# Shape Displays: Spatial Interaction with Dynamic Physical Form

**Daniel Leithinger**
*Massachusetts Institute of Technology*

**Sean Follmer**
*Stanford University*

**Alex Olwal**
*Google, MIT, and KTH – Royal Institute of Technology*

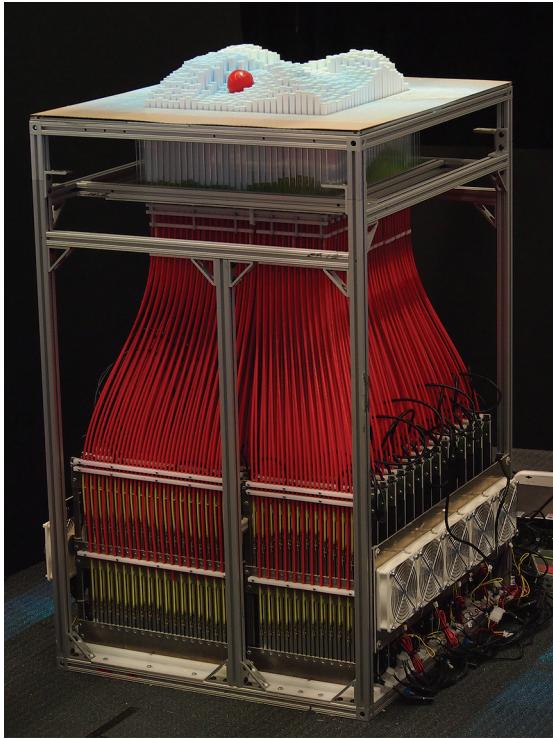**Hiroshi Ishii**
*Massachusetts Institute of Technology*

Shape displays are a new class of I/O devices that dynamically render physical shape and geometry. They allow multiple users to experience information through touch and deformation of their surface topology. The rendered shapes can react to user input or continuously update their properties based on an underlying simulation. Shape displays can be used by industrial designers to quickly render physical CAD models before 3D printing, urban planners to physically visualize a site, medical experts to tactually explore volumetric data sets, or students to learn and understand parametric equations.

Previous work on shape displays has mostly focused on physical rendering of digital content to overcome the limitations of single-point haptic interfaces—examples include the Feelex[1] and Lumen[2] projects. In our research, we emphasize the use of shape displays for designing new interaction techniques that leverage tactile spatial qualities to guide users. For this purpose, we designed, developed, and engineered three shape display systems that integrate physical rendering, synchronized visual display, shape sensing, spatial tracking, and object manipulation. This enabling technology has allowed us to contribute numerous interaction techniques for virtual, physical, and augmented reality, in collocated settings as well as for remote collaboration.

Our systems are based on arrays of motorized pins, which extend from a tabletop to form 2.5D shapes: Relief[3] consists of 120 pins in a circular tabletop, a platform later augmented with spatial graphics for the Sublimate[4] system. Our next-generation platform, inFORM,[5] renders higher-resolution shapes through 900 pins (see Figure 1). The Transform system consists of 1,152 pins embedded into the surface of domestic furniture.[6] To capture objects and gestures and to control visual appearance, we augment the shape displays with overhead depth-sensing cameras and projectors.

In this article, we wish to introduce readers to some of the exciting interaction possibilities that shape displays enable beyond those found in traditional 3D displays or haptic interfaces. We describe new means for physically displaying 3D graphics, interaction techniques that leverage physical touch, enhanced collaboration through physical telepresence and unique applications of shape displays. Our current shape displays are based on prototype hardware that enabled us to design, develop, and explore a range of novel interaction techniques. Although the general applicability of these prototypes are limited by resolution, mechanical complexity, and cost, we believe that many of the techniques we introduce can be transferred to a range of special-purpose scenarios that have different sensing and actuation

potential to enable three types of functionality for creating dynamic UIs:

- facilitating through dynamic physical affordances,
- restricting through dynamic physical constraints, and
- manipulating passive objects through shape change.

Because shape displays allow for simultaneous control over multiple parameters of rendered objects, they provide designers with a rich toolkit for affecting the perceived and real affordances of rendered objects (see Figure 2).

### Shape and Form: Dynamic Physical Affordances

The shape of rendered objects can provide multiple affordances:

- Perceived affordances involve a user's understanding of what the shape represents.
- Real affordances indicate how the shape can be touched, grasped, and manipulated.

The quality and expressiveness of the shape is tightly coupled to the resolution as well as the degrees of freedom (DOFs) of the underlying hardware. The user perceives adjacent pins as a whole connected shape—a cognitive process explained by the law of closure in Gestalt theory. This resulting shape can move sideways, rotate, tilt, and grow along different dimensions than the DOFs of individual pins would mechanically allow.

Touching rendered content on the interface allows users to experience an object's physical shape. A touch may also trigger software actions, such as selecting an object, moving it, painting its surface, or annotating it. The user can also press into or pull on a shape to deform it. The shape's material and haptic feedback communicates to the user if it affords actions like deformation. By programmatically controlling the resistance of a pin when pressed by the user, a system can render shapes

needs, potentially even using a completely different technical approach. We thus hope that our work will inspire future researchers to start considering dynamic physical form as an interesting approach to enable new capabilities and expressiveness beyond today's flat displays.

## Physical Rendering and Spatial Interaction

Unlike other spatial 3D display technologies, shape displays allow for direct physical contact. Users can interact by touching physical shapes rendered through the surface of the display and also deform the shapes by applying a stronger force.

Past research has primarily focused on rendering, with less emphasis on investigating dynamically changing physical user interface (UI) elements. We explore dynamically generated physical features with specific affordances that guide the user on how the system can be used and provide passive haptic feedback, enabling interaction at a lower cognitive cost. Shape displays have the
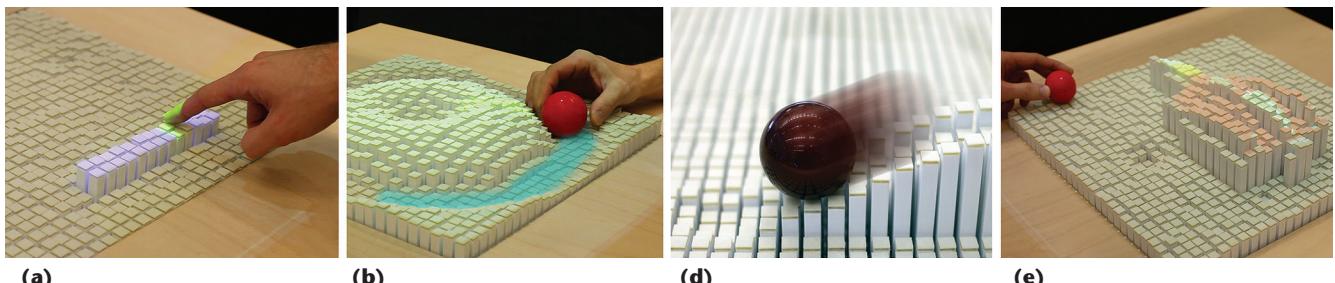


(a)   (b)   (d)   (e)

**Figure 2. Interaction techniques for shape displays. UI elements through (a) dynamic affordances, (b) guiding interaction with dynamic constraints, (c) object actuation, and (d) physical rendering of the content and UI.**

that vary from stiff to soft or that provide dynamic feedback, like vibration or elasticity.

In addition to deformable content, we render dedicated UI elements such as buttons, touch sliders, touch areas, and handles on demand. They react to touch or deformation (such as pushing and pulling) and can change shape to reflect a program state. For example, when a user presses a triangular "play" button, it can transform into a square "stop" button, and vice versa. They can also enable smooth transitions between input dimensions—for example, pressing a button could cause it to transform into a 2D touch panel. Affordances can also move out of the way of physical objects or complement them to increase functionality. As a device is placed on the table, relevant physical UI controls can appear, a phone could be complemented with a large answer button, or a tablet could have game buttons appear around it.

### Appropriating Passive Physical Objects

When a physical object is placed on a shape display, it mechanically interacts with the dynamic shape underneath. Constraints like wells, slots, and ramps limit the object's movement through shape and can thus guide user interaction. We can also appropriate passive objects, independently actuating and manipulating them by applying mechanical force and causing an object to move, rotate, or tumble. In this way, passive objects are augmented with dynamic capabilities, expanding their possible use as tangibles or tools that reflect program state or other functionality.

This greatly expands intermaterial interaction and the system's expressivity and opportunities, and it addresses a problem inherent in passive tangible systems: keeping the physical and digital states of objects synchronized. Additionally, it allows the shape display to output greater DOFs (such as lateral movement) and provides the user with more DOFs for input.

### Mid-Air Gestures

Similar to appropriated passive objects, mid-air gestures can provide more DOFs than direct touch, while maintaining a clear causal link between hand movements and the resulting shape actuation. Examples include deictic gestures to select and move many pins simultaneously, an operation that may be cumbersome through direct touch. Beyond controlling shape change, mid-air gestures also allow users to interact with spatial 3D graphics.

### Physicality and Spatial Graphics
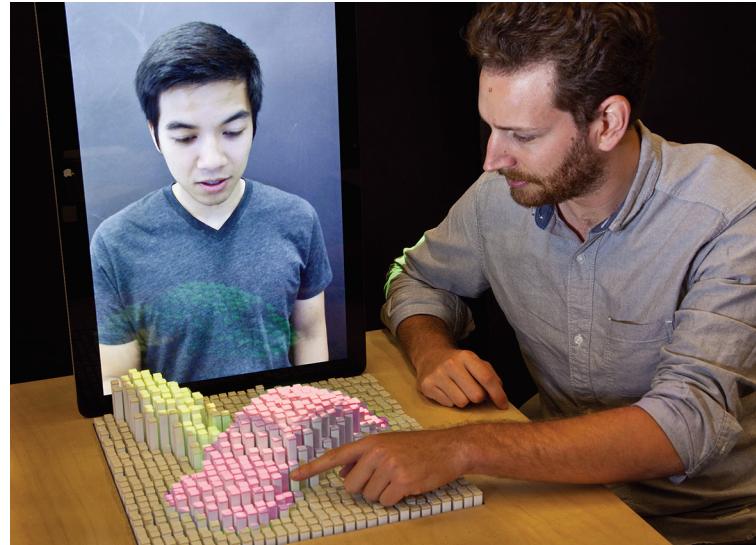
Shape displays can leverage embedded displays[2] or



**Figure 3. Physical telepresence provides physical embodiment, remote manipulation and new capabilities through computer-mediated teleoperation. Here, local and remote users interact physically with a 3D car model.**

projection mapping to provide additional information and a higher level of detail through color and texture. For spatial 3D graphics beyond the interface surface, we employ augmented reality (AR) display techniques, such as optical see-through displays, and video see-through with handheld tablets. Our vision is that 3D information can be rendered in space as physical shapes or virtual graphics. Our Sublimate system[7] introduces the capability to modify a rendered object's perceived physicality to transition between a solid object and a floating 3D object. We believe that the most interesting aspect may not be either state alone, but rather the combination and fast transition from virtual to physical, and vice versa.

This approach is different from typical AR applications, where elements are either physical or virtual, but do not switch between these states. This transition enables new interactions, such as partially replacing physical models with floating graphics to allow the user to manipulate an interior part. Virtual interface elements become physical when they need to be touched or modified.

## Shape Capture and Transmission for Physical Telepresence

Physical telepresence[8] extends the physical embodiment of remote participants, common in telepresence robotics, and combines it with the physical embodiment of shared content, common in remote tangible user interfaces (TUIs). Figure 3 shows the hands of a remote collaborator along with a shared digital model, materialized on a local shape display. Each of these shared workspaces captures the appearance, geometry, and interaction
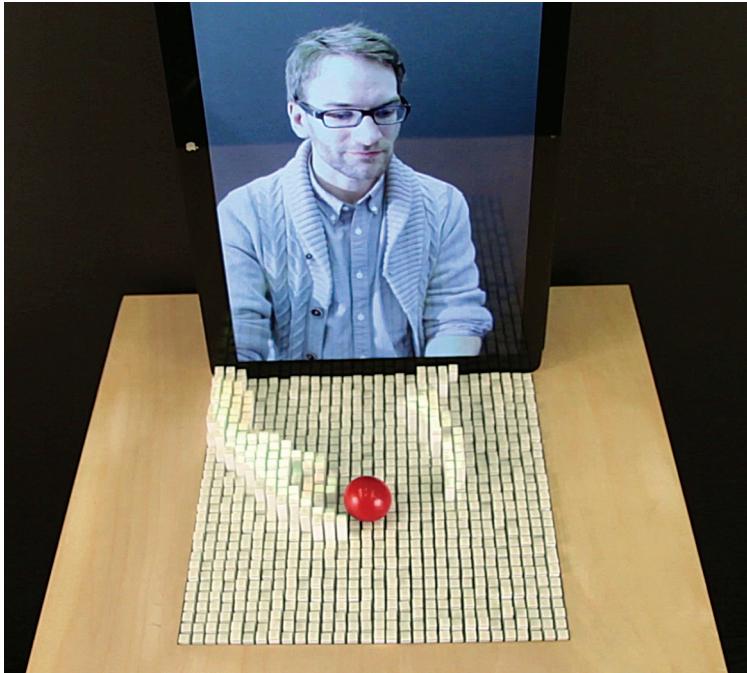
**Figure 4. Direct shape transmission. A user manipulating a sphere through his remote physical embodiment.**

way, the user can manipulate remote physical objects as the rendered shape applies a force to them (see Figure 4). By observing how the object reacts to the transmitted gesture, users can improvise to expressively move and rotate a variety of objects.

Transforming the physical form alters users' representations to amplify their capabilities for teleoperation and to overcome physical limitations. Users can apply transformations to their rendered body representation, for example, through scaling, translation, rotation, shearing, stretching and other distortions. Translation and rotation can extend reach, with potential ergonomic benefits. Scaling can make a hand larger or smaller to manipulate objects of varying sizes (see Figure 5a). A small hand could avoid undesirable collisions in dense topologies, while an enlarged hand could carry multiple items. Replication or mirroring allows users to approach objects from multiple angles.

Beyond transforming geometry, users can switch between different representations, for example, to enable selective rendering of users' hands with shape, but the arms using only graphics—or to let the user switch back and forth between graphics and shape rendering. The hands can also morph into other shapes that are optimal for the task. Examples include tools with specific properties that facilitate or constrain the interactions (see Figure 5b), such as grippers, bowls, ramps, or claws.

of local participants and objects. The system then interprets, transmits, and materializes them on a remote workspace. We developed different interactions for physical telepresence and collaboration using inFORM.

Direct shape transmission captures the physical shape of remote users and objects and dynamically renders them on the remote shape display. This
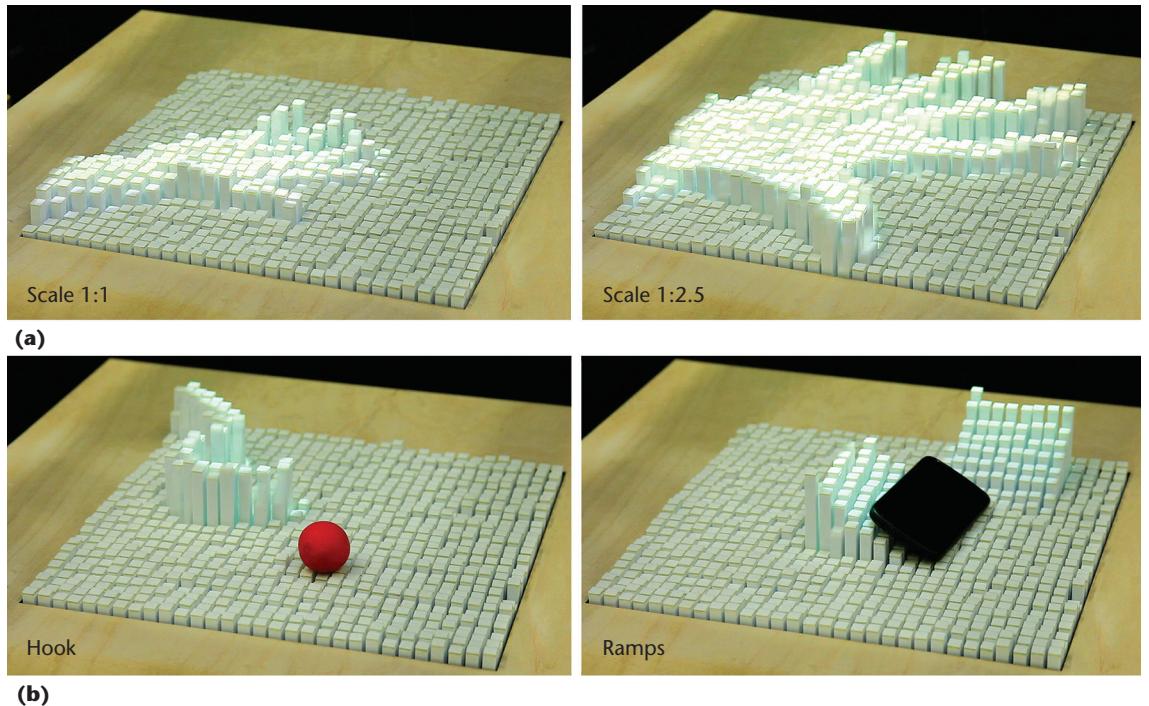


**Figure 5. Transforming the physical form. (a) Scaling a user's hand to interact with larger objects. (b) Replacing hands with a hook to reach or ramps to slide objects.**

Linked tangible objects placed on the surface can represent synchronized remote objects. As the user moves an object, the corresponding, linked remote object moves through shape actuation. This makes it possible to go beyond the limited DOFs of the shape display, while allowing for shared control over content represented by the objects.

Lastly, shared digital models are rendered simultaneously on both linked workspaces and provide a shared frame of reference during discussions. Deforming a model's shape on one site will change the synchronized model on the connected workspace.

## Applications

Physicalization of abstract data is an exciting application domain for shape displays.[7] We explored applications in mathematics education to physically render equations that can be represented as 3D surfaces. As students modify equation parameters, the surface changes accordingly and allows them to, for example, explore local minimum and maximum intuitively by moving their hands on the surface (see Figure 6).

Another application domain with rich possibilities is geospatial visualization. CityScape uses high-resolution shape output with a large wall display to allow urban planners to view and annotate a dynamic city model. This data can be updated in real time and change over the day. The shape display shows a portion of the city, and a user can pan through it using gestures, while direct touch provides annotation. The user can also switch to represent different data physically (buildings, population data, or energy use).

In the medical imaging field, volumetric data is often hard to visualize and is typically navigated layer by layer. Using Sublimate,[4] datasets such as MRI scans can be rendered as high-resolution 3D graphics that are spatially colocated with physical shape output. The user can use physical deformation to create nonplanar cross sections through the volume (see Figure 7) and save or load them, as well as define parametric shapes. The shape can be conveniently flattened and moved computationally, and the user can intervene at any time by modifying it by hand.

## Design Guidelines for Spatial Interaction with Shape Displays

Shape displays must allow for different modes of interaction and rendering to suit different applications. In our systems, we use touch for spatially relevant parameters and gestures to control more global, abstract and view-oriented parameters.
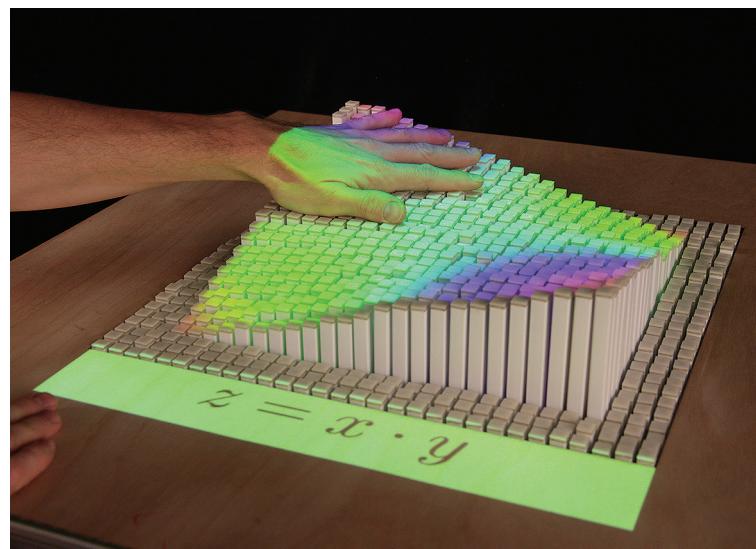


Figure 6. Data visualization application. inFORM allows users to represent 3D surface equations physically.



Figure 7. Medical imaging application. Using Sublimate, users can view and annotate volumetric medical data.

Similarly, not all information is best represented physically. To allow for different modes of interaction and rendering, we thus consider allowing users to switch between physical and graphical representations while interacting.

Designers should consider the scale of the data they want to represent on a shape display. One important challenge is the range of the shape display's actuators. Although 3D information might fit in the surface plane, it might extend beyond the actuators' height limits, which makes the scale of data an important consideration. Should the object be cropped, squashed, or scaled? Additionally, spatial 3D graphics can render visuals that exceed the physical boundary of shape output.

Shape displays can allow for new types of intermaterial interaction not possible on other 3D displays. Because shape displays render surfaces

**Figure 8. Transform table. This prototype table enables the exploration of the ways that shape-changing furniture can allow for different means of interaction as well as supports a wide variety of activities.**

physically instead of just points, other objects can be placed on them and the rules of physics apply to their interaction. Designers can leverage this to take advantage of intermaterial interaction. For example, a ball placed on a shape display will roll to the local minimum, such as in the math equation example.

Shape change in user interfaces is uncommon, so users may not expect it. In our studies and informal observations, we have noted that users can find rapid shape change jarring.[4,5] Thus, it is important to consider the speed of change, especially if users are directly touching the display. Graphics to visualize impending physical motion can be helpful.

## Future Research Directions

Shape displays are limited by many factors that make it challenging to render certain types of 3D information, such as overhangs. This also poses many challenges for interaction because users can currently only physically deform a shape display in the upwards direction. By increasing the degrees of freedom (DOFs) of output and input, we could enable richer interactions.

Current 2.5D shape displays are limited by their rigid arrangement and large size. Users cannot hold them in their hands nor move them to gain different views. In addition, they cannot move nor rearrange parts of the display to leverage spatial reasoning. Modular shape displays could allow users to rearrange parts, for example, to compare different sections of a dataset.[9] As opposed to 3D surfaces, shape displays could be made in a chain

form factor, allowing users to display line charts or other linear forms. These different geometries would allow for different means of interaction.

We envision a future in which information and interaction is everywhere, and it not only blends into the world around us, but can also physically reach out. Shape-changing furniture may be able to support a wide variety of activities. For example, it can create geometry and surfaces to provide ergonomic interaction at different heights or tilt up to provide more privacy. A desk could rearrange its contents to better support an activity, similar to changing tool palettes for different modes in desktop applications. These interactions could be contextual—a user picks up a pen, and the surface changes to a drafting table. Or the surface could create different emotional patterns to set the mood for contexts, similar to how users may change the lighting to match a task.

Shape-changing furniture can also be used as ambient displays to convey information. They could be arranged around physical objects on the table and moved and animated to follow them. For example, keys left on the table could be physically shaken as a reminder when a user walks by to leave. We have begun to explore these interactions with Transform,[6] a shape-changing table (see Figure 8).

Shape displays still need to address challenges in resolution, scale, and cost before we can expect widespread adoption. However, as VR and AR

become increasingly mainstream, users will want to touch, grasp, manipulate, and feel what they see. We believe that shape displays can enable this type of rich physical interaction, while seamlessly supporting users without the need for worn haptic devices. Shape displays enable exciting possibilities not only for shape output, haptic feedback, and deformable input, but also for manipulating and representing remote physical objects, as shown in our physical telepresence work. In this article, we have presented some of the promising applications with which shape displays can enable urban planners to redesign cities using dynamic physical models or to help surgeons physically explore volumetric data. We hope that our novel hardware, interaction techniques, and applications have shown shape displays' potential for extending the ways that we traditionally interact with the physical world, empowered by digital computation.  ⌁

## References

1. H. Iwata et al., "Project Feelex: Adding Haptic Surface to Graphics," *Proc. SIGGRAPH*, 2001, pp. 469–476.
2. I. Poupyrev, T. Nashida, and M. Okabe, "Actuation and Tangible User Interfaces: The Vaucanson Duck, Robots, and Shape Displays," *Proc. 1st Int'l Conf. Tangible and Embedded Interaction* (TEI), 2007, pp. 205–212.
3. D. Leithinger et al., "Direct and Gestural Interaction with Relief: A 2.5D Shape Display," *Proc. 24th Ann. ACM Symp. User Interface Software and Technology* (UIST), 2011, pp. 541–548.
4. D. Leithinger et al., "Sublimate: State-Changing Virtual and Physical Rendering to Augment Interaction with Shape Displays," *Proc. 31st Ann. ACM Conf. Human Factors in Computing Systems* (CHI), 2013, pp. 1441–1450.
5. S. Follmer et al., "inFORM: Dynamic Physical Affordances and Constraints through Shape and Object Actuation," *Proc. 26th Ann. ACM Symp. User Interface Software and Technology* (UIST), 2013, pp. 417–426.
6. H. Ishii et al., "TRANSFORM: Embodiment of 'Radical Atoms' at Milano Design Week," *Proc. 33rd Ann. ACM Conf. Extended Abstracts on Human Factors in Computing Systems* (CHI EA), 2015, pp. 687–694.
7. F. Taher et al., "Exploring Interactions with Physically Dynamic Bar Charts," *Proc. 33rd Ann. ACM Conf. Human Factors in Computing Systems* (CHI), 2015, pp. 3237–3246.
8. D. Leithinger et al., "Physical Telepresence: Shape Capture and Display for Embodied, Computer-Mediated Remote Collaboration," *Proc. 27th Ann. ACM Symp. User Interface Software and Technology* (UIST), 2014, pp. 461–470.
9. J. Hardy et al., "ShapeClip: Towards Rapid Prototyping with Shape-Changing Displays for Designers," *Proc. 33rd Ann. ACM Conf. Human Factors in Computing Systems* (CHI), 2015, pp. 19–28.

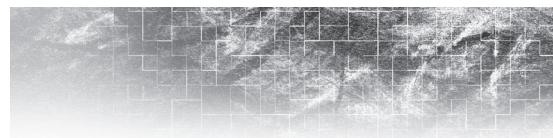**Daniel Leithinger** *is a PhD candidate at the MIT Media Lab. Contact him at daniell@media.mit.edu.*

**Sean Follmer** *is an assistant professor in Stanford University's Mechanical Engineering Department. Contact him at sfollmer@stanford.edu.*

**Alex Olwal** *is a senior interaction researcher at Google, research affiliate at the MIT Media Lab, and affiliate faculty at KTH – Royal Institute of Technology. Contact him at alx@kth.se.*

**Hiroshi Ishii** *is a professor of Media Arts and Sciences and head of the Tangible Media Group at the MIT Media Lab. Contact him at ishii@media.mit.edu.*

*Contact department editors Frank Steinicke at frank.steinicke@uni-hamburg.de and Wolfgang Stuerzlinger at w.s@sfu.ca.*

cn Selected CS articles and columns are also available for free at http://ComputingNow.computer.org.