# Low-cost Sensors for Balancing Indoor Air Quality and Energy Usage

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## ABSTRACT

Saving energy and improving indoor air quality (IAQ) and thermal comfort in buildings are traditionally competing goals. Facilities that manage one of these objectives tend to compromise the other. Building automation systems (BAS) have been limited in their ability to sense these characteristics of a building and therefore cannot act on them. A majority of buildings define IAQ in terms of supply air temperature alone, and manage energy consumption by scheduling. There is a large potential to improve both IAQ and energy consumption through innovative control strategies. These strategies are independent of developments in the energy conversion equipment itself by enhancing its control. Good control requires good feedback, and feedback for IAQ is complicated by a lack of sensors able to be easily integrated into BAS that can record other contributions to IAQ such as $CO_2$ and the presence of trace gases. Since BAS have not traditionally had access to these types of data, there is little experience of how to best apply this new information in a dynamic system to achieve reduced energy consumption while improving IAQ. This article will discuss development and integration of low-cost microsensor arrays into affordable BAS. Multi-function sensor packages are in development that can measure $CO_2$, temperature, humidity, room occupancy, and potentially other trace gases of interest. The sensor package can communicate with the BAS wirelessly or over existing building power wiring. Communications have been developed for a low-cost implementation with algorithms focused on security and robustness.

## INTRODUCTION

Traditionally, saving energy, providing thermal comfort, and improving indoor air quality (IAQ) are competing considerations. Why are these topics important in buildings? Residential, commercial, and industrial buildings are responsible for 43 percent of the US $CO_2$ emissions [1]. Poor indoor air quality has been estimated to cost the U.S. annually (in lost production) between $17B and $48B and to affect as many as 80 million persons [2,3]. Finally, various studies have indicated that introducing energy saving technologies and efficiencies can reduce energy consumption by 10-30 percent [4]. Facilities that manage one of these objectives (saving energy or thermal comfort or IAQ) tend to compromise the others. There are several reasons for this trade-off. Improved IAQ often means additional ventilation air as called out in ASHRAE Standard 62 Ventilation for Acceptable Indoor Air Quality, which usually means raising outdoor air flow rates into the building. Typically this increased outdoor air must be conditioned, increasing energy use. The additional outside air also translates into humidity variations and control; again, potentially increasing energy consumption [5]. Additionally, building automation systems (BAS) do not have the ability to comprehensively and continuously assess IAQ and thermal comfort because low cost, easy-to-use sensors for carbon dioxide, humidity, air flow, and trace gas concentrations are not readily available. Also, since these measurements are not normally taken, little thought has been given to integrating their feedback into BAS or where the best locations are for placing these sensors. In the absence of reliable, quantitative measurements, the building designer is often left with the only option of providing a supply of fresh air that may or may not need to be conditioned and filtered before entering the building space. Having accurate and current IAQ thermal comfort data would allow the BAS to reduce energy consumption. Making significant progress towards least-energy IAQ requires efforts in both sensor technology and developing experience and logic that effectively utilize the sensor data.

## METHODOLOGY

Acceptable IAQ and thermal comfort is typically not obtained through just one approach. It is achieved by applying several methods such as contaminant source control, adequate filtration, humidity management, and proper ventilation [6]. Much of the perceived conflict between IAQ and energy efficiency results from just two elements of an energy strategy—the tendency to minimize outdoor air ventilation rates and the willingness to relax controls on temperature and relative humidity to save energy. Energy reduction activities are generally recognized as having a significant potential for degrading the indoor environment and causing problems for the building owner and occupants [6]. To help achieve a balanced approach between IAQ, thermal comfort, and energy savings, numerous approaches have been tried or suggested. The goals of most of these include [4]:

1. Ensure that the energy conservation measures have no adverse influence on IAQ or thermal comfort.
2. Quantify the improvements in IAQ and the energy reductions resulting from implementation of the energy conservation measures.
3. Verify that selected IAQ parameters satisfy the applicable guidelines and standards.

To verify that these goals have or have not been met will require measurements and analysis. To reduce the uncertainty to acceptable levels for the calculations and comparisons, numerous measurements will be needed. The economics demand that the measurements be made by low-cost instruments/sensors, and for the reduced uncertainties the measurement must be accurate and located in appropriate places. Some examples of improving thermal comfort or IAQ while providing energy conservation are described in the following, and more details are contained in reference [4]. To ensure thermal comfort one would measure air temperature, mean radiant temperature, relative humidity, and air velocity at multiple heights in multiple workspaces. Instrumentation cost for one workspace would exceed $5k. This system could be moved from place to place providing only short-term data at each location. Monitoring and control of outside air ventilation rates which can directly influence energy costs and IAQ have often included measurements that account for natural and mechanical ventilation, outside air flow into air handlers, and in various ducts. If measurements can be made on a continuous basis, real-time ventilation control can be implemented. However, these measurements are often expensive, hard to use, and cost over $10k, in total. The final example is the real-time measurement of $CO_2$. $CO_2$ concentration measurements are often used to monitor occupancy rates and ventilation efficacy, which may indicate other pollutants associated with occupancy. In some buildings this does not work well because of temporal variations in occupancy, uncertain rates of $CO_2$ generation, and concentration changes on different time scales than occupancy or ventilation. Typical cost for $CO_2$ analyzers are $1k or more. Lower cost sensors are now available for ~ $300 that are reasonably accurate, although baseline drift can be an issue.

When attempting to achieve acceptable IAQ via ventilation, ASHRAE 62-2001 offers two methods for determining the amount of outdoor air required to properly ventilate indoor occupied spaces. The two methods are the ventilation rate procedure and the IAQ procedure. The ventilation rate procedure prescribes both the quantity and the quality of the ventilation air necessary to assure adequate dilution of contaminants generated in the occupied space. A three-step approach is described [6]:

- First, determine the quality of the outdoor air. The standard cites the levels for particulate or gaseous contaminants. Particulate or gaseous filtration is necessary if outdoor air exceeds the threshold levels referenced.
- Second, if the outdoor air is unacceptable, the standard advises that it be cleaned or filtered.
- Lastly, determine the amount of outdoor air required in each space. Standard 62 states:
  "IAQ shall be considered acceptable if the required rates of acceptable outdoor air in Table 2 are provided for the occupied space." Table 2 lists the amount of ventilation that must be supplied by room type and by volume per person or by volume per square foot.

Although Standard 62 is prescriptive, concise, and complete on most issues, it is unclear on others. For instance, in unoccupied space, contaminants could accumulate and Standard 62 does not call for ventilation unless it is needed to prevent contaminants that are injurious to people, contents, or structure. Many contaminants are difficult to measure; the designer may need to do routine ventilation when not really needed. The IAQ procedure is a performance-based method for obtaining IAQ by setting limits on contaminants. In particular, the procedure sets the limits for 10 contaminants. Tables are given that list the levels that must not be exceeded; however, acceptable IAQ is not necessarily assured. "Tables B-1 and B-3 do not include all known contaminants that may be of concern, and these contaminants' limits may not, ipso facto, ensure acceptable indoor air quality with respect to other contaminants." (Section 6.2.1 of ASHRAE Standard 62-2001) This procedure also addresses odor specifically. The designer cannot comply with the IAQ procedure without a subjective evaluation of the completed system. In summary, the standard provides an alternate method for obtaining acceptable IAQ through direct contaminant control. This would seem to be the preferable method from an energy conservation perspective; unfortunately, the standard only includes a short list of contaminants and requires post-design, subjective evaluation for odors. The requirements to ensure IAQ for contaminants and odors that are not specified and often difficult to measure (and health limits may not be established) leave the designer without a clear definition of acceptable indoor air quality. Consequently, most designers prefer the ventilation rate procedure because of its more prescriptive and clearer requirements, even if it may result in more energy consumption.

When applying either of these two methods, complications arise when there are multiple-space systems, occupied and unoccupied spaces, intermittent occupancy, building use changes, and other dynamic situations. The ASHRAE Standard may not require measurements; however, the dynamics of providing building ventilation tend to make continuous measurement essential to real-time control strategies.

What are the common indoor air pollutants? The list includes:

Formaldehyde
Radon
Combustion by-products
Pesticides
Asbestos
Tobacco smoke
Household chemicals
Allergens & mold

The concentration that may cause health effects vary with each pollutant type and can range to < 1 part per million (ppm) to a few percent [7]. As buildings have become better constructed and better sealed, air changes per hour have been reduced significantly, as much as 200 percent. Some research has shown that for each 30 percent reduction in air exchange, a 43 percent increase in indoor air contaminants resulted [7].

Because most buildings based ventilation requirements on air flow per person per type of room, designs are usually based on a minimum level of outdoor air ventilation required for the designed occupancy level. It has been argued that the $CO_2$ levels in a room are a good indicator of the occupancy in that space and can be used for controlling ventilation. Numerous studies and reviews have been conducted for $CO_2$-based demand-controlled ventilation [4, 6, 8, and 9]. Various methodologies have been applied for different spaces from homes to schools to hotels to offices. These efforts have included field experiments and computer modeling and simulations. The general consensus is that $CO_2$-based ventilation control is effective for public buildings, educational facilities, and retail establishments [8]. $CO_2$-based ventilation control also appears to be effective in the office environment if there is:

- unpredictable variation in occupancy;
- heating and cooling required most of the year; and
- low pollutant emissions from nonoccupant sources.

Energy savings were documented or estimated to range from 5 percent to over 25 percent with active demand ventilation control. The exception for this control methodology is where nonoccupant contamination sources are significant. These sources could include building materials, humidity control effects (mold), and outdoor sources. Without sensors and measurements, maintaining a baseline ventilation rate at all times has shown to be adequate and reduce the amount of energy savings [8]. Significant energy savings have been demonstrated using $CO_2$ as an indicator of the number of occupants in large rooms [10]. Approximately 35 percent of the savings were found in air-conditioning costs, and 25-50 percent on overall HVAC costs were estimated if implementation was completed correctly. This system included on-demand ventilation; however, no mention was made concerning the rooms' IAQ.

Once again the balance between IAQ and energy savings is highlighted, as well as the need for sensors. Two major issues for $CO_2$ instrumentation are performance (accuracy, reliability, stability) and location. Not much detailed work has been done in determining the proper location for sensors, experimentally or by the creation of predictive tools [11]. There is evidence that $CO_2$ sensors are adversely affected by humidity and temperature (resulting in baseline drift) and calibration issues. These types of concerns have been raised for humidity sensors as well.

An excellent survey on sensor and measurement methods is contained in the *Indoor Air Quality Handbook* [11]. In 2001, finding measurement technologies that were well suited for monitoring IAQ was difficult. The situation has improved some, but is still far from ideal. There are several reasons for this:

1. For the most part, there is a lack of regulations in place for IAQ.
2. This couples with the lack of a large market so that the incentives for significant R&D investments are not there.

The improvements in performance and the reduction in cost have progressed slowly for IAQ instrumentation. Individual gas sensors have dropped from the $1k-$2k range in the 1970s to $500 each in the 1990s to the $250 range in the early 2000s (Table 1). Power consumption is often too high for battery use (10s of milliwatts) or scavenging power from the environment (microwatts).

**Table 1. Comparison of Current Sensor Technologies**

| *Sensor Power* | *Cost* | *Size* | |
|---|---|---|---|
| Humidity | <1 mW | $10 | Micro |
| $CO_2$ | 3 W | $100s | Hand |
| Sensor Array | 5 W | $1000s | Hand |
| Next generation microsensor arrays | Microwatts | $10s | Micro |

Occupancy sensors are now under $100 per unit and continue to drop, mainly because of their use for lighting control. Stable, repeatable, accurate humidity sensors are still difficult to obtain for under $1000, although some recent developments are encouraging [12]. Low-cost sensors for monitoring volatile organic compounds (VOCs) and other household chemicals are generally not available.

## RECENT SENSOR ADVANCES

To achieve low-cost sensors (multiple measurements for <$100, Table 1) the technology will most likely involve microtechnologies like microelectromechanical systems (MEMS) and eventually nanoelectromechanical systems (NEMS). Many of the pieces needed to create an inexpensive multimeasurement instrument package are progressing very well. The microelectronics industry, with its high volume manufacturing, has created low-cost, reliable analog and digital circuits for conditioning, filtering, processing, and controlling sensor systems [13]. Microelectronics are also available for power management and robust communications [14]. Recent thrust areas for R&D in microelectronics are ultra low-power circuits to enable scanning power from the environment [15, 16] and robust, secure wireless communications [17]. These microelectronic technologies have been integrated with a variety of sensing approaches (microcantilevers [18], microcapacitors [19], and carbon nanotubes [20]). For the most part, there has been limited market penetration with these commercial products. Over the past couple of years, research has begun to move toward multiple sensors in an integrated package, thus reducing per measurement costs and overall footprint. The goal of the cost reduction and miniaturization is to create larger markets. Commercialization, however, will not occur quickly, as there is still a significant amount of R&D required to achieve stable, reproducible MEMS gas and vapor sensors. Most MEMS rely on the analyte (gas) of interest to adsorb on and desorb from a coating. Developing a coating that is sensitive to only one gas or environmental parameter is unlikely. Typically a coating will adsorb, say carbon monoxide and water and perhaps one or two other gases. Often the coating will degrade with repeated exposures or thermal cycling. Additionally, response time can be a significant issue depending on the surface kinetics. At room temperature, adsorbing and desorbing could be seconds for one reaction and hours for another.

Some of the R&D for VOC detection is typified by the work underway at Seacoast Sciences [21]. A low-cost, low-power microsensor array has been developed based on micromachined capacitors (Figure 1).

A polymer is used to fill the gap between the capacitor plates. The polymer absorbs the analyte of interest, which changes the permittivity of the polymer and thus the capacitance of the sensor. An array of these microcapacitors is co-located on a single substrate with each individual sensor filled with a different polymer. The various responses from the array are collected and analyzed to determine the identity of an unknown VOC. The measured sensitivity of these sensors to most of the VOCs is in the low parts per million range. Response time to

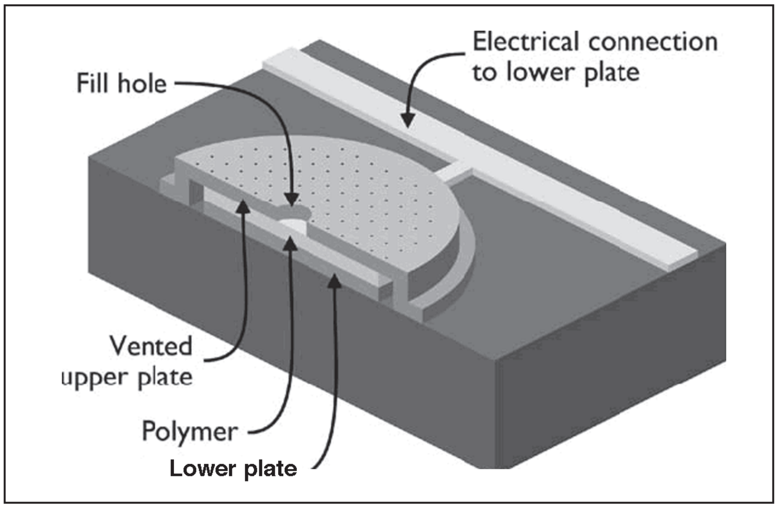

**Figure 1. Micromachined Parallel-plate Capacitors (Seacoast Sciences [21]**

equilibrium can be in the minutes range, but can be reduced with geometry and operating at temperatures above ambient conditions.

A significant amount of research has been underway in using microcantilevers (MCs) as chemical sensors and infrared detectors. Microcantilevers, tiny diving boards about the size of a human hair, have shown to be very sensitive detectors (Figure 2). The MCs are approximately 200 micron long by 20 microns wide and 1-3 microns thick.

A thin film coating is placed on the upper surface of an MC; when a substance is adsorbed into that film the MC deflects. This movement can be sensed optically or electronically and is a function of the amount of material adsorbed by the film. Figure 3 illustrates a capacitive readout arrangement where the polysilicon beam and the bottom plate act as a parallel plate capacitor. Very low-power and sensitive microelectronics have been developed that can detect a nanometer deflection which translates to parts per billion or part per million sensitivity. Coatings have been developed for $CO_2$, VOCs, hydrogen, mercury, and other toxic or environmentally important measurands.

Additionally, work has been done to create a low-cost infrared (IR) imaging detector with microcantilevers. The cantilever design is different than the one for gas measurements (Figure 4), but the same

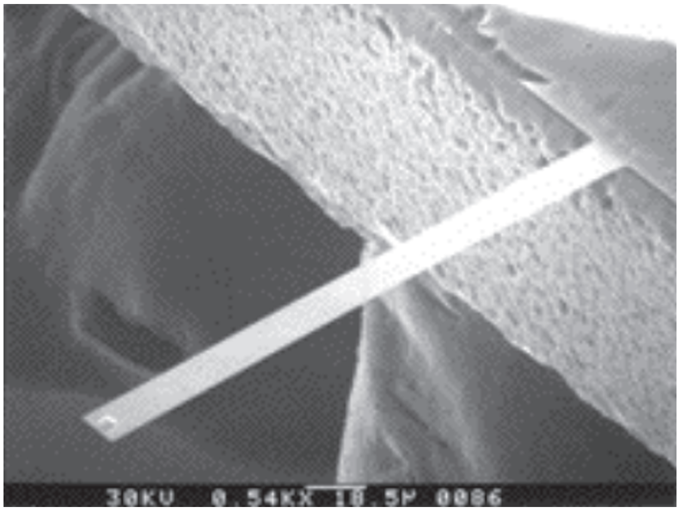

**Figure 2. Microcantilever Sensor**

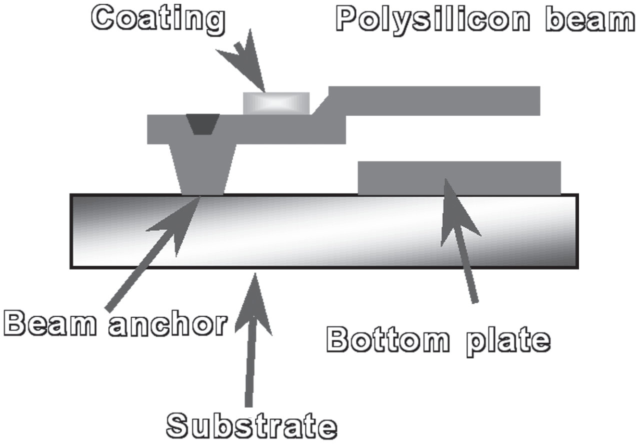

**Figure 3. MC Arranged for Capacitive Readout**

capacitive readout can be used for both. As the MC absorbs IR energy, it bends due to a biomaterial effect [22]. As the temperature of the biomaterial structure changes, the lengths of the two layers change by different amounts and the resulting stress causes the structure to bend.

Using an array of the IR MCs, an image of the object can be formed. This image can be used to detect occupancy and motion in a

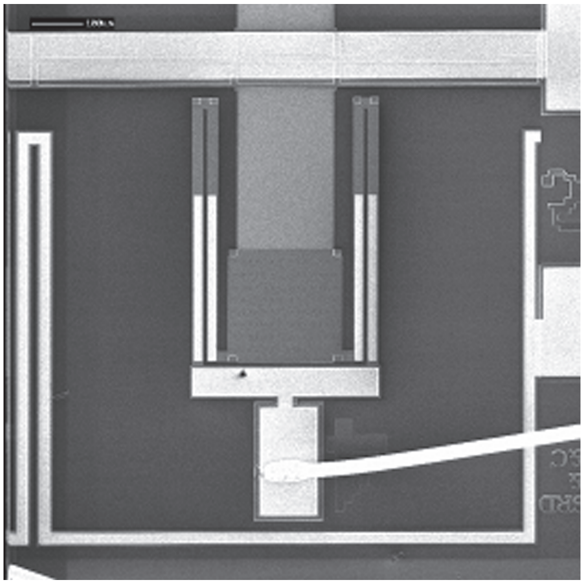

**Figure 4. IR Imaging MC Detector**

room or building space.

Recent R&D at Oak Ridge National Laboratory has focused on the area of multiple measurement MC arrays that can detect various gases or vapors, temperature, and room occupancy. The objective is to create very low-power, low-cost, wireless microsensor arrays that can aid in balancing IAQ and energy conservation. Micromachined arrays were designed and integrated with readout electronics that provide signal conditioning, power management, filtering, and functional control. Up to ten MCs can be read out along with a temperature sensor. The readout and conditioning electronics for the MS system were designed to be operated on ultra-low power (<1mW continuous operation or ~100μW in sample mode) [23]. The electronics (Figure 5) can also handle additional analog inputs and, in this case, a low-cost commercial humidity sensor was added.

The vapor/gas and IR MCs were developed using standard semiconductor processing fabrication technology. This was also true for the microelectronic readout unit; thus, the heart of this multiple measurement array can be fabricated and assembled for a very low cost in volume production. The final piece to the integrated microarray package was communications. Both wired and wireless communica-

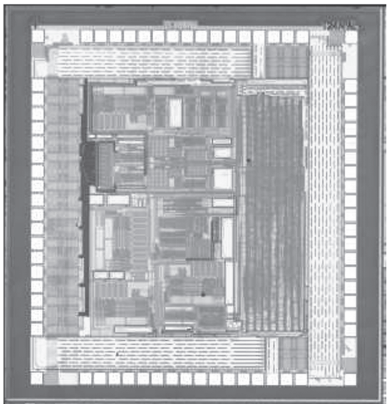

**Figure 5. Microelectronics for MC Array**

tion schemes were developed to handle existing buildings and new structures, respectively. In some cases, it may be easier to use existing power wiring to transmit the microsensor array data to the energy management center or building automation system. For this case, a low-cost line coupler was developed to allow the sensor package to be plugged into an 110V outlet. The package received power from the circuit and transmitted its data on the same wiring. An algorithm was created to improve the data security and reliability for the wired network. In new buildings, a wireless implementation may be the easier method for communicating data and information. A robust, low-power wireless communication methodology has been developed to achieve a fully integrated microsensor array system. A prototype of the wired communication microsensor array package is shown in Figure 6. The package can monitor temperature, relative humidity, room occupancy, and $CO_2$ levels. The $CO_2$ sensor can measure concentrations from 50 ppm to over 3000 ppm, easily covering the indoor environment requirements of 300-1500 ppm. The package communicates data and receives power over existing wiring. A final version would be the size of a cell phone that plugs into an electrical outlet. A wireless version would be about the same size and could mount essentially anywhere in a room. The current wireless version requires batteries, but the goal is to reduce the power consumption to where energy scavenging would handle the power requirements and batteries would not be needed.

To be clear about the current status of this research, the $CO_2$ sensor requires more research to obtain a stable, drift-free measurement and the IR MC requires more refinement to consistently detect occupancy and

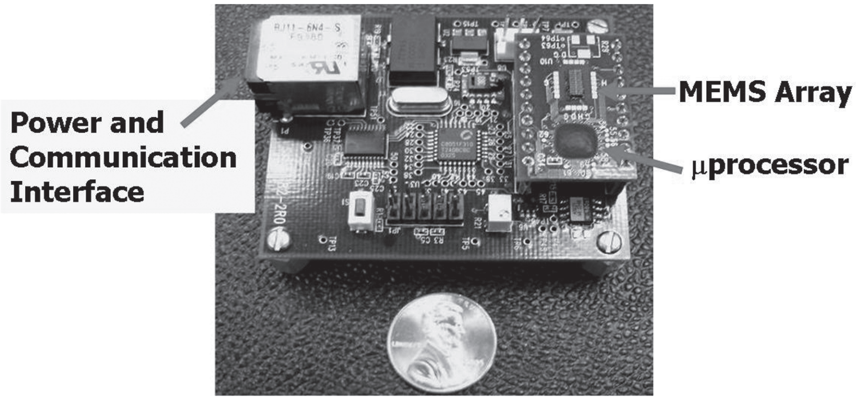

**Figure 6. Integrated Microsensor Array**

then detect motion. The microelectronics and wireless circuit designs are pretty well complete, but could be miniaturized more and the power consumption reduced by one half.

## SUMMARY

Achieving energy conservation, thermal comfort, and acceptable IAQ are often competing goals. Successful balancing of these priorities in a dynamic setting requires real-time information and controls. Various schemes and methodologies are being developed to better balance energy savings and IAQ but often fall short in implementation due to lack of accurate data, improper sensor positioning, or not enough information. To improve this condition, low-cost, robust, and accurate sensors are needed. Currently, this combination is not available; however, research is underway that is addressing this need. Microsensor arrays, using standard semiconductor fabrication techniques, have the promise of providing low-cost solutions (especially in high volumes). Prototype sensor arrays and sensor communications are becoming commercially available, and with some more development will provide the necessary information to achieve an economical and safe balance for buildings.

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