Pillavate

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Abstract

Congestive heart failure is a chronic condition where the heart muscles are unable to effectively pump blood [1][2]. When this occurs, blood and fluid can build up in the lungs, which affects the person's ability to breathe comfortably[3]. As a result, when this occurs, patients have to elevate their upper body in order to open their airways to make breathing easier. One instance in which this can significantly affect people is during their sleep [4][5][6]. Since most people sleep horizontally, the typical sleeper's upper body is not elevated at an angle. This is not an option for people with CHF since it would cause severe discomfort and can be very dangerous to the patient's health [7]. As a result, patients must sleep with their heads and shoulders elevated compared to the rest of their bodies. In this project, we propose an affordable portable device that patients can attach their pillows to, which goes under the patient's head and shoulders. Our product, Pillavate, provides patients with a solution that they do not have to adjust manually, making it the first of its kind. The device uses a Pulse Oximeter to detect a change in the patient's heart rate, and when identified, it signals a linear actuator to go up or down. As the patient's heart rate goes up, the linear actuator is signaled to also go up, increasing the angle of the patient's head and shoulders. Once the patient's heart rate settles again, the system returns to its neutral state. The suggested concept was developed using plywood, a linear actuator, an Arduino, and a multitude of various sensors, which were put together to make up our first prototype. Field tests with different people and environments confirmed the expected operation. The proposed device could prove to be a transportable, affordable, and adjustable assistive device for patients suffering from congestive heart failure. Allowing them to have a restful night without them needing to awaken to adjust their head angle manually.

1 Introduction

Heart failure remains a highly prevalent disorder worldwide with a high morbidity and mortality rate. It has an estimated prevalence of 26 million people worldwide and contributes to increased healthcare costs worldwide [8]. Congestive heart failure (CHF) is a condition that affects people of all ages, from children and young adults to the middle-aged and the elderly [9].

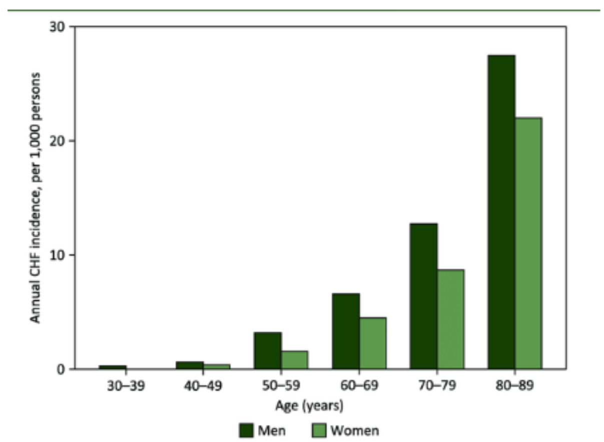

Figure 1- CHF Rates [10]

As can be seen in the graphic above, 5 million people in the US suffer from this condition, and the cases keep increasing. As per projections, more than 8 million people could be suffering from congestive heart failure by 2030. The most common problem for patients with this CHF is a condition called orthopnea, which causes difficulty breathing while lying down. From a study consisting of 173 people suffering from Congestive heart failure, it is found that people with Congestive heart failure report insomnia symptoms, including difficulty maintaining sleep (34 to 43 percent of sampled patients), falling asleep (23 to 47 percent), and waking too early in the morning (35 to 39 percent). After speaking to Neeha Gambhirrao, who is currently pursuing her MD and works around patients with CHF, it became clear that it is very important that these patients sleep with their heads and shoulders elevated. This is because an elevation of the head and shoulders can help open the patient's airway, which makes it significantly easier for patients to breathe. Currently, a limited number of solutions exist for patients with orthopnea. The two main products consist of adjustable bed frames and adjustable recliners. An example of an adjustable bed can be seen below;

Figure 2 - Competitive Example

There are also some invasive products; however, these are typically meant for patients with sleep apnea and not those with orthopnea. Additionally, patients typically favor noninvasive aid. Both of the physical systems available effectively raise the head, neck, and shoulders of the patients, and the patient can adjust the angle of the upper portions as needed to incline themselves [11][12]. However, both options are also very limiting. Adjustable beds and chairs cost hundreds of dollars. Additionally, both choices really anchor the patient to one location, as it takes quite a bit of effort to move a heavy bed frame or recliner. Finally, both systems rely on manual adjustments meaning the patient has to wake up if they need more of an incline. As a result of the cons, many patients opt for stacking pillows which means picking a correct angle becomes a guessing game, and patients have to readjust throughout the night. By making the angle a guessing game, there are many risks, as too low of an angle does not effectively open the patient's airway, and according to the National Library of medicine, too high of an angle can significantly increase the average and peak pressures of the cranial and cervical regions. Additionally, pillows can compress or fall over during the night, making them ineffective at supporting the patient's head, neck, and shoulders. This is where Pillavate offers a new solution that patients can transport from one place to another without too much difficulty and that is able to adjust in angle based on the patient's breathing patterns which means the patient does not have to wake up in order to elevate their head. Additionally, Pillavate is much more affordable than the current options.

2 Proposed Solution

2.1 Design Requirements

At the start of the project, our team narrowed down our design requirements to four critical points that we considered essential to the functionality of our product, as shown in Table 1;

TABLE 1: Design Requirements

Critical Variables	Target Values
Elevation Angle	15 - 55 degrees
Actuation Noise	< 40 dB
Affordability	< $200
Transportability	< 25 lbs

Our first requirement is that our product has to meet the angle requirements for the resting and raised head elevations. This is essential to ensure that our product actually helps people. For patients with orthopnea, the angle of the resting state differs from someone without their condition, as their "resting head elevation" already has to be slightly raised. Based on our research, the resting state ranges from 15-30 degrees, and for the raised state, it is 40-55 degrees. Ensuring that our device effectively reaches these angles was critical as this was our main true test of Pillavate's effectiveness since we are not working directly with patients. Our second design requirement is that it is essential that our product does not make a lot of noise so that it does not disturb a patient in their sleep. Our goal was for the device to make approximately the same amount of noise as a common fan maxing out at around 40-70 decibels. In order to be available to all patients, our goal was also to keep the cost lower than 200 dollars, which is half of any available products. Finally, in order to ensure that our system is transportable, we have set the expectation that any of us should be able to transport and set up our system by ourselves.Throughout the creation of our product, we heavily focused on our design requirements, and as a result, we successfully accomplished all four points.

2.2 Proposed Design

Based on our design requirements and the existing solutions, our team developed our proposed design. The system was designed around sensing and actuation. Our proposed solution consisted of a system that can be placed under the patient's head and shoulders and can elevate and lower the patient based on the desired sensing heuristics. Several sensing options were investigated for detecting breathing patterns and heart rate, including, but not limited to: heart rate sensors, blood oxygen saturation sensors, a respiratory sensing strap, and a microphone to detect snoring or wheezing. Although existing devices can measure snoring/breathing, extracting data from these devices is quite difficult [13]. The team pursued two different approaches to detecting the onset of congestive heart failure. A SpO2 sensor and Microphone. Due to other sources of heart rate variability during normal resting patterns, the team decided that filtering out the signal from the noise would be illogical for this application. The complexity of creating a Respiratory sensing strap using a strain gauge has similar drawbacks, filtering out the noise [14]. A system similar to existing wearable technologies was selected to ensure only user data was sensed. A pulse oximeter was worn either as a ring or around the wrist [15]. Existing patient data with congestive heart failure allowed the team to simulate our target scenarios where patients needed additional elevation [16]. With the sensing modalities selected, the team focused attention on the actuation system [17]. Similar to the sensor selection, many systems were considered, such as an inflatable pneumatic system and an electrical motor. However, the pneumatic system would not meet our noise constraints, while the electrical motor would challenge the weight and cost constraints. Therefore, the team selected a simple linear actuator to elevate our system. The speed limitations, lower voltage requirements, limit switches, and other safety features made this the easy choice. After selecting our methods of sensing and actuating, our team was able to develop our proposed workflow, which can be seen below;

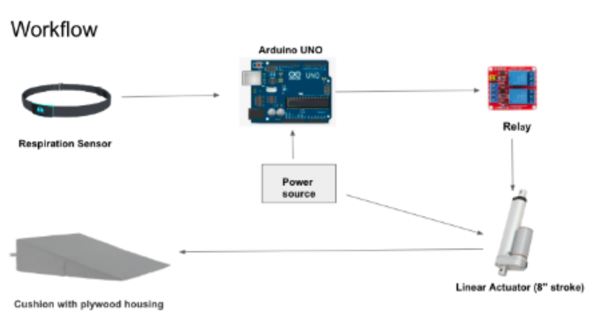

Figure 3 - Workflow

The workflow consists of our sensor connected to an Arduino UNO board serving as the input of our system. The Arduino board is connected to both a relay and our power source. Within our proposed design, this power source consisted of a battery. However, we ended up using a power supply that we plugged into the wall due to some power issues with the initial materials. The relay and power supply are also both connected to our actuator. Finally, we planned to house all of our components in a triangular plywood housing. Overall our final product very closely represents our proposed design.

3 Implementation

3.1 Final Model

The final design is very similar to the initial design presented in the proposed solution and can be seen below;

Figure 4 - Final Design

It uses a base of plywood cove covered in a bedsheet that hides and safely houses the linear actuator, external DC power supply, motor controller, and logic controller which can be seen below. When the linear actuator is activated by our sensor, the actuator extends increasing the angle of our system as the user needs additional elevation. The images below show this difference in angle with the system on the left showing the resting state, and the system on the right showing the elevated state.

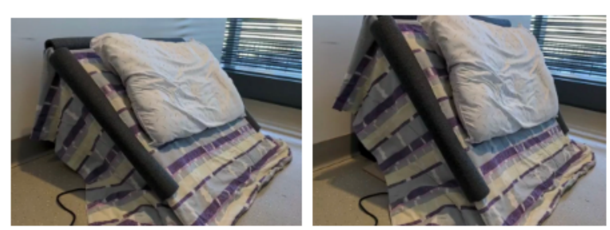

Figure 5 - System Elevations

When looking at our design requirements, our team successfully accomplished all of our goals. Our system is able to alternate between the two critical angles as needed by the user. Additionally, our system is very quiet and would likely not be audible when actuating over the person breathing especially when they are struggling to do so. Pillavate is also much cheaper than any of its market competitors with the total cost coming in at around 118 dollars making it even cheaper than we expected. Finally, each of us was able to pick up and set up our system to meet our transportability requirements. This preliminary design can certainly be improved upon in future iterations, methods of which will be discussed in a future section however overall we were able to accomplish everything we set out to do.

3.2 Simulation of Final Model

The 3D model, shown in Figure 5, below provides a view of the design once all components have been assembled. The actual base and pillow base dimensions were chosen based on the linear actuator length and the minimum and maximum angles we wanted to maintain. It is placed at the extreme end of the plywood to provide comfortable lifting and ensure that it is not placed exactly under the patient's head. It also produces good torque with minimum effort. The other components like the Arduino, H-bridge and the battery can be housed on the actual base just beside the actuator.

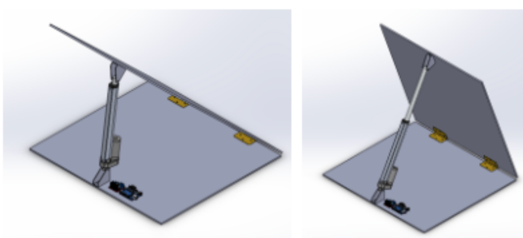

Figure 6: CAD

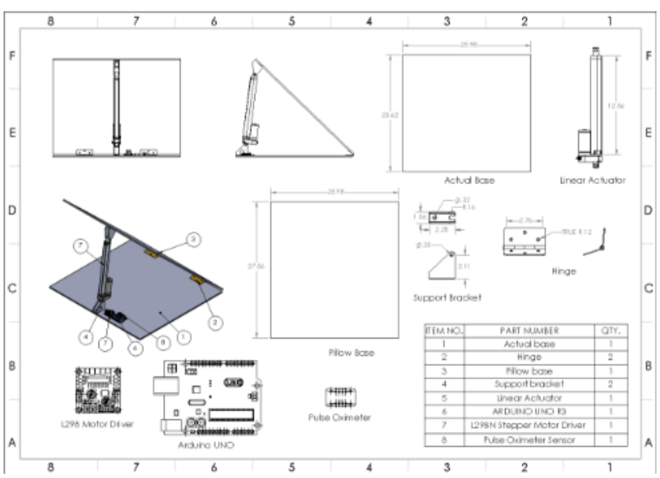

Figure 7: CAD Drawing

3.3 Software

The prototype was simulated in an Arduino Uno microcontroller environment using 6 pulse width modulation digital output pins and 8 analog input pins to connect the pulse oximeter sensor to detect the ranges and a 12V DC power to drive the linear actuator [18]. Pre-processing of RAW data: After including the libraries required for communication and data processing , working mode is selected .MAX301002 has 2 modes [19].The first one uses only IR light .This mode is sufficient if we are only measuring heart rate .To measure both the heart rate and the blood oxygen level, the second mode is selected . A DC filter is implemented to remove the DC offset and to stabilize the oscillations that are found in the IR value graph .To further smoothen the signal to reduce the high level harmonies, the signal is passed through a low pass filter. Calculation of heart rate and blood oxygen level: Beats per minute is calculated by taking the difference between the timestamps of the pulses and using the standard formula shown in Figure 7 . Blood oxygen percentage is calculated by taking the ratio of red and IR light wavelengths as shown in Figure 8 and using the required formula shown in Figure 9 .The resultant heart rate and SpO2 levels are displayed on the serial plotter. Actuation: Using the heart rate and SpO2 values, conditions for actuation are checked .Failsafe methods are employed such as making the linear actuator stay still in case the BPM and SpO2 percentage are above or below the ideal range of values when resting (55<BPM<100) and (88<SpO2<100).The optimal range for resting heart rate and blood oxygen level is 50-70 bpm and 88-93 SpO2 percent .As the heart rate increases from 70-100 bpm or if the blood oxygen level drops below 93 percent,the linear actuator rises for 8 seconds . The sensor values are checked again to see if they are in the optimal level. Linear actuator goes down if favorable levels are reached .Otherwise, it rises again and the process is iterated . The process is explained in a concise manner using the flowchart shown in Figure 10.

$$BPM = \frac{60000}{\text{current beat timestamp} - \text{previous beat timestamp}}$$

Figure 8: Formula Used for Beats per Minute

$$R = \frac{AC_{\text{RMS RED}}/DC_{\text{RED}}}{AC_{\text{RMS IR}}/DC_{\text{IR}}}$$

Figure 9: Ratio of Red and IR Wavelengths

$$SpO_2 = 110 - 25 * R$$

Figure 10: SpO2 Formula

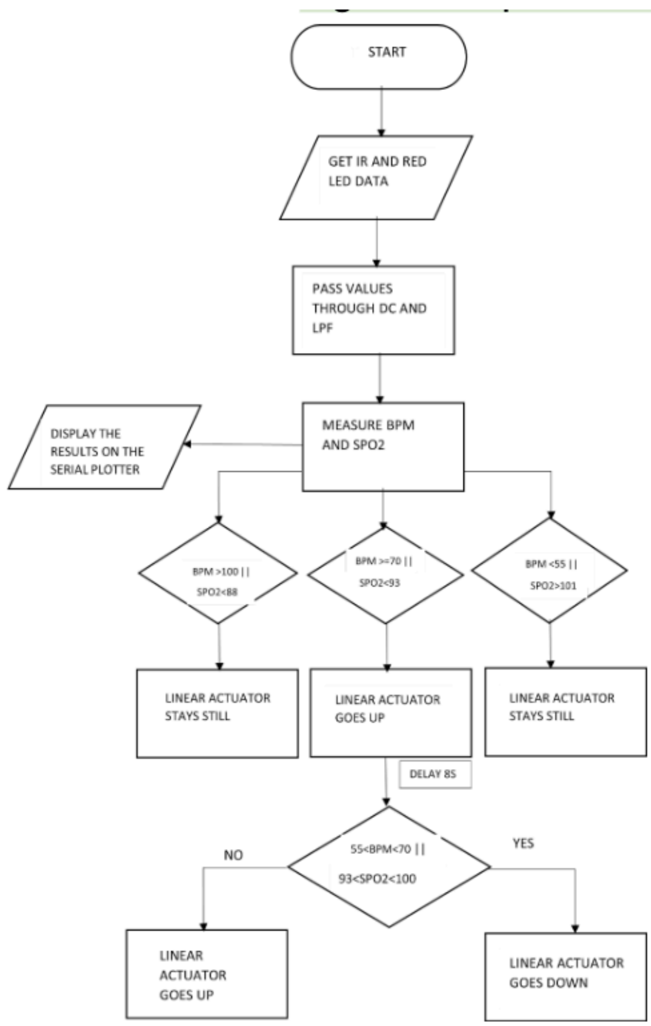

Figure 11: Software Flowchart

3.4 Prototype Bill of Materials

The brain of Pillavate is an Arduino microcontroller that receives information from the sensors and outputs commands to the motor controller. The motor controller, in turn, commands the 8"-stroke linear actuator to raise or lower the wedge-shaped plywood-based platform with an attached pillow. The linear actuator that we selected travels at 0.39 inches/sec, which is fast enough to reach the necessary angles as needed but also relaxed enough to permit continued sleep while the system is operating. The actuator is made of a high-quality aluminum alloy material that is sturdy enough to withstand the torso of the individual and has a built-in high-quality limit switch. The biometric sensor that we selected can be integrated into a wearable device for heart rate and blood oxygen collection and can be worn on fingers, ear lobes, wrists, and other places. This flexibility enables unrestrictive integration for the devices and easy access for the data. The MAX30102 heart rate sensor and pulse oximeter was chosen because it has lower power consumption (3.3V, 600 microamperes), an I2C interface for communication, and a FIFO buffer for holding and sampling 16 different readings. This sensor generally comprises of two LEDs that generate light, one in the red spectrum (650nm) and the other in the infrared spectrum (950nm). The sensor is positioned on your finger or earlobe, where the skin is thin enough to allow both light frequencies to readily pass through the tissue. For instance, after shining both of them through your finger, a photodiode is used to quantify the amount of absorption. Additionally, the ratio of absorbed red light to IR led will vary based on the amount of oxygen in your blood. The full prototype bill of materials is shown in Table 2 below.

Table 2: Prototype BOM

Component	**Quantity**	**Cost**
Elegoo Arduino Uno	1	17.99
Motor controller Driver	1	11.49
Linear actuator(12V DC)	1	33.95
Heart rate sensor breakout board	1	6.99
Heart rate sensor module	2	12.99
Hinges	3	6.67
Plywood	1	28.50
Total		**118.58**

The total cost of our system was 118.58 dollars making it significantly less expensive than any of the system's competitors. Additionally, this total is well below the 200-dollar limit that we set for ourselves as a part of our design requirements. The cost of our product was split over a couple of different materials however the most expensive component was our linear actuator. The above costs also include excess hinges and plywood so the cost per unit is even lower.

4 Testing

To prove that our system effectively raises and lowers the user as needed, our team completed various tests. We started by seeing if the sensor could detect changes in heart rate as a team member held their breath while touching it. The images below show two outputs from the Arduino Serial Monitor of some of these tests. As defined within the Software section, based on the software logic, the orange line shows the user's heart rate, and the blue line captures information regarding their SpO2 levels.

Within the first test, our team member held their breath for a while and then quickly released it, this caused their heart rate to rapidly increase beyond the defined safe resting heart rate threshold, resulting in the system's actuation to raise the pillow. The figure below shows when this increase in heart rate occurred:

Figure 12: Testing Results

We also verified that our system was able to identify when it should actuate when someone's heart rate increased at a more gradual rate. The figure below shows the graph that resulted from this test and our system successfully actuated once the user's heart rate had passed our defined threshold. Once we had proven that our sensing system was working we were able to move to tests with our fully integrated system.

Figure 13: Testing Results

Although many tests were performed on this system throughout the product iteration and improvement lifetime, the two following experiments proved our system's efficacy. In the first test, the user laid on the pillow in its resting state, breathing normally. The user then proceeded to hold their breath and then started gasping, which caused their heart rate to climb. The sensor detected the change beyond the defined threshold and began to raise the pillow. When the user caught their breath, their heart rate returned to a nominal sleeping level, signaling the system to lower the pillow back down for comfort. For our second test, we wanted to apply the system to someone with congestive heart failure since this product was designed to help users with CHF sleep. Although no members of this team have congestive heart failure, we were able to test our system for our target audience by feeding in a data stream that matches what could be expected from a patient with congestive heart failure. Because our system focuses on heuristics, the system works with any imported data, and succeeded in our goal of raising the sleeping angle of the user when needed. Both tests generated similar results as the pillow was raised as needed and then lowered when the heart rates returned to normal. The figures below show one of our teammates testing the system;

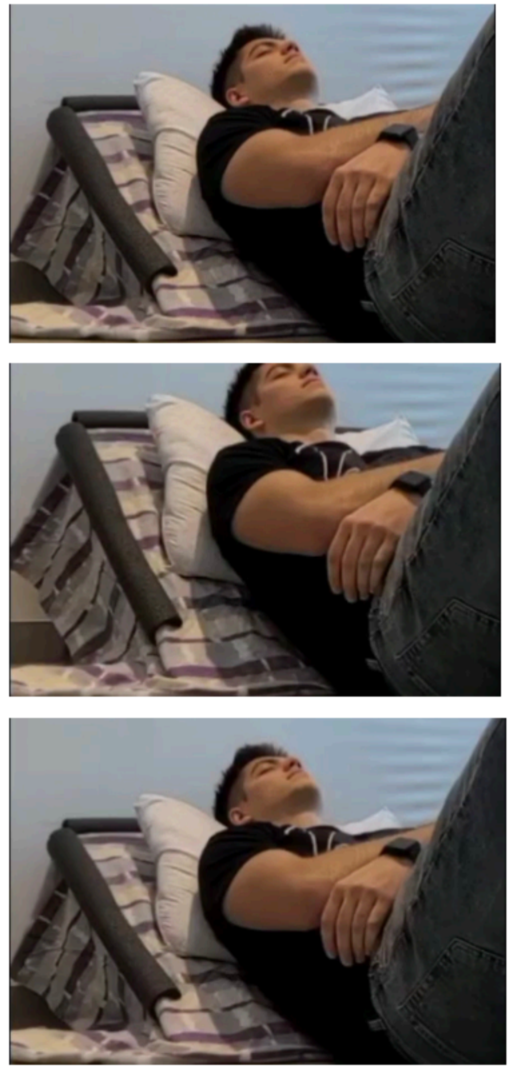

Figure 14: Testing

The top image shows the system's initial resting state. The second image shows the system at its maximum incline, indicating that the user's heart rate increased beyond our identified threshold and continued to be elevated. The final image shows the system when the user's heart rate has returned to normal, causing our system to return back to its resting state.

5 Discussion

5.1 Maintaining the Original Comfort of the Pillow

The pillow is designed to retain the comfort of sleeping on a pillow normally and not cause any disturbances during the sleep cycle due to discomfort. The device has foam around it to provide additional cushioning and a velcro strap provided to prevent the pillow from moving while sleeping. Also, it supports the shoulders too to prevent any type of neck injuries in long-term use. It gives the same feel as sleeping on a stack of pillows without worrying about how high or how low the stack needs to be.

5.2 Inexpensive

The existing solutions which are automated are large and expensive (over 200 dollars). They cannot be carried everywhere as per comfort and convenience. The other solutions, which are inexpensive compared to these, have to be manually operated and need to be adjusted throughout the night to guarantee easier breathing during sleeping. The whole idea of having this pillow is to have an uninterrupted sleep while being portable for the patient to carry with them while traveling. Our pillow ensures that and is much cheaper than the existing automatic lifting chairs or beds. Anyone with a breathing problem can easily access it without worrying much about the cost.

5.3 Adaptable to User

Since the pillow takes real-time readings to acquire the pulse rate to estimate the angle by which the pillow should be raised, it is very flexible to use as per the user's requirements. The threshold limits for the pulse rate and blood oxygen calculation can be set as per the requirements for the prospective

5.4 Future Developments

The final product can be worked upon for serving its extended potential in the future which enables users to fully utilize the functionality and remotely access it to get the intended data for treatment purposes. This can be done by integrating an app in the smartphone or smartwatch which enhances data collection and usage across devices and makes up for a hassle-free experience with added functionality for manually operating through the device if the user intends to. The prototype can be interfaced with doctor's devices through IoT for real-time alerts which would help the doctor to keep track of the patients' data when the values or parameters exceed the required threshold. On top of that, we could incorporate artificial intelligence to detect the average resting heart rate and snoring pattern of the patient to get more accurate sensing data and a more reliable operation of the elevation pattern. For future developments, we could use voice activation or voice recognition for a more seamless experience of the product.

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