# A Series of Tubes: Adding Interactivity to 3D Prints with Hollow Chambers and Pipes


**Valkyrie Savage** †⋆
valkyrie@eecs.berkeley.edu

**Tovi Grossman** †
tovi.grossman@autodesk.com

**Ryan Schmidt** †
ryan.schmidt@autodesk.com

**Björn Hartmann** ⋆
bjoern@eecs.berkeley.edu

⋆ **UC Berkeley EECS**
† **Autodesk Research**



## ABSTRACT
3D printers offer extraordinary flexibilty in prototyping the shape and mechanical function of objects. However, in spite of recent work, a 3D printer's role in prototyping *interactivity* is still not clear. While macro-scale digital fabrication devices cannot manufacture electronics in-place, there have been many clever approaches to redirecting interaction onto 3D prints. We describe the design space of tubes and hollow chambers for interaction design: there are a variety of types, topologies, and inserted media for tubes that can be leveraged to create diverse inputs and outputs. We present a technique and design tool for routing tubes of various topologies through the interior of 3D printed parts. Our design tool is integrated into a 3D model manipulation program. It allows users to select begin and end points for tubes, then uses A* path routing and physics-based simulation to minimize the bending energy of routed paths. We present several totally tubular prototypes we created using this tool to show its flexibility and potential, as well as to explore new points in the tube design space.



## Author Keywords
Prototyping; Fabrication; 3D Printing; Electronics

## ACM Classification Keywords
H.5.2 [User Interfaces (D.2.2, H.1.2, I.3.6)]: Prototyping.


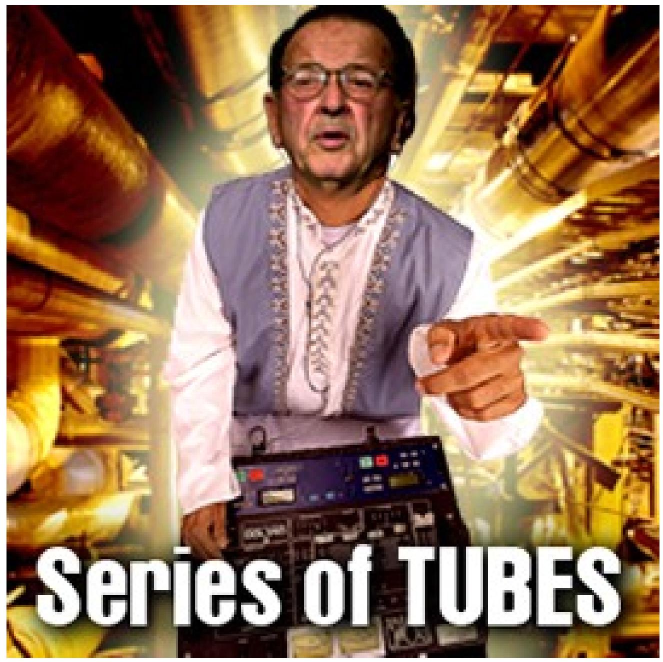


**Figure 1. Here's a teaser figure of some cool stuff we did. Probably it should show one of our example objects, or we can make it really big (figure*) and show them all!**

## INTRODUCTION
Makers, as well as professional designers, leverage 3D printers as tools for design work. A wide array of objects, ranging from bicycle helmets to jewelry to video game controllers, are now prototyped or even manufactured using these machines. However, most devices fabricated by 3D printers are passive: accessible printers are not yet capable of creating integrated active systems.

Willis, et al., "envision a future world where interactive devices can be printed rather than assembled; a world where a device with active components is created as a single object, rather than a case enclosing circuit boards and individually assembled parts" [22]. This is a vision we eagerly share: 3D printers are capable of greating arbitrary geometries not feasible to manufacture using traditional processes, and we see these capabilities being underutilized by makers and designers. We see many opportunitities to increase the interactivity of 3D prints using today's printer technology.

Using specially modified printers or extra machinery, it is possible to create electronics on the surface of 3D prints [12] [18]. These techniques, however, require a high capital investment and technical expertise. In addition, they lack flexibility: the printed circuits must be routed in 2D to be created on the objects' manifold exteriors, and they can only be used to create electronic circuits. **VS: what?**

In addition to electronics, many other means of interactivity exist.

**VS: Points to hit: there is more than electronics to worry about, like fluids and the organic haptic feedback they afford; tangible interfaces are important (do I have to say this every time??); assembly sucks**

## RELATED WORK

Our work is related to three existing research areas: fabrication, interaction techniques, and routing.

### Fabrication

Previous work has investigated the integration of interactivity into the fabrication process. [22] used light pipes, solid clear tubes, to create integrated displays. [16] investigated the use of computer vision to track interactions with physical mechanisms.

- [16] - Sauron. computer vision of mechanical components obviates electronics installation.
- [23] - InfraStructs, identification of 3d printed objects using Terahertz imaging
- [22] - Printed Optics. doing cool stuff with clear material (touch sensing and display)
- [19] - robots that are made of squishy stuff where air pressure changes are sensed. input components designed to react to different manipulations (pushing, squeezing, twisting, etc.)
- [10] - I'm a little unclear on what they did, but they fabbed something with a "3D circuitboard" that has a bypass that goes into 3D. they don't offer a routing algorithm or anything, though.

*Printing Electronics*

- [14] - this uses an airspray machine to add conductive paths to surface of 3D prints
- [?] - fancy machines that spray conductive film
- [18] - the RepRap people using a syringe of hot solder to squirt flat circuits into flat channels
- [6] - an instructable I followed to make my first batch of conductive paint

### Routing

- [17] - Midas. routing in 2D to connect up capacitive sensors
- [13] - similar to injection of liquid metal, above
- [9] - inject liquid metal into really thin tubes in a soft substrate, sense stretching by changing resistance

### Interaction Techniques

- [15] - Touché. It's like Touché with sound, but without sound. SFCS.
- [2] - fabricate latex + acrylic buttons and pressurize with air
- [21] - air vortex generation in free space. air haptics.
- [24] - PneUIs, creating interfaces with pneumatics
- [20] - creating silicone bendy things with embedded electronics to sense flexing, stretching, etc., supported by those shapes.
- [7] - a display made up of many balloons that inflate and deflate to change the shape
- [11] - the Touché with sound paper from last year's UIST
- [1] - Jamming User Interfaces
- [8] - a basic mouse, but it inflates so you can store it and also use it more reasonably than a flat mouse
- [5] - hold a speaker in your hands, and air pressure changes make it feel like you're holidng a living, squirming thing

## THE DESIGN SPACE OF TUBES

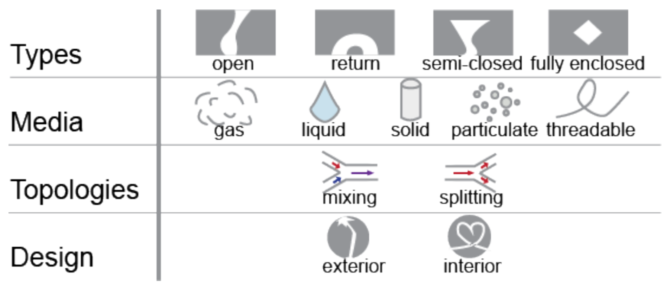


**Figure 2. The design space of tubes. Tube types, media, topologies, and design are discussed more fully in the text.**

### Types of Tubes

Tubes can come in four types: open, return, semi-closed, and fully enclosed. Each of these types offers distinct interaction capabilities (see Figure 2).

Open tubes originate from the system side and connect the user side, with both ends of the tube open. This type of tube may be used to create, for example, capacitive sensors: an open tube filled with conductive paint can be connected to a sensing platform (e.g., Arduino) on the system side, while a user can touch the uncapped other end of the tube. Using Swept Frequency Capacitive Sensing [15] or other techniques, a user's touch of the open end can be sensed. An open tube can also be used for output, for example by creating in-air vortices as in [21].

A return tube originates at the system and returns back to it. By threading an electroluminescent (EL) wire through a clear return tube, a maker can create a custom piece of neon art. If a return tube passes very close to the surface of a 3D printed model, warm or cold water passed through the tube could be used for temperature-based haptic feedback.

Semi-closed tubes are open at the system end (for control of the enclosed medium) and closed at the user end. We believe this closed interface is most interesting when it is fabricated from a mobile material: for example, a series of tubes terminated in thin rubber membranes on the user side can be actuated by an air pump to create haptic feedback. Without a printer capable of fabricating flexible material, a maker could affix a balloon to an open tube's end to behave similarly; another possibility is to use semi-closed tubes as audio-generating resonance chambers.

While possible to create, a tube which is open on the user side and closed on the system side is outside our focus is on computer-mediated interaction, and we therefore do not discuss these tubes.

A fully enclosed tube has no openings on either the system side or the user side. Fully enclosed tubes can be used as resonance chambers (e.g., for object identification), or as air bubbles (e.g., as used in [22] for internal display). Their physical design space is very limited, as any support material required to create their internal geometry cannot be accessed for removal.

### Media in Tubes

Tubes can be filled with a variety of media to create different interface affordances and capabilities.

"Gas" comprises all compressible fluids. Use of fluid pressure inside tubes can create haptic feedback at semi-closed interfaces, or the gases can be used as carriers for scents or fog. As in [19], structures can be engineered to change in air pressure when manipulated correctly (e.g., a spiral that changes pressure when twisted, but not pressed), and thus fluid pressure can also be used as an input.

Incompressible fluids ("liquids") can perform many of the same interface tasks as gases. One opportunity with liquids is to fill the interior of tubes with them and cap the ends. In addition, one can use driable conductive fluids, such as copper paint, to coat the interior of tubes and allow them to function as arbitrarily-shaped wires. This is especially helpful for the creation of a shared ground, or for creating single-wire capacitive interfaces amenable to sensing with SFCS [15].

Tubes need not have hollow centers: in the case where routed tubes are filled with solid material—in particular, a solid material different from the model material—, interactions such as those in [22] are possible.

Particulates, either printed in-place or inserted, can be of varying densities. A single particle can be used for display. Sparse particles in a stream of fluid can provide haptic feedback. Dense particles in a semi-closed tube allow for jamming-based interactions at any point on the surface of an object [1].

Threadable inserted elements, such as electroluminescent (EL) wire or fiberoptic cables, are those that can be threaded through tubes post-printing. This allows overcoming limitations of printers: for example, a Printed Optics-style interface can be created on an inexpensive consumer-grade 3D printer using tubes and inserted fiber optic cable.

### Topological variations

Tube topology enables different types of interactions.

Splitting or mixing tubes offer flexibility in output. If a maker wished to create a painting device, she might wish to have two system-side tubes feeding in primary-colored red and blue paints which mix in varying ratios, allowing their pigments to combine before purple exits from the device (see Figure 2). Splitting can also be useful, for example if our maker wants red paint output in two locations from her painting device, she could have one system-side tube, but split the tube into two (see Figure 2).

Star and tree topologies are extensions of the splitting and mixing primitives. Using a star topology in which the tubes were filled with conductive paint, we created a toy with several touch-sensitive areas, see Figure 6.

### Features of Tubes

Tubes may emphasize either their exterior features (connection points) or their interior paths. These two features lead to different kinds of interfaces. An example interface that focuses on the exterior connection points is the touch sensitive toy in Figure 6, where tubes must exit the toy at the eyes, ears, tail, etc. An interface focused on the internal path of the tube is the neon sign in Figure 10: output is based on the shape of the tube.

### Inputs and Outputs

**VS: we can just include related work in this section? we basically cover it in the table, anyway.**

**VS: optimally, we can just describe this thoroughly in the chart, and avoid spending a bazillion paragraphs talking about each thing individually here**

### Inputs

*Flexing*
Much like [20], we can sense flexing and bending of prints made on the Objet. We can make prints on the Objet and tunnel through them, though, without making crazytastic silicone molds. We can make things flex using muscle wire and cleverly-placed expandable air pockets.

*Touch*
Capacitance (digital). SFCS.

*Pressure*
Pressure (via SFCS or fluid pressure).

*Tapping*
Tapping (audio/resonance?) carried through particular tubes, like we talked about hard tubes in a soft thing. We use hard tubes in soft things, anyway, for the conductive goo.

*Other stuff?*
Could be.

*Traditional Components*
Obviously you can hook up traditional buttons, etc., the same way as always. With copper paint instead of traditional wiring, we can share grounds, and we don't have to solder.

### Outputs

*Visual*
EL wire. Colored liquids. Mechanical motion by pushing light or tube-plugging (like a big ball) objects with fluid.

| | Gas | Liquid | Solid | Particulate | Threadable |
|---|---|---|---|---|---|
| Visual | PneUIs, latex buttons, *smoke display* | Splash Controllers, *paint mixer* | printed optics | *embedded hourglass* | *faux neon sign, fiber optics (see:light pipes)* |
| Aural | *Helmholtz resonance* | *bubbling/ splashing* | | *CNC maracas* | |
| Tactile/Haptic | PneUIs, *haptic textures* | Splash Controllers, *warm/cold liquid* | *resonance for vibration* | Jamming UIs, *sparse particle haptic textures* | Otherlab robots, *high resistivity heat wire* |
| Olfactory/ Gustatory | *perfume mixing* | *cocktail mixing* | | | |
| Touch/ Pressure | latex buttons, Slyper robot armature | SFCS, *capacitance, flow meter* | | Jamming UIs | capacitance on wires |
| Other | Slyper robot armature | *traditional components* | | | *traditional components* |

**Figure 3. The design space of tube-based interactions. Existing systems are written in regular font. Those created with fabrication are in blue. In *red italic* are unexplored interactions creatable with custom-fabricated tubes. Darker grey is output. Lighter grey is input. VS: I don't know what else might go in the blank spaces... looking for suggestions! Also, I'm not confident this breakdown is the most clear: for example, the "liquids" category includes the copper paint, which functions as wires ("threadables"), but takes the form of a liquid...**

*Aural*
Resonance chambers. Air cavity design for sound/amplification (see passive iPhone speakers). I mean, this is basically just 3D printing instruments, which we know has been done.

*Haptic*
Compressible and incompressible fluids for actuation. Recreation of PneUIs. Tactile output. Adding particles to add extra feedback.

*Olfactory/Gustatory*
Different chambers filled with different scented/flavored fluids. We can mix them using pipes and pressure.

### Identity

Tubes included in printed objects allow for their identification. While the tubes need not be visible (especially in the case of fully-enclosed tubes), their presence, location, and length change the acoustic resonance properties of a printed object.

Both identification by recall and intentional encoding are possible. As seen in [11], different objects have different acoustic signatures. The presence of tubes changes this, thus allowing for recall of a shape once its acoustic signature has been recorded. In addition, semi-closed tubes can function as resonance chambers: the first resonant frequency $F_1$ Hz of a semi-closed tube length $L$ meters can be found by $F_1 = \frac{c}{4L}$ (where $c$ is the speed of sound). All odd harmonics (i.e., $3*F_1$, $5*F_1$, $7*F_1$, ...) of this frequency are also resonant frequencies of the tube.

An object's resonant frequency can be measured by attaching a speaker and microphone to it, sweeping frequencies with the speaker, and performing a Fourier transform on the resultant signal from the microphone. Peaks in the transformed data correspond to stronger returned impulses: the resonant frequencies of the object.

**VS: in my experiments so far, it seems that the material printed does conduct sound fairly well, so this is feasible. I think we should get some equipment and do a small test, though, since I don't know how the resonance will change with the big hunk of plastic around the semi-open tube. hopefully discussing this with Alex soon.**

## A SERIES OF TUBES

### Tool for Tube Design

We created a tool which novice designers can use to create tube-powered interfaces in arbitrary 3D models. This tool allows users to brush over the surface of their model to either select exterior connection points of their tubes (see Figure 5) or to author the tubes' interior paths (see Figure 4). Once the user's selections are made, our tool creates an initial shortest-path routing using A* to estimate the routed distance between points. This routing is used to create a rod; we run physics-based simulation steps on the rod to minimize its bending energy (and thereby minimize the bend radius of the tubes). The resultant routing is subtracted from the user's mesh. The modified mesh can then be 3D printed.

*Selection*
**Exterior Connection Points**

Focus on shape of points and location of points.

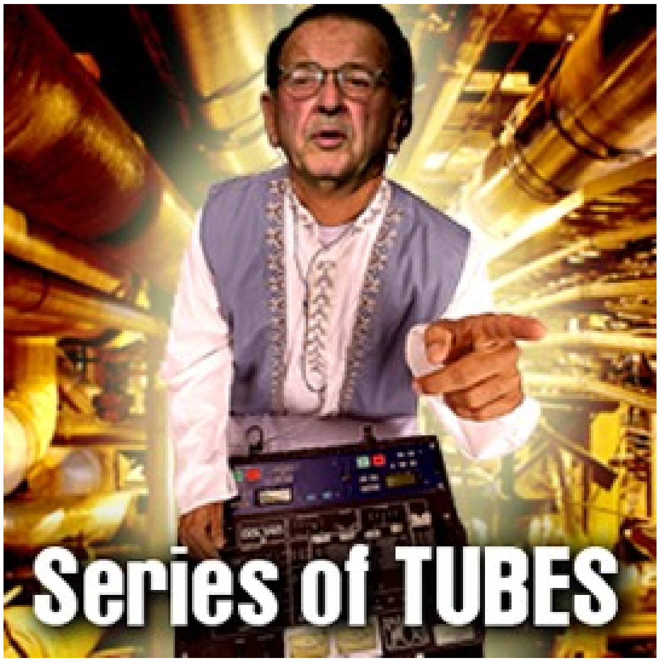


Figure 4. This figure has several sub-figures. a) shows a model with exterior connection points brushed. b) shows initial routing with A*. c) shows our physics-based, energy-minimizing rod/tube, d) shows the printed object with the tube (with something in it, copper paint presumably)

### Designing Interior Paths

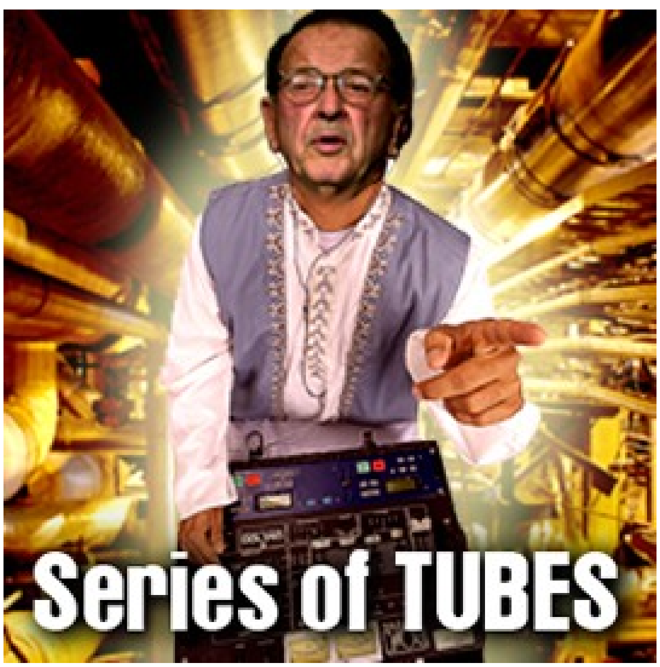


Figure 5. This figure has several sub-figures. a) shows a model with path shape and exterior connection point(s) brushed. b) highlights the points which can't be tubed as drawn (if they are not connected, too tight, etc.). c) shows our physics-based, energy-minimizing rod/tube and any path-smoothing that we do, d) shows the printed object with the tube (with something in it, EL wire presumably)

take into account bend radius of desired material - no need, we just do the minimum-bending path

*Routing*

Our basic first-pass routing algorithm uses the A* routing algorithm [4]. The path cost in our implementation is based only on shortest distance between the starting and ending points, without weighting for distance from the surface.

*Physical Simulation*

*Mesh Modification*

### Fabrication Techniques

*printing*

- different strategies with Objet (all print-in-place) and Makerbot (may need to add things like balloons afterwards). Ryan just got flexible material, we should see how stretchy it is...! We could also consider assembleable things that are easier to create using parts that clip together... probably out of scope.

*hand tools*

- post-fabrication modification is possible using hand tools. We can mark the surface to show where conduits are and how deep. I can also use this to test things beforehand.

## EXAMPLE OBJECTS

Totally tubular examples. We are making

### Touch-sensitive Toy

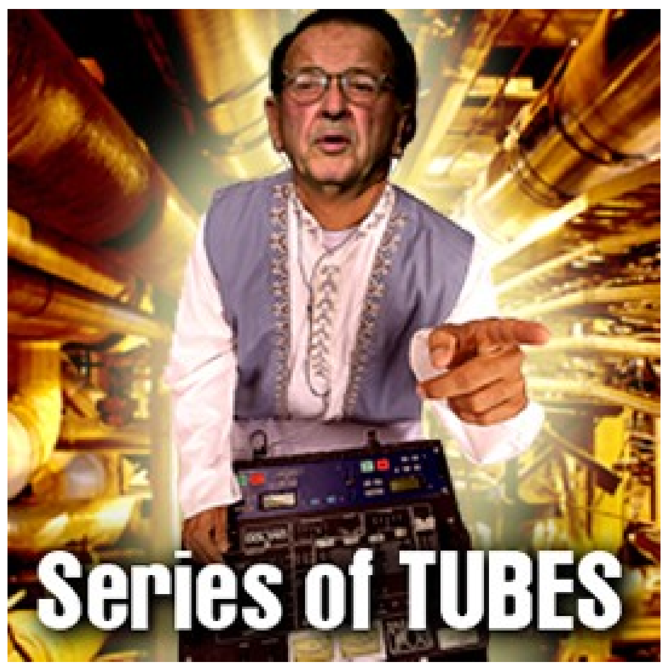


Figure 6. A touch-sensitive rabbit whose tubes are filled with conductive paint. Sensing is done on a single wire via SFCS. Inset shows the internal structure of the tubes generated by our design tool.

We created a touch-sensitive toy and an app that goes along with it, reminiscent of the boat application in [3]. This toy has an interior star

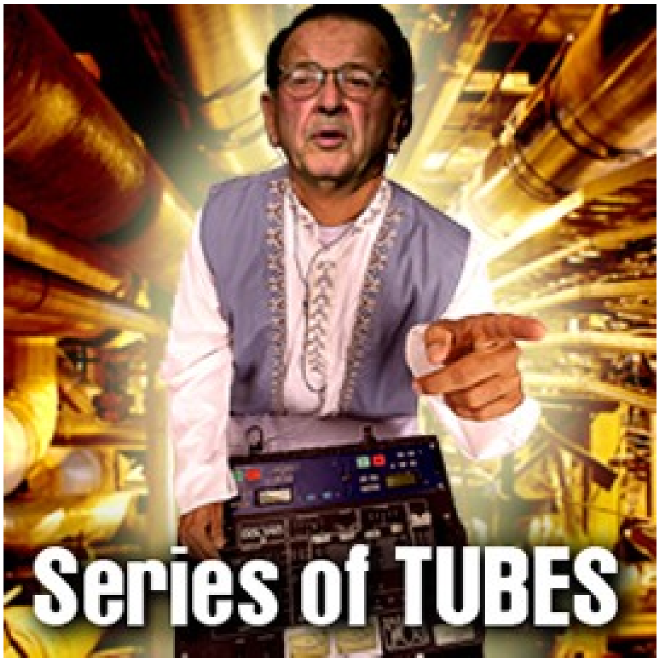


**Figure 8. This radio is assembled from traditional electronic components connected by copper-filled tubes. The case was designed to allow the components to recess into it slightly. Inset shows the internal structure of the tubes generated by our design tool.**

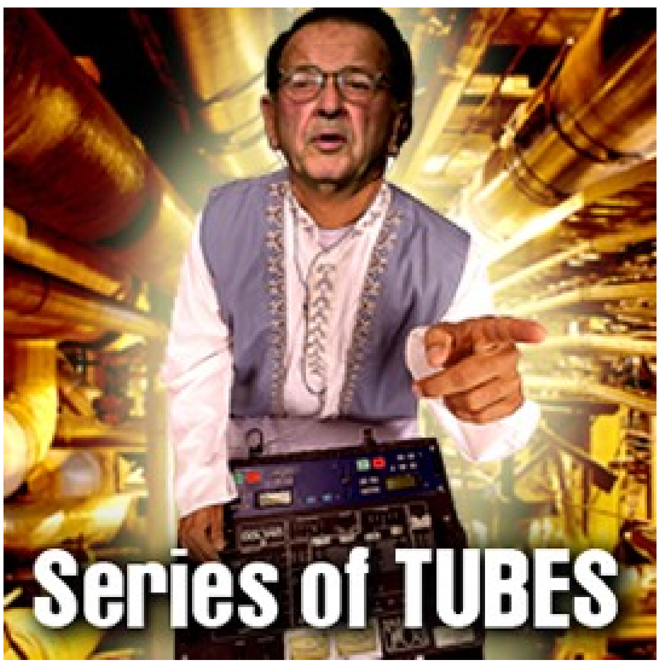


**Figure 9. This pen holder (a) uses Wimmer's FlyEye technique VS: can't add direct citation here?? (b) to sense the presence or absence of an object in each of its tubes. Inset shows the internal structure of the tubes generated by our design tool.**

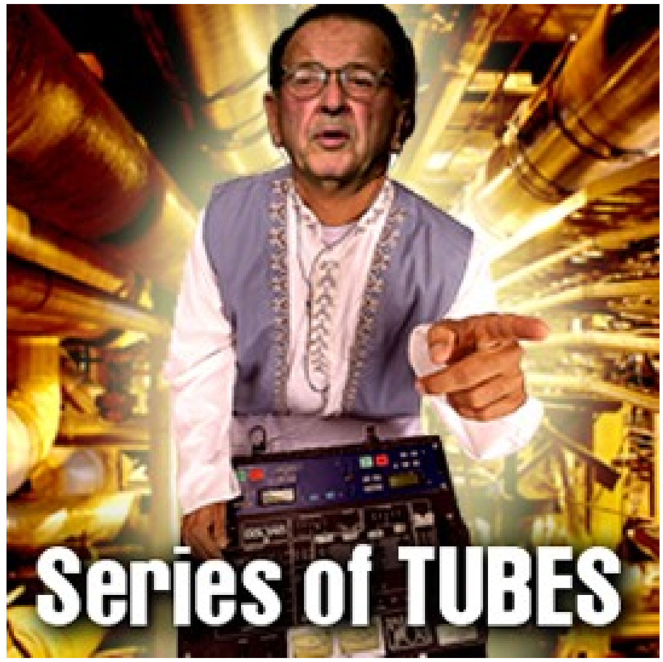


**Figure 7. This box has 6 individually-actuated semi-closed tubes capped with rubberlike material. When air pressure is changed in these tubes, the caps inflate or deflate. By actuating these tubes in particular sets, we can create braille letters. Inset shows the internal structure of the tubes generated by our design tool.**

### Braille Learning Tool

### Custom Radio

### Presence-aware Pen Holder

### Animated Neon Sign

## LIMITATIONS

Issues of drying time for fluids in long tubes. Flexible material doesn't work forever. Water in Objet prints discolors them. Can be difficult to get certain materials through certain kinds of tubes. Makerbot tubes must be at particular angles for printing (w/o support). Some tubes are hard to clear on Objet.

## CONCLUSION

In conclusion, tubes are cool. You can do lots of things with them. There are different kinds and topologies of tubes. There are different things you can put in them. This is cool for makers and also people with really expensive machines.

## ACKNOWLEDGEMENTS

So long, and thanks for all the fish.

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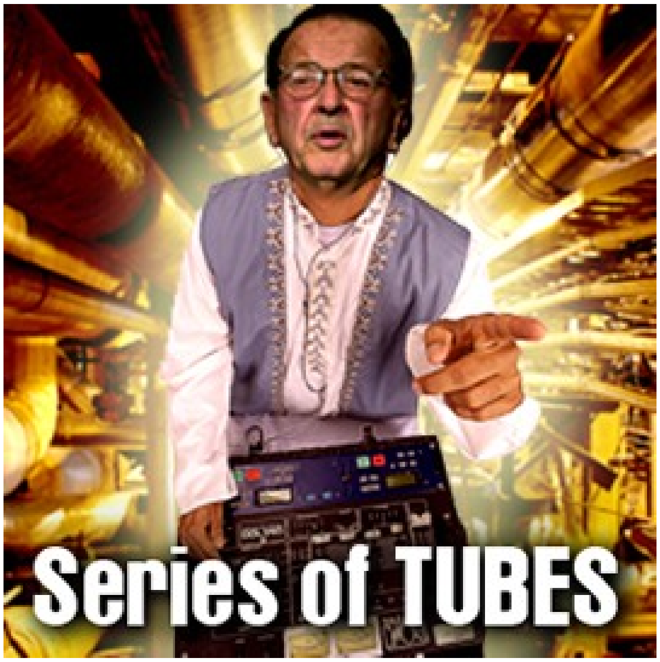


**Figure 10. A neon sign designed using our tool. The tubes contains four separate electroluminescent wires, lit in sequence to create animation (a). (b) shows the selections we made to generate our tube structures. (c) shows the internal structure of the tubes generated by our design tool.**


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## APPENDIX

### INJECTION MEASUREMENTS

We injected the copper a distance of 1.16m (according to the spiral length calculator at http://www.giangrandi.ch/soft/spiral/spiral.shtml ) in a spiral whose cross-section was a square of area $9mm^2$. I suspect that is about as far as we can go without using a vacuum at the end.

### OBJET 260 CONNEX DIGITAL MATERIALS

Softer materials (concentration of $> 65\%$ Tango-series material) do not easily accept the copper paint (it cracks when bent and is easy to wash off). This may preclude flex sensors made of interior copper paint (conductive thread or other materials may be able to be used for some parts of this).

### BEND RADIUS MEASUREMENTS

- EL wire diameter 2.3mm: minimum bend radius .35in = 8.89mm
- Water: uh. None?
- Muscle Wire: ?
- Fiber Optic Cable: ?

### MATERIAL PROPERTIES

| Name | Material | Resistance | Drying Time | Application Notes |
|---|---|---|---|---|
| CuPro-Cote Coating | Copper | 2Ω/inch | O(1 day) | Syringe |
| Spectra 360 Electrode Gel | Liquid/Electrolytes | 125kΩ/inch | O(hours) | Does not conduct dry |
| Wire Glue | Carbon/Graphite | 23.6kΩ/inch | O(minutes) | Syringe, very runny |
| Bare Conductive Electric Paint | Carbon/Graphite | 110Ω/inch | O(days) | Syringe |
| Homemade Conductive Paint | Carbon/Graphite | 120Ω/inch | O(hours) | Too thick for syringe, apply externally with brush |
| Conductive Thread | Steel | 1.8Ω/inch taut<br>2.5Ω/inch loose | N/A | Difficult to feed through turns |
| Solder Paste | Lead | 2Ω/inch | N/A | Too thick for syringe, must bake to conduct |