Computing Heaters - An Energy-efficient Way to Provide Computing Services

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Abstract—New data centers for cloud services rapidly increase energy consumption of IT services. Now electricity is used both to power the computing hardware and to remove the heat computing generates. On the other hand, heating is needed e.g. for buildings and for hot water. However, reusing heat from data centers, e.g. for district heating, is complicated and expensive because of relatively low temperature of exhaust heat and a need for expensive infrastructure investments. In this paper, we will study the feasibility and the technical solutions for distributing computing to where heating is needed. For this purpose compact and reliable computing-heating units are developed. Computing tasks are distributed to these units based on the heating requirements in their environment. In this way the electricity used for computing is substituting the energy of the heating elements.

Index Terms—energy, distributed computing, green ICT

I. INTRODUCTION

Energy consumption of the ICT industry has become a real issue [13]. With the increasing need of computing to satisfy the computational needs of business, administration and science, massive data centers are needed. A growing concern is the energy consumption of needed computing. There seems to be at least two major concerns. First, companies that are operating large data centers are very interested in cutting their electric bill [12]. Second, so called “green ICT” activities focus on improving the environmental sustainability in a global scope [3].

In a suitable climate, this heat from computing could be used for heating buildings. For example, Finland uses annually 14 168 GWh of electricity to heat houses every year [14]. In Finnish climate apartments must be heated almost constantly [5]. The electricity used by data centers in Finland is around 1000 GWh that is 0.5-1.5% of all electricity consumption of the country but the electricity need of data centers is growing rapidly: the consumption doubled between years 2005-2010. As a result, a small part of the electricity used for heating would be enough to cover all electricity needed in data centers in Finland.

The trend has been to concentrate computing to massive data centers and equip them with efficient cooling solutions. An example of this is the Suvilahti data center, built jointly by the companies Atos, Academica and Helsingin Energia, which reaches high energy efficiency by reusing the wasted heat of the facility using Helsingin Energia’s district heating/cooling systems [11]. In this paper we investigate the opposite approach. Instead of producing the heat in a centralized data center and then transporting the heat to its users, we consider distributing the computational tasks to places where heat is needed. In particular we are looking for ways to heat houses, or produce heating elements for household use, which would do computing. From the extreme point of view, computers are devices that convert electricity into heat - and, as a by product, do useful computations.

There are some previous studies on the topic. In 2011 Liu et al. [8] proposed a concept of a data furnace which meant that instead of having the computing done in massive data centers, the computing would be distributed to homes and used as a source of heat in them. Besides the concept itself the authors also presented an analysis of the heating and revenue potential of such an approach. In this paper we extend their work and analyze the technical challenges for the feasibility of such approach.

At the moment two startup companies are already investigating this idea. A German company, Cloud&Heat Technologies (www.cloudandheat.com), aims to equip homes with locked metal cabinets containing a number of servers that are connected to a water tank. The hot water would then be used for heating the house and for the hot water. The Cloud&Heat solution is rather similar to the concept Liu et al. [8] proposed. The system requires quite a bit of space and is non trivial to install as it needs to be connected to the water and heating pipes. The system also set high requirements for network connection: at least 50 Mbit/s are required. Qarnot Computing (www.qarnot-computing.com) is a French company aiming to a more light-weight solution in form of heating units resembling electric radiators distributed in multiple rooms. The solution by Qarnot is similar to ours in that respect that we are looking for a way to create heaters that would be simple to take into use (only a regular electricity socket and network connection (wireless or wireline) is needed). However, their solution is based on high-end servers making the heating units expensive and thus requiring high utilization.

Although the basic idea is simple, a number of problems need to be solved. These include:

1) What is the optimal hardware for such a computing
heater? Aspects to consider include heating and computing capacity, ways to emit the heat, the operating temperature of the system and its influence to the lifetime, and the cost of the system.

2) What is the reasonable workload for such a system? Because distribution brings additional delay and unreliability to the system it can be hard to use for delay-critical applications. Instead we are looking how the system would work in scientific computing, where the computing times are long and the computational effort of a task high.

3) What is the necessary software solution? For instance, how would the control of the computing be handled as a function of the sensed temperature.

4) What kind of solutions make most sense? Indoor heating of buildings is an obvious case but suffers from seasonal variations. Hot water would be continuously needed. What about more specific heaters: warm plates, toasters. Or, car heating: the seats and the motor. Especially with electric vehicles the motor is not a very good source of heat anymore.

5) What is a good form factor? The heat should be emitted efficiently but ideally there should not be any noisy moving parts like fans. The components should be protected from accidental spills but still be able to emit as much heat as possible.

6) Finally, what is a good business model? Who would own the equipment (e.g. home owner, electricity company, computing company)? What kind of computing would provide the best revenue stream? How could the seasonal variations be compensated?

The list of issues to consider is long and a lot of investigation is still needed before this technology would mature. In this paper we focus on the technical aspects of the solution and investigate through prototyping the challenges that arise and what kind of solutions could be applied. In particular, the key contributions of this work are:

1) We discuss the technical possibilities to create computing heaters (Section II) and propose an architectural solution for such a system (Section III).

2) Through the development of three prototype versions of the heater, we describe the practical implementation problems encountered (Section IV).

3) We also present an analysis of the form factor issues of such heaters, in particular, comparing the heaters with a fan and a solution without any moving - and noisy - parts (Section V).

4) We discuss alternative use cases for the computing heaters both in home and in cars (Section VI).

II. COMPUTERS AS A SOURCE OF HEAT

From physical standpoint, computers can be considered equivalent to electrical space heaters. The physical processes that convert the electricity to heat are more complicated in case of semiconductors, but the end result is the same: electrical energy is converted to heat energy. The major difference is indeed the fact that computers, and more specifically the processors in them, also provide us calculations and processing power. There are, however, differences between electric space heaters and computers mostly due to completely different design goals. The computers and the different electronic components within them are designed to operate within certain temperature limits. For most components, a limiting temperature is around 85 degrees Celsius. Exceeding these limits can cause errors and instability in operation and excessive wear of the components.

The electrical heaters however are typically based on heating elements that can reach very high temperatures at very rapid speed.

What this translates to is that any heat produced by computers has to be kept within limits set by the hardware in question. In many cases, this means effectively transferring the waste heat away from the system hot-spots such as the processor. In most cases this is done using heat sinks and forced convection using fans. The problem with this is that while the ordinary electrical heater can rely on natural convection, the fans required by the computers to cool the system generate unwanted noise, especially in heating use. There are other means of cooling computer systems, such as liquid cooling that utilizes water-based coolants that are circulated through cooling blocks installed on system hot spots. These however do not completely remove the need for airflow through components and the coolant itself needs to be cooled in some fashion. The specialized parts required by the liquid cooling also increase the overall cost of the system, making it viable solution in dedicated data centers, but not necessarily in small scale systems like the computer heater prototype discussed in this paper.

The second difference that is caused by the hardware temperature limitations is that computers tend to convert much less energy to heat than comparable sized electrical heater. Additionally, computers and processors are rapidly evolving towards even lower power consumption in order to reduce the ill effects of heat and to improve overall efficiency of the systems. The result of these facts is that in order to provide sufficient amount of heating power, we need several computers which almost directly translate into greater space requirements when compared to electrical heaters.

In the world of data centers and related research, we already have attempts to utilize the wasted heat in some meaningful way. In experiments run by the University of Helsinki, a rack server was utilized to provide heat for a small urban greenhouse throughout warm and cold seasons in Helsinki, Finland [10]. A similar project was operated by the University of Notre Dame in Indiana, USA, in which a larger greenhouse was heated using several rack servers [4]. The project also outlines a computerized space heater that operates in similar fashion to our prototype solution, that is, it uses distributed computational loads to heat up space to desired temperature.

III. KEY IDEA AND DESIGN OVERVIEW

Based on the core idea of generating heat using computers, we set a number of requirements for our system. First and fore-
most, the computers converting the electricity into heat would also need to provide us with useful computations. Secondly, the amount of heat converted should be controllable accurately enough to make the use of computers as heaters practical in general. Thirdly, the system should utilize cheap and widely available, common components in order to make the solution both financially and practically more feasible. And finally the system should not require extensive modification that would limit its use in current, standard computer equipment.

The requirements of such a system limits its suitability for providing on-demand or time-critical services, as the need for heating power dictates the available computing power. Additionally, whichever service is utilized as a workload, it needs to be able to provide necessary amounts of load to the heater computers. As such the system is in its best when used for services that can utilize the additional computing power whenever it is available. Thus a distributed computation, like projects attached to BOINC, are very well suited for the system. BOINC (Berkeley Open Infrastructure for Network Computing) is a software platform and a collection of tools to distribute scientific computing to public resource computing users [2].

The solution we came up with utilizes mostly technology available at low cost and computers that have been discarded as obsolete at zero cost. The only specialized part of our solution is the temperature control unit, which is built around Intel Galileo development board which controls the CPU usage client based on temperature readings from digital sensors attached to it through ATmega micro-controller. The temperature controller and the client computers providing the heat are connected by ordinary Ethernet network connection.

The energy consumption of computing units, which translates directly into heat, is dependent on the variable CPU utilization and on the largely constant overhead of other hardware components. Thus controlling the amount of CPU usage of the computational tasks allows us to control the amount of heat a single client produces. To control the total heat output, the number of active clients needs to be controlled as well, which requires management of the heat output during the transitions. This mechanism and usage levels during transitions are illustrated in Figure 1. What the mechanism actually does is simply matching the power levels when the overhead changes, based on pre-calculated values. For example, when the system is transitioning from three active client units to four active client units, the CPU usage is adjusted to 50 %. In similar fashion, while the system is using four active client units and the CPU usage drops below 50 %, the system will deactivate one unit and set the usage to 100 %. This mechanism that operates in gearbox-like fashion helps to maintain more even temperatures as there are less drastic changes in heat output and also helps to improve efficiency of the system.

The actual operation of the system is based on centralized control of the heating computer by the temperature control unit and BOINC distributed computation projects that provide the useful workload for the heating computers. The heater computers are installed with stock Ubuntu/Debian operating systems with no limit its use in current, standard computer equipment.

![Image](image.png)

Fig. 1. Prototype power consumption at different CPU usage levels and with varying number of active units. The black lines indicate change in CPU usage when activating/deactivating units

The server script running on the embedded Linux system of the Intel Galileo constantly measures the current temperature of the environment using the digital temperature sensors interface through the ATmega micro controller. Based on the measurements and given goal temperature, the control script calculates an adjustment value to current CPU usage limit using a simple proportional-integral-derivative (PID) controller. Before sending the new CPU usage limit to client computers, the system checks whether the new value necessitates a change in the number of active computers. If the value is too low or exceeds 100 %, the system activates of deactivates a single client in the system. The new limit and possible activation/deactivation commands are then sent using UDP-packets to all heater computers.

By design, the overall system is designed to be modular and scalable. The temperature sensors used in the system utilize One-Wire communication protocol which both minimizes the amount of wiring required by the sensors and at the same time provided easy expansion of the sensor network to hundreds of individual sensors. One-wire protocol also supports network length of several hundred meters, depending on the number of devices attached. In similar fashion, it is relatively easy to modify the control logic to include these additional sensors and to monitor and control temperature at several different locations. As heater computers are standard desktop machines running widely available Linux-operating systems with no
significant modifications, the number of client computers is limited by the capabilities of the used Ethernet network.

IV. HEATER PROTOTYPES

We have approached the problem with practical prototyping to see what are the possibilities and the limits of the technology. For the prototypes we have used components that have been available for us. In massive use dedicated computer boards optimized for this kind of use would solve many problems that we are facing.

A. First prototype

The first prototype concentrated on testing the basic concept of computerized heating and temperature control system. The test setup consisted of several desktop computers and an Intel Galileo board that was used to control the heat generation. A custom-built additional board was connected to the Galileo board to provide the system with readings from digital temperature sensors. The server-client structure upon which the control of the clients was conducted was created, tested and further expanded to utilize wake-on-LAN system. This allowed the temperature control server to control the number of active computers by remotely starting and shutting down them based on currently required CPU usage. The computational load for the computers was provided through select BOINC computational projects to test that they indeed were suitable for operation in this kind of environment.

The prototype showed us that it was possible to control the CPU usage of processes accurately enough for the concept to be viable. Combined with control over the number of active computers, the system was capable to reach and maintain the set target temperature in our initial test environment. Also, as expected, the computational tasks distributed by the BOINC were found to be suitable for this environment.

B. Second prototype

The second prototype was an attempt to make the system more in the form of typical space electrical heaters. It also incorporated improvements in terms of computing power and noise levels. These were achieved by using more modern computer hardware in heater computers and replacing the hard drives of the computers with USB memory sticks. The computer housing and frame of the heater was built from fiberboard and plywood, that contained all the electronics, network, Intel Galileo board and the six heating computers themselves. Like in the previous prototype, the operating system was a Debian system running the BOINC client and client script for CPU usage control.

The CPU usage control was improved from simple limiting of specified processes to a system that actively searches and targets all BOINC subprocesses. This was necessary in order to fully utilize the dual-core capabilities of the new machines. The control system was also modified to include a possibility of testing the system with dummy CPU loads. This feature made it possible to reliably test the power consumption of the entire system. Finally, the shutdown/start up logic of the heater computers was optimized based on the tested energy consumption of the Dell computers. A simple web-based monitoring interface was also added to the Galileo board to provide real-time data on the system.

The second prototype was a definite improvement over the first concept prototype but it was not completely problem free. The design choice of using USB memory proved to be effective, but not durable solution because the active disk usage of the operating systems shortened the lifetime of memory sticks only to couple of months. Thus, a more durable solution was required without excessively increasing the noise level of the system.

C. Revised second prototype

The revised second prototype replaced the USB memory sticks used initially in the second prototype with remote booting operating systems and a network file system. The architecture of the prototype is shown in Figure 2. The solution relies on the Diskless Remote Booting Linux (DRBL) server installed on one of the heater computers. The rest of the heater computers fetch their operating systems from this computer using the PXE network booting. After the boot-up is completed, the computer accesses its shared directory on the DRBL server where its individual data and scripts are stored, and proceeds to resume computation as per instructions of the temperature control unit. As the system now has only a single disk located on the DRBL server, the new method reduces the number of hard disks or mass storage devices required by the system and thus reduces the operating noise. The added benefit of this improvement is that it also makes the maintenance and scaling up the number of computers even easier.

The new system also makes it possible to consider deploying the system in a similar fashion to the central heating system. By separating the DRBL server into a separate technical space and distributing the clients as heaters throughout the building areas needing heating, we would have a system very similar to the central heating. The clients would fetch all necessary data, including the operating systems via the local network from the centralized server whenever heating is needed. This
would permit the use of a more powerful DRBL server, as the separation to technical space would remove the requirement for close to noiseless operation.

D. Low-power prototype

Right now we are building another prototype using many low-power processors, in particular, the Intel Galileo boards. The essential idea with this is that in this way we can develop a solution that does not have any mechanical parts, such as fans, making noise and wearing out.

Our next generation prototype, consisting of Intel Galileo boards, has very low power consumption, about 10 watts. This low heat is not a problem to transfer into surrounding environment with the natural convection. The idea of this prototype is to observe how much these boards can increase the room temperature, how easy it is to transfer their heat, and also have some conclusions how this would be possible to apply with higher power CPUs and larger heat sinks. This prototype due to its low powered processors is not able to replace space heaters completely in geographic areas where large amounts of heating is needed, as the size requirements would make system impractical.

E. Test measurements

The revised second prototype underwent testing in December 2014 and some of the results are presented in Figures 3 and 4. The main aim of the testing was to see how the prototype maintains the target temperature. The tests were conducted in a cubicle with internal volume of roughly 22 cubic meters (3 meters by 3 meters by 2.4 meters), that was located in a larger hall. The purpose of the cubicle was to reduce the amount of space to be heated to a level that could be controlled by the 1100 watt heat output of the prototype heater. The four sensors of the temperature control system were installed at height of 1.6 meters to provide comparable readings, with 3 sensors located inside the cubicle (Heater, Room 1 & 2) and one sensor (Environment) outside the cubicle. A single additional sensor was installed at direct vicinity of the computers to measure the temperature of the air exhausted from the computers. During the tests, the target temperature was compared against the average of the sensors Room 1 and 2.

In Figure 3 the target temperature was first set to +30 C to see how high the prototype could rise the temperature within the test environment. Even though the computers had difficulty in acquiring tasks to compute, which can be seen in the figure of CPU usage, the heater was still able to generate a difference of roughly 5 degrees Celsius between the ambient environment temperature of the hall and the test environment. For the rest of the test period, the temperature was set at constant level 23.2 degrees Celsius, which the prototype managed to keep almost perfectly regardless of the fluctuation of the temperature of the external hall environment. Around December 8th and 12th we can see few occasions when the temperature falls below the given target due to lack of computational tasks, which can be seen in the CPU usage figure. After the system received more tasks to compute, the temperatures returned back to the target level.

Figure 4 illustrates how the system adjusts the CPU use of the attached heating computers based on the measurements from the temperature sensors. The challenge here is that starting a new task does not immediately increase CPU load and, on the other hand, running tasks should not be terminated before they are completed. We can see that in normal functionality the combined CPU usage follows very well the target CPU usage. This means that the system is able to run the right amount of Boinc jobs. The slight differences between the target and actual CPU usage are usually caused by other processes running within the operating system.

![Fig. 3. Temperature measurements in the test environment during 21-day test period](image)

![Fig. 4. Heater target and actual CPU usage during the 21-day test period](image)

V. Heat Conductivity Studies

Regarding to heat a room with computers, one challenge is to conduct the heat from CPU to the air. This is usually done by forced convection using small fans blowing air through a cooling element on the top of CPU. However, replacing radiators with a bunch of computers, the noise of the fans...
becomes a problem. The life time of the fan is also limited. Therefore, to cooling CPUs without noise-making fans would be a better solution. There are two possible solutions: the first one would be using liquid cooling by moving the heat away from CPUs. There are commonly used solutions for this but it is still relatively complicated solution. The second solution is to cool CPUs with natural convection, i.e. using a large enough piece of metal to distribute the heat to the air. Natural convection is commonly used in electronics cooling. The design of heat sink is essential for optimal cooling [1], [7]. The benefits of natural convection compared to forced convection (e.g. convection with fans) is that there is no noise-making fans, no fans that might break down and no need for power for fans. The problem with this solution is that a lot larger heat sink is needed to transfer same amount of heat into environment than by utilizing fans.

The amount of dissipated heat with natural convection depends on the area of the surface that is in contact with the surrounding air. The following equation is used to estimate natural convection from a surface:

\[ Q = hA(T_{\text{surface}} - T_{\text{air}}), \quad (1) \]

where:
- \( Q \) = dissipated heat, i.e energy,
- \( h \) = a convection coefficient,
- \( A \) = the area of the surface,
- \( T_{\text{surface}} \) = the temperature of the surface, and
- \( T_{\text{air}} \) = the temperature of the surrounding air.

There are three main components in Equation 1: the convection coefficient which depends on the shape of the heat sink, the surface area (larger the area, larger the heat dissipation is), and the temperature difference.

Obviously, CPU should be attached into a heat sink with good heat conduction and large area. It makes sense to use heat sink with fins instead of just plane plate, because finned plate has a larger surface area with the same amount of material. This means that less material is needed with finned heat sink, which means less space, material, and weight are needed for the sink. Still it is not rational to have as many fins as possible to make as much surface area as possible, since the convection coefficient of the heat sink depends on how large spaces between the fins are, e.g. how well air is able to flow between the fins. Term \( h \) has its highest value when there is no fins at all in heat sink and lowest value when fins are infinitely close to each other. Therefore calculations are needed to find an optimal characterization for a heat sink. Naturally, the actual calculations how much heat is dissipated from CPU with heat sink are not as simple as Equation 1 shows, because it is also needed to estimate how heat conducts from the CPU into the sink and inside the sink, but the basic idea and relation between heat dissipation and area of surface are shown in Equation 1. Figure V shows a model of the heat sink used in our calculations and Figure V illustrates the used model.

Table I shows examples on different size of heat sinks when natural or forced convection is used. As we can see, a normal size server CPU (e.g. 100 W power consumption) requires relatively large heat sink when using natural convection. Instead with forced convection, i.e. using a fan to cool the heat sink, the size can be remarkable smaller. As a conclusion, it is easy to notice that only a low power CPUs can be used with natural convection. The numbers on the table can be used only as examples, since even small changes in parameters can cause large changes in cooling capacity. The air temperature refers to the temperature of air on the surface of the heating element. The actual room temperature is naturally lower, e.g. 22 C.

<table>
<thead>
<tr>
<th>Length (cm)</th>
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<td>114 W</td>
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Considering the material to produce the heat sink, three metals comes to mind because of their good heat conduction abilities: silver, copper, and aluminum. The price of silver much higher than the prices of two others, thus it is not a feasible solution in practice. Although copper has better heat conduction than aluminum, it costs more and has about three times the density of aluminum making constructions heavy. That is why we prefer aluminum over copper and silver. Aluminum conducts heat well enough and in practice, a bigger challenge is to transfer heat into air with convection rather than conduction inside the metal. Natural convection itself is not depended on the material choice. By exploiting anodized aluminum instead of regular aluminum we can also have some of the heat dissipated by radiating in addition of convection. Anodized aluminum also has better corrosion resistance, in case room environment might cause corrosion damages for the sink.

![Fig. 5. Heat sink model used in calculations](image)

**VI. Discussion**

An issue with building heating is that it is rather seasonal and only needed in certain geographic areas. Therefore, we have also been looking for other use cases. The two primary ones are heating of cars and heating of hot water.

The main benefit of heating of hot water is that it is needed throughout the year. However, transferring the heat from the processors and computers to the water inside the water tank is
For this, we can see two different approaches with both having their own difficulties. The first approach would be utilizing the existing liquid cooling solutions for computers to heat the water directly or indirectly using a heat exchanger. The direct approach would circulate the water through specialized cooling blocks installed on the processors. The main problem with this approach is that any leak in the cooling system could result in catastrophic system failure. Alternatively, a failure of the pumps circulating the water could result overheating of the processors. Several independent cooling circuits would be required with adequate failsafes against possible leaks, which would in turn increase the cost of the system. The use of separate circuits and a heat exchanger could remedy this problem if suitable cooling liquid is used. However, this brings a possibility of contamination of the heated water, mainly through leaks in the cooling circuit.

The second approach would be to transfer the heat directly into the hot water tank from the processors using heat pipes. This would allow more strict separation of the electrical components from the water to be heated. There are, however, significant design challenges in this approach as the processors would require more specialized cooling blocks that could be connected to the tank using the heat pipes. Again, the cost of such solution could be prohibitive.

Both of the approaches also suffer from limitations that are hard to overcome. As we mentioned in earlier sections, only about half of the waste heat in computers was result of CPU utilization. This means that if the water is heated solely by the CPU, a significant portion of overall heat generated by the computers is still wasted. There is also some safety regulations and recommendations that should be taken into account while considering water heating systems. That is, to prevent the bacterial contamination of the hot water supply, the temperature of the hot water should be maintained between 60-65 degrees [9] and in cases of system disinfection, the temperature should be as high as 70-80 degrees. While it should be possible to generate such temperatures using processors, the higher temperatures are close to the edge of the modern processor’s performance envelope, which could cause problems in operation or premature failures of hardware.

Since our aim is to replace electric heaters by computer heaters, we can also think other locations there electric heating could be used. These include e.g. cars, mobile homes or boats. Of course, we must assume that the location is connected to the electric grid. Usually a wireless network connection should be used but it does not necessarily increase the cost much if the target location has a good cellular data connection. Unfortunately, a fast enough or reasonably priced cellular data is not available in all locations which would require a different method to generate computational load. A large problem in these scenarios is a high need of heating power, often 1-5 kW, and limited space for the heating elements. Additionally, these locations are not used all the time, so the utilization of computing heaters would easily become too low to be economically meaningful.

VII. CONCLUSIONS AND FUTURE WORK

We have studied how computing could be distributed to places where extra heat can be used for heating instead of using electric heaters. In this way, the heat generated by the computers can be directly used for useful heating and no more energy is needed for cooling computers. This approach offers clear benefits over other heat recycling methods or even so called free air cooling in which no extra energy is needed for cooling but the extra heat is not exploited at all.

We have developed a prototype systems demonstrating how a computer heater works. The tests showed that such a system can maintain the given target temperature and perform a high amount of scientific computation. Our next generation computing heater will be based on low-power CPUs making it possible to run it without a fan. In this way, the computer heater does not have any moving parts and is totally silent. Simple structure also makes the elements cheaper to build and operate.

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