# BeeSmart - The Smart Way to Take Care of your Bees

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## Abstract

Nowadays the honey production has become a really profitable industry, however this business is characterized by the need to oversee many aspects of the beehives that can strongly influence the status of the beehive. For this reason we propose a solution called *BeeSmart* with the aim to keep under control the well-being of the bees through monitoring the most important physical quantities. These activity is usually challenging or even impossible for a direct human supervision.
With this technology we provide many fundamental features: detectors for internal humidity and both internal and external temperature measurements, the possibility to collect information on the bees activity through the detection of the flux of bees crossing the entrance.
Moreover our device presents a communication system between all the beehives and is able not only to transfer the information, but also to compare and elaborate them in order to make it easy to understand whether the situation is favourable or not. This allows the beekeeper to have a precise idea of the welfare of the entire apiary and even of a wide region that can contain many apiary.
The code can be found on Github [1].

## 1 Introduction

The interest in a device able to integrate and automate fundamental activities that characterize the beekeeper's work arises if we consider some data from this specific business.
In the United States, in 2019, 71 million kg of honey were harvested from 2.81 million bee colonies. The total value of production was 312 million dollars [2]. In Europe, in 2018, 283 million kg of honey were harvested from over 17 million bee colonies [3].
The device that we developed is able to measure many parameters without requiring on-site human supervision. Bees farming is not a simple activity since the hives are subject to various environmental factors that can affect their welfare, our product represents a solution to these main problems. Temperature and humidity are important factors when dealing with beehives, especially during crucial seasons of the year such as winter and summer [4]. There are precise ranges of values for these quantities that are ideal not only for the survival of the bees [5] [6] but also to obtain an optimal yield [7].
Our solution allows us to detect internal humidity and both internal and external temperature. This kind of monitoring is impossible to be made directly by the beekeeper, while with *BeeSmart* the detection is really accurate, not invasive since there is no need to open the beehive and it is made continuously after specific intervals of time.
It is also interesting to collect other kinds of data to understand the activity of the bees like the flux of bees through the entrance. This choice allows us both to be aware of the welfare and to know the working activity of the bees. Merging all this information with the period of the year we are able to propose to the beekeeper possible solutions to increase their productivity.
All the features explained above are really useful for the single beehive. However, *BeeSmart* is not just that, it also provides a great communication system. All the information collected for a single beehive is periodically transmitted directly to the beekeeper's home. With this function it is possible to compare all the single beehives in an apiary to understand the critical situations that require a field intervention or to have an idea of which cases are the best prospect for the production. *BeeSmart* does not just provide every single data collected in the apiary making it easy to understand if there's a specific problem, but it is also designed to analyse the data and communicate to the beekeeper the overall status of a beehive and the status of the apiary i.e. outlier beehives. Even though *BeeSmart* is able to report the recorded problems of an apiary, we developed a wider communication system: once the data are transmitted to the home they are uploaded to a server. This operation is the key to map all the regions where *BeeSmart* is implemented in such a way as to understand the ideal places to bring or create the bees farming. As a consequence, a beekeeper is facilitated in the decision of nomadism, technique in which the hives are moved in regions with better conditions. Furthermore, the spread of diseases and parasites as well as adverse environmental

conditions can be tracked day by day preventing big issues like economic losses. Lastly, we made the implementation of *BeeSmart* as simple as possible: all the sensors fit perfectly inside a generic hive or a crown board designed for this purpose can be implemented on a standard hive.

# 2 Related Works

Beehives monitoring is a complex activity because it implies keeping under control many variables like the beekeeper does. Temperature, humidity, weight, food, noise, internal activity, honey production, parasites are just some examples of the main factors that can be supervised for the well-being of the bees. Ideally the perfect system should be able to control all these aspects, but in practice it is really difficult and little efficient to do so, since some of these elements can provide more than an exhaustive idea of the status of the beehives, especially if combined.

That being said, it is not surprising to know that the products that can be found on the market try to find the right balance between various aspects like provided services, cost and level of intrusiveness. This means that there is a certain variety caused by the different kinds of controls and implementation that are chosen. The functions implemented in *BeeSmart* can be divided into two categories: sensors and communication systems. Below we show what is available up to this time following this division.

*Sensors*

The commercial products always provide temperature and humidity sensors since they measure two highly significant parameters and differ in the technology for temperature sensors and the choice of the other implemented sensors. Among the temperature sensors available on the market the most suitable and used are IR imaging and IC thermometers. The former has the advantage of giving data about heat distribution and the drawbacks of having a bad accuracy and a high cost. The latter has better accuracy, it costs less than the previous one and it can give spatial resolution if organized in a matrix shape.

*3bee* [8] sells devices containing IR imaging thermometers, scales for the beehive weight, humidity and noise sensor whose price starts from over 450€. *Solutionbee* [9] produces a really invasive device to monitor only temperature and humidity in a single point and a device to measure the weight at 319$, neglecting the price of the communication system. The market offers options that help to keep under control also parameters that are not physical quantities, i.e. the presence of parasites. An example of this kind is *IoBee* [10], a project that has received European funding. In addition to the above features, *IoBee* guarantees to be able to count bees entering/exiting the hive and detect the potential presence of invasive species thanks to optoelectronic sensors. These are interesting features, however *IoBee* devices are not available on the market yet. Another element that can be taken into account is the fact that a beekeeper could own more than one apiary that could be located in different places. This makes a feature like a communication system necessary.

*Communication System*

The main technologies available on the market are Wi-Fi, Bluetooth [9], data SIM card [8], Zigbee [4] and LoRa.

Devices based on Wi-Fi could lead to limitations due to some factors like the location of the beehives, but also advantages due to the unnecessary use of a gateway. The bluetooth can represent a first step to reach a gateway which will have to be in proximity of the apiary, therefore it isn't the definitive solution since it works within short ranges. Data SIM card is a more direct way to transfer data, however it is more demanding from an energetic point of view compared to the other technologies. Zigbee and LoRa are less exploited technologies but still represent a valid solution.

However it's difficult to find a service that exploits all the beehives from different beekeepers to compare them and create a bigger picture of the conditions in various regions. Usually, indeed, the products on the market equipped with a communication system provide only the data from a specific group of beehives.

# 3 Proposed Solution

The goal of our system is to control the status of the beehive. The vision behind this system is that every beehive in an apiary would be equipped with a series of sensors that will transmit their values to a server in order to elaborate them and help the beekeepers in their choices.

## 3.1 Specifications

The requirements are divided into two categories:

*Functional Requirements*

- **Capability to raise alarms when a beehive is in critical situations**: the system should be able to detect a critical situation (e.g. death, predicted death by colony collapse disorder (CCD)) and communicate it to the beekeeper,
- **Measure multiple physical significant quantities, each one with appropriate precision**: since the colony is a highly non-linear system there is the necessity to get a general idea of the hive's status through correlations and comparisons between different physical quantities.

*Non Functional Requirements*

- **Modularity**: due to the presence of multiple colonies in an apiary, the monitoring device should be modular and a single gateway unit per apiary should be used,
- **Low cost**: we want a competitive product to help the spread of the device and consequently the amount of data we can analyse to improve the decision algorithm [11],
- **Easy to implement**: the system should not need a high technical knowledge to be set up by the client,
- **Suitable for many beehive structures**: despite of the presence of standard structures for beehives, a lot of them are self made with recycled materials,
- **Wireless**: the presence of cables is often impossible due to

the various and often rural locations of the apiary,
**- Battery life**: the system should have low consumption to be able to run the device for few months without changing batteries,
**- Non intrusiveness**: it is essential that the device doesn't bother the bees.

## 3.2 Components

*Sensor Analysis*

To follow the requirements above, i.e. simple implementation, reduce intrusiveness and costs, we chose a limited number of sensors. At the same time we needed a selection able to give us a general idea of the status of the beehives.

| Colony state | T | S | W |
|---|---|---|---|
| **Individual colony** | | | |
| Death | Y-Y | Y-Y | Y-Y |
| Intensive brood rearing | Y-Y | ?-? | ?-N |
| Broodless state | Y-Y | ?-? | ?-? |
| Swarming state | 0-? | 0-? | 0-Y |
| **Colonies comparison** | | | |
| Illness | ?-? | ?-? | ?-? |
| Lack of food | ?-? | ?-? | Y-Y |
| Queenless state | ?-? | ?-? | ?-? |

Table 1: Table adapted from [11]. Legend: "T"=Temperature, "S"=Sound, "W"=Weight. The first letter in the cells indicates the passive wintering period and the second the active summer period. "Y" - can be identified; "N" - cannot be identified; "?" - unclear; "0" - event cannot occur

First of all we should consider which physical quantities we want to monitor and then we can analyse the available options. We went for temperature, humidity and the activity of bees. Therefore, we chose to implement 5 thermometers (1 outside and 4 inside the hive), an internal humidity sensor, and three PIR sensors.
The first and the second choices are justified by the fact that measurements of temperature and humidity are the most significant not only in terms of the quantity of information we can infer from them, but also in terms of their importance, see tab. 1, [12]. The humidity sensor provides data on the internal relative humidity helping to find critical situations like mold formation, high and low varroa mite infestation.
The third choice represents the most useful element to monitor the activity of the worker bees among our sensors. In some cases, indeed, the two sensors mentioned above are not enough to understand the status of the colony, so the PIR sensors placed at the hive entrance give us complementary information.
Other options were considered: sound and weight sensors.
Sound detectors must be microphones because we are interested in frequencies in the range of 100-1000Hz. Sound may be a useful tool to state the queen's health, but it presents some important drawbacks: it has an elevated power consumption, it requires high bandwidth in order to transmit the data acquired and it's complex to implement [13].
Weight scales must be appropriate for their goal: they should have an accuracy lower than 0.5 kg and a contained cost. However, the only information they could add is the lack of food (tab. 1), which is not so important since it isn't among the colony's main death causes. Moreover, it presents a high cost and its reliability depends on environmental factors e.g. presence of snow and rain.
In order to select the most promising solutions, a cost function was defined for each sensor using weights assigned to each parameter which is related to the system's specifications. Then for every sensor is set a score in that parameters from 0 (terrible) to 1 (optimal). The total score is computed through a weighted average.

| Fam./sens. | Suit. | Cost | Impl. | Acc. | Pow. | Avail. | Total |
|---|---|---|---|---|---|---|---|
| | 0.15 | 0.35 | 0.1 | 0.1 | 0.2 | 0.1 | |
| **Temp.** | | | | | | | |
| IR | 0.7 | 0.2 | 0.3 | 0.7 | 0.2 | 0.8 | 0.40 |
| Thermco. | 0 | 1 | 0.8 | 0 | 1 | 1 | 0.73 |
| Thermistor | 0.8 | 1 | 0.8 | 0.9 | 0.6 | 1 | 0.86 |
| Silicon IC | 1 | 0.8 | 1 | 1 | 0.8 | 1 | 0.89 |
| **Humid.** | | | | | | | |
| Capacitive | 0.8 | 1 | 1 | 0.6 | 0.8 | 1 | 0.89 |
| Resistive | 0.8 | 0.8 | 0.7 | 0.6 | 1 | 0.8 | 0.81 |
| **Bee flux** | | | | | | | |
| PIR | 0.4 | 1 | 1 | 0.4 | 1 | 1 | 0.85 |
| Photoelec. | 0.9 | 1 | 0.2 | 1 | 0 | 1 | 0.71 |
| IR reflec. | 0.9 | 0 | 0.2 | 1 | 0.2 | 1 | 0.40 |

Table 2: Scores of different sensor types on the market

Eventually we chose the DS18B20 (Silicon IC) and the DHT22 capacitive sensors since they have been tested in various scientific studies already without bothering the bees [14] [15].
Concerning the monitoring of the bees activity and well-being, an accurate bee counting is a really wasteful process, less precise measurements are indeed a more efficient option. However, sensors exploitable for bee counting were analysed to prove this statement: they presented really high power consumption, high cost, fixed dimensions which drops the general suitability and they easily get dirty. Eventually we went for the PIR sensor.

*Board Analysis*

We decided to exploit Arduino MKR WAN 1310 because of its low power consumption in deep sleep mode and its suitability to the testing phase.

*Communication System*

The LoRa communication system is appropriate for our purposes, in particular the LoRa Ra-02 model applied to a ESP32. This communicates with the Arduino MKR WAN 1310 in the apiary to get the data. The most remarkable feature of this module is its ability to transmit data within a long range with a maximum of about 10 km, but it also helps us in avoiding an increase of the consumption of energy. We also considered other possibilities, mainly WiFi, data SIM card (GSM shield module) and radio modules like NRF24. The former was discarded since it can show complications linked to a lack of coverage, whereas the data SIM card and other types of modules don't fit the requisite of low power consumption and long range communication.

### 3.3 General Architecture

In figure 1 it is shown the diagram of the arrangement of the sensors inside the beehive, it was designed to be compliant with a general hive.

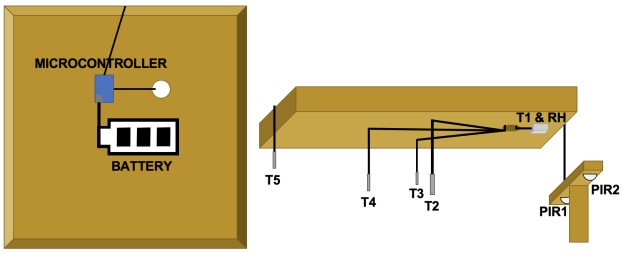


Figure 1: Sensors arrangement: T=temperature, RH=relative humidity, PIR=passive infrared sensors

The idea is to connect all the hives in an apiary to a gateway through the LoRa communication system. In this way we provide a constant update on the status of the bee colonies directly to the beekeeper. However, we want to provide a decision support system and the possibility to compare the situations with other apiaries in different locations. For this reason we developed a system whose overall scheme is reported in fig. 2.

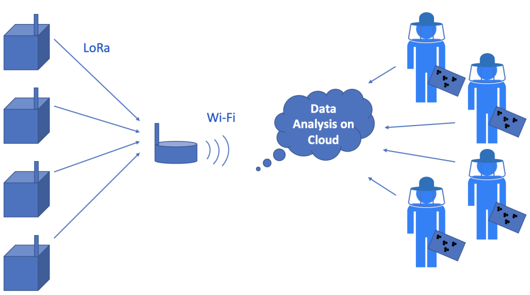


Figure 2: General Architecture

The information of the data conveyed to the corresponding house consists just in the values of the measurements. Eventually, if the location is provided with WiFi, they will be uploaded to a cloud in which the analysis phase takes place. All data on the cloud is available for anyone who possesses our device.

### 3.4 Algorithm

*Setup*

The device will enter a setup phase when turned on. During this phase a LED will turn on and the system will try to connect to the gateway. After the connection has been established the LED will turn off.

Once the data are uploaded the algorithm processes them. There are two possible analyses: status of the single beehive and of the whole apiary.

*Single Beehive*

The algorithm is able to distinguish three different situations: dead, critical and healthy beehive.

In particular the critical situation is the more complex one to analyse, in this case the algorithm can recognize different causes for a critical situation (e.g. symptoms of CCD colony collapse disorder, possible mold formation and diffusion, presence of parasites like Varroa) and report them to the beekeeper. The algorithm checks if the values of the parameters are out of the ideal range and, according to the specific anomaly, it communicates the possible causes.

*Whole Apiary*

In this case it does not make sense to create a unique distinction between critical and non critical status. The algorithm distinguishes different situations e.g. beehives with values out of the mean with respect to the whole apiary, adverse environmental conditions, anomalous mortality in the whole apiary, spread of parasites.

The system behaves as a DSS thanks to the knowledge acquired from papers and informs the beekeeper if there's the necessity of a human intervention and its possible causes.

## 4 Experimental Results

### 4.1 Prototype

*BeeSmart* is a device consisting of two different systems: the one designated to make measurements and send the data and the one projected to receive data and upload them to the cloud.

To realize the former system we exploited seven sensors: four DS18B20 for the temperature, one DHT22 for relative humidity and temperature and two PIR sensors for the bee activity. They were all controlled by the Arduino UNO placed on the hive. We developed two different ways to collect data: the LoRa Ra-02 module to transfer data from Arduino UNO to ESP32 and the SD to save data in loco. The latter was essential to easily get experimental data due to the distance between us and the beekeeper's apiary (NOT between his house and his apiary, since it would not have represented a problem for LoRa). Successively we also tested the Ra-02 module and we verified that it sends data as we wanted, since we projected an error check to reduce the probability to read incorrect data due to a wrong bit transmission.

The receiver system consists of a LoRa Ra-02 module and an ESP32-WROOM-32 chip mounted on a NodeMCU development board which is responsible for the upload of the data to the cloud. The images of the two systems and their physical implementation are reported in fig. 3. In particular the arrangement of all the elements is coherent with the one presented in fig. 1.

### 4.2 Results

We used the system described above to collect data for two weeks on a beehive from 21 Nov to 6 Dic in Meda

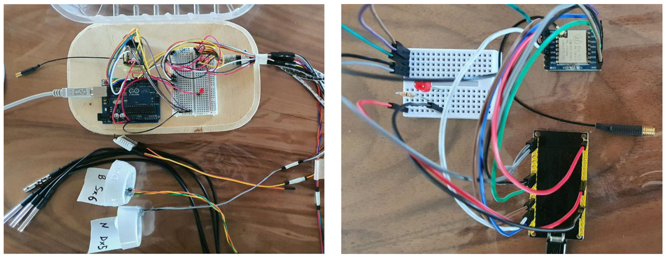

Figure 3: Prototype Transmitter ArduinoUNO and Receiver ESP32

| | |
|---|---|
| **Error rate** | 0.04 |
| **Accuracy** | 0.96 |
| **Precision** | 0.96 |
| **Sensitivity** | 0.99 |
| **Specificity** | 0.81 |
| **False positive rate** | 0.19 |
| **F-score** | 0.97 |

Table 4: The calculated parameters of the device

(DATA1). Firstly we sampled every 3 minutes, but after the data analysis on the results we noticed that this rate was oversampling, so we present results characterized by a sampling rate of 15 min. We used this data together with others coming from beehives in Campagnatico, Tuscany (DATA2) that we found on a website [16]. To analyse them we programmed with Matlab and Thingspeak. We performed a moving average on the set DATA1 to decrease the noise as reported in fig. 4.

We divide the results of the experiments into two categories: physical implementation and analysis of the code.

Concerning the physical implementation of the device the experiments showed that the solution we adopted is indeed non intrusive, since the bees were not stressed by the presence of any sensor. The device was not affected by the rain during the days of data collection thanks to it's smart positioning. Employing Arduino MKR WAN 1310, we estimate that the device can work for about three months with a 27000mAh. Unfortunately the amount of data we could collect was limited due to the death of all our hives and the short amount of time we had, but it was enough to verify the functioning of our code.

The first thing we checked was the classification algorithm, so the ability to recognize the hive status: dead, critical or healthy. This algorithm is based upon [14] [17], standard values of honeybee survival and our experience. The first step consists in the recognition of the extreme states: dead or alive (critical and healthy states are included in the alive state). Therefore, we run our algorithm upon data with the intent to distinguish them. Due to the complexity and non-linearity of the weather trend and of the beehive system, we consider each day as independent and not as the evolution of the same beehive. In tab. 3 we report the confusion matrix built with the number of days in which the status was recognized correctly. We obtained an overall accuracy of 81% for death recognition.

| **n=356 days** | **Predicted: Alive** | **Predicted: Dead** | |
|---|---|---|---|
| **Actual: Alive** | 14+273 | 0+2 | 14+275 |
| **Actual: Dead** | 0+13 | 2+52 | 2+65 |

Table 3: Confusion matrix of the status detection experiment. The data are organized as (DATA1)+(DATA2)

The critical state can be divided into a lot of substates, each with more than one cause and various effects. We focus on: CCD, cluster positioning, brooding attempts and values outside optimal ranges.

For CCD detection the algorithm recognizes low bee activity and population. This is done by comparing the external temperature with the internal one, the latter will have a similar trend but shifted at higher T due to the presence of the bees. This is possible only if no brood is present.

For cluster positioning we exploited the arrangement of the sensors calculating the maximum temperature values and a noise estimator calculated as the maximum of the averages of the absolute difference between the temperatures and their corresponding values filtered with the moving average. The cluster of bees was identified correctly in DATA1 thanks to the temperature sensors T1 and T4. The code extracts spatial information also from the PIR sensors, since a significant higher activity from one of them means the bees enter in the hive through a preferred side. In our experiments the beehive was quite symmetric (see fig. 5).

For brooding attempts recognition the code counts the number of brooding days and alerts the beekeeper if the brooding lasts before 22 days. In the fig. 4 we can see an unsuccessful brooding attempt that was correctly recognized by the code, as a matter of fact no brood was seen during the positioning of the sensors and the graph of the following week confirms that no brood was present.

Concerning values outside optimal ranges in our experiments (DATA1) and in DATA2, we successfully detected one day of too high internal humidity DATA1 (the beehive was healthy also because it received an extra varroa treatment) and a critical situation (CCD and low humidity) before death in DATA2.

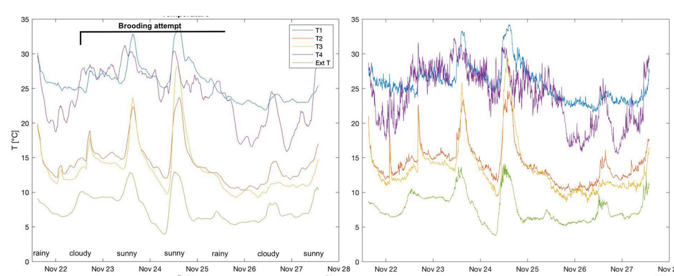


Figure 4: DATA1: Comparison between data before (right) and after (left) the moving average. The code warns about a possible brooding attempt

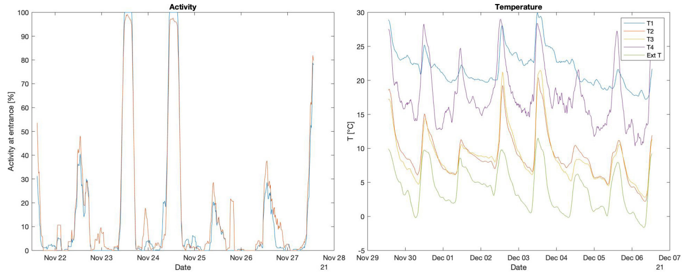


Figure 5: DATA1: Bee activity during the first week (left). First week after the possible brooding attempt (right). Internal temperature oscillates

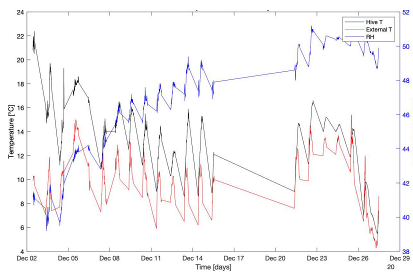


Figure 6: DATA2: the code warns about a critical low humidity and temperature before the death

Lastly the consumer can receive a user friendly feedback every 8 hours that summarises the overall status of the beehive which is reported as a text on Thingspeak.

### 4.3 Errors Check

The complexity of the whole process, from measurements to the upload and analysis of the data, generated by the high number of steps that compose it, raised the need to come up with some error checks. Firstly we created a method to identify the sensors that do not work correctly exploiting errors calculated with respect to a moving average, in this way if we find a sensor whose error is too big with respect to the others, we know it may be a failure. Moreover, when the sensors do not answer to the call properly, their output is set equal to a precise value (-127 for temperature, -126 for humidity), so we can ignore them. A visual check for the correct functioning of the LoRa Tx and Rx module was implemented using a led that turns off when LoRa is ready. Lastly we designed a system to transmit the data bit by bit in order to minimize the communication traffic, the possibility of errors and include the beehive identifying characters. These characters have been chosen to be at least 2 bit far from each other. This made it possible also to implement a check of the length of the packet that with this method is fixed. In addition the packet is rejected if it presents more than 1 out of 3 identifying characters wrong.

## 5 Conclusions

As shown above the prototype is able to classify the status of the hive and warn the beekeeper about the main problems before a death event. In addition the costs are really low when compared with the options on the market: $(75 \cdot n + 25)$€ where n is the number of the hives with BeeSmart implemented. These results were reached without renouncing the modularity, the ease of implementation and the possibility to keep under control the hives from home.
Further improvements consist of:
- increase of the number of the data and the corresponding ground truth that would improve the ability of the code to predict and analyse data with a greater variability,
- algorithm comparisons between different beehives of the same apiary to gain greater accuracy in the recognition of critical states,
- implementation of Fuzzy Logic.

A fundamental future implementation is the possibility for any consumer to access to the data of the whole territory, that is one of the peculiarities of this project. Furthermore, AI based DSS could be used in future thanks to the possibility of fast diffusion on the market of the product due to its low cost.

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