Ultrasound Probe as Tool for Tangible Sound Performance Using Physically Sculpted Phantoms

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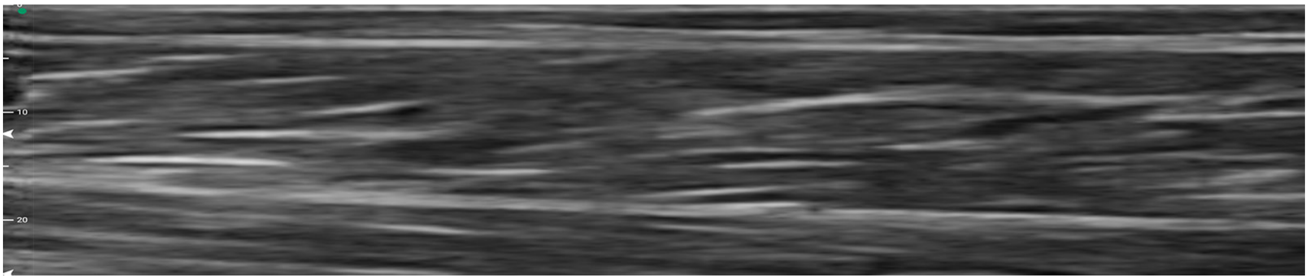

Figure 1: Linear probe image result from author's leg muscle (depth = 0-25mm).

Abstract

Recent development in point-of-care (POC) ultrasound probes have provided a boon to the medical field through their small size, low power and comparatively low cost. Such probes provide a unique ability to generate tissue density data at a range of depths. This imagery can be manipulated and converted into sound via Fourier transformation of the output imagery, wherein depth (distance from probe) is associated with frequency and tissue density at that depth represents the volume of that spectral character.

In medical training, a dyed-opaque gelatin mold known as a phantom is used to simulate organic tissues, via selected materials suspended in the medium. This allows the practitioner to learn the coordination required in their craft in the absence of a patient. While typically designed with simulation of tissue and medical procedure in mind, one can alternatively select materials and placements based on creative image output. This paper demonstrates that one can use intentionally designed phantoms as a physical, compositional source via physical probe manipulation and the above image to sound transformation.

CCS Concepts

• **Applied computing** → **Performing arts**; • **Hardware** → *Biology-related information processing*.

Keywords

radiology, ultrasound, physical manipulation, organic structures

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1 Introduction

Ultrasonic imaging technology provides a unique ability to safely probe the interior of organic subjects using sonic phased array technology, algorithmically controlled to act as both waveguide and focus. This, combined with different probe designs such as linear and convex, allows for a wide range of depths and tissues to be imaged. Further common controls for gain, noise reduction and dynamic range allow significant control of the image output. This work explores the use of this output as performative sound generator through the tangible use of gelatin phantoms.

The exists a long history of appropriation and creative reuse of medical sensors and technology in artistic and musical practice [6, 13, 15]. When the term *ultrasound* is referenced as a data mapping source for musical interface, it is most commonly in reference to the use of distance sensors. Beyond a general overview of non-musical MIDI use for data mapping of medical technologies [17], there seem few references in the literature of the potential for *medical* ultrasound in musical contexts excepting a couple notable examples. The outputs of radiology have been pursued for spatialization of volumetric data sets in the work *Musical Exploration of Volumetric Textures in Mixed and Virtual Reality* [1]. This research considers sound-based contexts for radiological data, but not that of live radiological input. More directly, *Tongue 'n' Groove* [18], providing a model using optical flow with contour determination to extract control values from the user's tongue. These are then able to be mapped to any array of parameters with their examples referencing common tongue function such as frequency shaping, temporospatial articulation, and tongue-based object manipulation. This research is a partial inverse of theirs. *Tongue 'n' Groove* explores manipulation of the medium in the form of the tongue, yet with the probe in a preset static position. This paper attempts live sonic performance via the manipulation of the probe upon the predesigned physical medium.

1.1 Image-based Synthesis Approach to Ultrasound

Spectral analysis via the IFFT has long been used for creative audio generation using common visual imagery. These have included a number image-to-sound converters with use manifesting in such audio Easter eggs as those hidden in the Aphex Twin's *Windowlicker* album [2] or the *Doom* (2016) soundtrack [9]. For intentional creative generation of sound in this vein one can as well look to *Spear* [12]. Jasmine Butt's *Pattern Organ* [4], demonstrated the use of video (from live manipulation of light patterns) as source for sound performance using pixel value as wavetable source. Using existing tools for spectral audio from imagery, it is possible to convert the depth density information from ultrasound into multi-spectral output. Interestingly, as the ultrasound's response has a falloff as tissue depth increases, this can result in a semi-natural high frequency decays expected from recorded sound, being as well the result of the ultrasonic waves' absorption and loss of phasing coherence by various tissues; something modeled for in traditional phantoms [19].

1.2 The Phantom as Imaging Source

While it is possible to use one's body as the focus of the probe (a technique for which these devices was designed), and the body's use has performatively been put into practice with ultrasound, this paper addresses another source, with fewer potential complications and greater potential for intentional design - that provided by the medical *phantom* upon which the ultrasound is used in training. These molded forms incorporate an array of elements suspended in opaque-dyed medium, often gelatin [8], to simulate actual conditions under which a medical practitioner might operate [5, 14]. In this way they can build the hand-eye coordination necessary to hold the probe while manipulating a sub-dermal tool, such as a needle, while looking at a screen for target guidance. Instead of designing for the practicalities of professional training, it might instead become a medium for creative exploration of spectral sonification and tangible manipulation.

Figure 2: Scanning of a gelatin phantom with a linear probe. The onscreen vertical line is the current position sampled by the IFFT. The suspended forms here include tofu, grape and orange peel.

Such phantoms can allow a creative, performative approach to the idea of composition. As opposed to distance information from only the surface of a solid, the ultrasound can provide multilayered depth information to translate into a soundscape, with registration of densities at different depths providing multiple frequencies and amplitudes. In addition to manual compositional creation in choosing immersed elements and their placement within the gelatin mold, there is multi-dimensional physical application of the probe (figure 2). The range of motions can include sliding, twisting, tilting, applied pressure and contact/removal, all providing varied sonic responses.

2 Phantom Design

Typical phantoms are designed with materials or *masses* including synthetics such as balloons, plastic balls, or gloves and/or organic materials including grapes and hot dogs [3]. The experiments undertaken here have kept to food-based selections, due to their ready availability, and the minimization of waste (either through post-performance consumption or their biodegradable nature). Additionally, while a typical training phantom is expected to be dyed in an opaque color to simulate the inability to see past the surface of a patient's skin, the ones produced here are kept transparent to aid in performance and on-stage visual appeal. While a variety of foods have been tested for relevance to tissue simulation, table 1 gives an overview instead of properties relevant sound character output. Some of these can be seen in figure 4. Higher concentration of the gelatin than typical for food preparation (approx. 20g/250ml) is generally favorable, as it continues to be principally transparent to the ultrasonic waves and better permits stability against physical damage in performance. In addition to solid components, powdered materials are often added to simulate absorption characteristics of fat or fibrous muscle tissue [7]. These have been used here as well, but in an alternative capacity to instead *fill in* the sound with a form of physically generated noise between other masses. Depending on gain settings this noise can have a frequency falloff more quickly than solid items.

Figure 3: An example in which tofu is cut along one axis in a saw pattern and another a sinusoidal form. Rotation of the probe along the vertical axis could allow movement to result in linear or smoothed pitch variation, or a merger of the two if traversed along the diagonal.

When deciding on materials and placement, considerations must be made for buoyancy, There is often little control when adding the gelatin solution in its liquid state to maintain intended localizations as even carefully added fluid tends to push even a carefully arranged assemblage around to some degree. This is especially true for anything that floats. It should be remembered that in adding the gelatin to the water, the density of the fluid changes, such that some materials that might not be expected to float, shall. The use of toothpicks can provide some measure

Table 1: Possible food-based materials that can be added and potential for audio character results.

Type of medium	Example	Result
Thin membrane	grape skin, leaves	narrow band frequency.
Thick membrane	orange peel, bell pepper	mid-band frequency response.
Soft (wet) material	orange slice, peeled grape	wide-band low energy frequency response, possibly multiple peaks from cellular structure or seeds.
Soft airy material	mushrooms	thin frequency line, potential to shadow lower depths.
Semi-dense material	tofu	broad frequency response with shadowing.
Loose powder	fine coffee grounds, dissolved fiber tablets	white noise to otherwise unoccupied portions of the spectrum.
Dense irregular materials	grape stems	irregular frequency patterns by movement.
Hard surface	table below the phantom	potential for banding reflected harmonics.

Figure 4: An example spread of prepared food items used.

of control, depending on the material. This can also be a consideration for any powder added to the solution, as many will not maintain a homogeneous density throughout the fluid depending on when they are added in the process and how.

Depth of the mold container needs also be considered. Any mold not sufficiently thick will likely incur reflectance of the ultrasound from the resting surface. As listed, this can result in a series of repeating bands which may produce a comb of frequencies, but might be an unwelcome surprise if not considered beforehand.

3 Physical Operations

There is a broad range of potential manipulations available to the operator by moving and turning the probe along various axes. Moreover, once removed from its mold, the phantom need not be probed purely top-down, but can as well operate from any side or orientation. Most of the explored manipulations are listed in table 2. These motions in some cases might be alternatively organized by axis rather than movement. The reasons for this are that the variation of a push along z is similar to the result of a pivot on x, as both give a progression of the full image, where-as a pivot on z and a shift along x present a similar result in the sideways shifting of the image,

In practice, there are considerations for the feel of the probe across the material. These include that some pressure is always needed to maintain proper contact, however the deformability of the material makes that pressure relevant to any attempt to move the probe. The surface moisture also affects the potential for motion across the surface as condensation provides a lubricative function and open air evaporation can result in some difficulty in non-rotational motions. The soft quality of the medium and how this affects performance is briefly addressed later in 5 as it relates more to performative potential than the discrete per-axis motions discussed here. While only explored in a limited capacity due to the technical concerns also in 5, one might also manipulate the phantom itself. Compression (squeezing) and shaking have been the primary techniques investigated, with former used as a manipulator (on x) resulting in a warbling of pitch as also suggested by probe compression (on y). The later gives a similar result but with a greater complexity largely due to the physicality of holding the probe consistently against the surface while doing so.

When considering these actions and interpolations between them, there is some accustomation needed to device operation. Primarily this is in the orientation of the visual result as manifested through the on-screen plane versus the orientation of physical device. As well, the variations to magnified depths and the degree of spread (in phased array and convex modes) takes some time to acclimate to. This adaptation took place over only a few uses, and the complexities in this interface present themselves more in the construction of the phantoms and the software side's interpretation thereof.

4 Synthesis from Image

In this conceptual demonstration, it seemed unnecessary to develop new image resynthesis techniques. Thus, as the imagery was being interpreted via the VVVV visual coding software [11], the *IFFT* node present in the included VL.Audio NuGet(library) was selected for simplicity, although any number of similar or better algorithms may interpret the array after pixel value sampling. The image conversion began by creating a sample line (typically vertical column) of pixels starting at the probe's surface and extending to those representing its maximum depth. The pixels along this line we resampled (bicubic interpolation) to an array of 1024 pixel brightness values mapped linearly from black to white as values 0.0 to 1.0. This was then fed to both the real and imaginary components of the IFFT node with Hann windowing. This node performs a direct inverse discrete Fourier transform on the complex-value spectra with no phase-reconstruction algorithms and, as the implementation provides the same scalar values to both real and imaginary components of each spectral bin, results in constant phase across all frequencies resulting in deterministic reconstruction and uniform phase. No inter-frame phase continuity or estimation is performed. This also means that, in the current implementation, it may be better considered an additive sinusoidal synthesis of the mapped bins than the

Table 2: Results from simple motions. For this table assume x and y as equivalent to the image plane and z as tangent to that plan (long edge of the probe surface correlated to x axis)

Type of motion	Result
Push (movement along z)	Image progression of the pattern based on placement along z
Shift (movement along x)	Image shift with variation, equivalent to shifting sample line along x axis
Press (movement along y)	Compression of medium and spectra, typically more as shallower depths
Tilt (rotation on x)	Image progression, further as deeper depths; spectral character stretches with deeper samples stretching more.
Twist (rotation on y)	Minimal variation to central sample line; variation to image and progressions from other motions
Roll (rotation on z)	Typically lost contact without associated pressure; with sufficient pressure for degree of rotation a rotation of image frame, and variation to and stretching of spectral content as per tilt.

true spectrographic synthesis that would result from the use of more audio-oriented software with phase consideration. Another consideration is that the current method does not permit frequency range selection or logarithmic binning. Each bin is based on division of the 48 kHz sampling rate by array size, resulting in 4̃6.9 Hz per bin. This is not ideal and, once again, other software would provide a better result.

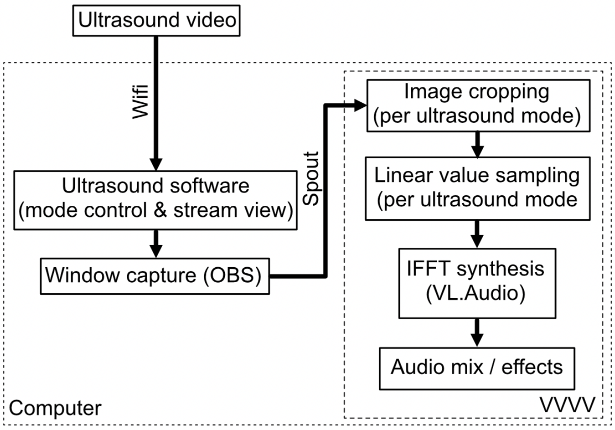

Figure 5: Simplified signal flow diagram.

For more complex sound output, multiple sample lines may be interpolated. In the case of convex or phased array probe function, the sample lines took into account the arc of the scan when sampling away from the vertical center (figure 6). In this implementation, the positions of secondary and tertiary sample lines were attached to low frequency oscillators (LFOs) to allow independent variation, while the overall image from which they sampled varied with manual control of the probe.

The result of this implementation is that it generates a signal that can frequently be over-expressed in higher frequency bands while limited in pitch dynamics at lower ones. While the increased phase aberration at greater depths from the ultrasound probe results in some natural falloff response at high frequencies, further compensation was required through EQ manipulation. Unfortunately, there is nothing to increase complexity at lower frequencies. As may be apparent, this current implementation is sonically limited as further discussed in 6.1. Performance physicalities compensates for this, but more work is needed to improve dynamics if this is to be featured in longer performances. Some compensation has been made in the limited application of other techniques as addressed in 6.2.

The system introduces some level of latency, primarily stemming from initial image acquisition and transmission probe->probe software->OBS->VVVV. In practice this amounts to approximately 1 frame (at 30 Fps) latency (3̃3 ms). Further sub-frame latency from the VVVV processing itself occurs as well with an estimated maximum total latency below 70 ms. As the ability of this probe to resolve fine detail without some level of visual blur, and variation of pixel values does not typically rapidly change per-frame, the latency did not perceptually manifest in ways meaningful to performance. The greater need for inter-frame sampling results from IFFT node in that the variations to pixel values across the sampling line and the resultant frequency bands volume can create a kind of chirp. Once again, another implementation capable of such interpolation would improve the sound result.

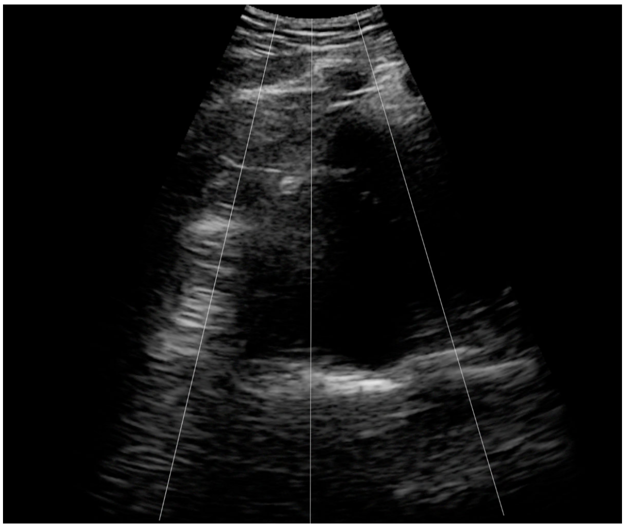

Figure 6: Example of multi-synthesis. Each angled line represents a vector of value samples from a convex probe.

5 Performative Results

The existing performances using this system have done well to demonstrate both its potential, while highlighting some current limitations to this applied strategy. What is here presented is brief descriptions of personal considerations for how it manifests in real-world performance, both tangibly, and sonically as well as information garnered from audience members.

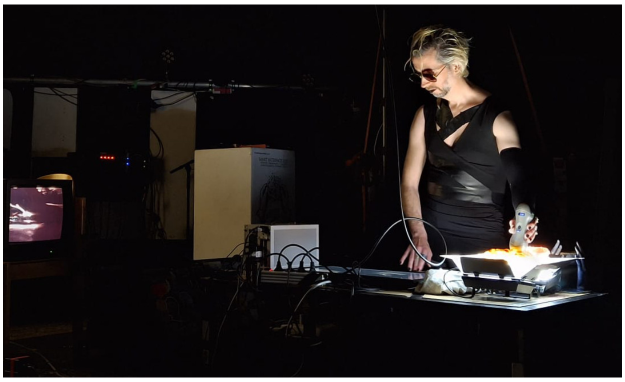

Figure 7: Performance during Sankt Interface 2025, Kapu, Linz.

5.1 Probe Handling

In performance, one primarily handles the probe with one hand and software/controllers with the other. This creates certain limitations to use. In personal use, this meant control of the probe with the left hand while the right manipulated common USB controllers for parameters including sample line count, LFO frequency, and audio mixing / filtering. This approach for separation of physical manipulation and software control was largely fluid, however there existed some difficulty in that the probe's proprietary software, which must be used for any switching of mode or function, must be visible and full-screen at all times. As linear, convex and phased array probe modes allow for significant variation in depth of sampled medium, the performance regularly switched between them. This required awkward handling of a mouse and attention to the screen in early performances and further prevents the (otherwise ludic and engaging) manual phantom manipulation in the interest of keeping the control surfaces clean and dry. The handling concern has been significantly improved via the inclusion of a touchscreen, although this nonetheless must be kept clean. Prior noted latency was not significant enough to noticeably manifest.

The physicality of handling the probe itself, and moving it against, around and into the gelatin was (subjectively) satisfying, with the sensorial reaction to bouncing the probe against the surface or alternatively pushing into and through the surface particularly so. The response of an instrument with compressive and elastic physical properties provides many responses in sensation and tangible interaction as suggested in continuous TUIs as suggested by Ishii, et al. [10], albeit while still handling a hard-surface interface in the form of the probe, and with the further caveat that while deformable, the phantoms are not malleable. While it felt very quickly intuitive to learn the physical manipulations of the probe with the phantoms, it was certainly not as compositionally so as intended. In performance, the phantoms held their form against pressure for the most part, although when molded into more eclectic forms could suffer from breakage over time. This breakage, and the ability to intentionally destroy the surface over time as well became an engaging part of the performance. Surface moisture and small perturbations in surface could also affect the ability to smoothly move across the surface and a drying or overly concave/convex surface would require repositioning the probe or limiting local motions to those of rotation.

5.2 Audience Response

The response of audience members has been incredibly positive. Much of this can be attributed to their interest in the performance media and its novelty which has inspired much more inquiry and conversation than the (still somewhat limited) resultant sound - manifesting primarily as noise performance in its current format. The regular shifting of the probe, combined with abstracted displays of it's visual stream and the audio sampling were mentioned as points of performative attentiveness beyond the primary interest in the gelatin molds and the device itself. Current attempts to control the sound result have resulted in some limitation to the expressive speed and range of motions, but this is changing as such motions have better engaged the audience.

6 Discussion

This research has presented some of the functional possibilities available to use ultrasonic medical probe in combination with the gelatin bodies to create a playful and physically expressive performance. To expand upon the provided technical and performative considerations, some of the research interest as well as that of audience members is in the occulted and ethereal quality of the familiar imagery of the ultrasound, as it reveals typically unseen elements in a format that itself can be difficult to discern without training. The physicality and transparency of these phantoms manifests some clarity to this imagery. There becomes here a somewhat philosophical interest beyond the typical considerations of a NIME through the medical use of the term, 'phantom.' While the audience does not respond to this little-known naming convention, it becomes a point of consideration in the work's production. Phantoms are a synthesis of the body, while this work uses the ultrasound result to synthesize sound. Thus we have a synthesis from a synthetic - a kind of philosophically performative phantasm of simulation. Whether or not such conceptual considerations manifest materially, this work demonstrates that phantoms designed not for medical training, but for synthesis capabilities, create not only an avenue for unique, multi-spectral auditory soundscapes, but visually interesting, manipulable objects with which to perform.

6.1 Limitations

While the suggested ability to create spectral synthesis via suspended materials in molds provides an interesting result, it is significantly limited in many regards. The first of these is that one is unlikely to be able to construct the molds with any great level of precision. Attempts at any precise or accurate frequency outputs will likely be met with frustration. It should also be considered that, while the use of alternative software for synthesis than implemented here, as well as audio filtering can help, the raw audio output frequently has a character familiar to users of such image-based spectral synthesis techniques, and seemingly quite diverse phantom designs can result in frustratingly similar sounding outputs. Compounding any spectral resolution considerations for the IFFT is the fact that the resolution for these probes is frequently quite low (figure 8) and present diminishing quality at lower depths even for quite expensive devices.

From the perspective of access to such devices, medical ultrasound technology, while safe, is still considered a medical device. Beyond the associated costs there-in, there can exist difficulties in procurement of new equipment. While purchase used or through

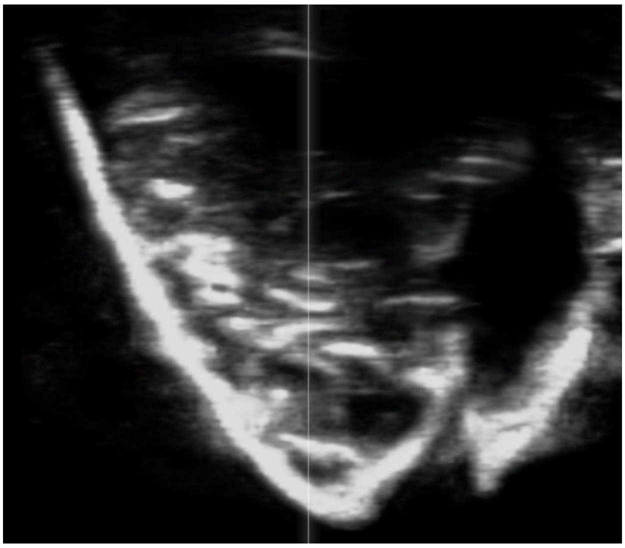

Figure 8: A cropped view of a piece of orange as rendered by linear probe ultrasound.

other channels is possible, many official POC manufacturers require demonstration of a medical license before sale. One should investigate whether there exists any regional laws on licensed operation of a medical device before engaging this research, although typically this is only of concern if used within medical contexts.

6.2 Further possibilities

The use of the IFFT node in the visual software package is quite limited, operating only on a fixed-frequency width bins and without phase consideration. One can expect better representation in human-range spectra with alternative software. Beyond the specific signal manipulations presented, other sound generation techniques have been explored and implemented in performance. Most directly following the scope of this paper is simple translation of the sample line to MIDI notes (with a simple example video included in the supplements). Another option, although thus far seemingly limited in sonic variation, is the use of linear and circularly sampled pixel values as a source for wavetable. Finally, most probes feature Doppler-based listening of regions on the scale of millimeters. This can be used as a kind of frequency modulated microphone, listening to vibrations or movements within a medium and thus has an interesting sonic character on its own, while also providing potential for unique feedback.

For ease of demonstration, the phantoms used have kept to roughly rectangular solids, but the medium lends itself to far more creative and stage-worthy visual shapes that have been used in performance. Regarding the use of gelatin, it is not unique in it's transmission of ultrasonic waves. Other potential mediums include agar agar (to avoid animal-based products), manipulations in water (with a properly protected probe) to allow variation from free-floating materials, and the organic body (the probe's original design intent). In the latter, temporal variation of the body's natural processes can also play a role, as well as intentional variation such as tightening of a muscle or compression via the probe. In the discussion of how NIMEs intersect with bodily awareness [16], one can readily consider the body's interior as instrument, via realization through POC ultrasound.

7 Ethical Standards

No elements of this research were conducted in any medical capacity. All research presented is in the context of sound design and using the non-living materials presented. Research was conducted fully independently and thus features no conflicts of interest with any entity.

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