Title
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Journal
ACS Omega, 3(9)

ISSN
2470-1343

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Publication Date
2018-09-30

DOI
10.1021/acsomega.8b01673

Peer reviewed

ACS AuthorChoice

ACS OMEGA

Article

Cite This: ACS Omega 2018, 3, 11026−11032

http://pubs.acs.org/journal/acsodf

Musical Instruments As Sensors

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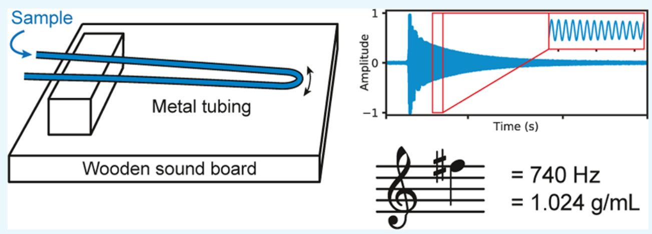
Supporting Information

ABSTRACT: The frequencies of notes made by a musical instrument are determined by the physical properties of the instrument. Consequently, by measuring the frequency of a note, one can infer information about the instrument's physical properties. In this work, we show that by modifying a musical instrument to contain a sample and analyzing the instrument's pitch, we can make precision measurements of the physical properties of the sample. We used the mbira, a 3000-year-old African musical instrument that consists of metal tines attached to a wooden board; these tines are plucked to play musical notes. By replacing the mbira's tines with bent steel tubing, filling the tubing with a sample, using a smartphone to record the sound while plucking the tubing, and measuring the frequency of the sound using a free software tool on our website, we can measure the density of the sample with a resolution of about 0.012 g/mL. Unlike existing tools for measuring density, the mbira sensor can be made and used by virtually anyone in the world. To demonstrate the mbira sensor's capabilities, we used it to successfully distinguish diethylene glycol and glycerol, two similar chemicals that are sometimes mistaken for each other in pharmaceutical manufacturing (leading to hundreds of deaths). We also show that consumers could use mbira sensors to detect counterfeit and adulterated medications (which represent around 10% of all medications in low- and middle-income countries). We expect that many other musical instruments can function as sensors and find important and lifesaving applications.



1. INTRODUCTION

Musical instruments create sound by vibrating at a frequency within the range of human hearing. Different types of instruments have different vibrating parts, and this distinction has long been used to categorize musical instruments. For example, in the Hornbostel−Sachs system of musical instrument classification, membranophones like drums and kazoos have vibrating membranes; chordophones like pianos and guitars have vibrating strings; aerophones like flutes and pipe organs have vibrating columns of air; and in idiophones like bells and triangles, the whole instrument vibrates.[1]

The precise frequencies of sound created by a musical instrument are largely determined by the physical properties of that instrument. For example, the pitch of a drum is a function of the size and tension of the drum head; the pitch of a guitar is determined by the length, mass, and tension of the strings; the pitch of a pipe organ is a function of the length of the pipes; and the pitch of a bell is a function of its size and shape. When a musician tunes a musical instrument, they are altering the instrument's physical properties to obtain the desired pitch.

The relationship between a musical instrument's physical properties and its sound frequencies raises an interesting prospect: could an instrument's sound be used to infer information about the instrument's physical properties? More specifically, could we add a sample to a musical instrument, measure the resulting change in the instrument's frequency, and use this change to determine information about the sample and its properties?

In this work, we demonstrate that musical instruments can be used as practical sensors in important real-world applications. For this initial demonstration, we focused our efforts on the mbira, a 3000-year-old African musical instrument[2] also known as the karimba, kalimba, or thumb piano.[3] The mbira (Figure 1A) usually consists of metal tines of different sizes and lengths attached to a wooden sounding box; these tines are plucked to create musical notes. As an idiophone, the mbira's sound is influenced by the physical properties of the metal tines: longer or larger tines create low notes, and shorter or smaller tines create high notes. In general, the frequency f_n of a plucked mbira tine is

$$f_n = \frac{\lambda_n^2}{2\pi}\sqrt{\frac{EI}{\rho A L^4}} \quad (1)$$

where n is the mode of vibration (n = 1, 2, 3...), λ_n are eigenvalue solutions of the frequency equation of a cantilever beam (constants), and the remaining variables are known properties of the tine: E is Young's modulus of the tine material (often steel), I is the second moment of inertia (a function of the cross-sectional shape of the tine), ρ is the density of the tine material, A is the cross-sectional area of the tine, and L is the length of the tine.[4] Equation 1 shows that at least five different physical properties of the mbira tine

Received: July 16, 2018
Accepted: August 8, 2018
Published: September 12, 2018

DOI: 10.1021/acsomega.8b01673
ACS Omega 2018, 3, 11026−11032

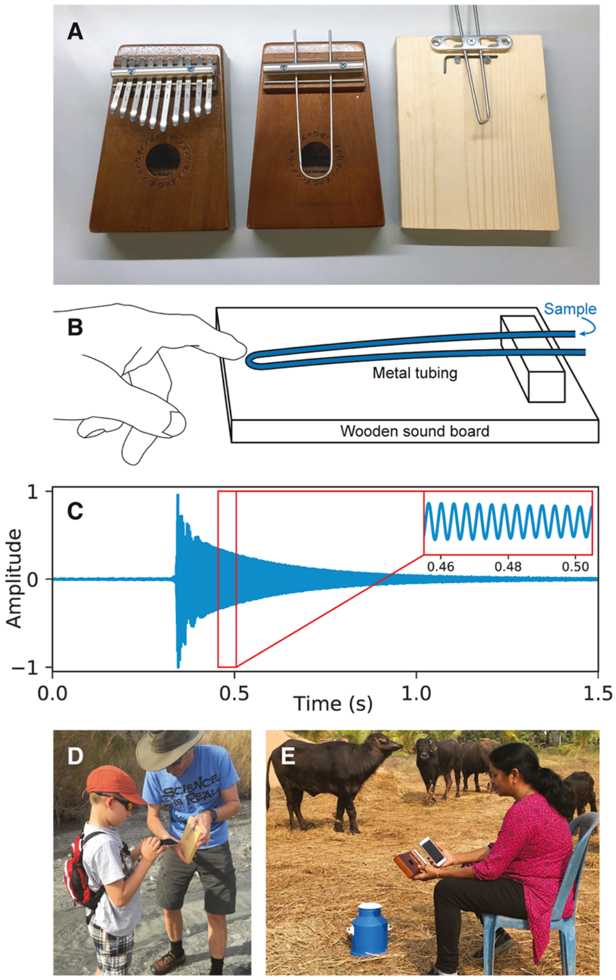


Figure 1. (A) This conventional mbira musical instrument (left) has 10 metal tines of different lengths mounted on a wooden sounding box; plucking the tines creates musical notes. By replacing these tines with a length of stainless steel tubing bent into a U shape (center), we create a sensor capable of accurately measuring the density of any sample inside the tubing with a resolution of 0.012 g/mL. Mbira sensors can also be made using scrap lumber and hardware (right). (B) Waveform plot of a sound recording of plucking an mbira sensor, obtained using a smartphone's voice recorder app and our analysis website (http://mbira.groverlab.org). The early part of the sound (C) exhibits inharmonic overtones, whereas the rest of the sound (inset) consists of a pure tone. By performing a Fourier transform on this portion of the sound, we determine the fundamental resonance frequency of the tubing, which is inversely proportional to the density of the sample inside the tubing. Using the mbira sensor and a smartphone to test river water in California (D) and bison milk in India (E).

influence the pitch of an mbira note (and could therefore in principle be measured by analyzing the frequency of an mbira note).

In this study, we primarily focused on ρ, the density of the tine material, as our physical property of interest when using the mbira as a sensor. If we change the density of the tine material, the frequency of the mbira note will change by a predictable (and measurable) amount. In particular, if we use hollow tubing as a tine, then the frequency of the mbira note will be influenced by the density of the tubing material (which is constant) and the density of the sample inside the tubing (which can be anything we like). When the tubing is filled with a low-density sample (like air), the net density of the tubing is lower, which results in a higher frequency when the tubing is plucked. When the tubing is filled with a higher-density material (like water), the net density of the tubing is higher, which results in a lower frequency. In general, for a hollow-tubing-based mbira vibrating in its first resonance mode (n = 1), eq 1 becomes

$$f_1 = \frac{1.875^2}{2\pi}\sqrt{\frac{EI}{(\rho_t \pi(r_o^2 - r_i^2) + \rho_s \pi r_i^2)L^4}} \qquad (2)$$

where r_i is the inner radius of the tubing, r_o is the outer radius of the tubing, ρ_t is the density of the tubing material, and ρ_s is the density of the sample inside the tubing. If we know the tubing's dimensions, density, and Young's modulus, we can use eq 2 to predict the frequency of the mbira sensor when filled with a sample of a density ρ_s. And even without any information about the tubing, we can approximate eq 2 as

$$f \approx a\rho_s + b \qquad (3)$$

where a and b are calibration constants for a particular mbira sensor. By measuring an mbira sensor's frequency f when filled with two or more samples of different known densities ρ_s and plotting f vs ρ_s, we can obtain a and b for the mbira sensor from the slope and Y-intercept of the plot. Then, by filling the mbira sensor with a sample of unknown density, measuring the sensor's frequency, and solving eq 3, we can determine the density of the sample. Figure 1A shows two mbira density sensors, one made from a commercial musical instrument (middle) and one made from scrap lumber and hardware from the author's garage (right).

Why is measuring sample density a worthwhile first application for a musical instrument sensor? Density provides valuable insights into the physical, chemical, and biological state of a sample. For example, brewers routinely measure the density of fermenting beverages to determine the sugar or alcohol content, marine biologists measure the density of seawater to determine the salt content, and physicians measure the density of urine to diagnose a range of kidney conditions. Although several tools exist for accurately measuring the density of a substance, these tools are precision instruments that require great skill to fabricate, calibrate, and use.[5] For example, hydrometers are glass floats that are placed into the liquid to be measured; the hydrometer sinks or floats to a height that is proportional to the density of the surrounding fluid. Hydrometers can make very precise measurements of fluid density, but they require glassblowing for fabrication, laborious calibration, relatively large volumes of sample (hundreds of milliliters), and great care in their use and storage. Similarly, pycnometers are glass vessels with precisely known volumes; by filling a pycnometer with a fluid and measuring its mass, the density of the fluid can be determined. Pycnometers are also very precise tools for density measurement, but they share the same disadvantages as hydrometers (and also require the use of a costly and sensitive analytical balance). Refractometers can measure a liquid's index of refraction, which is often proportional to the liquid's density. Refractometers require less sample than hydrometers or pycnometers, but they are only usable with transparent liquids, and since the precise relationship between refractive index and density varies for different substances, refractometers cannot be used to directly measure density without prior knowledge of the chemical composition of the sample. Finally, vibrating tube

DOI: 10.1021/acsomega.8b01673
ACS Omega 2018, 3, 11026−11032

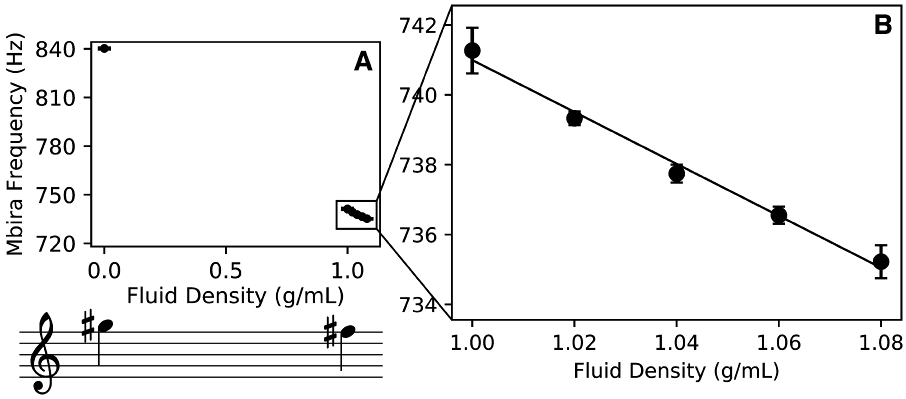


Figure 2. Plot of mbira sensor frequency vs density of tubing contents: (A) shows that air and water can be easily distinguished by listening to the pitch of the sensor; in musical notation, the notes form a major second interval. Zooming in on the water measurements, (B) reveals a series of sodium chloride solutions of different densities; their frequencies are too similar to be distinguished by ear but are easily distinguished using our mbira recording analysis website. Error bars are ±1 standard deviation.

densimeters developed in the 1960s use a continuously oscillating quartz tube and an electronic readout to measure sample density;[6] these sensors are convenient but cost thousands of dollars. In contrast, the mbira sensor can be made and used by virtually anyone using scrap materials, requires only a small volume of sample (~250 μL), requires no calibration to distinguish two samples, and measures true density.

2. RESULTS AND DISCUSSION

2.1. Distinguishing Samples by Ear Using Mbira Sensors. To distinguish samples with large differences in density using an mbira sensor, one can simply hear the different pitches of the mbira when it is filled with different samples. For example, Figure 2A shows the pitch of a 50 mm long mbira sensor when filled with air (density = 0 g/mL) and water (density = 1.00 g/mL), presented using both a scatter plot and musical notation. When filled with air, the mbira sensor has a pitch that is close to the $G^{\#}$ two octaves above middle C on the piano ($G_5^{\#}$; 830.61 Hz). When filled with water, the sensor pitch drops to the $F^{\#}$ two octaves above middle C ($F_5^{\#}$; 739.99 Hz). This frequency difference corresponds to a major second interval and is easily distinguished by ear.

2.2. Measuring Sample Density Using Mbira Sensors. To actually measure the density of a sample (or to distinguish two samples with similar densities) using the mbira sensor, listening to the sensor is not enough: we need a way to precisely measure the musical pitch or frequency of the sensor when filled with the sample. Various tools exist for measuring the frequency of a musical note, but we cannot assume that a potential user of an mbira sensor would have access to these tools. However, we can increasingly assume that potential users have access to smartphones. As of 2018, there are 5.2 billion active smartphones in the world;[7] this means that nearly 70% of the world's population has smartphones. To enable any user with an mbira sensor and a smartphone to make precision density measurements, we created a freely available online tool that analyzes sound recordings of mbira sensors. To use the tool, the smartphone's microphone and built-in sound recording app are used to record the sound of an mbira sensor being plucked several times. The user then visits http://mbira.groverlab.org in the smartphone's web browser and uploads their mbira sensor sound recording. Our software then identifies the "pings" in the uploaded file, locates the part of each ping that contains a pure frequency without overtones (shown in Figure 1C), and performs a Fourier transform on this section of each ping to determine the frequency of the mbira sensor's notes (details in Methods). The average frequency, uncertainty of the frequency, and other information about the recording are then returned to the user. This online tool was used to analyze the mbira sensor measurements in this work.

To demonstrate precision density measurement using the mbira sensor, we prepared sodium chloride solutions of known densities (1.00−1.08 g/mL), loaded each solution into one of our sensors, recorded 15 pings for each solution using a smartphone, and used our analysis website to measure the frequency of each ping. Figure 2B plots the average mbira frequency for each fluid density measurement. By fitting the results to a line and using eq 3, we obtain a slope a = 74.30 Hz/(g/mL), which can be used as a calibration constant when measuring unknown fluid densities using this mbira sensor.

In another experiment, we used a smartphone to record 100 pings of an air-filled mbira sensor. A histogram of the frequencies of these pings (Supporting Information Figure 1) has an average frequency of 840.8 Hz, with a standard deviation of 0.44 Hz. This corresponds to a sample density resolution of 0.012 g/mL for this mbira sensor (obtained using eq 3 and a 95% confidence interval for the frequency measurement).

2.3. Exploring Optimal Mbira Sensor Length. Mbiras intended for use as musical instruments use tines of different lengths to create notes of different pitches. For example, the mbira on the left in Figure 1A has 10 tines of lengths ranging from 38 to 57 mm that produce notes ranging from C_3 to E_4, a span of more than one octave. The tine's pitch is extremely sensitive to its length L: eq 1 predicts a tine's frequency varies as $\sqrt{1/L^4}$ or $1/L^2$, meaning that doubling the length of a tine decreases its frequency by a factor of 4 (a decrease of two octaves).

To explore the effect of tubing length on the function of our mbira sensors, we varied the tubing length of an mbira sensor from 50 to 100 mm and used smartphone recordings and our analysis website to measure the frequency of the sensor at each length. Figure 3 confirms that doubling the length of the tubing decreases the frequency by a factor of 4, as predicted by eq 1 (gray curve in Figure 3). This relationship enables us to easily

DOI: 10.1021/acsomega.8b01673
ACS Omega 2018, 3, 11026−11032

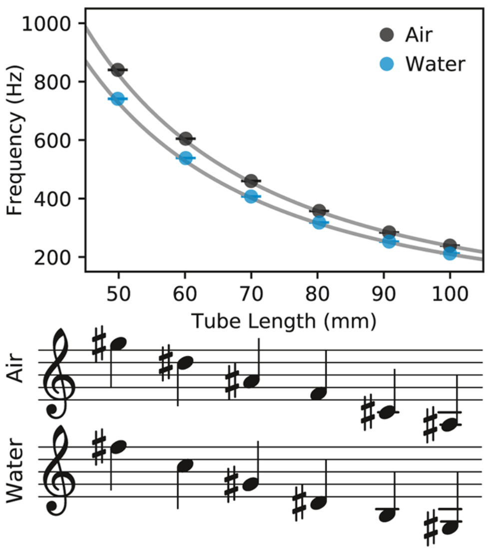


Figure 3. Frequency of an mbira sensor containing air (black points) and water (blue points) while varying the tubing length from 50 to 100 mm, represented as both a conventional plot (top) and musical notation (bottom). As predicted by eq 1 (gray lines), doubling the tubing length decreases the sensor's frequency by a factor of 4 or a decrease of two octaves in musical notation. Additionally, the difference in frequency between air and water increases as tube length decreases, indicating that shorter mbira sensors are more sensitive density sensors. Error bars are ±1 standard deviation.

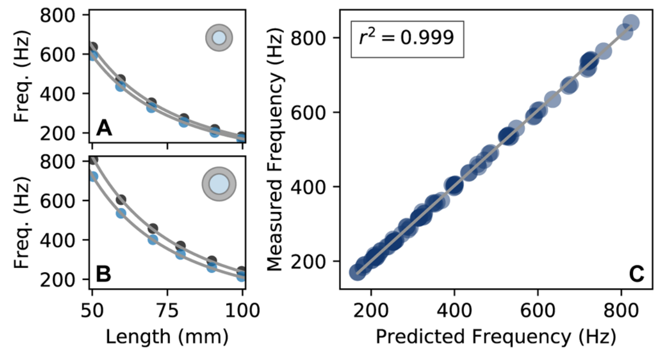


Figure 4. (A) Mbira sensor frequency vs tubing length for a sensor built using stainless steel tubing with an inner radius r_i = 0.90 mm and an outer radius r_o = 1.21 mm, when filled with air (back points) and water (blue points). (B) Repeating the experiments in (A) using tubing with r_i = 1.27 mm and r_o = 1.53 mm (see cross-sectional scale models for comparison). The larger ratio r_i/r_o in (B) means more of the mbira sensor's mass is filled with sample, which results in a more sensitive sensor (a larger separation between the air and water measurements in (B)). (C) Correlation between mbira sensor frequencies predicted by eq 2 and the experimentally measured frequencies for all 90 mbira sensor experiments in this study. In each case, eq 2 successfully predicted the frequency of the mbira sensors.

create mbira sensors that operate in a desired frequency range. Additionally, we observed that the difference between frequencies of air- and water-filled mbira sensors is greatest in sensors with shorter tubing. Therefore, for maximum density sensitivity, the length of the mbira sensor should be kept as short as possible. In practice, we found mbira sensors shorter than 50 mm to be relatively inflexible and difficult to pluck by hand so we established 50 mm as a practical lower limit on mbira sensor length.

2.4. Exploring Optimal Tubing Cross-Sectional Dimensions. The tubing we use in our mbira sensors is available in virtually any desired cross-sectional dimensions (usually expressed as inner diameter and outer diameter, or inner radius r_i and outer radius r_o in eq 2). We hypothesized that using tubing with a larger ratio r_i/r_o will improve the sensitivity of our mbira sensors because more of the vibrating mass will be sample (not tubing material). In other words, keeping the tubing wall as thin as possible should maximize the effect of sample density on the mass (and frequency) of the tubing.

To test this hypothesis, we built mbira sensors using tubing with various values for inner radius r_i and outer radius r_o and measured the frequencies of these sensors when filled with air and water. Figure 4A,B compares representative results from two sensors with different cross-sectional dimensions. The tubing in Figure 4A has r_i = 0.90 mm and r_o = 1.21 mm for a ratio r_i/r_o = 0.74, and the tubing in Figure 4B has r_i = 1.27 mm and r_o = 1.53 mm for a ratio r_i/r_o = 0.83 (similar results from additional tubing dimensions are provided in the Supporting Information). Since the tubing in Figure 4B has the larger ratio r_i/r_o, we predict it will be more sensitive to sample density differences, and our measurements support this prediction: the larger difference in measured frequencies between the air and water measurements in Figure 4B confirms that this sensor is more sensitive to sample density differences than the sensor in Figure 4A. These and other measurements confirm our hypothesis that for maximum sensitivity, mbira sensors should be built using tubing with r_i/r_o as large as possible (i.e., tubing with a thin wall).

2.5. Validating Our Model for Mbira Sensors. The gray curves in Figures 3 and 4A,B are predictions made using eq 2; they agree well with the experimental data shown in those figures. To demonstrate that eq 2 applies to a wide variety of different mbira sensor experiments (not just the ones shown in these figures), we used eq 2 to predict the frequency of all 90 mbira sensor experiments we performed in this study. These experiments include six different tubing lengths, six different sample densities, and three different tubing cross-sectional dimensions. Figure 4C confirms a very close agreement between predicted and measured frequencies.

2.6. Detecting Counterfeit Medications Using Mbira Sensors. The World Health Organization estimates that 10% of all medicines in low- and middle-income countries are counterfeit.[8] These counterfeit drugs not only waste tens of billions of dollars each year, but they also endanger health, prolong illness, promote the spread of drug-resistant pathogens, undermine public confidence in healthcare, and fund criminal syndicates.[8] There is an urgent unmet need for simple tools that healthcare professionals and consumers can use to distinguish counterfeit drugs from authentic ones.[9]

If two drugs have different densities, they must have different ingredients. We can use this fact to identify a counterfeit drug by comparing its density to the density of a known authentic sample of the drug. Interestingly, when using an mbira sensor to perform this analysis, it is unnecessary to calibrate the sensor. One need only compare the frequencies of an mbira sensor when filled with the samples of suspect and authentic drugs; if the frequencies differ by a statistically significant amount, then the suspect drug is known to be chemically different from the authentic drug.

To use an mbira sensor to distinguish authentic and counterfeit versions of a particular drug, we assume that the

DOI: 10.1021/acsomega.8b01673
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density of the authentic drug remains constant over time (in other words, samples of the drug manufactured on different dates have the same density). To confirm this, we used mbira sensors to measure the density of six samples of a known authentic drug with different lot numbers and expiration dates. We used NyQuil Severe Cold and Flu medicine (a liquid medication containing acetaminophen, phenylephrine, doxylamine succinate, dextromethorphan, and glycerol) with expiration dates (and, presumably, manufacture dates) spanning a four-month period (see Table 1). The measured frequencies of our mbira sensor when filled with these six drugs never differed by more than 0.187 Hz (a 0.025% difference); this difference is not statistically significant and supports the claim that all six samples of the medication are identical (Figure 5, left). If a drug claiming to be NyQuil Severe Cold and Flu medicine was measured with this mbira sensor and found to have a frequency other than 735 Hz, this would be strong evidence that the drug is counterfeit or otherwise adulterated. We believe that any consumer with an mbira sensor, a smartphone, and a known authentic sample of a drug can use this procedure to test the authenticity of a suspect sample of the drug.

Table 1. NyQuil Severe Cold and Flu Samples Used in Figure 5

	lot	expiration date	mbira frequency (Hz)
1	7299171931	September 2019	735.205
2	7298171931	September 2019	735.353
3	7275171941	August 2019	735.385
4	7235171931	July 2019	735.287
5	7334171932	October 2019	735.309
6	727717193U	September 2019	735.197

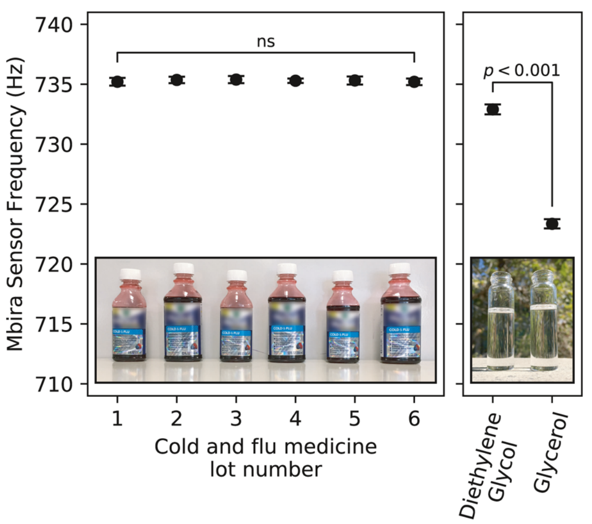

Figure 5. Using the frequency of an uncalibrated mbira sensor to determine the authenticity of medicines and identify toxic pharmaceutical ingredients. The frequency of an mbira sensor does not significantly change when the sensor is filled with commercial liquid cold medicine from six different manufacturer's lots (left); this supports the claim that the medications are all identical. If a consumer measured a significantly different frequency for one of the medications, this would be definitive proof that the medication is chemically different from the others and may be counterfeit or adulterated. When the same mbira sensor is filled with toxic diethylene glycol and nontoxic glycerol (right), the resulting sensor frequencies are significantly different ($p < 0.001$) due to the slightly different densities of the substances; this confirms that an uncalibrated mbira sensor can easily distinguish two similar chemicals that are sometimes tragically mistaken for each other in drug manufacturing. Error bars are ±1 standard deviation.

2.7. Identifying Toxic Substances Using Mbira Sensors. To demonstrate that the mbira sensor can be used to identify (or rule out) a substance by its density, we used an mbira sensor to discriminate between glycerol and diethylene glycol, two very similar substances that are occasionally mistaken for each other (sometimes with deadly consequences). Glycerol, a sweet-tasting, viscous, clear liquid, has long been used as an excipient in liquid medications like cough sirup. In 1937, a chemist at the S. E. Massengill Company in Bristol, Virginia was developing a liquid form of the early antibiotic sulfanilamide; he attempted to dissolve the sulfanilamide in glycerol but found it was insoluble. He then discovered that sulfanilamide does dissolve in another sweet-tasting, viscous, clear liquid: diethylene glycol. One hundred and sixty gallons of this diethylene glycol-based "Elixir Sulfanilamide" were produced and sold across the U.S. before reports surfaced of patients who died shortly after taking the drug. A massive government recall effort limited the number of deaths caused by Elixir Sulfanilamide to about 100, and the toxicity of diethylene glycol became common knowledge.[10,11] But incredibly, this was far from the last time that diethylene glycol would be substituted for glycerol in medication. Since 1985, fatal mass poisoning caused by medicines containing diethylene glycol has been occurring somewhere in the world on an average of every 2 years, with a combined death toll in the hundreds.[12] And while many techniques exist that can easily distinguish between toxic diethylene glycol and benign glycerol (techniques like gas chromatography−mass spectrometry and infrared spectroscopy), these techniques require expensive and complex instruments, and pharmaceutical companies in developing regions do not always use these techniques to confirm the identity of the chemicals they use. A simple and low-cost method for distinguishing between glycerol and diethylene glycol could help these pharmaceutical companies confirm the safety of their products and save hundreds of lives.

The densities of toxic diethylene glycol (1.118 g/mL) and nontoxic glycerol (1.261 g/mL) differ by only about 13%, but this difference is easily detectable using an mbira sensor. Figure 5 (right) compares the measured frequencies of an mbira sensor filled with diethylene glycol and glycerol. The ∼10 Hz difference in measured frequencies is statistically significant ($p < 0.001$) and confirms that the two substances are chemically different. This demonstrates that uncalibrated mbira sensors can be used to distinguish two similar substances by their densities.

3. CONCLUSIONS

We have demonstrated that a 3000-year-old musical instrument can make a surprisingly good sensor, a sensor that can be applied to problems as diverse as identifying toxic substances and detecting counterfeit drugs. The mbira sensor is easy and inexpensive to build: in addition to the steel-based sensors shown here, we have also built functional mbira sensors out of discarded plastic pipets, lengths of flexible tubing stretched like guitar strings, and other commonplace materials. And the mbira sensor is simple and economical to use, requiring only a

DOI: 10.1021/acsomega.8b01673
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smartphone to analyze the sensor's pitch and determine the density of its contents with high precision.

In this work, we focused on using the mbira to measure sample density. However, in principle, an mbira could be used to measure any of the values in eq 2. For example, this equation suggests that mbira instruments might be even better at length measurement than density measurement: although doubling the density of the mbira tine material decreases the tine's frequency by a factor of $\sqrt{2}$ or ~1.4, doubling the length of a mbira tine decreases the tine's frequency by a factor of 4. In fact, using the uncertainty in our mbira frequency measurements of 0.44 Hz, we estimate that by measuring the frequency of a properly calibrated mbira, one could determine the length of the tine with a resolution of 24 μm, about the size of a single white blood cell. We are currently exploring the potential for mbira sensors as simple and inexpensive but precise length measurement tools in various applications.

The mbira sensor is also interesting for bridging the worlds of science and art. As a scientific instrument and a musical instrument, the mbira sensor blurs the line between measurement and music. This enables novel ways of thinking about the mbira sensor and its data, such as the musical notation shown in Figures 2 and 3. We have found that describing our work in terms of science and music makes our research accessible to a broader audience: nonscientists readily recognize the mbira instrument, see the different musical notes corresponding to different samples in the mbira, and immediately understand how the mbira sensor works. To encourage other researchers to do the same, we created a free and open-source software tool that converts frequency measurements to musical notation[13] and used this tool to create Figures 2 and 3.

Finally, it is worthwhile to note that the mbira is but one of the hundreds and hundreds of different musical instruments in the world. In principle, any musical instrument could be used as a sensor. The vibrating elements in a musical instrument seem particularly well suited for use in measuring physical properties, and since all objects have fundamental physical properties like mass, density, and length, musical instrument sensors that measure these properties should find many different applications. However, there is no reason to assume that musical instruments are limited to sensing these properties. Any physical, chemical, or biological phenomena that reproducibly alters the pitch-determining properties of a musical instrument could in principle be measured by the instrument. We hope that our work inspires a search for musical instruments (both modern and ancient) that can function as useful sensors and solve important problems.

4. METHODS

4.1. Making Mbira Sensors. In principle, any object that (a) can contain a sample inside it and (b) has the right shape and rigidity to vibrate when mounted on a board and plucked, could be used as an mbira sensor. In this work, we used ready-made inexpensive stainless steel tubing with different inner and outer diameters. The tubes were bent into a U shape and clamped at different lengths ranging from 50 to 100 mm. Bending sometimes causes this tubing to collapse at the bend (see Figure 1A, right), but as long as the path for fluid through the tubing remains unobstructed, the tubing will still function as a sensor. The bent metal tubing is then mounted to an object that serves as a sound board, which amplifies the sound of the vibrating tubing. In this work, we mounted tubing to wooden sound boxes scavenged from commercial mbira instruments (Figure 1A, center) and scrap wooden boards (Figure 1A, right).

Our results in Figure 3 indicate that shorter (and therefore higher frequency) mbira sensors are generally more sensitive than longer (lower frequency) sensors. Theoretically, with a tubing outer radius r_o = 3.05 mm and inner radius r_i = 2.54 mm, an mbira sensor with a length L of approximately 4 mm would have a frequency of approximately 20 000 Hz (the maximum audible frequency for humans); however, this is not practical because of the difficulty of manually pinging such a short sensor and recording such a low-amplitude sound using a smartphone. In practice, we found that ~50 mm long sensors had the highest sensitivity without sacrificing the ease of use of the sensors or the quality of the sound recordings.

4.2. Mbira Sensor Calibration. To measure sample density using an mbira sensor, the sensor must first be calibrated using two or more materials with known densities (note that this calibration is unnecessary when using the mbira sensor to determine whether two samples are different). We prepared sodium chloride solutions with precisely known densities by combining masses of NaCl and water, as calculated by our software tool NaCl.py.[14] A typical calibration curve is shown in Figure 2, and additional curves for mbira sensors with other tubing lengths are provided in the Supporting Information.

4.3. Analyzing Mbira Sensor Data. Analyzing sound data from musical instruments can be challenging because of the complexity of the sounds. For example, as shown in Figure 1C, the initial portion of an mbira note (the "attack") has inharmonic overtones that obscure the primary resonance frequency of the note.[4] We developed a website (http://mbira.groverlab.org) that runs a custom Python program that analyzes sound recordings of mbira sensors. After the user uploads a sound file containing recordings of several pings of an mbira sensor filled with a sample, the software first locates the high-quality portions of the audio recording. It accomplishes this using three user-specified thresholds. First, a ping entry threshold is crossed when the audio signal exceeds 50% of the maximum signal; this marks the beginning of the ping. Second, a signal threshold is crossed when the audio signal drops below 40% of the maximum signal. This marks the beginning of the portion of the signal that has a single dominant frequency (and therefore will be used for frequency analysis). Finally, a baseline threshold is crossed when the audio signal drops below 1% of the maximum signal. This marks the end of the ping and the end of the portion of the signal to be analyzed. The reported values for these thresholds were used for all of the mbira sensor data analyzed in this work; however, if necessary these thresholds can be modified by the user on our analysis website. Once the portion of each ping to be analyzed is identified using these thresholds, the software applies a Hanning window to the signal to reduce spectral leakage, then performs a fast Fourier transform to determine the frequency of the ping. This process is repeated for each ping in a recording, and the website finally provides the user with the average ping frequency, plots of each ping, and other statistics.

4.4. Measuring Pharmaceuticals and Drug Ingredients with Mbira Sensors. Six bottles of liquid cold medicine (NyQuil Severe Cold and Flu, Procter & Gamble, Cincinnati, OH) with different lot numbers and expiration dates were obtained from pharmacies in Riverside, California. A sample from each bottle was loaded into an mbira sensor

DOI: 10.1021/acsomega.8b01673
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using a syringe. For each sample, a volume approximately 3 times the volume of the tubing was flushed through the tubing to ensure complete removal of water used to rinse the sensor between samples. The tubing was plucked 15 times for each sample and recorded using a Samsung S6 smartphone. Diethylene glycol and glycerol samples (Sigma-Aldrich, St. Louis, MO) were also measured in this manner, with additional rinsing between samples using water and air.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsomega.8b01673.

> Distribution of frequency measurements for 100 pings of an air-filled mbira sensor made with 50 mm long tubing (Figure S1); additional calibration data from measuring known fluid densities using mbira sensors with varying lengths of tubing (Figure S2); frequencies of mbira sensors made using three different steel tubes when filled with air and water (Figure S3) (PDF)

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The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

The authors thank Dr B. Hyle Park and Reed E. S. Harrison for helpful discussions. This work was supported by the National Science Foundation under award DBI-1353974 and the Bill and Melinda Gates Foundation's Grand Challenges Explorations program under award OPP1191214.

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DOI: 10.1021/acsomega.8b01673
ACS Omega 2018, 3, 11026−11032