

SUPERVISORY CONTROL FOR PEAK REDUCTION IN COMMERCIAL BUILDINGS WHILE MAINTAINING COMFORT

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ABSTRACT

This paper describes a supervisory control strategy for limiting peak power demand by small and medium commercial buildings while still meeting the business needs of the occupants and without compromise in comfort. This control strategy has two features that make it relevant to new and existing buildings. First, it is designed to operate with building equipment, such as air conditioning and refrigeration systems, as they are presently installed in most small and medium commercial buildings. Therefore, the supervisory control could be realized as a software-only retrofit to existing building management systems. Second, the proposed control acts as a supervisory management layer over existing control systems, rather than replacing them outright. The individual controls make requests to the supervisory control which strategizes its responses to accomplish energy performance objectives.

INTRODUCTION

Reducing the peak power demand by a building can reduce electricity expenses for the

building owner and contribute to the efficiency and reliability of the electrical power grid. For the building owner, reducing peak power demand can reduce expenses by eliminating peak power charges from electricity bills. For the power system operator, reducing peak power demand leads to a more predictable load profile. This favors scheduling the operation of cost-efficient but inflexible power generating resources such as large coal and nuclear plants. Additionally, it can reduce the need for more flexible, but less efficient and more expensive, generating resources used to meet unanticipated short-term demand.

The supervisory control strategy described here is targeted to limit peak power demand by small and medium commercial buildings. This is particularly useful to reduce the overall peak demand for building owners while maintaining a relatively flatter energy use profile. The algorithms described accomplish these objectives without sacrificing the occupants' needs with an option to degrade gracefully in extenuating conditions.

BACKGROUND

The application of different types of supervisory control in buildings has been well studied [1]. Various approaches including the application of genetic algorithms [11], optimization using thermal loads [1, 5], personalization [12], as well considerations for networks for remote supervisory control [9] has been investigated.

The control strategy presented here features two key aspects that make it useful for new and existing buildings. First, the algorithms

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are designed to work with existing equipment such as HVACs and control equipment which are typically present in most small and medium commercial buildings. Therefore, the supervisory control can be realized as a software-only retrofit to existing building management systems. Second, the control strategy acts as a supervisory management layer over existing control systems rather than replacing them or requiring significant modifications to existing building management system design.

The primary idea of this approach is that the controls for individual building equipment request energy resources for a control action and the supervisory control examines the requests and decides which control actions to allow while satisfying a limit on peak power demand.

SUPERVISORY CONTROL ALGORITHM

The control strategy borrows key concepts from prior theoretical work on scheduling electrical loads to limit power consumption while meeting criteria for the satisfactory performance of the loads. The essential ingredients of these control strategies are

assumptions concerning the behavior of the electrical loads and the information that is available regarding their operation. In the approach presented here, the following assumptions have been made:

- Each electrical load has its own control strategy that determines when the load should be idle and when it should be active according to its application, such as heating or cooling.
- Information concerning this strategy is not available to the supervisory control. In particular, the supervisory control does not know a priori when the loads will desire to operate and what the desired duration of that operation will be.
- The electrical load will become active only upon obtaining permission from the supervisory control, and will become idle upon receiving such a request from the supervisory control. This is illustrated in Figure 1.

The electrical load supplies two items of information with its request to be activated: (i) the minimum length of time that the load must be active before it can be turned off and (ii) the maximum length of time for which the load can wait before its request is served.

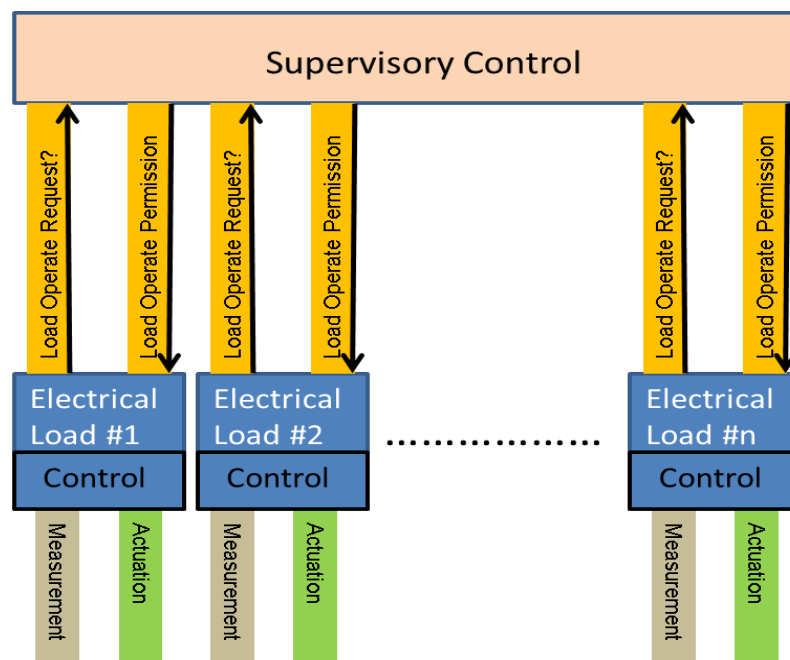


Figure 1: Illustration of supervisory control.

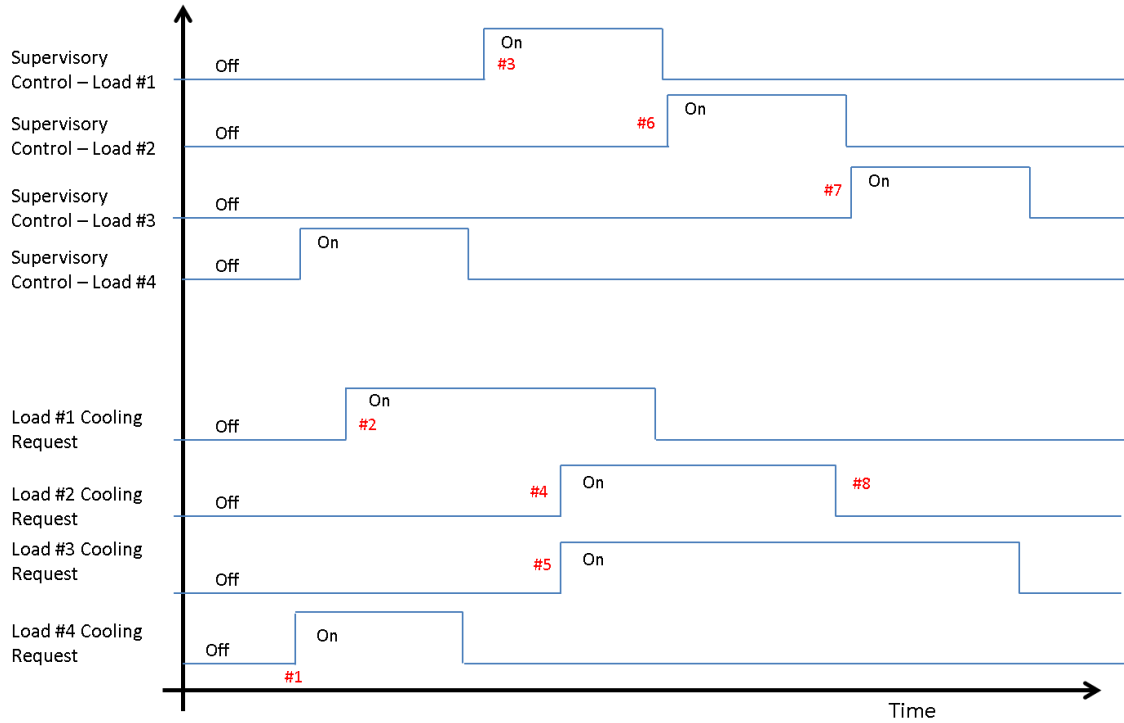


Figure 2: Supervisory control of four loads with limit of one operating.

Say, there are N electrical loads that can operate simultaneously without incurring peak demand charges. The objective of the supervisory control is to operate no more than N loads at all times while satisfying the constraints and to exceed N only when the constraints cannot otherwise be satisfied. The control strategy could be extended to use a limit on total energy rather than number of units, and if the load energy is known, then the algorithm could operate units to maintain this energy limit. This could create an opportunity to coordinate loads and distributed generation.

Basic Control Concept

Before proceeding to the details of the control algorithm, we provide an illustrative example to create an intuitive understanding of the essential concepts. Figure 2 illustrates four identical HVAC cooling loads that are limited by the supervisory control to only operate one unit.

The four loads experience conditions that require cooling, and this causes the loads to send requests for energy for cooling to the

supervisory control.

Event #1 in the figure is Load #4 requesting cooling. Because only one load is requesting activity, the supervisory control concurs with the Load #4 request for cooling.

Before Load #4 finishes cooling, Load #1 requests cooling (event #2). The supervisory control postpones the operation of Load #1 until Load #4 finishes so that it satisfies the limit of one unit operating, after which Load #1 is enabled (event #3).

While Load #1 is operating, Loads #2 and #3 request cooling (events #4 and #5). The supervisory control postpones their operation because Load #1 is already in operation. After Load #1 finishes cooling, the supervisory control directs Load #2 to provide cooling (event #6) and postpones the operation of Load #3. Load #3 is enabled after the completion of Load #2's operation (event #7).

In this example the effect of balancing load limits versus building cooling needs demonstrates the complexity of managing

identical loads. Loads that differ in energy consumption, time scales of responses, and priority – a pertinent example for supermarkets and convenience stores is air conditioning and refrigeration - will further complicate the load management. Addressing these complications is the goal of the supervisory control that is presented in the next section.

Control Algorithm

The supervisory control maintains three lists:

- A list of requests that are waiting for service (the wait list),
- A list of requests that are being served but have not yet met their minimum active time (the run list), and
- A list of requests that are being served and have met their minimum active (the slack

list).

A timestamp is associated with each request in a list. For the waiting list, this timestamp is the time by which the request must be served (i.e., the time of receipt plus *maxDelay*). For the running list, this timestamp is when the load can be safely deactivated (i.e., the time of activation plus *minActive*). For the slack list, this is the time of activation.

The control operates on four types of events: i) the arrival of a new request, ii) the cancellation of a request, iii) the expiration of the timer set on the first request in the wait list, and iv) the expiration of the timer set on the first request in the run list.

New requests are started immediately if this will not exceed the limit on the number of requests being serviced simultaneously. If not, the longest running job that has exceeded its

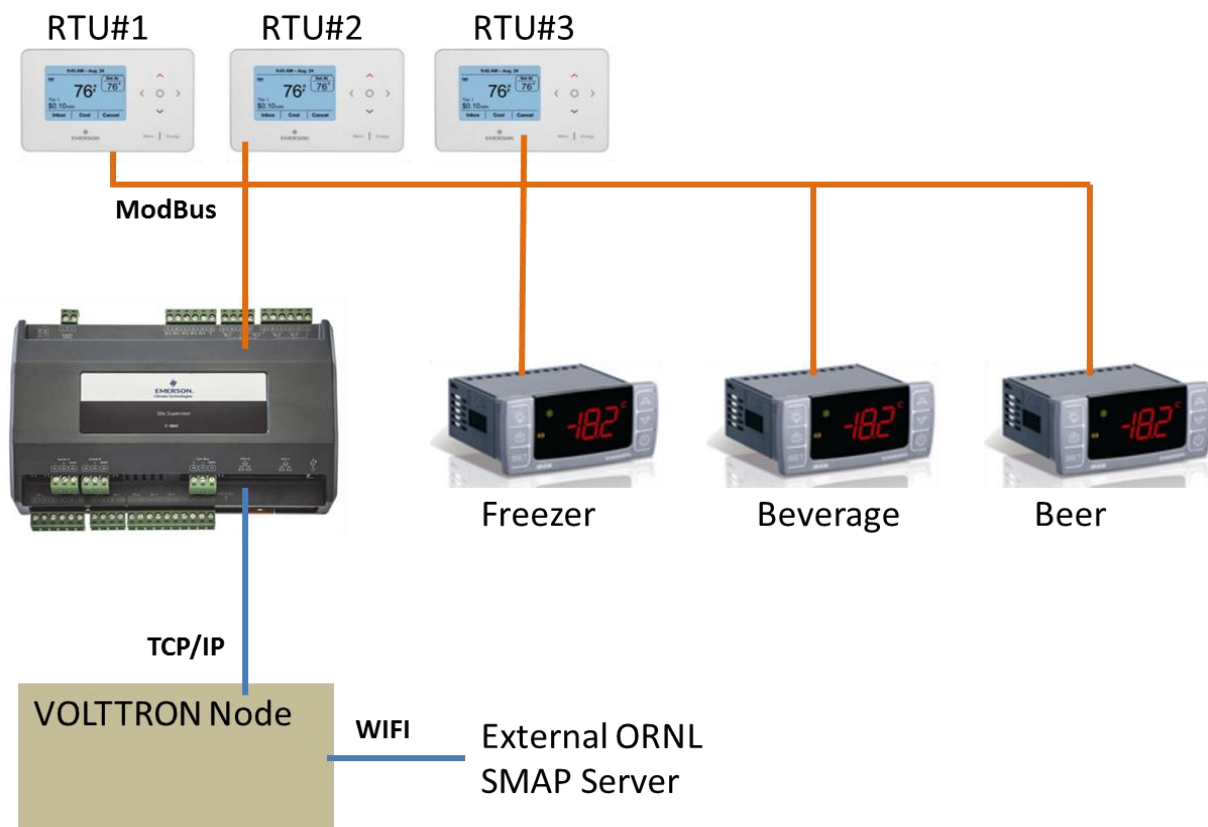


Figure 3: Deployment Site Control Architecture.

minimum requirement is deactivated and the new request is serviced. Otherwise, the new request is put into the wait list.

The cancellation of a request causes it to be removed from the list it resides in. If this is a job in the run list, then the first waiting request will be serviced as long as any limit on simultaneously active equipment is not violated. Timer expiry triggers the control algorithm to evaluate the job queues and transition jobs across lists. When the timer for the wait list expires, the waiting job can wait no longer and is immediately serviced. When the timer for the run list expires, service for the first request in the wait list is started or the expiring request is moved to the slack list.

The above procedure favors waiting requests that have not met their activation deadline over running requests that have met their minimum running time are still in operation. A different set of procedures could be constructed that reverses these priorities while still satisfying the goal of keeping the number of active equipment at or below N unless the deadline constraints cannot otherwise be met. It is not immediately clear which prioritization is preferable, or if any preference can be reasonably justified. This question remains a topic for future research.

VOLTTRON-BASED IMPLEMENTATION

The next stage of control development was implementing the algorithm as an agent within the VOLTTRON infrastructure [1] and to test the algorithm in a real-world setup. VOLTTRON is an agent-based platform for distributed control. Emerson Climate Technologies (ECT) obtained permission for Oak Ridge National Laboratory (ORNL) to perform collaborative testing at a convenience store in Kennesaw, GA. The deployment site has an ECT Site Supervisor building management system which uses ModBus to communicate with thermostats and refrigeration case controllers. The Site

Supervisor controls three roof-top units, one low temperature and two medium temperature refrigeration cases, lighting, and various other miscellaneous loads in the store. The thermostats control the three HVAC roof-top-units (RTU's).

ECT provided technical guidance to the ORNL team to enable the development of communications capabilities for reading and writing information (GET and SET) from a VOLTTRON node and the Site Supervisor. The deployment of the VOLTTRON application involved establishing reliable communication and functionality with the equipment controller and deploying the VOLTTRON agent onsite with the controller to monitor and issue commands to control the equipment.

One of the major difficulties encountered in development of communication with the Site Supervisor was determining deployment specific application configurations. Buildings have equipment configured in unique configurations. Further, these configurations changes lead to changes within the Site Supervisor which are time consuming and error prone to discover manually.

To meet the challenges in identifying equipment configurations and their relationship to the Site Supervisor, a deployment and configuration agnostic auto-discovery tool was developed to help with automatically generating an Application Programming interface (API) for a given Site Supervisor installation.

Most of the development and development testing was performed at ORNL with an ECT Site Supervisor and a thermostat that was provided to ORNL by ECT. There was no store equipment connected to the Site Supervisor and the thermostat at the ORNL location. Therefore, most of the development required an emulated setup.

The deployment was the first on-site experiment and a cautious step-by-step set of tests and controlled equipment triggering was

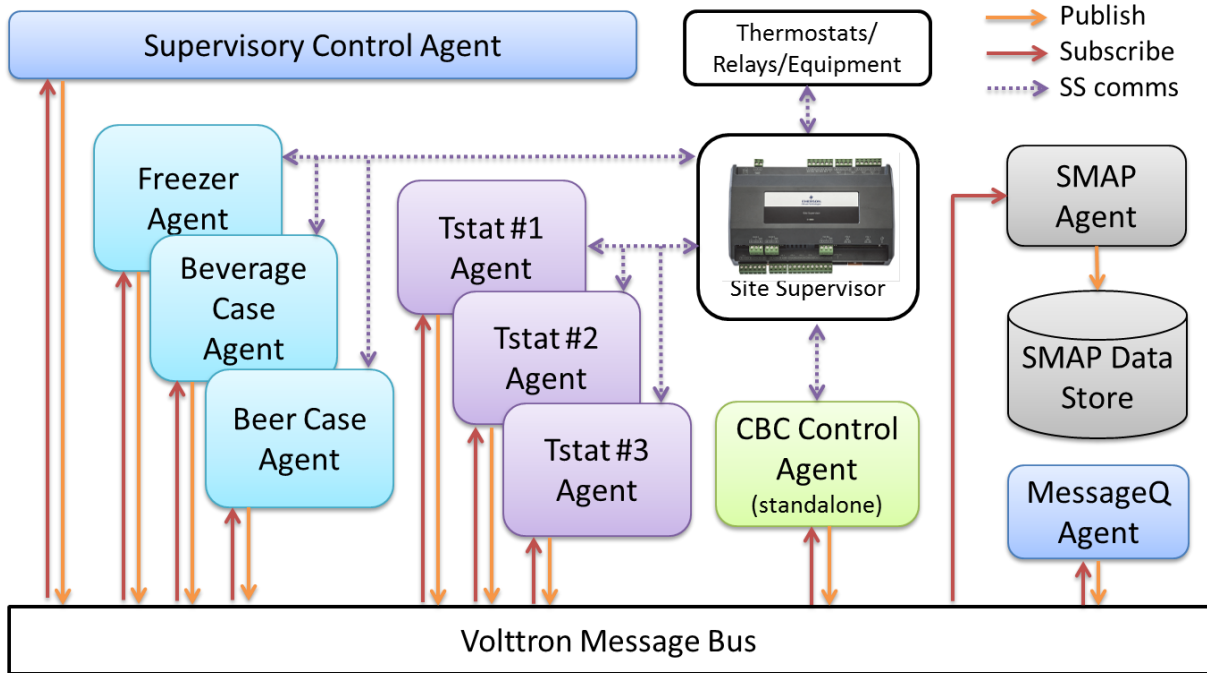


Figure 4: Agent architecture for the supervisory control algorithm and other agents.

done to gain confidence in a real-world setting. The rest of this section elaborates the implementation of the VOLTTRON agents in-depth.

Agents on the VOLTTRON Platform

The convenience store in Kennesaw houses three refrigeration cases: one low temperature freezer, and two medium temperature beverage/beer cases, and three roof-top units with three White Rogers thermostats, and all control actions are coordinated through the Site Supervisor. On-demand defrost and supervised control of roof-top units were the chosen applications to demonstrate peak reduction.

Several agents were developed to interact with the Site Supervisor and with each other through the VOLTTRON message bus. Figure 4 illustrates the overall software agent architecture and the sections below describe the various agents. Note that all the agents logged their observations as well as control decisions on an *Institution* hosted data store (SMAP server).

Refrigeration agents for demand defrost

- Freezer Agent
- Beverage Case Agent

- Beer case Agent

All refrigeration agents implement the same demand defrost algorithm. If the discharge air temperature exceeds a specified threshold, a fixed time duration defrost event is triggered. Once the refrigeration unit comes out of defrost, the agent allows the equipment to cooldown for a specified period after which it begins to observe the discharge air temperature again waiting for it to rise. The overarching logic is that rising discharge air temperatures indicate frost buildup on the coils necessitating an on-demand defrost event whose trigger can be supervised.

Roof-top unit control agents: Tstat Agents

The convenience store had three thermostats monitoring room temperatures in three zones with one roof-top unit for each zone. A Tstat Agent was developed which monitored the temperatures and performed the switching of modes for the corresponding roof-top units. Three separate instances of this agent were used to control the three separate thermostat and roof-top unit pairs.

Peak Reduction Supervisory Control Agent to control Refrigeration and RTU agents

A peak reduction supervisory control agent

was implemented which interacted with the Freezer, Beverage Case, Beer Case, Tstat #1, Tstat #2, and Tstat #3 agents to provide supervisory control. Each of these controlled agents, when running in the supervised mode, requests the Supervisory Agent for permission to run. The Supervisory control running the peak reduction algorithm responds to the waiting agent when it schedules its execution. Each request is accompanied by a maximum wait time value and a minimum required period of execution for equipment safety which the supervisory algorithm honors.

MessageQ Agent

The development of control logic in a laboratory setting without having the actual equipment is challenging. A simple MessageQ agent was developed to supply a constant stream of equipment messages to facilitate rapid development.

RESULTS

The control software running on the VOLTRON platform was found to execute successfully and as expected. Several equipment issues were detected (such as fan not running) which prevented a full-scale testing of the algorithms in order to prevent potential equipment damage.

Even with these issues, the refrigeration demand defrost application was tested on two medium temperature cases. Multiple VOLTRON agents were

simultaneously executed controlling two refrigeration cases and monitoring the RTUs for control decisions while pushing observed variable values and control commands to a remote data store.

Figure 5 illustrates the supervisory control in operation for controlling the three roof-top units. Because of the time of the year in which these experiments were conducted, human intervention, such as placing a finger on a thermostat was required to trigger the control to issue supervisory commands.

CONCLUSION

The VOLTRON applications were tested and demonstrated in an in-store deployment. Even with the limited testing that was possible, the experiment provided proof-of-concept that the strategy could be effective.

The primary difficulty in making an

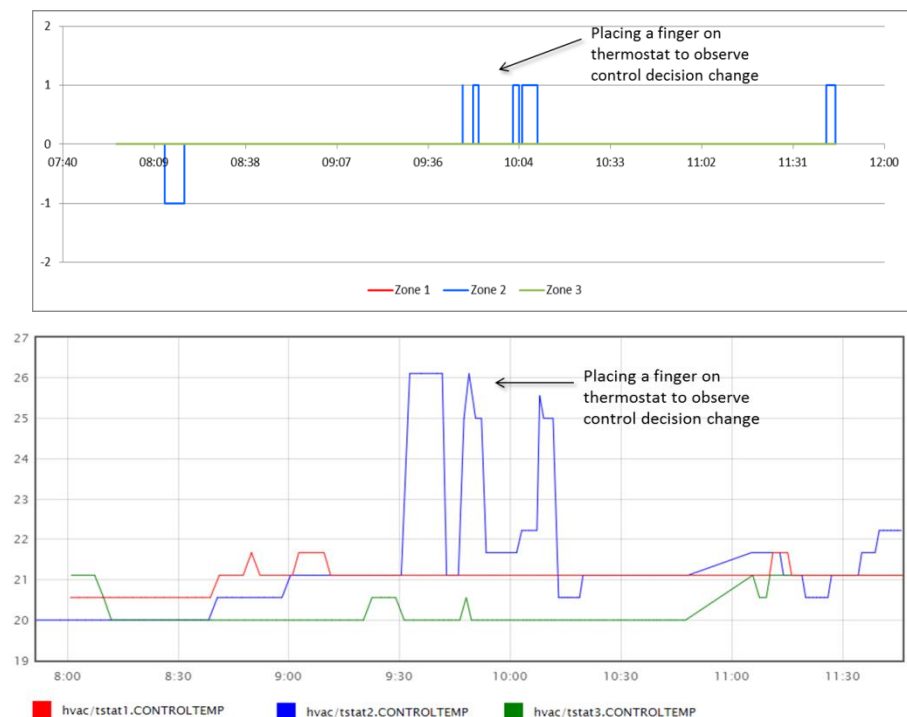


Figure 5: (Top) Decisions taken by the Supervisory Control. The states are 1 = COOL, 0 = OFF, and -1 = HEAT. (Below) Temperature recorded in the three zones. Note the spikes in Zone 2 as a result of placing a finger on the thermostat to manually trigger behavior.

extension to control arbitrary loads is the difficulty to obtain appropriate *maxDelay* and *minActive* values for the equipment in question, and to obtain a reasonable model of the systems that could be used for testing and refinement of the control strategy prior to live tests in a supermarket or convenience store.

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