The Quake-Catcher Network: Citizen Science Expanding Seismic Horizons

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INTRODUCTION

The Quake-Catcher Network (QCN) is a seismic network that implements distributed/volunteer computing with the potential to provide critical earthquake information by filling in the gaps between traditional seismic stations. Microelectromechanical systems (MEMS) sensors detect vibrations within the frequency range of local seismic waves (0.1–20 Hz), so any internet-connected computer with an internal or external MEMS accelerometer can become a strong-motion seismic station. The QCN, a distributed computing project, uses idle computer cycles and MEMS sensors to increase the number of seismic stations, which may soon provide faster and more accurate detection and characterization of moderate to large earthquakes. We present accelerograms and triggering analysis of an M_b 5.1 earthquake recorded by laptop MEMS accelerometers during early testing of the QCN system. In addition, we present here the advantages of distributed computing and MEMS accelerometers for seismic monitoring, as well as basic triggering algorithms.

The QCN capitalizes on the main advantage of distributed computing—achieving large numbers of processors with low infrastructure costs—to provide a dense, large-scale seismic network. While MEMS accelerometers are less sensitive than typical broadband or short-period sensors, a higher number of stations is advantageous for both the study of earthquakes and, potentially, earthquake early warning (Allen and Kanamori 2003; Wurman *et al.* 2007). Volunteer computing reduces overhead by limiting instrument, operation, and maintenance costs associated with traditional seismic networks (Anderson *et al.* 2002).

Distributed computing brings many advantages to the field of seismology. Data are analyzed on an individual's laptop or desktop, and only minimal data are transferred to a central server for further analyses. This differs from the traditional approach of uploading continuous waveform data to a central server for analysis (Allen and Kanamori 2003; Wurman *et al.* 2007). By pushing the analysis to the sensor level, a greater volume of seismic data can be processed in a shorter amount of time. The QCN, with the potential for thousands to hundreds of thousands of sensors, aims to provide nearly instantaneous detection and characterization of large earthquakes. Simulations show that by distributing the detection algorithms over many internet-connected seismic computers, earthquake detection for large earthquakes may be made faster than by standard methods. The sensitivity of the QCN sensors is lower than that of traditional sensors, but the method is well-suited for moderate to large earthquakes (magnitude > 5.0) that occur in populated regions. Rapid detection and a dense network are imperative for an earthquake rapid response alert to provide reliable information with few to no false positives.

GROWTH OF THE NETWORK

The QCN has grown rapidly in the first few months of limited release by successfully adopting a variety of proven computational tools and actively involving the public. In 2006, SeisMac demonstrated that Macintosh laptops with internal accelerometers could help educators teach students about seismic signals (Griscom 2007). The Berkeley Open Infrastructure for Network Computing (BOINC; http://boinc.berkeley.edu/), (a freeware architecture for distributed computing projects) allowed us to easily utilize internal or external accelerometers by networking volunteer-computers (Anderson and Kubiatowicz 2002; Korpela *et al.* 2001; Christensen *et al.* 2005; Zagrovic *et al.* 2002). This is the first documented scientific project utilizing distributed computing to monitor and analyze sensor data collected by personal computers. The success of distributed computing projects, including QCN, is dependent on interested individuals willing to donate CPU time to projects they believe are meaningful (Anderson and Kubiatowicz 2002). Distributed computing projects that participants believe are worthwhile and societally relevant tend to flourish (Anderson and Kubiatowicz 2002), *e.g.*, SETI@home (Korpela *et al.* 2001) and Folding@home (Zagrovic *et al.* 2002).

The rapid development of QCN software was facilitated by the sizeable accumulation of community experience with BOINC and the architectural improvements made over the past decade. In particular, the trickle message application

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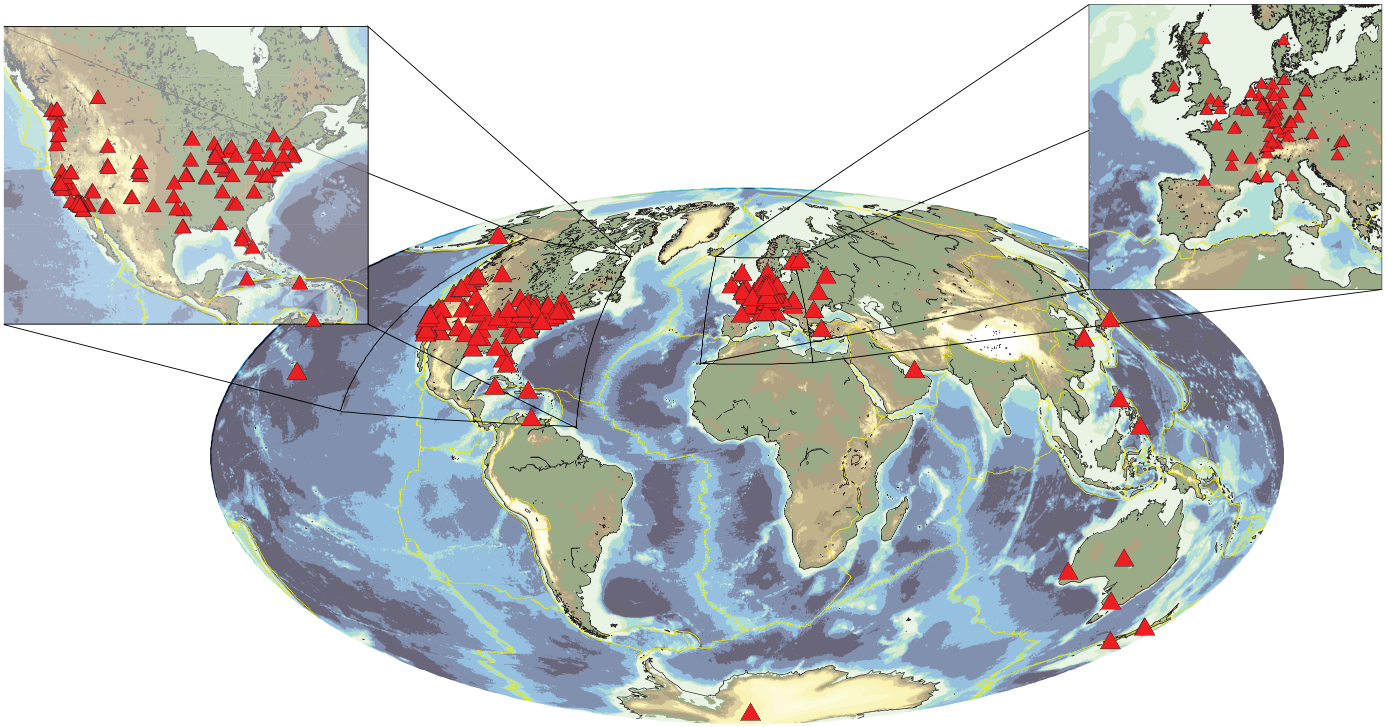


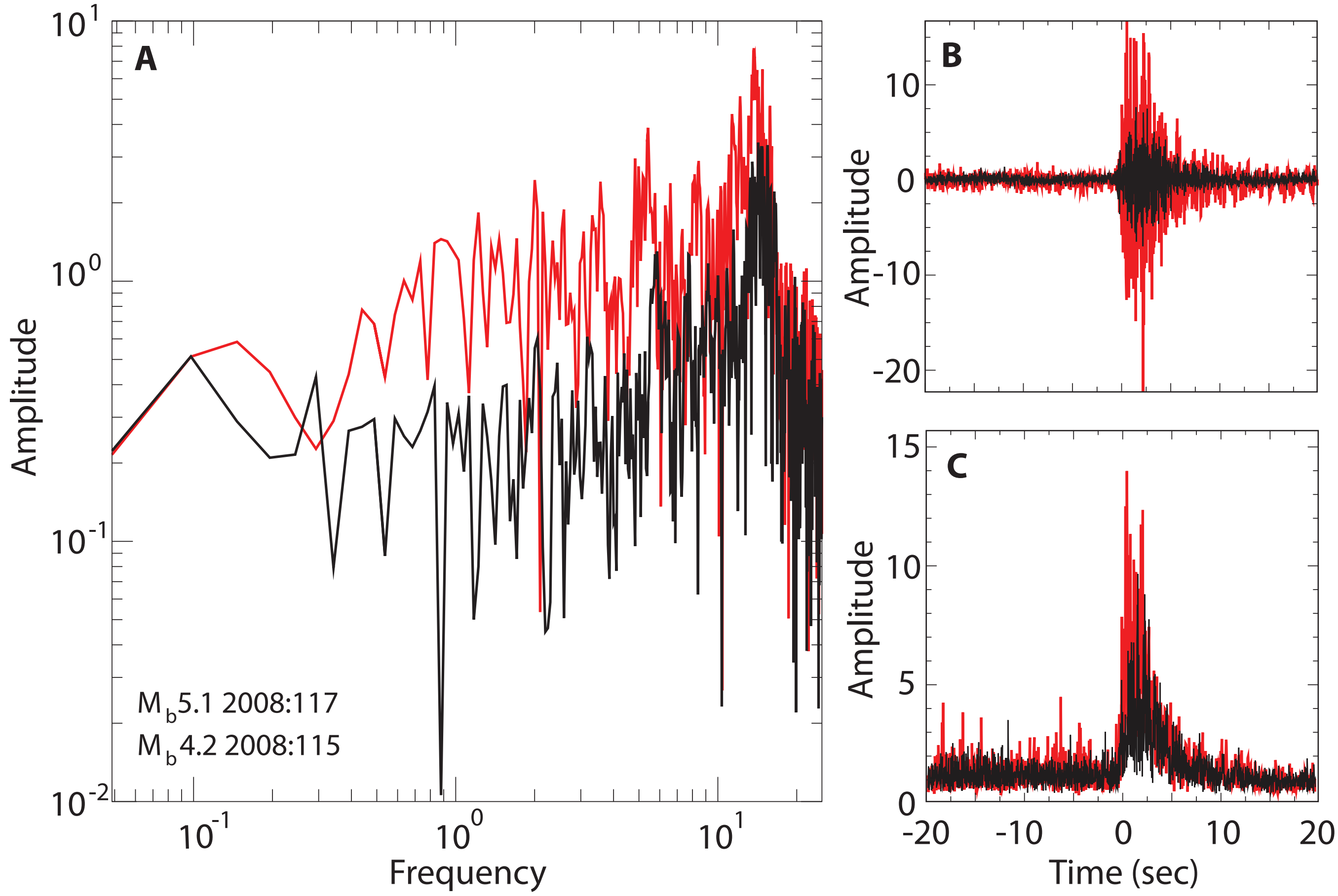
▲ **Figure 1.** Global Distribution of QCN Stations. QCN laptop-sensor locations (red triangles) as of April 2008 on a topography map. Maps of North America and Europe show a higher density of laptop sensors. The symbols for many laptop locations overlap in metropolitan areas.

is critical for rapid data transfer from the client to the server (Christensen *et al.* 2005). Proven internet-based technologies also provide the QCN with robust tools for two of the most fundamental observations needed to analyze seismic signals: accurate sensor time and location. In addition, previous work has shown that MEMS accelerometers record high-fidelity seismic data and provide linear phase and amplitude response over a wide frequency range, typically 0 Hz to greater than 250 Hz (Farine *et al.* 2004; Holland 2003).

On 4 April 2008 the QCN released a beta-release of the software for Macintosh laptops only from the Web site http://qcn.stanford.edu. By 25 April 2008, more than 300 users from around the globe had joined the QCN (Figure 1). The spatial distribution of volunteer computers is largely focused in North America and Europe. A more recent distribution of QCN added Thinkpad to the list of supported systems. The number of volunteers is expected to increase further when other laptop brands (*e.g.*, Hewlett-Packard, Acer) are added to the beta test; a platform-independent release is planned for late 2008. Work is underway to incorporate an inexpensive (U.S. $30–$100) USB-connected accelerometer for use with desktops running any operating system. By July 2009 the Quake-Catcher Network in California also will include 1,100 USB sensors deployed at schools and museums. USB-connected accelerometers will provide a stable backbone for the network with continuous sensor monitoring; the software currently only runs when a laptop is inactive to avoid noise from keystrokes. The USB accelerometers can also be mounted to the floor, better coupling the sensor to ground motion, albeit through a building. In the future, other accelerometer-equipped peripherals such as phones, clocks, or remote controls may contribute to the QCN.

TRIGGERING ALGORITHMS

The QCN is designed to rapidly monitor a very large number of seismic sensors by using the computers directly linked to accelerometers for both data collection and triggering algorithm computation. The triggering algorithm compares the current acceleration to the average signal recorded over the previous 60 seconds to determine if the signal is outside the norm. When the magnitude of the current signal (taking into account the horizontal and vertical amplitudes) is more than three times the standard deviation of the prior 60 seconds, we know with 99% confidence that the emerging signal is not representative of the noise recorded in the past minute. When a significant detection occurs, the sensor-computer issues a “trigger” to the QCN server, indicating the time, signal amplitudes, Internet protocol (IP) address, and other pertinent information. Because the trigger incorporates minimal information, not full waveform data, the trigger transfers to the QCN server very rapidly, typically < four seconds for computer-sensors in the continental United States and within five seconds globally. The number of triggers detected by individual laptop-sensors varies significantly, between 0 and 800 triggers per day, with a median of 35 triggers per day. Waveform data from an event is uploaded from the sensor to the server once the occurrence of an earthquake is confirmed. Thus, the upload server is not subjected to a high data load. The sensor computer only deletes data once the server



▲ **Figure 2.** Response Spectra Comparison. This figure shows the similarity between vertical (A) amplitude spectra and (B) vertical component time series, and (C) significance filter recordings of an Mb 5.1 earthquake (red: 2008/06/26 06:40:10 UTC) and an Mb 4.2 earthquake (black: 2008/06/26 06:40:10 UTC) recorded by the same PowerBook laptop running QCN software to monitor the internal MEMS accelerometer. The M_b 5.1 event was recorded with greater amplitudes.

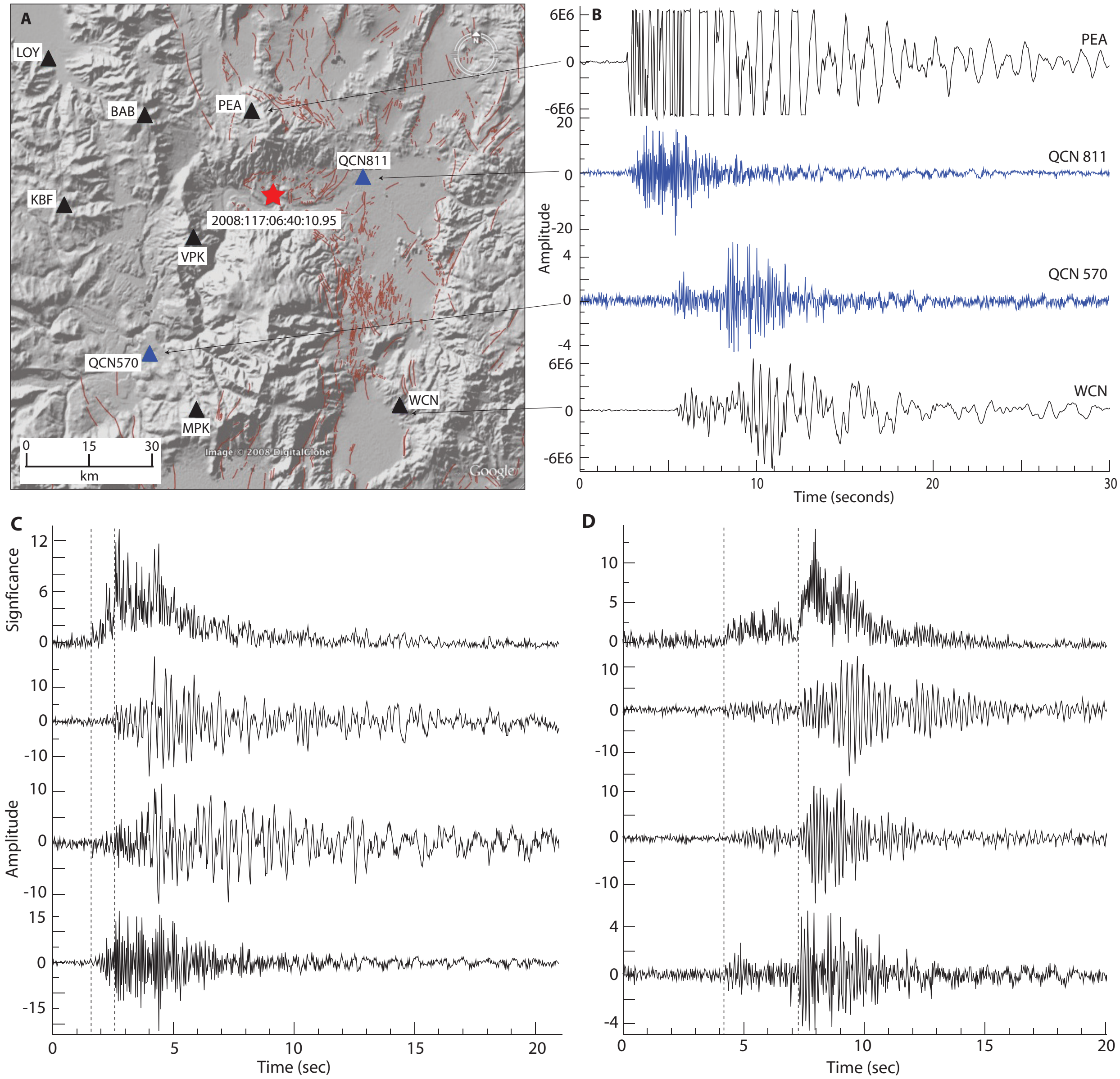
has a digital copy, the trigger is verified as being false, or a week has transpired.

To determine if an incoming set of triggers represents a "probable earthquake," the QCN server uses a significance filter similar to that used by the sensor-computers. The server monitors incoming triggers and determines if the number of triggers in a geographic area is more than six standard deviations above the average rate of triggers per second in the past 10 minutes. If the trigger times can be modeled by circular spreading of seismic waves from a single source, then the earthquake is upgraded to a "likely earthquake." At this early stage of the QCN network, server-side triggering algorithms are simulated with earthquakes recorded by the current (not real-time) seismic network in California. Preliminary simulations suggest identification and location of a likely event is both robust and rapid. The existing seismic networks in California are not ideal for earthquake early warning in their current form due to delays in the telemetry of data caused by ten-second-long data packets (Wurman *et al.* 2007). The QCN is particularly well-suited for early warning because of the instant transmission of trigger information and the expected large number of sensors with which to corroborate a trigger.

RENO EARTHQUAKE SWARM

The QCN had several early opportunities to test the client-side triggering algorithms during a swarm of earthquakes that began near Reno, Nevada, on 28 February 2008 and during the recent 19 July 2008 M 5.4 Chino Hills earthquake in California. Here we focus on data from the Reno swarm. On 26 April 2008 at 06:40:10.95 UTC, the largest event in the sequence, an M_b 5.1 earthquake, occurred west of Reno (Northern California Earthquake Data Center, USGS Northern California Catalog, http://www.ncedc.org).

Two QCN laptops located 10.7 and 23.5 km from the hypocenter issued triggers at three and six seconds after the earthquake origin time (Figure 2). These laptops joined QCN two and three days before the 26 April earthquake. While only one of the two volunteers felt the earthquake (personal communication), both computers measured the vibrations and issued triggers. The triggers were registered in the QCN database within eight seconds of rupture, only 1.5 seconds after the later QCN trigger was measured. A data request from the server uploaded the data within 48 hours.



▲ **Figure 3.** M_b 5.1 Reno Earthquake Records. (A) Locations of regional sensors (black triangles), two QCN laptop sensors (blue triangles), and the M_b 5.1 earthquake on 26 April 2008 (red star). (B) Digital seismic records for two regional broadband sensors (black) and two QCN laptop sensors (blue) in order of closest to farthest from the earthquake epicenter. All of the regional network sensors (short-period and broadband) are clipped except WCN, rendering the amplitudes meaningless for magnitude estimation. Map made with Google Earth. Significance, two horizontal components, and vertical component records for (C) QCN-811 and (D) QCN-570.

Following the earthquake, a request for additional information was sent to the two QCN volunteers who recorded the earthquake. One response was received from the owner of laptop-sensor QCN-811. He reported that the measurements were taken from a "wobbly" table in the first floor of a house. According to the report from the owner of QCN-811, nearly everyone on the same street felt the earthquake shaking, but there was no reported damage to any structures, which is consistent with the reported "Did You Feel It?" modified Mercalli intensity of IV (http://earthquake.usgs.gov/eqcenter/dyfi/). Both volunteers had set their computer locations using the QCN Google application programming interface (API) prior to the triggers, thus improving the accuracy of the sensor locations. The signal-to-noise ratio observed on the two QCN servers is lower than those of the permanent broadband sensors (Figure 3) due to the much higher noise floor of the Macintosh laptop accelerometers (roughly 8 mG for PowerPC laptops and 1 mG for Intel laptops) and reduced coupling between the ground and the sensor. The MEMS accelerograms provide an unclipped record of the event with visible *P*- and *S*-wave arrivals (Figure 3). The QCN stations provide the closest three-component, on-scale recordings of the M_b 5.1 earthquake that were available as of 28 April 2008.

In the future, as more computers join the QCN, triangulation using only first trigger times may yield near real-time hypocenters. The S-minus-P time (3.03 s) calculated from the first trigger on the horizontal and the vertical components, respectively, from sensor QCN-811 yields an earthquake-to-sensor distance of 24.2 km (only 1-km error). Sensor QCN-570 yielded no S-wave trigger due to the more emergent nature of the phase. Many of the short-period recordings from the Nevada Network (NN) go off scale at the time of an M_b 3.3 earthquake, 11 seconds before the M_b 5.1 event. The M_b 3.3 earthquake is not detectable on the QCN records due to the lower sensitivity of the MEMS accelerometers.

The magnitude of the trigger amplitudes from QCN-811 was 0.187 m/s^2, compared with 0.46 m/s^2 from QCN-570. The amplitude ratio between the two sites (0.40) is only marginally lower than the ratio of 0.45 expected from geometric spreading of body waves in an elastic medium. Once a large number of trigger amplitude/distance measurements for QCN sensors have been observed for moderate to large events, it may be possible to determine a real-time magnitude for events recorded by multiple QCN sensors.

We present a comparison between the spectra of an M_b 4.2 (2008/04/26 22:55:49 UTC) and an M_b 5.1 (2008/06/26 06:40:10 UTC) earthquake recorded by a Macintosh PowerBook running QCN software approximately 11 km away, near Reno, Nevada (Figure 2). The second laptop, located approximately 20 km from the epicenter, did not record the M_b 4.2 earthquake, suggesting this event was at or below the threshold of triggering sensitivity. The spectra for the two events are similar, but the amplitudes are larger for the M_b 5.1 than for the M_b 4.2 event, as expected. Peak amplitudes are recorded between 10 and 20 Hz. The magnitudes of the trigger amplitudes (registered by the server within 1.5 seconds of recording for both earthquakes) are 0.23 m/s^2 for the M_b 5.1 earthquake and 0.21 m/s^2 for the M_b 4.2 earthquake. The MEMS accelerometers provide repeatable signals from two closely located events despite the low signal to noise of the records.

Distributed computing provides a novel way to improve the density, response, and functionality of seismic networks. In the future, distributed computing seismic networks with MEMS accelerometers, such as the Quake Catcher Network, may provide rapid earthquake detection and have the potential for earthquake early warning at relatively low cost.

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