call these sets “granular molecules” in analogy to their atomic-scale cousins. We can construct granular molecules of arbitrary shape by varying the number of constituent spheres, their size, and the degree of overlap among neighbors.\(^1,3\) Letting the computer optimize the granular molecule configuration with respect to a targeted goal for the aggregate behavior then represents a path toward identifying the best shape. An example outcome is shown in figure 36.5, where the task was to find the shape that produces the densest packing when particles are poured into a container and then the container is lightly tapped to settle the particles. For this task, the best-performing shape turned out to be a planar triangular particle;\(^4\) but, just as with speciation in flora and fauna, the artificial evolution process can lead to strikingly different granular molecules for different tasks or different processing conditions.\(^1\) The real power of using an evolutionary strategy, however, goes far beyond the ability to identify specific molecule shapes as optimal solutions for specific tasks. From the many shapes tested and then discarded along the evolutionary pathway, we can extract general design rules that make it possible to find appropriate solutions for whole classes of related tasks.
Figure 37.1
Rock Print: a towering mass supported by four legs, a counterintuitive configuration of rock and string (figure 37.1). Rock Print was designed to display the potential of jammed structures in architecture at the inaugural Chicago Architecture Biennial 2015, “The State of the Art of Architecture,” where it was exhibited as a 4-meter-high centerpiece in one of the Chicago Cultural Center’s largest rooms.

Rock Print is distinguished by its material system, which exploits the power of contemporary digital design and fabrication tools while using bulk raw materials as cheap and sustainable building material (figure 37.2). The structure is fabricated solely out of rock and string, two ordinary materials with opposite structural behavior. Combining the compressive strength of the gravel, the tensile strength of the string, and the digital control of the amalgamation process of the materials allows for the creation of solid structures with unique material properties. Furthermore, the material system can be fully reversed to its initial state of raw bulk material by simply unwinding the string reinforcement.

The design principle of the artifact accentuates the specific characteristics of the material system. The base of the structure consists of four slender legs, indicating the structural capacities of the system, which meet and form the massive, star-shaped and cantilevered upper body of the structure. The legs start with an almost round profile, growing toward their neighbors until they merge and extend to the boundary of the robotic operational range. The upper part accommodates a higher amount of mass than the lower, to increase the compression of the bottom part and thereby assure a stronger surface strength on the parts more exposed to visitors. Leftover material from the fabrication process is left surrounding...

Figure 37.2 (left page): Close-up of Rock Print revealing the surface texture of the rock-string amalgam.

Figure 37.3 (top): Isometric drawing of the digital blueprint for the string reinforcement.
(a) Diameter of the string pattern circles.
(b) Smaller offset of the pattern circles at vertical surfaces.
(c) Larger offset of the pattern circles at cantilevering surfaces.

Figure 37.4 (bottom, 3 images): Iterative experiments focusing on surface texture:
(a) Double string pattern and no packing, resulting in clearly visible pattern layers and weak surface texture.
(b) Double string pattern touching the walls of the box and packing, resulting in surface texture and geometry from the box while still clearly showing the pattern layers.
(c) Single string pattern not touching the walls of the box, dissolving the pattern layers and resulting in an articulated surface texture.
the base, to root the exhibit to the space as well as create a natural barrier for the visitors.

**Jammed Structures**

The construction system of Rock Print uses jamming, the physical phenomenon in which granular matter becomes rigid under certain conditions, for example when the free volume per particle is decreased, thereby increasing the strain between the aggregates, making them more and more constrained. The “jamming transition” allows not only a change from a nonsolid, liquid-like state into a solid state, but also for the inverse transition.

**Designing with String**

Since the clustering of the aggregates is difficult to predict, one cannot precisely estimate the distribution of stress along the force chains. To handle this uncertainty, redundancy is an important factor for the layout of the string pattern. As a basic established rule, the string should always be in tension, to assure the structural integrity of the fabricated artifact, with as little string as possible. Experiments have shown that a circular string pattern improves the geometrical relationship between area and circumference. If a circular string loop is placed on a layer of aggregates and then compressed, the aggregates will try to spread equally in all directions. The string holds the aggregates in place. The string circles are deployed in a layer-based arrangement, forming horizontal string patterns. In fabricating the tower, the most important parameters were the diameter of the circles (figure 37.3a), the planar distribution of the circles, and the distance between the layers (figure 37.3b—c).

Iterative physical experiments (figure 3.4) made it possible to predict and assess the probability of buckling and failure at the outer surface and to react with a corresponding string pattern and tensile reinforcement. There is a direct correlation between the distance between layers and the circle radius: smaller circles require decreasing the distance between layers. The diameter of the circle further informs the possible geometries, particularly in convex forms. The curvature of a convex outer surface cannot be smaller than the radius of the respective string circles, and the smallest circle diameter found to be efficient was approximately eight times the average particle size, while the maximum distance between individual layers also relates to the average particle size.

Varying the layer-based string pattern from layer to layer allows for complex volumetric geometries (figure 3.3). This variation, however, always has to take into account the pattern of the adjacent, upper and lower, layers in order to guarantee a continuous...
reinforcement in all directions. For example, a cantilever requires decreasing the distance between its layers, whereas a conical shape requires adding circles with an increasing layer area. Having a constant number of circles for all layers, while compensating for geometrical variation only by enlarging the overlap between the circles, results in a string pattern that is too dense, cutting off the connections between the aggregates and thus leading to a weaker structure.

The experiments conducted revealed that the larger the distances between circles, and the subtler the curvature of the boundary condition and the cantilever of the outer form, the greater the structural integrity. Depending on the global shape, the string pattern may have fewer circles in the center of a single layer for flat, vertical geometries or a denser string pattern close to its outer boundary, whereas geometries with high curvatures and cantilevers require a dense string pattern throughout.

TYING STRING AND ROCK

The string pattern is not alone in affecting the overall structural performance of the fabricated structures; the raw material also has a major impact. The aggregate size affecting the resolution of the string pattern has already been mentioned. Factors such as geometry and surface friction of the aggregates, as well as material characteristics of the string, also had to be evaluated since they influence the way the composite binds. Since Rock Print was in an indoor exhibit, it was necessary to exchange heavy crushed rock for lighter aggregates. Glass foam aggregates for self-insulating concrete from Misapor proved to be a good choice in terms of their form and coefficient of friction. By choosing a size range of 16–32 mm, it was possible not only to achieve a suitable resolution for the structure but also to balance the aggregate size and the layer height with an appropriate fabrication speed. Just as with the size and the friction attributes of the aggregates, the string also has to have certain properties. It has to be flexible to be able to form into the desired pattern, and it has to be inelastic to fulfill the function of tensile reinforcement. Rock Print used a 3 mm cord made of a combination of polyester fibers and recycled material from the textile industry.

Rock Print was robotically fabricated in situ, within the exhibition space. The setup consisted of a modular, two-axis gantry system coupled with a lightweight robotic arm, a string-laying end-effector, and an incrementally assembled box. The gantry was used to position the robot at the desired location, whereas the robot was used to lay the string according to the pattern blueprint. The size of the box was equal to the work envelope of the robot, measuring 1.2 x 1.5 x 4 m, allowing use of the full reach of the machine. The box consisted of a frame onto which 20–cm-high segments were attached consecutively. The fabrication process was split into two phases. The first consisted offabricating the structure inside the box. During the assembly (figure 37.5a–d) the robot placed a layer of string, then aggregates were manually deposited by the team. A concrete compactor, applied at every second layer, assured a correct packing of the aggregates during the construction. New frame elements were added to the box after every 20th layer. This procedure was repeated until the full structure was assembled. The second phase consisted of releasing the box and brushing the support material to reveal the final structure (figure 37.5e–h).

PULLING THE STRING

Rock Print was designed and built to allow the deconstruction of the structure by simply reversing the fabrication process, separating the string from the aggregates. Since the structure is fabricated by layer, from bottom to top, the structure was simply dismantled by unwinding the string network with a pulley system and an electrically driven spool (figure 37.6). For an uninterrupted deconstruction, the string layout has to be continuous during the entire fabrication process. For Rock Print in Chicago a string for each leg was thus connected to a single string for the upper part of the structure. The speed of the unwinding was adjusted so the aggregates flew off the structure without breaking the string. Because the unwinding happens fast, the artifact remains stable during the whole unravelling, so the jammed structure doesn’t collapse and tangle the string. After 10 km of string was unwound, layer after layer, for two hours, the first Rock Print was restored to its original raw material: a pile of rock and a spool of string.

CONFIGURING AND RECONFIGURING WITHOUT WASTE

Rock Print demonstrates the fascinating potential of jammed architectural structures. With a growing understanding of the interrelation of aggregates and string, jammed structures can be shaped into nonstandard structures. Furthermore, the material phenomenon works with a large variety of aggregates and gravel types, making it possible in the future to use local materials more widely in fabrication. Since jammed architectural structures can be fully returned to their original state, this construction system presents a shift to a granular architectural material approach, and enables the infinite reconfiguring of the composite into different architectural forms. This idea is supported by a closed life cycle that begins by assembling readily available and cheap building material. As such, Rock Print formulates a striking response both to the ideal of a consumer-oriented (customized) architecture and to the call for sustainability. It simply produces no waste and is 100% recyclable.
NOTES


