UNFROZEN MUSIC
Designing and Programming Digital Water Walls

William J. Mitchell and Andres Sevtsuk

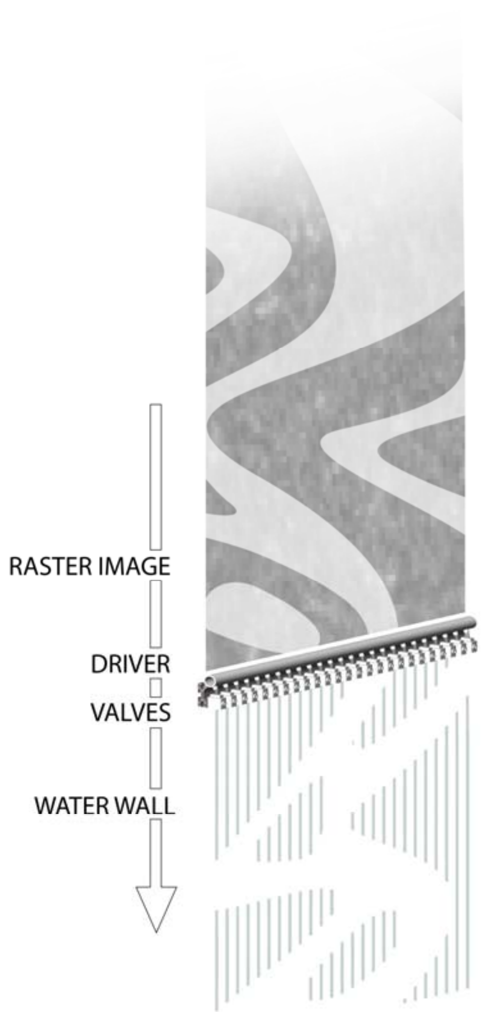
One of the many natural forms taken by water is that of a cascading sheet. Waterfalls generate such sheets at various scales, and so do the regularized stone cascades of Mughal gardens.

Regularized, precisely controlled cascade in the Shalamar Bagh, Srinagar, Kashmir. (The niches behind the water hold flowers during the day and candles at night.)

The technology of the digital Water Wall – which was conceived and prototyped in the Smart Cities group at MIT's Media Laboratory, and then developed into robust and useable form by Lumiartecnia – provides a way of creating precisely controllable, dynamically reconfigurable, visually spectacular cascades that use very little water.

A Water Wall consists, in its essentials, of an array of fine-gauge, computer-controlled solenoid valves arranged along a water supply pipe running through the air. Typically the valves are about 4cm apart, and they operate at a frequency of at least 100 hertz. Opening and closing a valve creates corresponding solids and voids – that is, one-bit-deep pixels – in the narrow vertical jet that the valve controls. By programming a line of valves, it is possible to create openings and complex patterns in a sheet of falling water. When it has completed its descent, the water is captured in a gutter at the base of the wall and recycled.

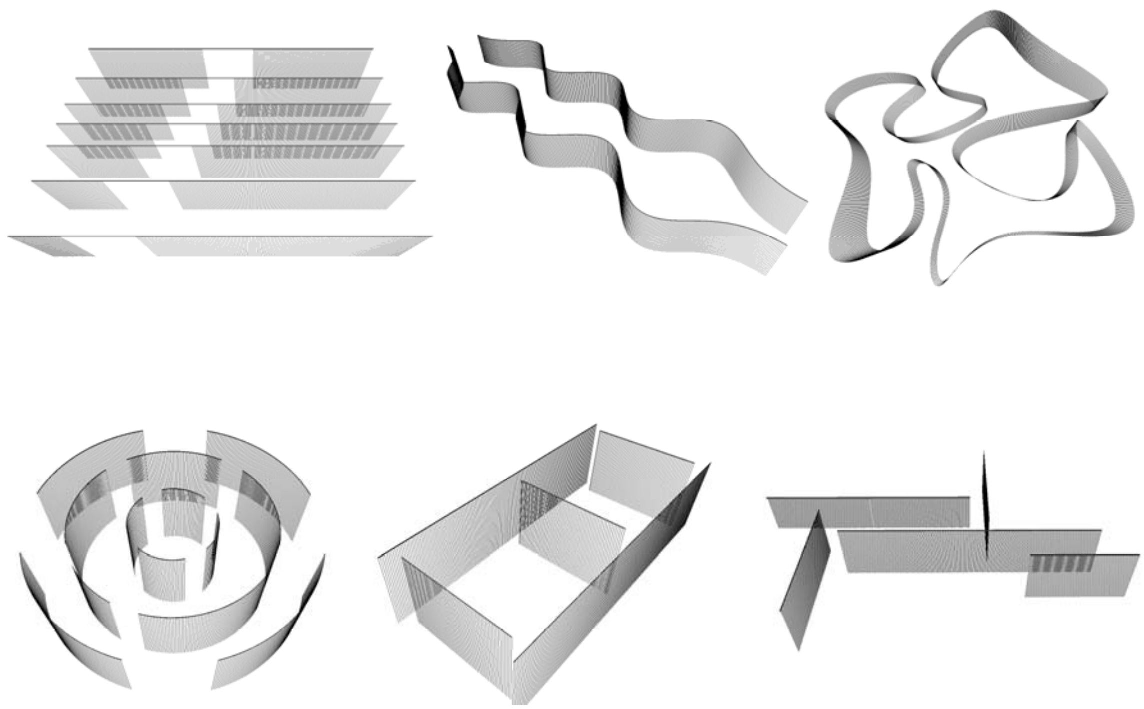
From an artist or programmer's perspective, a Water Wall is a specialized type of large computer graphics display. Graphic content to be displayed can be specified either in the form of a raster image or a procedure that generates shapes and patterns. A graphics device driver converts this content into commands for the solenoid valves.



Creation of a modern, digital Water Wall by computer-controlled solenoid valves.

The simplest form of Water Wall is a single rectangular sheet. But Water Walls may also be curved, they may be arranged in layers, they may become cylinders and other closed loops, and they may be configured to create rooms and architectural sequences of spaces.

Water Walls do not produce very precise corners, as sheets of glass do (especially when there is significant air movement), so when configuring spaces with them it is appropriate to consider corner details that respond in reasonable ways to the particular character of the material. It generally works well, for example, to detail corners with an air gap between the planes of water – and there is no functional downside to this, since Water Walls do not seal up a space anyway.

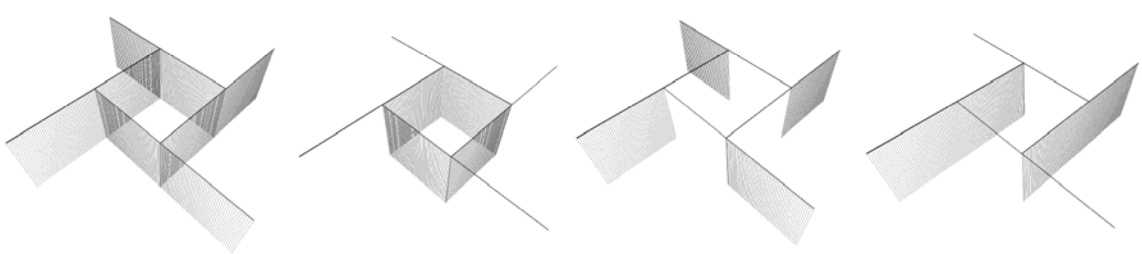


Some possible configurations of Water Walls: layers and enfilade, allée, closed loop, room plans, and free plan.

Since entire Water Walls can be switched on and off at will, the spaces defined by them are dynamically reconfigurable. Furthermore, wall segments can "slide" horizontally along the lines of their supply pipes, like sliding doors on overhead tracks – but at any speed. And vertical slot openings can be introduced at any location, at any time. These slots (the inverses of "sliding doors") can also move horizontally. Thus Water Walls provide architects with a highly dynamic means of defining spaces and managing pedestrian flow into and through them. Architectural compositions made from Water Walls need not be static arrangements, but can be programmed to evolve and transform over time, as with the patterns of dancers in ongoing performances.

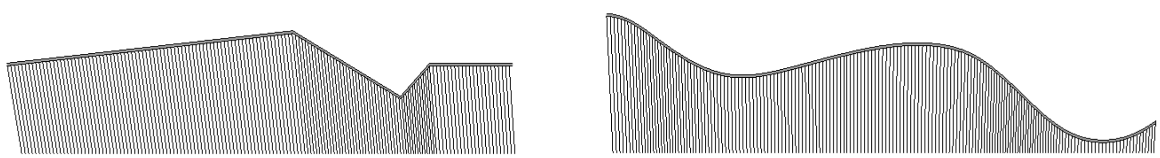
Essentially, the infrastructure of overhead pipes and solenoid valves defines a shape, composed of walls, that appears when all the valves switched on. By selectively switching valves off, and thereby erasing wall segments, any subshape can be produced.

These subshapes can remain stable for extended periods, or they can be programmed to morph into other subshapes. Animated sequences of subshapes can be produced by a technique analogous to that of key-frame animation.



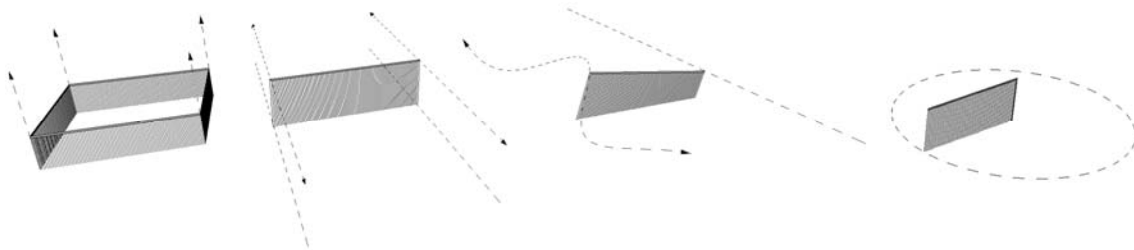
Selectively switching water off produces varied subshapes of a Water Wall shape.

In the vertical dimension, the simplest kind of Water Wall is created by a horizontal pipe fixed at a particular height. But, at the cost of a little more technical and construction complexity, pipes creating Water Walls can be angled and curved.



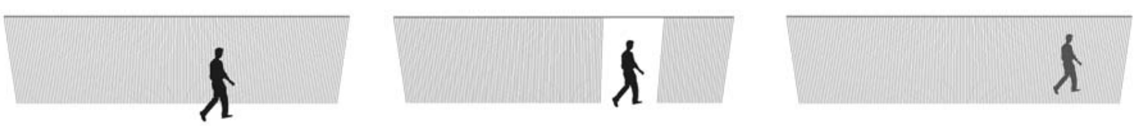
Three-dimensional angling and curvature of Water Walls.

The pipes generating Water Walls need not be static. Through the introduction of suitable actuators, they can move – like, for example, the booms of the center-point irrigation circles of the American West that sweep out cylindrical volumes. They can also translate horizontally, like gantry cranes, to sweep out rectangular volumes. And they can even move along non-parallel tracks at either end to sweep out volumes bounded by ruled surfaces. Unlike walls made from solid materials, they can expand and contract freely in both vertical and horizontal directions.



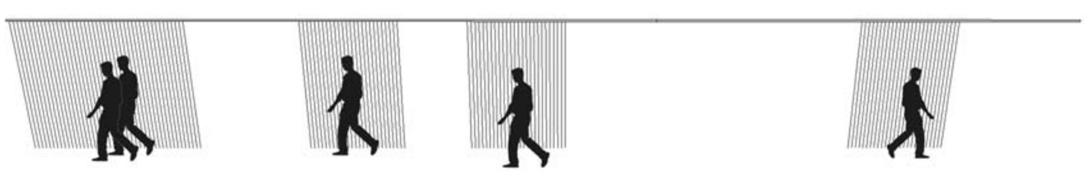
Water Walls produced by mobile booms can translate vertically and horizontally, rotate, and sweep out ruled surfaces.

Through introduction of sensors, any of the size, shape, and motion variables of Water Walls can be programmed to respond to changes detected in the surrounding natural environment, and to pedestrian movement. As a pedestrian approaches, for example, a Water Wall might open like the Red Sea for Moses, and then close again after the pedestrian has passed through. Or a circular opening might drop down to meet a ball thrown at the Water Wall – allowing it to pass through without getting wet. These sorts of possibilities enable a profound rethinking of our conceptions of door openings and entries, and of windows and fenestration patterns.

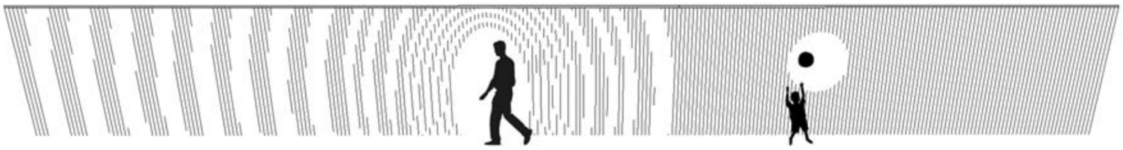


Walking through a Water Wall.

There are many other possibilities, as well. As a pedestrian walks alongside a water wall (or between parallel water walls) a panel of water might accompany her to provide privacy and cooling. As natural lighting conditions and views change, Water Walls might adjust in response. And, when the wind blows too strongly for comfort, a Water Wall might automatically shut down.



Pedestrians accompanied by moving Water Wall panels.



Water Wall with complex dynamic responses.

As architectural theorists like Gottfried Semper have discussed extensively, walls typically have patterns resulting from their production processes. Thus architects work with the characteristic patterns of both regularly cut and random stonework, brickwork bond patterns, tile patterns, curtain wall fenestration patterns, board and shingle patterns, textile weaves, and so on. Water Walls are, of course, no exception; their patterns derive from the possibilities inherent in parallel, interruptible streams of falling water.

However, more traditional production processes result in "frozen" wall patterns that may imply dynamic processes, but don't actually move. A Water Wall, by contrast, consists of streams of water in constant downward motion. While it operates, it can *never* be static. It is the continuous trace of a real-time production process.

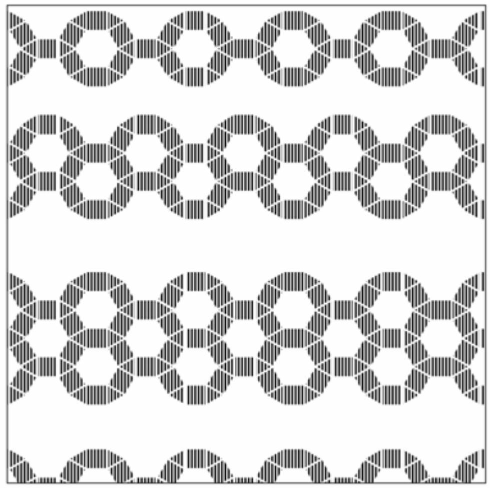
The patterns exhibited by a Water Wall are always defined by solenoid valve actions along a line at the top of the wall area. Once a horizontal array of solids and voids has been created at this line, it begins to fall downwards, and thereafter it does not change (apart from fairly minor effects of wind, gravity, and so on) until it reaches the gutter at the bottom. The effect is like that of a computer line printer that is fed by a roll of paper above the wall area, repeatedly prints lines of pixels on the paper as it crosses the line at the top of the wall area, and thus produces a picture that becomes visible as it scrolls down across the wall area and eventually disappears into the gutter at the bottom.

For programming purposes, it is convenient to adopt the convention that an image simply exists on a roll of paper on a feed spool above the screen area, becomes visible as it traverses the screen area, and eventually gets collected on a take-up spool below the screen area. This image may be explicitly predefined (by scanning or text input, for example), or it may be constructed on the fly by some algorithm. It may be finite in length, or it may be unlimited.

Since solenoid valves are 4cm apart, since the downward velocity of the water is close enough to uniform, and since the valves operate at sufficiently high speed, it is usually convenient to program patterns in terms of 4cm square pixels. However, much finer vertical resolution (resulting in rectangular pixels) is certainly possible.

The most obvious outcomes of the Water Wall production process are patterns with translational symmetry along a vertical axis. At their simplest, they consist of regularly spaced horizontal bars. These may be elaborated into regular frieze patterns, with any of the seven frieze group symmetries that are described in textbooks on plane symmetry.

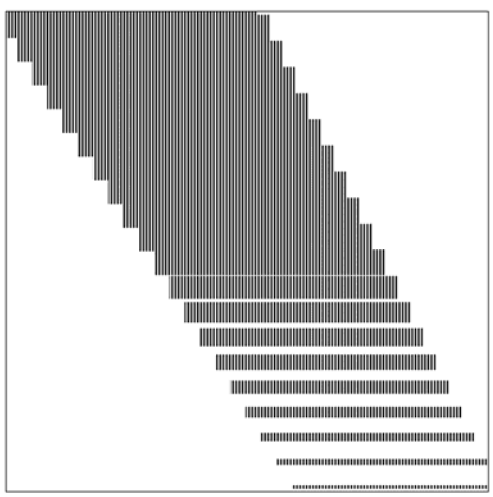
This introduces the architectural concept of a “falling frieze” – a frieze that establishes a temporal rhythm instead of a static horizontal datum.



A falling frieze motif.

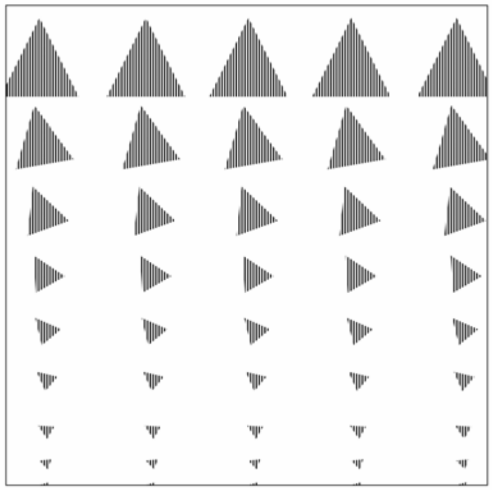
There is not, however, any inherent requirement for repeating falling shapes to be symmetrical patterns. They can have arbitrary, irregular forms; they can be figurative images; or they can be lines of text.

In any case, repeating falling shapes can be produced by simple, iterative programs that instantiate the same figure at regular intervals – some finite number of times, or else infinitely.



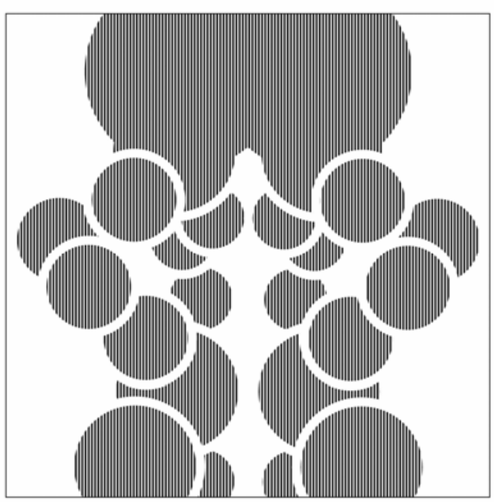
A Water Wall pattern with an inclined axis.

Programs of this sort can be elaborated by not only translating, but also introducing additional transformations, at each iteration. For example, figures, or the intervals between them, might be scaled up or down at each iteration, or squeezed, stretched, or otherwise parametrically varied. They might be horizontally offset at each iteration to produce the effect of an inclined axis. Or the intervals between them might become a Fibonacci sequence, and so on.



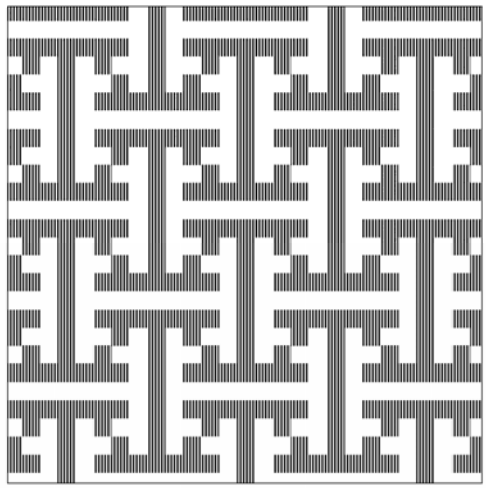
Incrementing multiple parameters at successive iterations.

It is also possible to program vertically scrolling, infinite patterns with reflective symmetry about a vertical axis. This is the dynamic, Water Wall equivalent of the traditional architectural device of bilateral symmetry. If a water-free gap is permanently left at the center, this creates and celebrates an entry point in classical architectural fashion.



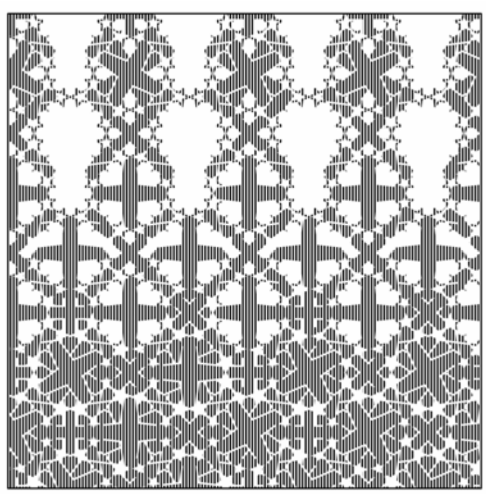
Dynamic bilateral symmetry.

A further generalization of these principles is to the seventeen plane symmetry (wallpaper) groups. These are produced by translating, rotating, reflecting, and glide-reflecting standard figures on square, rectangular, triangular, and hexagonal grids. They are described in standard texts on symmetry, and there are many examples in classic works on decorative patterns, such as Owen Jones's *Grammar of Orn*ament, and Daniel Sheets Dye's *Chinese Lattice Designs*. Any regular pattern with wallpaper group symmetry can straightforwardly be programmed and displayed on a Water Wall.



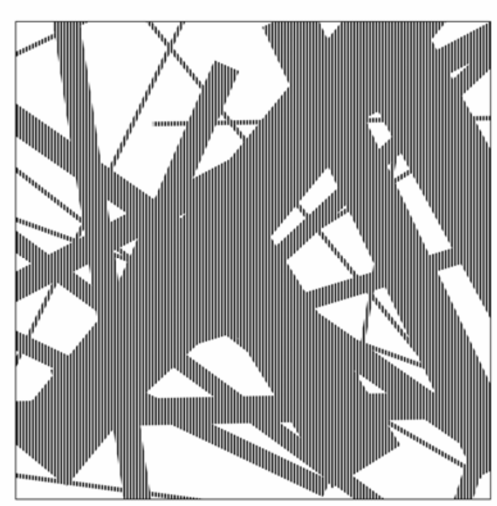
Water Wall pattern with wallpaper group symmetry.

Many variants on patterns with wallpaper symmetry can be produced by scaling or otherwise parametrically varying the repeating figures at each iteration in the vertical direction. This produces the effect of a pattern continuously changing as it scrolls down.



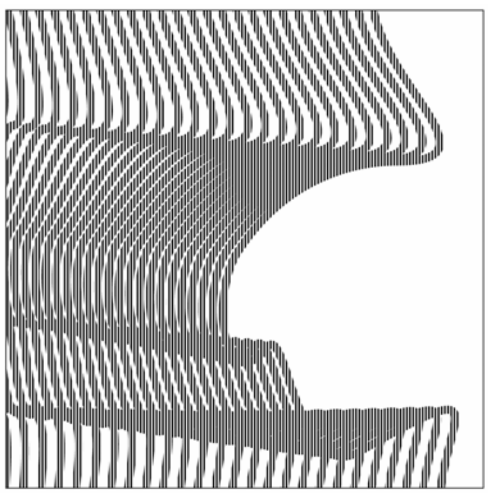
Wallpaper pattern with transforming motif.

Yet another possibility is to use a random number generator to select the coordinates, scale coefficients, and other parameter values for instances of a motif. This produces the effect of endless variation. It can be extended by introducing, as well, random selection from a specified vocabulary of motifs – much like random selection of tracks on an iPod.



A random pattern.

So far we have considered discrete motifs. Another possibility is to program continuous curves that run in a roughly vertical direction. This produces the effect of waving lines running across the display area. These curves might be regular (produced by iterative evaluation of a function) as with sine curves. Or they might be irregular, produced by random selection of parameter values for some function at each iteration.

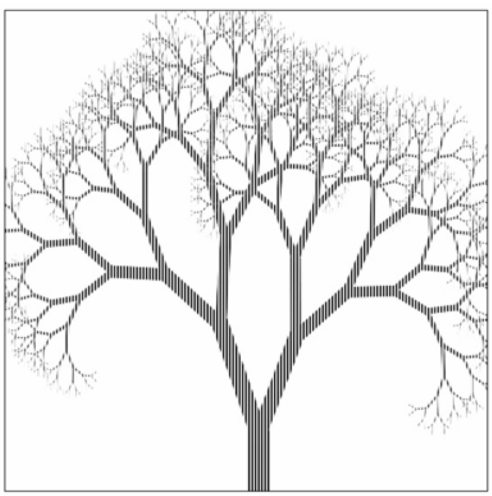


Continuously evolving, waving curves.

The effect of “waving” is a special case of an illusion characteristically produced by shapes scrolling past an aperture, and therefore of Water Walls. Consider, for example, a long diagonal line that extends beyond the top and bottom boundaries of the wall area. As it scrolls down across the screen area, it will appear as a shorter line segment translating horizontally. The interplay of this sort of illusions with the downward motion of the water can create many paradoxical and compelling effects.

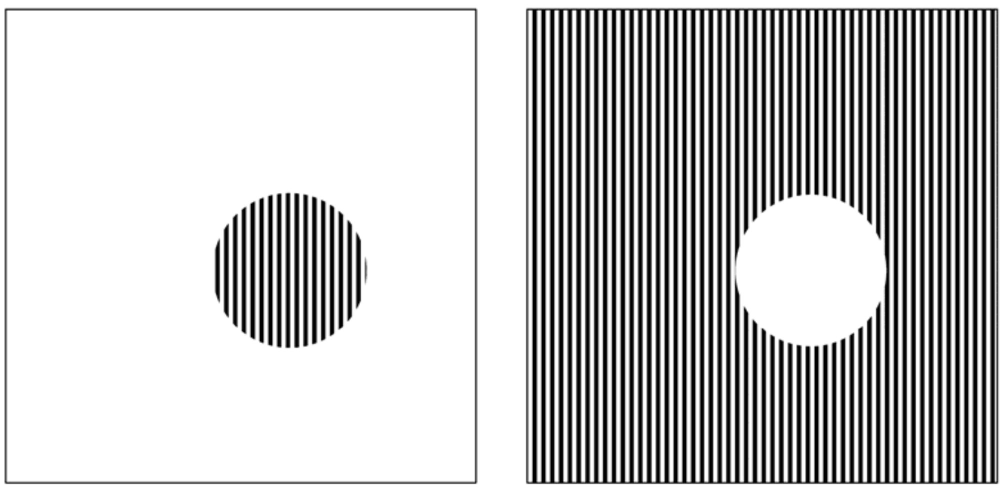
The illusion of transverse motion.

Curves are not the only things that can evolve continuously. So, for example, can tree-like branching patterns – which can also be constructed by the iterative application of simple rules. These create the impression of a camera panning up from the roots of trees into the canopy of a forest. Other evolving pattern possibilities include cellular automaton patterns, Voronoi and other space subdivision patterns, and (most generally) patterns generated by shape grammars.



A rule-generated branching pattern that produces the effect of a camera panning up into the canopy of a tree.

Many of the patterns that we have shown will read, in architectural contexts, as semi-transparent screens, lattices, or curtain walls. Their use extends the tradition represented by Japanese shoji screens, Chinese and Korean latticework, and modernist glass curtain walls. Others, however, create discrete openings in continuous sheets of water – recalling the architecture of punched openings. Yet others reverse this figure/ground relationship to create the effect of discrete objects suspended briefly in space. This is analogous to the arrangement of free-floating objects in space in the modernist free plan, but here the principle is transferred to a vertical plane and the objects become dynamic rather than static.



Figure/ground reversal in a Water Wall changes the reading from a free-floating object in space to an opening in a membrane.

This brief survey by no means exhausts the possibilities for programming Water Walls, but the examples that we have given should suffice to illustrate the fundamental principles. We should also point out that we have discussed only the effects obtainable with single-layer Water Walls – but it is also possible to create two-layer walls from double lines of valves, three-layer walls, and so on. Ultimately, multi-layer Water Walls create three-dimensional grids that can be used to sculpt three-dimensional instead of two-dimensional shapes in water. We leave the exploration of these additional possibilities as an exercise for the reader.

There is, in summary, a very close analogy between Water Wall programming and musical composition. Like a piece of music being performed, a Water Wall program unfolds over time. Through repetition in the vertical dimension it can have a rhythm – perhaps, though not necessarily, laying down a regular beat. There are both diachronic and synchronic relationships among graphic motifs – just as there are such relationships among musical figures. Diachronic graphic structures, analogous to those constructing musical melody, result from shape and spatial relationships among graphic motifs that follow each other in time. Synchronic structures, analogous to those creating musical harmony, result from shape and spatial relationships among motifs that are simultaneously visible on the Water Wall surface. A satisfying program will have development and resolution of these structures – not merely simple repetition or randomness. And, within this, there may be opportunities to intervene, respond, and improvise.

Just as music may have words, Water Wall programs may incorporate text and figurative imagery. But, if there is too much reliance on these elements, a Water Wall becomes merely a gimmicky and technically limited computer graphics display – and quickly becomes boring. The true task of Water Wall programmers is to explore the possibilities of a genuinely new, time-based, graphic and spatial medium.

And finally, the relationship to pedestrian movement and the human occupation of space – particularly public space – is crucial. Water Walls are best used at human scale, in locations where they can engage and direct pedestrian motion. They should not be treated merely as spectacle, but as large-scale interactive devices. Like music at a good party, they should be an irresistible invitation to dance.

Water Wall architecture is unfrozen music.