Development of a Cost-Effective Smart Wearable ECG Watch for Enhanced Cardiovascular Health Monitoring

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Abstract. Electrocardiography (ECG) is an important diagnostic device that can be used to assess the health of the heart and provide real-time recording of the electrical activity of the heart. The recent wearable technology offers continuous and non-invasive measures of ECGs in nonclinical settings. This paper will introduce the design, development and implementation of a smart wrist-worn ECG monitoring device which incorporates energy efficient hardware, signal acquisition and wireless transmission of data. The system will consist of an ECG component, microcontroller (Arduino Nano), Wi-Fi component, and OLED display, which allows real-time local visualization and remote monitoring using cloud services. The microcontroller has a 6th-order Bessel filter that reduces noise and maintains the fidelity of a waveform, thus improving the signal clarity. The device features a small and robust casing, intuitive user interface, and affordable parts, which will make it appropriate in accessible cardiac monitoring in a wide variety of locations, such as developing areas. The suggested system shows good combination in hardware design, signal processing, and connectivity, providing a low-cost, reliable, and portable system to monitor the ECG continuously, and hence, can fulfil the requirements of sustainable development goal (SDG) 3.

Keywords: Wearable ECG, Arduino Nano, Smart Watch, Bessel Filter, SDG 3.

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1 Introduction

Electrocardiography (E0CG) is one of the most important diagnostic tools in the current clinical practice, and it is employed to record and analyze the electrical activity of the heart [1]. The technological innovations during the early and mid-20th century, such as vacuum tube amplifiers, better recording devices, and portable diagnostics units, greatly increased the accuracy and practicability of ECG devices [2]. At the end of the 20th and the beginning of the 21st centuries, the combination of digital signal processing and computer-assisted interpretation expanded the use of the ECG, as it facilitated automated diagnosis and real-time cardiac monitoring [3]. The increasing cases of cardiovascular diseases have increased the need of constant and available cardiac monitoring technologies. Wearable ECG devices offer continuous and real-time monitoring of heartbeats and can send the information to medical practitioners to analyze it remotely [4]. This feature enhances early arrhythmia detection and enables customized cardiac treatment, so it makes supervision available beyond clinical settings [5]. The developments are in line with the international healthcare trends of preventive medicine and decentralized monitoring of patients.

An ECG is used to record electrical impulses of the heart through electrodes on the skin [6]. ECG signals mostly vary from 10 µV to 5 mV in amplitude and are mostly concentrated between 0.05 Hz and 35 Hz frequency [7]. The monitored waveform is a series of typical segments and intervals, as seen in Fig. 1, and each of them is related to a particular stage of cardiac electrical conduction [8]. P wave is a sign of atrial depolarization and PR interval is delay in conduction between atria and ventricles. The QRS complex is the rapid depolarization of the ventricles, then the plateau of the ST segment and then the T wave is the ventricular repolarization. U wave is occasionally seen and associated with Purkinje fiber repolarization or myocardial remnants. Other metrics like the QT and the RR also allow some information about stability in the cardiac rhythm and ventricular activities. These features are crucial in diagnosing arrhythmias, myocardial ischemia, electrolyte imbalance, and structural cardiac abnormalities and therefore they require accurate interpretation.

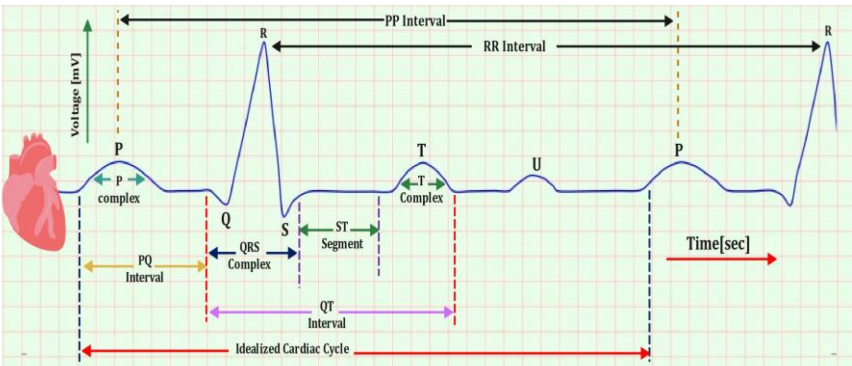


Fig. 1. Normal waveform of an ECG.

Either simulations tools or hardware components can be tested to investigate the hardware projects in the research phase. Various commercially available software tools like Proteous [9-10], Simulink [11-12] and Cadence [13-19] are widely used for software implementation. Although hardware implementation requires cost, time and stress [20], this provides the real-time investigation, as observed in the reported works [21-25] of various hardware projects. Therefore, this work focuses on hardware implementation of an ECG monitoring system for its real-time investigation.
The small wearable ECG devices have been made possible through the recent developments in low-power electronics, miniaturized sensors and wireless communication platforms. Constant observation in every-day life is particularly useful in the prevention of cardiac crisis and enhancement of long-term treatment. The old method of acquiring ECG involves clinical visits, electrodes, which are put in various parts of the body and the presence of well-trained personnel which is inconvenient to patients who need regular monitoring. In order to overcome these shortcomings, this paper will present a smart wrist-worn ECG appliance that is suitable in daily life and provides real-time cardiac signal capture and transmission. The system comprises of small electrodes that are placed in a wrist band, a signal processing microcontroller that is energy efficient, Bluetooth based communication with mobile devices and OLED display to visualize the waveforms instantly.
The main objective of the study is to develop a low-cost and user-friendly ECG monitoring system that can be used in large scale especially in the developing world where there is minimum access to medical facilities [26]. The device suggested focuses on low power usage, small hardware integration, and simplicity. By putting a finger on the wrist interface, users are able to receive the measurements, and the processed ECG data can be shown locally and can also be transmitted to a remote server to do additional analysis. The created system proves the feasibility of the cardiac monitoring to be incorporated into the daily wearable devices and assist with the constant health consciousness and remote clinical monitoring.

2 Implementation

The implementation of the proposed ECG monitoring system can be divided into three parts: i) breadboard implementation, ii) PCB design, and iii) microcontroller programming. These are briefly described as follows.

2.1 Breadboard Implementation

In the experimental set up, a breadboard is used as the main platform on which all the hardware components are integrated and tested. The breadboard allows quick prototyping, flexible routing of signals, and quick and easy adjustments without having to solder. The ECG analog front-end (AFE) circuit is a crucial part of an ECG system, processing weak electrical signals from the heart to produce a clean output for digital processing. The circuit consists of two stages: the electrode interface, where electrodes contact the skin, and the instrumentation amplifier (IA), which amplifies the signals while rejecting common-mode noise and interference [27]. The IA uses a differential amplifier configuration to amplify the difference between voltages from two electrodes while keeping the common-mode rejection ratio [28] as high as possible, ensuring the integrity of the small ECG signals. Fig. 2 demonstrates that the ECG module is connected to the power supply, microcontroller, Wi-Fi communication unit and display module. The breadboard implementation helps to record the cardiac bio-potentials and condition them using the analog front-end and digitization and then transmit them wirelessly to a remote device. Testing also enables the real-time visualization to check quality of signals and system responsiveness.

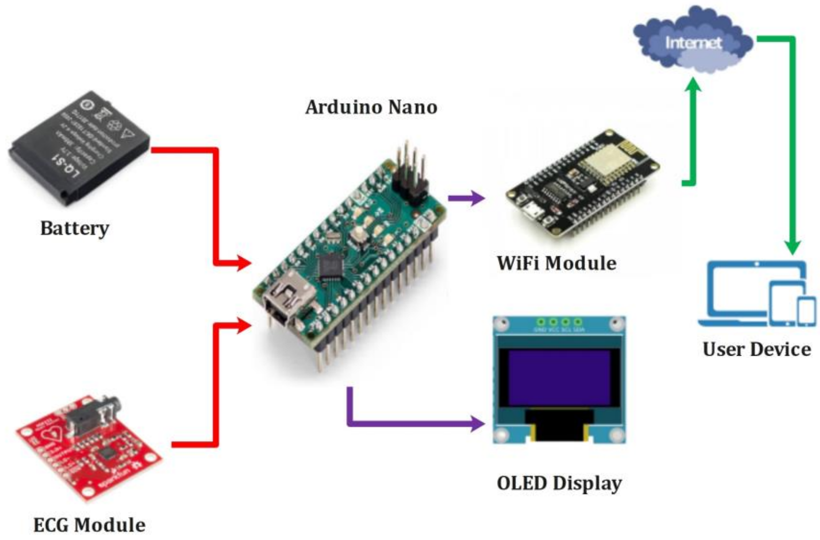


Fig. 2. An electrocardiogram (ECG) breadboard circuit diagram of a circuit consisting of several electronic components.

2.2 PCB Design

The ECG monitoring system printed circuit board (PCB) design is based on a workflow that is organized in such a way that it starts by defining system specifications and functional requirements. A schematic diagram is elaborated to show all the electrical connections and interactions of the components. Design tools like the Altium Designer [29] are used to define the schematic, check component choice and verify the electrical correctness. The next phase of the layout design after schematic completion is to perform an optimal layout design in order to reduce noise coupling and maintain a signal integrity, especially the low-amplitude ECG signal pathways. Routing schemes consider short trace lengths, adequate grounding and isolation of analog and digital realms to alleviate interference. Signal simulations and design rule checks (DRC) are done to detect and rectify any layout violation. After the validation of the design, Gerber files are created to be used in PCB fabrication. The production phase entails the production of board, assembly of components, and soldering. After fabrication, PCB is subjected to electrical continuity, functional tests and performance tests to verify that the PCB meets the system requirements. The entire process of PCB development is summarized in Fig. 3.

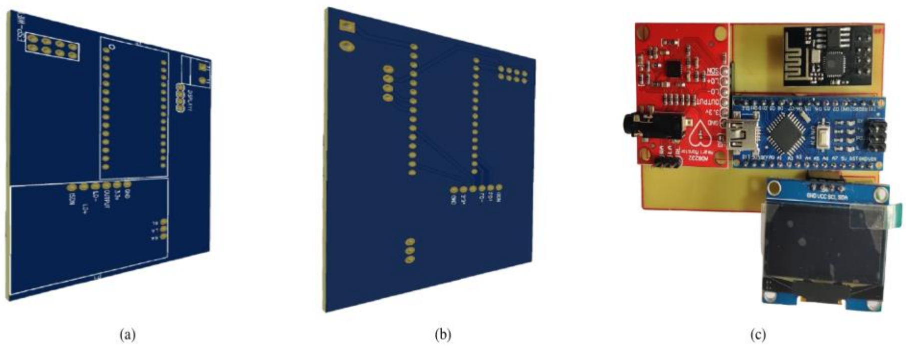


Fig. 3. PCB Design Process Overview of an ECG Monitoring System.

The last prototype consists of the PCB, sensing module, microcontroller, wireless communication system, and user interface integrated into a small and easy-to-use device. The design is focused on durability, precision of signal and usability. The casing is made of strong materials like ABS or polycarbonate to offer shield to internal electronics and offer an ergonomic feel. Additive manufacturing (3D printing) and CNC machining methods are applied to create an accurate geometry of the enclosures and ensure stable component positioning. Functional tests of signal acquisition accuracy, Wi-Fi transmission stability, and real-time display responsiveness are also part of performance tests. Durability tests look into mechanical resilience and reliability during repeated use. User testing is done to perfect enclosure shape, interface clarity and general handling comfort. The final assembly attained constant ECG monitoring capabilities and proved to be viable towards further refinement and clinical adjustment. The prototype layout is completed as shown in Fig. 4.

Fig. 4. ECG Monitoring System Final Prototype Development Overview.

2.3 Microcontroller Programming

A 6th order Bessel digital filter is used by the microcontroller to filter and condition the ECG signal. Bessel filters are chosen due to its linear phase properties that do not alter waveform morphology, a necessary feature in the interpretation of ECG signals. The analog prototype filter is designed using MATLAB and the poles and zeros of the filter are obtained. The cutoff frequency is changed with the lp2lp function, and the analog filter is converted to a discrete-time version using c2d function [10], that can be executed on a microcontroller. The filter coefficients obtained are incorporated into the Arduino program, and real-time processing of incoming analog-to-digital converter (ADC) samples is carried out. A recursive difference equation is used to perform the filtering operation, and the output samples are computed with numerical stability. Fig. 5 shows the entire programming scheme, including the filter design in MATLAB, and the real implementation in the Arduino platform.

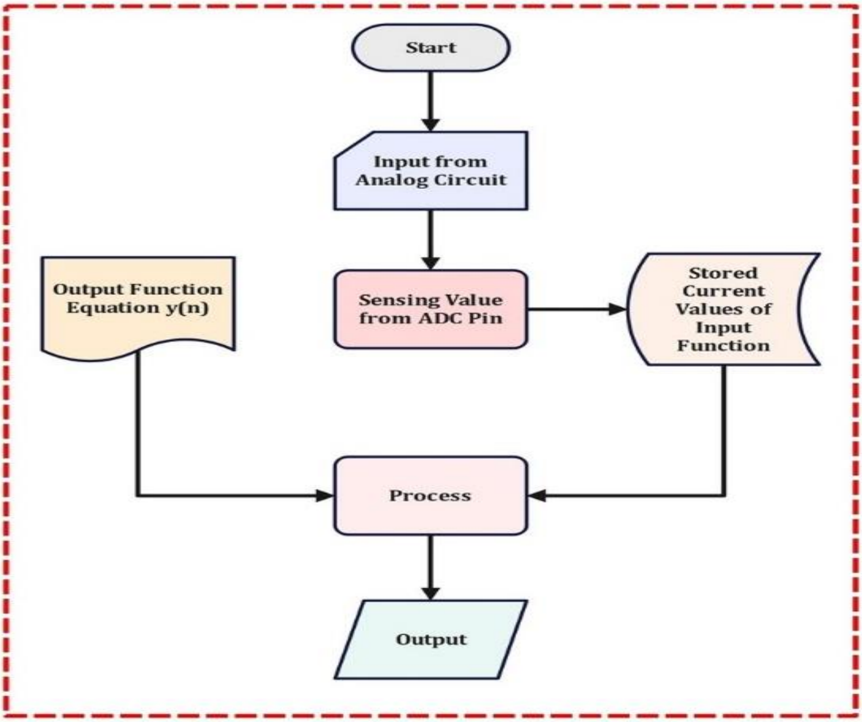


Fig. 5. Arduino Code Implementation ECG Signal Filtration.

3 Results and Discussion

The ECG monitoring device was created in a systematic process that involved digital filter design, signal processing with microcontroller, real-time display incorporation, and remote transmission of data. The first test of system performance was done with unfiltered ECG signals to check the quality of baseline signals. Fig. 6 shows that the raw ECG output had a high noise and motion artifact. Such artifacts compromise important aspects of the waveforms including P-waves, QRS complexes, and T-waves, which have adverse clinical implications. Baseline wander, power-line interference, and muscle noise indicate that signal conditioning is essential, as raw data can cause inaccurate characterization of waveforms, or can be misdiagnosed.

Fig. 6. Raw ECG Signal Data of Arduino IDE Serial Plotter.

A 6th order Bessel filter was run in the microcontroller to enhance the quality of the signal. Bessel filters are also better suited to biomedical applications where the most important aspect is a maximally flat group delay to keep the temporal shape of ECG waveforms intact [30]. The filtered signal in Fig. 7 shows that the noise is much lower and the waveform is much smoother. The complexes of QRS were more pronounced and fine morphological details were preserved. Such preservation is essential since proper interpretation of the ECGs depends on the preservation of the original signal shape without alteration on the timing of waveforms or amplitude [31-32]. This increases the accuracy of visual analysis and algorithmic feature extraction, making it possible to analyze the rhythm and detect abnormalities more accurately due to the increased clarity of signals.

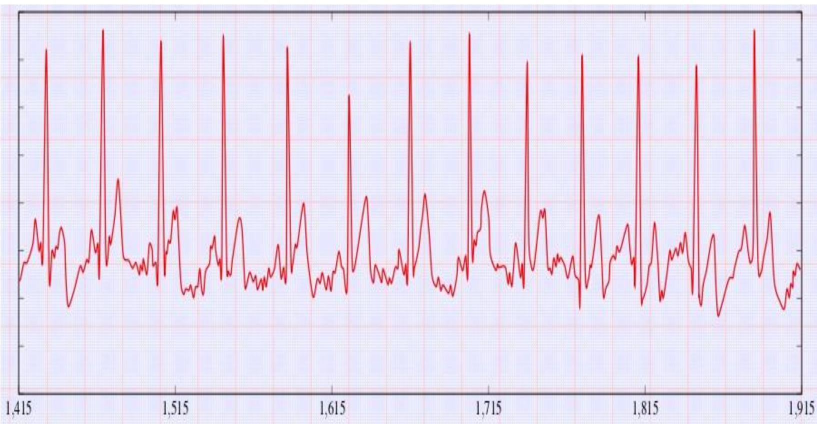
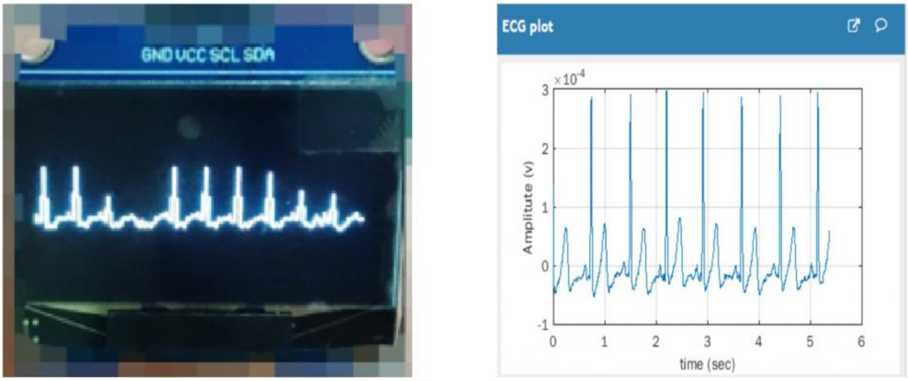


Fig. 7. Arduino IDE Serial Plotter Filtered ECG Signal output.

The filtered ECG signal was also real time monitored on an OLED screen which would allow real time visualization on the device. The display as indicated in Fig. 8(a) illustrates a clear and understandable waveform, which can be used on-the-spot. In addition, remote monitoring was also facilitated by use of ThingSpeak IoT platform [33]. Fig. 8(b) indicates that wireless data transmission and cloud visualization are successful and users or clinicians can access ECG data at any place as long as the location has internet facilities. It has this feature to aid telemedicine applications and continuous monitoring of health of at-risk people. The remote monitoring of the heart activity enhances early detection of the cardiac abnormalities and promotes timely intervention.



(a) (b)

Fig. 8. (a) Filtered ECG Signal on OLED Screen (b) ECG Signal on ThingSpeak Server Remote Monitoring.

All in all, the system is effective in the acquisition, filtering, display, and transmission of ECG signals. The Bessel filter is useful in enhancing the signal and a combination of local and remote visualization proves that the system is versatile. The remaining issues are to optimize the filter to achieve more computational efficiency, to make the OLED interface more user-readable, and to provide a secure encryption of the data transmission to provide privacy and cybersecurity in the process of wireless transmission. Irrespective of these points, the device has high potential to be an effective tool of real-time ECG monitoring and remote cardiac assessment.

3.1 Cost Analysis

The projected total cost of development of the proposed ECG monitoring prototype is about 20.17 USD, comprising of the Arduino Nano, ECG sensing module, OLED display, ESP8266 Wi-Fi module, rechargeable battery, and other related electronic parts. Comparatively, Apple Watch Series 4 starts to retail at around 399 USD [34]. The additional investment in research and development and the sophisticated hardware miniaturization, embedded ECG-grade sensors, the additional health tracking features, proprietary software ecosystem, and higher cost of the Apple Watch is the reflection of advanced hardware miniaturization, embedded ECG-grade sensors, and additional health tracking features. The prototype concentrates on the basic ECG measurements and monitoring capabilities with low-cost off-the-shelf components. Although it is currently lacking in size and functionality compared to commercial wearables, significant cost savings could be realized by mass production, in-house PCB assembly and component optimization. This price difference, as evident from the pie chart cost analysis presented in Figs. 9 (a,b), shows the possibility of the prototype being a cheaper alternative to be used in communities with limited access to advanced medical equipment, as long as additional refinement is done.

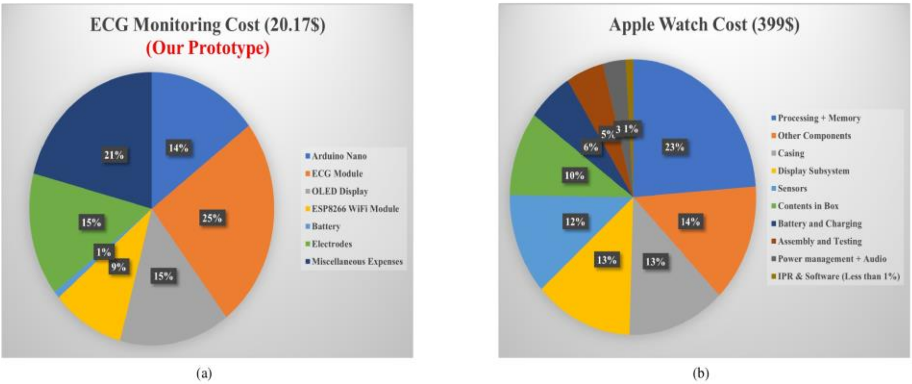


Fig. 9. (a) Pie Chart ECG Watch Prototype Cost Analysis (b) Pie Chart Apple Watch Cost Analysis [35].

3.2 Size Comparison

The prototype of the ECG watch is 3 x 2 x 1.5 inches in size as indicated in the 2D cross-sectional images in Figs. 10(a,b). Conversely, the Apple Watch has a smaller and more convenient shape, which means that it can be easily put on the wrist during everyday activities. The greater dimensions of the prototype are mostly attributed to the discrete character of its parts, such as, ECG sensor module, Arduino Nano microcontroller, Wi-Fi module, and circuitry support. Future design solutions can involve the creation of a special purpose integrated circuit (IC) or System-on-Chip (SoC) that integrates sensing, processing, and communication into a single chip. This miniaturizing would save on space, enhance portability and make it more marketable. Switching to flexible PCB and integrated electrode design would also increase the comfort and ease of use, and make the device more in line with the current wearable health technologies.

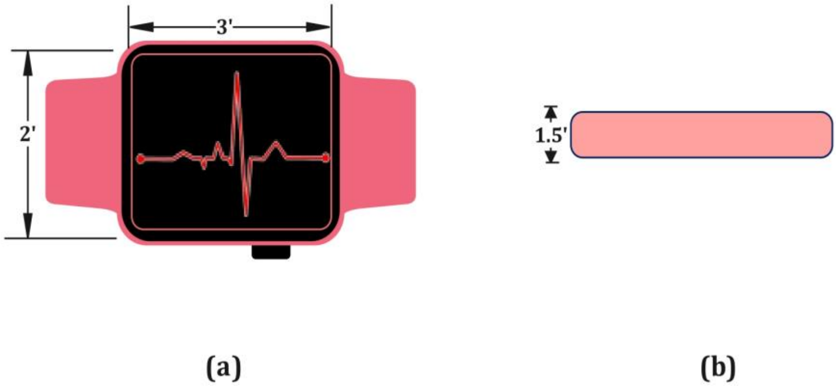


Fig. 10. (a) 2D Front View ECG Watch Prototype (b) 2D Side View ECG Watch Prototype.

4 Conclusion

This paper proposes the design and development of a wearable wrist-worn ECG monitor that combines low-energy consuming hardware, signal collection, filtering, and wireless communication. The gadget works well to record and analyze ECG signals through 6th -order Bessel filter with better results in clarity of the waveforms and elimination of noise artifacts without degrading the signal quality to measure the heart rate. The combination of real-time visualization with an OLED display and the remote monitoring with cloud integration proves the possibilities of the device both in the local and telemedicine. The prototype is focused on the affordability, durability, and user-friendliness, which allows the high-quality cardiac monitoring to be available in resource-limited environments. According to quantitative assessment, the system can deliver credible ECG signal representation that can be used in a diagnosis. The next generation of work will be aimed at miniaturization based on integrated hardware design, optimization of filtering performance, improvement of user interface, and the introduction of secure data transmission protocols. Altogether, the suggested device is an important breakthrough in the field of wearable cardiac monitoring equipment, and it will lead to the mass adoption and better heart health management.

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Disclosure of Interests. The authors have no competing interests.

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