Simultaneous Microwaving Architectures: An Efficient Scheme for Multiplate Heating

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Abstract

Traditional food processing technology often encounters a performance bottleneck with regards to throughput of heating. Stoves, ovens, and handheld flamethrowers have all been applied to the task of efficient food heating, with varying results. Here we present Simultaneous Microwaving (SMW), an alternative architecture for the warming of plate-based foods, and also generalize it to other categories of consumables. We evaluate the limits of the parallelism introduced by SMW and compare it to other state-of-the-art techniques. We conclude that SMW is a suitable design for the implementation of highly energy- and time-efficient food warming systems.

Keywords High-Energy Physics, Family and Consumer Sciences, Computer Architecture, Dependent Types, Machine Learning, Byzantine Fault Tolerance

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1 Introduction

From the beginning of time, people have always been interested in cooking their food. Since the dawn of agriculture, many techniques of food preparation have been devised. In the past few millennia, cooking has advanced to roasting over a campfire to self-timing induction cooktops, even as the underlying principle of food preparation has remained the same.

Cooking has several advantages that make it an attractive process. Food that has been cooked is more nutritious, more likely to be safe from pathogens, is easier to digest, and has an improved flavor profile. However, cooking is a time-consuming process that often requires several hours of continuous attention from human operators on a daily basis. Automating the preparation of food therefore has the potential to save billions of person-hours of time per year.

The microwave oven (MWO, for short) was developed in 1947 and is widely regarded one of the most influential food preparation technologies of contemporary engineering. Derived from early investigations into electromagnetic radiation in the twentieth century, including the development of radar, the potential of using radiation to heat food was quickly exploited and marketed to the masses. Modern MWOs are now found in even the most basic of households, and are regularly operated by unskilled individuals such as children. It is difficult to imagine the modern culinary environment without the microwave oven.

1.1 MWOs

The operating principles of the MWO are conceptually simple: a cavity magnetron powered by an electric power supply emits 2.45 GHz microwave radiation into the interior of the apparatus. Reflective surfaces inside the inner compartment deflect the radiation until it strikes the target food medium. Polarized molecules within the food are excited by the radiation and gain kinetic energy, eventually increasing the overall temperature of the food medium. An image of a typical microwave oven follows in Figure 1.

For those readers who may be unfamiliar, the simplified operation of the MWO is as follows:

1. The door of the MWO is opened, usually by depressing a conspicuous button at the lower-right corner of the front face of the apparatus.
2. Any existing contents of the MWO are removed, except for a circular plate at the bottom; this is commonly known as the "turntable".
3. Food to be heated is placed on the circular disk.
4. The door is restored to its original closed position.
5. The electronic interface of the apparatus is used to select parameters of heating. The parameters vary highly

*Made you look.

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Figure 1. A typical microwave oven.

depending on the manufacturer and model of the device; common parameters include duration of heating and a power level.

6. A user interface element usually labeled "start" is activated and the heating begins, continuing until an alarm (usually auditory) is triggered.
7. At this point the heating is complete. The door may be opened and the prepared food removed. The door should then be once again closed.

As is evident, correct usage of the MWO is burdensome and carries much overhead especially for inexperienced operators. Large-scale food processing requires minimization of the total time and energy required to complete the process. In this paper we will not focus on energy as it is generally accepted that a higher power rating for the MWO decreases heating time though in a nonlinear fashion. We will refer the interested reader to further reading on this subject later in the report. For now, we assume a fixed power level for the MWOs we consider.

1.2 Processing Time

The total processing time t_{MW} for a volume of food may be computed as:

$$t_{\text{MW}} = t_{\text{fixed}} + t_{\text{variable}}$$

where t_{fixed} is the fixed time overhead and t_{variable} is the variable component of processing. Fixed contributors include the time to open and close doors and (with a small degree of error) the time to specify parameters of heating. They will be treated as constant for the purposes of our analysis.

The variable component may be further broken down:

$$t_{\text{variable}} = t_{\text{load}} + t_{\text{heat}}$$

where t_{load} is the time to load and unload the contents of the MWO, and t_{heat} the time duration when the magnetron is activated and the food is being heated. The second generally dwarfs the first, and usually especially dominates the fixed component.

2 Sequential Operation

Consider the batch processing of n items of food $x_1, x_2, \ldots, x_n$. The best-known sequential algorithm to heat all units of food follows in Algorithm 1.

Result: Output vector out_i is the heated result of x_i
for $i \leftarrow 1$ **to** n **do**
  openDoor();
  insert(x_i);
  closeDoor();
  setParams();
  pressStart();
  wait();
  openDoor();
  $\text{out}_i \leftarrow$ remove();
end

Algorithm 1: Naive sequential algorithm

The time complexity of the algorithm is

$$n \cdot t_{\text{fixed}} + \sum_{i=1}^{n} t_{\text{variable}}(x_i)$$

However, in practice this process is inefficient for two reasons. The first is that the fixed cost is repeated for every food item when it may be possible to amortize it over batches of inputs. The second is that the maximum capacity of the MWO is normally not reached in the sequential approach. If we process several food items at once, we would alleviate both of these concerns. However, how this form of parallelism may be achieved in general is not obvious.

3 Difficulty of Parallelization

To see how parallelism may be challenging in practice, we consider the structure of a typical food item in a batch workload. An item consists of *food medium* held by a *food container*. The container can take many forms, ranging from polystyrene foam or paper boxes to ceramic bowls. One particularly common container is the *plate*, a flat, circular disk structure usually made from paper, plastic, or ceramic material bent gently upwards at the edges. The plate has pleasant topological properties that make it a popular choice for many types of food.

Suppose we wished to insert and heat multiple items in every iteration of the outer loop of Algorithm 1. Since plates may not physically overlap, only a limited number of plates may be placed on the turntable of the MWO. To minimize the number of total iterations of the loop, plates must be packed in an optimal configuration each iteration. This is an instance of the well-studied packing problem. Given a set of plates of varying sizes, determining the maximal number of

Figure 2. Arrangement of plates in space.

plates that will fit on the turntable is **NP**-hard. Furthermore, the greedy approach of using locally maximal fits into each iteration does not guarantee a globally optimal arrangement of plates, as the sequence of plates may need to be rearranged for an optimal batch process. Two levels of optimization are thus required in some sense, and determining the optimal arrangements is computationally complex and infeasible. A diagram of the arrangment of plates on the turntable is contained in Figure 2.

There is a further problem: even with an optimal arrangment of plates on the turntable, the vast majority of space within the MWO is wasted since the space above the plates is left empty. In practice, heuristic and approximate algorithms are used to arrange plates on the turntable each iteration, achieving respectable but less-than-optimal results. However, almost no implementations of MWO operation utilize available capacity along the vertical dimension. This optimization is the basis of our new proposed architecture.

4 Simultaneous Microwaving

We now introduce the Simultaneous Microwaving (SMW) architecture as an evolution of traditional MWO management algorithms. We first make several assumptions that hold true on almost all practical MWO batch workloads:

1. All food items are held by plates whose size does not exceed that of the turntable.
2. The height of each food item above the plate is bounded by a constant c which is less than a ratio $1/k$ of the height of the heating compartment, where $k \geq 2$. We denote k the *plating count*.
3. Plates are made of a material resistant to vertical compression, such as hard plastic or ceramic.
4. The thickness of a plate is negligibly small compared to c.

The key innovation of SMW is the utilization of available vertical space. Vertical arrangement of plates is normally impossible due to undesirable contact of foodstuffs with contaminants from above. However, it is possible to safely stack plates vertically through the use of *interlock plates*: upturned plates inserted between each vertical stage. The interlock plates protect food from contact with any surface other than the concave side of a plate. The architecture is depicted in Figure 3. We refer to the physical stack of plates as the *pipeline*, each pair of food item and interlock plate as a *task*, and the processing of each stack as a *cycle*.

Figure 3. Physical stacking of plates within the heating pipeline.

With the assumptions we have made in place, the number of food items that may be processed per iteration is at least k. The parallel time complexity of the food processing algorithm is thus

$$\frac{n}{k}\left(t_{\text{fixed}} + \max_{1 \leq i \leq n} t_{\text{variable}}\right)$$

which is a significant improvement over the sequential algorithm.

5 Task Scheduling and Pipelines

The simplifying assumption that the height of each plate is bounded by a constant means that the parallel speedup is attainable regardless of plate arrangement. Of course, this restriction may be relaxed and scheduling techniques applied to increase the utilization of space. Though we will not focus on that computationally complex problem in this paper, we acknowledge it as a possibility.

For now, we address a critical difficulty in the management of SMW schemes of heating, namely *pipeline stalls* when some food items take longer to heat than others. Suppose of the plates in one cycle, one plate takes significantly longer to process than the others. And in the worst case, this plate resides at the top of the stack. Since the stack is a LIFO structure, it is impossible to safely remove tasks that have finished heating before this task at the top, without iteratively popping from the stack in linear time. In the worst case, tasks may happen to be arranged in reverse order of heating time required, causing this reshuffling to take quadratic time. Therefore, we simplify the architecture by only inserting and removing entire batches rather than manipulating individual tasks in the stack with finer granularity. This has the effect of possibly overheating certain food items, which for our workflows is generally tolerable but may be a concern for some operators.

Since we take a coarse-grained approach each cycle, the duration of a cycle must be equal to the maximum of the required durations of each item. If it were possible to predict heating time required, this issue could be avoided, but such prediction is impossible in general. It is possible within our implementation to annotate each task with a hint, inserted automatically by the food manufacturer, in order to improve the balancing of fast and slow tasks. This information is usually printed on the documentation of the foodstuff. Such duration hints are valuable but are not universally accurate or trustworthy, so we must take the conservative approach of assuming we have zero information available before heating begins.

6 Limits to Parallelism

Ideally, a SMW system would achieve speedup of at least a factor of k over the sequential algorithm. However, in practice this does not occur for a very important reason. Since microwaves do not propagate after they impact a food medium and impart kinetic energy, increasing vertical space utilization in the MWO reduces the relative heating efficiency of the entire system and causes an effect of diminishing returns. The remainder of this paper will thus focus not only on the efficiency of implementing the parallel stacking of plates, but also the effect of decreased heating energy available to each task. A trade-off must carefully be considered, and for some systems, it is counterintuitively the case that a somewhat reduced vertical space utilization leads to overall faster heating time.

7 Implementation

We did not implement the system due to lack of time before the conference submission deadline. If we had, we would have used a 1000 W microwave oven and a wide variety of common foods amenable to microwave heating. We would have conducted the following experiments and concluded the results following thereafter. Naturally, since we did not perform any of the experiments, the following data are all fabricated.

First, we evaluated the overall heating time of several food workloads under sequential heating and also under a SMW architecture. We evaluated using the following food benchmarks. Each benchmark was calibrated to have a plating count $k = 4$.

- Bulk white rice, pre-cooked;
- "Cup" ramen noodles, chicken flavor, filled to line;
- Spaghetti with Alfredo sauce;
- Italian-style beef meatballs with breadcrumb coating;
- Dry Froot Loops® brand breakfast cereal;
- Water buffalo entrails;
- Crushed glass and pig blood;
- Literally just mayonnaise.

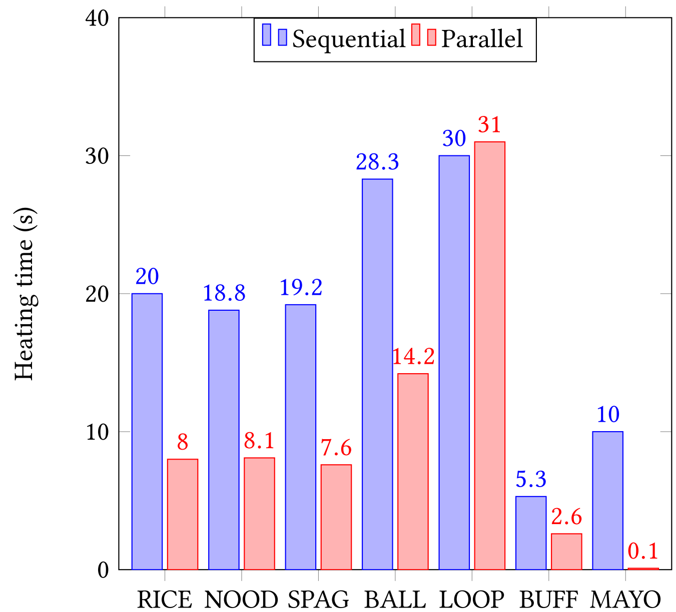

Figure 4. Comparison of sequential and parallel heating for each food type.

Using the first three benchmarks, we also adjusted the degree of stacking used, from 1 (sequential) to 4 (maximally parallel). We evaluated the relative speedup of the different options.

Finally, we evaluated the impact of plate material on heating efficacy under the maximally parallel scheme. We used polycarbonate, porcelain, clay, and silver-coated brass platings.

8 Evaluation

Figure 4 shows the heating comparison. We were able to achieve at best a 2.5× speedup over sequential heating, for the rice and spaghetti tasks. Other food types, such as meatballs, and buffalo entrails, saw somewhat more modest speedup of approximately 2.0×. Unfortunately, we were disappointed with our results for the dry breakfast cereal, which actually slowed down under SMW heating. The crushed glass task failed to heat appreciably under either regime and was excluded from the final results. Finally, we are amazed by the performance of the mayonnaise, which promptly vaporized after less than one second under SMW heating.

Figure 5 depicts the relative speedup as the stacking degree increased for the bulk starch tasks. It appears that increasing stacking degree to 2 nearly doubled the speed of heating. However, increasing it to 3 had a more modest improvement, and increasing it to 4 had almost no effect at all. It is clear

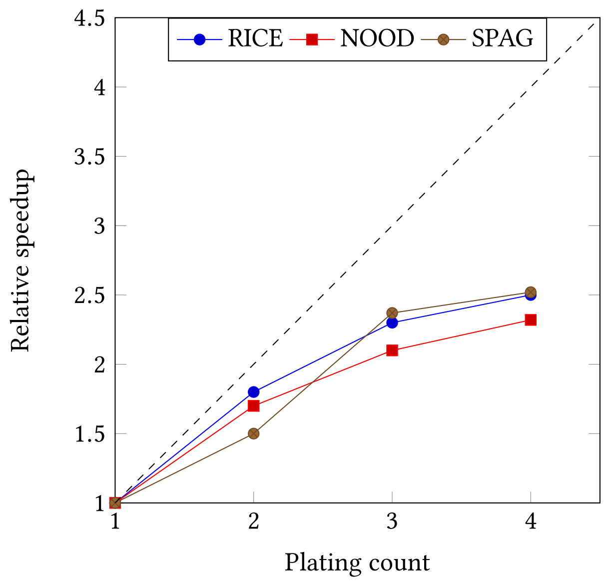

Figure 5. Relative speedup as degree of stacking increases.

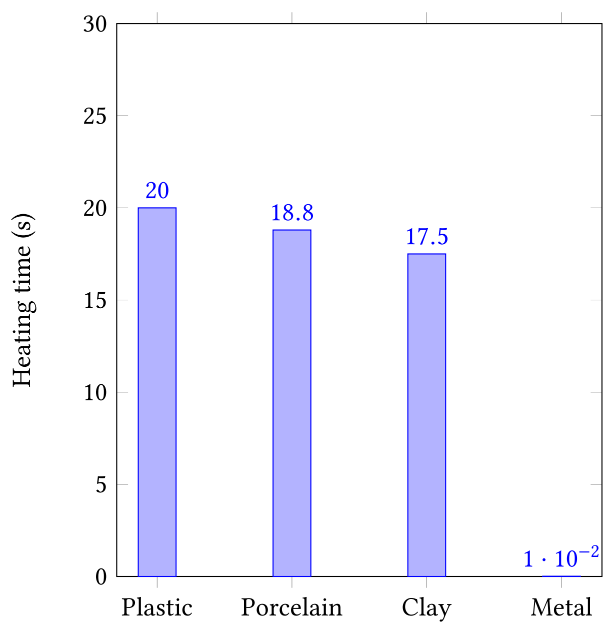

Figure 6. Effect of plate material.

that the bottleneck of microwave penetration bandwidth is reached relatively quickly.

The last study, Figure 6, shows the effect of plate material. The choice of plastic or ceramic plate material appears to have had no significant effect on heating efficiency. Upon the fourth trial with silver-coated brass plating, a large blue arc appeared inside the MWO and caused a large electrical fire which took approximately one hour to contain and destroyed the experimental appratus. We assume the food was cooked in that circumstance, though we were unable to recover the sample.

9 Conclusion

We have introduced Simultaneous Microwaving (SMW), an effective mechanism for improving the work efficiency of heating common foods using microwave ovens. It is relatively simple to implement and has been demonstrated to present marked improvements for a wide variety of food workloads. Despite the presence of a significant performance bottleneck of microwave penetration, systems that use a modest degree of SMW parallelism observe a large increase in heating efficiency. We believe this technology is an exciting tool that will revolutionize the culinary world.

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