bricks are laid on one plane, the wall can still appear three-dimensional. Structural patterns, plasticity, and transparency can change dramatically depending on where the viewer is standing or the angle of light (figure 9.31).

9.31. Different "programmed walls."

The appearance of the wall is not only affected by a purely surface effect, but by its depth. The quality of this third dimension cannot be designed two-dimensionally or described pictorially. The geometry of the walls has to be programmed, i.e. algorithmically, procedurally defined; it can only be experienced in physical space in time, through movement of the body through space.

We asked students to produce it using the wall had to be 3 m (about 400 bricks). Students to define the space to procedural logic. The layout of a brick to describe the sequence. A brick is laid next to the wall and rotated until the end is shifted by half of the repeated, and so on. Programming, this pattern, one for the horizontal direction (figure 9.3).

9.34a-f. A different kind of a brick wall.

Students examined with various criteria bonding effect. First of the concepts (figure 9.3) their findings to a site expand and redefine. The students did not construct logic to organizing material production data for.

In the end, the rationalized, design both the archaic produce differentiated quality and information created previously unknown element of the cons
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9.32. This "programmed wall" is defined by two nested loops, one for the horizontal direction and one for the vertical direction.

We asked students to design a "different" brick wall and to produce it using the industrial robot in our research lab. The wall had to be 3 m in length and 2 m in height (containing about 400 bricks). Students developed algorithmic design tools to define the spatial disposition of the bricks according to procedural logic. These tools drew upon the knowledge that the layout of a brick wall is based on a system of rules that describe the sequence of operations needed to build a wall. A brick is laid next to another brick, shifted, and perhaps rotated until the end of a row is reached. The next row is then shifted by half of the brick width, and the previous procedure repeated, and so on, until the desired height is reached. When programming, this process can be described with two nested loops, one for the horizontal direction and one for the vertical direction (figure 9.32).

Students examined different brick bonding schemes along with various criteria for brick laying, stability, and overall bonding effect. First, they manually tested the feasibility of the concepts (figure 9.33). Afterwards, they transferred their findings to a simple computer script, which they could expand and redefine through an iterative, step-by-step process. The students did not design a geometric system, but rather constructive logics that created an architectural form by organizing material in space and this directly provided the production data for the robot.

In the end, the walls – products of a digital, highly rationalized, design process and built by a robot – contain both the archaic presence of the material as well as the differentiated qualities of their procedural design. Acting information created a new, different kind of a brick wall, of previously unknown forms coming from a familiar and trusted element of the construction industry (figures 9.34a–b).
SCREENS

The German writer Kurt Tucholsky once said, "A hole is where there is nothing." Around the hole is a material from which it has been carved. If the holes (i.e., perforations) increase in size, a grid structure develops in the material between the holes and the attention shifts from the holes to the resulting mesh-like structure or screen.

Screens are a common and rich architectural device that can separate spaces, while maintaining a certain visual (and often audible) transparency. In contrast to glass, screens have a strong spatial presence and offer great potential for variation in material, color, texture, etc. The architectural definition of the screen mesh, i.e., its width, alignment, and form, can guide the eyes' glance, obstruct it selectively, or allow full views.

Grid-like structures make the structural depth of a building layer tangible. According to where they are positioned, hybrid structures like screens can assume other functions, such as passive shading (sun protection) or façades. Screens have been used throughout the history of architecture by very different cultures; they have developed in many different ways due to a wide variety of available technological means. As an example, consider the screens in Islamic religious architecture: highly perforated grid structures separate women from the main room of prayer. Besides a purely ornamental value, these highly sophisticated devices allow observation of the events in the main prayer hall without the viewers being seen.

Our work with screens is in many ways a continuation of the previous experiments with the perforated walls—with a shift in focus from the openings to the material remaining between them (figure 9.35). We asked students to produce full-scale prototypes (2 x 1 m in size) in styrofoam. We also varied the forms of the openings, i.e., we didn't limit the explorations to the round holes only. With the help of algorithmic tools, we were able to manipulate the contours, dimensions, angles, and the sequence of openings, which could take any regular or irregular form (figures 9.36-4). Moreover, in addition to being at an angle to the surface, the openings could also be distorted three-dimensionally, meaning that the front and the back of the screen-wall element could be different in appearance.

CONCLUSION

The projects presented express our empirical approach to the physical and constructive reality of architecture as well as our understanding of the digital as a tangible and sensual reality. We believe that a truly substantial discussion on "digital architecture" can only arise from built projects that physically manifest the underlying logic of this technology. We want to know how it looks, feels, smells, sounds and how much it costs. To do this, we adopt a strategy of operating in small steps and experiments, finding ways (or creating them, if necessary) of integrating this technology into projects we are actually building, testing their architectural potentials as well as their limits in terms of technological and economic feasibility. We work, wherever possible, at full scale, using the real materials and construction methods. This provides us with substantial feedback for our design process, both at a conceptual and technological level and allows us to understand the real consequences of digital technologies on architecture.

The beauty and power of digital technology lies in its universality and its generic quality. Binary data is an abstract entity that can contain anything we want. We consider it a new raw material in our hands that we can creatively manipulate to a degree of complex which is limited only by our own capability and imagination. An infinite variety of possibilities becomes an open-ended, uncontrollable process of creation, which is not yet fully explored.

Involving our hands and minds in the process of analog construction, we are able to create a new technology that is directly linked to the design and built environment that are actually a part of us. To overcome these challenges, we have developed a technology of our own, using the tools already available to us. To us, this means working together with the tools that are meant to be used. The fundamental idea of "digital materiality" remains of course an abstract one and is thus subject to interpretation and use. The subjective experience of using these projects will convey its own intuitive, sensory, and economic aspects. But it is a process that is always relevant and always current. The future will be shaped by the ideas that we develop today. While the technical possibilities of digital technologies are expanding, it is clear that the most important aspect of digital architecture is the human element. This is where the future lies: in the hands of the designers who are exploring these new frontiers.
The German writer Kurt Tucholsky once said, "A hole is where there is nothing." Around the hole is a material from which it has been carved. If the holes (i.e., perforations) increase in size, a grid structure develops in the material between the holes and the attention shifts from the holes to the resulting mesh-like structure or screen. Screens are a common and rich architectural device that can separate spaces, while maintaining a certain visual (and often audible) transparency. In contrast to glass, screens have a strong spatial presence and offer great potential for variation in material, color, texture, etc. The architectural definition of the screen mesh, i.e., its width, alignment, and form, can guide the eye's glance, obstruct it selectively, or allow full views. Grid-like structures make the structural depth of a building layer tangible. According to where they are positioned, hybrid structures like screens can assume other functions, such as passive shading (sun protection) on façades. Screens have been used throughout the history of architecture by very different cultures; they have developed in many different ways due to a wide variety of available technological means. As an example, consider the screens in Islamic religious architecture: highly perforated grid structures separate women from the main room of prayer. Besides a purely ornamental value, these highly sophisticated devices allow observation of the events in the main prayer hall without the viewers being seen.

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The beauty and power of digital technology lies in its universality and its generic quality. Binary data is an abstract entity that can contain anything we want. We consider it a raw material in our hands that we can creatively manipulate in an infinite variety of ways with a degree of complexity we would not dare attempt by hand. It is like a brick, its generic nature does not impose one given architectural form but rather offers the potential for an infinite variety on a given theme. Programming thus becomes an open and self-evident exploratory technique like sketching and model building.

While the technology necessary to change from mass-produced serial parts to mass-produced custom parts certainly does exist, and is thriving in other industries, it is not yet available to architects. This is largely because architecture-specific interfaces for digital fabrication do not yet exist. If we want to take full and creative advantage of the amazing technological possibilities at our hands and finally fuse the seemingly separate worlds of analog construction and digital design data we have to get involved in the conception of these interfaces and directly link the design data we produce and the machines that are actually able to fabricate architecture in both directions, technically and conceptually. We should be able to "get our hands dirty," so to speak, and proactively develop a technological savoir-faire that directly relates to the way architecture is conceived, processed, built, and used today. Technology needs to be demystified and (re)integrated into the architectural discipline, not just as a source of inspiration but as an integral part of the professional vision.

The fundamental architectural potential of the "digital materiality" we have been describing here remains of course to be explored through more built projects and at larger scales. One can still question whether or not the deterministic and rational nature of digital logics really is compatible with the creative and subjective practice of architectural design. Our work attempts to dispel this doubt and we hope that our projects will convince others who will in turn make their own contributions to this effort. Indeed, we feel that our own experience proves that digital technologies do not contradict the architectural process. If we understand its nature and use it as a complementary tool to our intuition and intelligence, digital technology will unleash its systematic, aesthetic, and poetic potential.
NOTES

1. The project’s clients were Zurich’s Bahnhofstrasse Association and the Electric Utility Company at the City of Zurich.
2. The project’s clients were Martha and Daniel Gantenbein. The façade was designed in cooperation with Herzog & de Meuron Architects.
3. Despite the relatively slight deviation from linearity, the human eye could detect even the finest rotations with the slightest light reflection, making them architecturally noticeable.
4. The wall panels for the Gantenbein vineyard were manufactured within the framework of a pilot project at our research facilities at the ETH in Zurich.
5. While we were laying the interior of the space using prototypes, we realized that it would be difficult to read the design if the openings between the bricks were too large. For this reason, we laid the bricks as close as possible, so that the gap between two bricks at full reflection was nearly closed. The eye reads this as maximal contrast value.
6. The robotic brick-laying production method was initially developed for an elective course entitled “The Programmed Wall.” We had to optimize it for the 400m façade, so that the production time and the quality of the elements could be guaranteed. Besides further developing the picker arm and the feeding chute, this mainly involved developing an automated process to apply the two-component bonding agent. We installed a pneumatic, hand-held, hot glue gun as a fixed external tool onto the robot, linked its activation mechanism with an interface to the robot’s control unit, and integrated the application of the bonding agent into the automated process.
7. The courses were: Das schief liegende Loch (The oblique hole) elective course offered in the winter semester in 2005/2006 academic year; Die perforierte Wand (The perforated wall) elective course offered in the summer semester in 2006; and Die perforierte Wand (The perforated wall) graduate elective course, also offered in the summer semester in 2006.
8. There were other difficulties too: the forces resulting from the pouring of concrete had to be dealt with by geometrically complex braces in the framework.
9. These themes were explored in the “programmed wall” (Die programmierter Wand) graduate-level elective course, offered in the winter semester in 2005/2006 academic year and also during the seminar weeks in 2007 at the Donnerzona Swissbau Lounge.
11. The screens were first explored in the “disintegrated wall” (Die aufgelöste Wand) elective course offered in the winter semester of the 2006/2007 academic year; these explorations were then continued in an elective course during the summer semester in 2007, when we asked the students to design a safety fence that surrounded the construction site for the new Science City Campus at the ETH Zurich.