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A survey on thermal management techniques of microprocessors

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Abstract—*The basic theory behind cooling a processor is the concept that heat flows from a region having a low temperature to a region having an higher temperature. The equation governing this transfer is Fourier's law which can be basically stated as q = k A dT / s, where A = area available for heat transfer , k = the thermal conductivity of the material , dT = temperature difference across the material, and s = material thickness. All the techniques that is discussed in the paper uses this principle as the basics in one form or the other. Conventionally this has been done with the help of heat pipes and an heat sink. Almost all of the CPU cooling done in consumer PCs and laptops follows this variation of the above technology. Another method is using nanotubes in which, Joule's law states that heat is produced by an electric current flowing through a conductor and is directly proportional to the resistance and the amount of time, current flows in the conductor. It can concur that the amount of heat generated is directly proportional to the number of transistors.*
From this we can see that overheating in a microprocessor is a major issue and must be addressed right away.

Index Terms*—hotspots, heat sinks, heat pipes*

I. INTRODUCTION

In the past few years the computing performance have seen a rapid increase in all aspects of modern life. Year by year the microprocessors have seen a rapid change in its size and properties. The microprocessor has become a flagship product by semiconductor industries as they doubled transistor density in an increment of two years. Amount of heat generated is **directly proportional** to the number of transistors in a microprocessor. Following Moore's Law and number of transistors in a processor rise exponentially, concerns of overheating increases as well. We can see that overheating in a microprocessor is a major issue and must be addressed right away. As power dissipation of electronic devices reach the limit of cooling capacity of current heatsinks, the demand for new developments in cooling technologies is increasing. During functioning in a user environment. Managing the thermal environment is essential to ensure reliable, long-term performance.

This paper will elaborate the issues and possible methods to overcome the huge amount of heat dissipation. We will highlight the increased understanding of the thermal management challenges and show some of the innovations developed to meet these challenges. We start with explaining the current technologies used for cooling a microprocessor. These include techniques like Vapor Chamber Cooling, Liquid Metal Cooling and other Increments of the current cooling technologies. Then we go on to explain the latest trends that are being adopted for more efficient cooling of multi-core, multi-processor systems. We will focus on use of carbon nanotube fins and embedded water cooling using micro channels. These new technologies we have focused on, can be vital for improving the thermal management capacities of future multi-processor systems. For eg., thermal conductivity of CNT is higher than that of diamond or any other natural materials due to its high stability. This is followed by description of Dynamic Thermal Microprocessor Cooling strategies with an in-depth analysis of Wattch Model and Thermal-aware scheduling model. The paper concludes with brief description about why the technologies we have discussed in this paper is integral for rapid advancement in processor development.

Basics of cooling a processor

The basic theory behind cooling a processor is the concept that heat flows from a region having a low temperature to a

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region having an higher temperature. The equation governing this transfer is Fourier's law which can be basically stated as q = k A dT / s, where A = area available for heat transfer , k = the thermal conductivity of the material , dT = temperature difference across the material, and s = material thickness. All the techniques that is discussed in the paper uses this principle as the basics in one form or the other. Conventionally this has been done with the help of heat pipes and an heat sink. Almost all of the CPU cooling done in consumer PCs and laptops follows this variation of the above technology.
The heat pipes are made of highly conductive materials (mostly copper) kept in contact with the top of the processor . Usually a thermal paste is applied to aid the transfer. The heat pipes have a design as shown in the diagram below

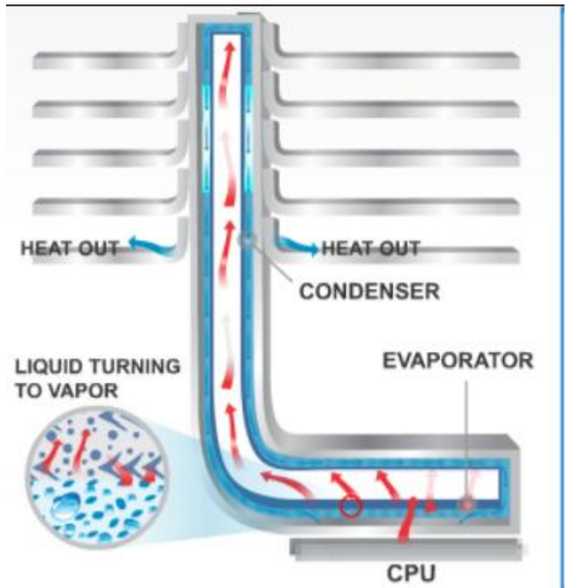
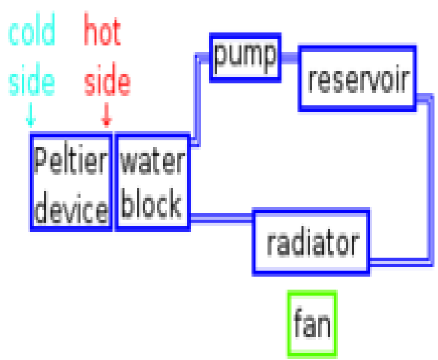


Figure1: source https://www.gamersnexus.net/guides/981-how-cpu-coolers-work

Basic heat pipe design

Heat pipes as evident from the name has a cavity inside housing the coolant. It usually is ammonia or ethanol or such liquids having a lower boiling point. The temperature of the CPU evaporates the liquids and it moves to the cooler regions acting as a condenser through the heat pipes. When the liquid coolant comes to the cooler region it condenses and forms a liquid which is absorbed by the wicks present inside the which transfers it back to the hotter regions through capillary action.
Heat sink is the region where the heat from the heat pipes is discarded. They have a large surface area to increase the cooling effect as per the above Fourier's formula. Current literature survey on traditional cooling techniques using heat pipes and heat sinks *Pelitier based cooling with a liquid heat sink*



In the paper "peltier based cabinet cooling system using heat pipe and liquid based heat sink", Nandini K.K., Muralidhara the authors uses a Peltier based cooling technique[1]. It works on the Peltier effect which is when DC current is passed through a semiconductor the heat from one side is passed onto the other side. The resulting effect is that one side becomes cool and the other side becomes hot. So in this paper the author has implemented a system where hot side is attached to liquid and the cool side attached to the heat pipes. The liquid is cooled with the help of radiators and the liquid is recirculated again. The heat pipes on the colder side are not directly connected to the processor, but the resultant cooling effect is dissipated inside the PC cabinet through fins. In most of the room temperature conditions the authors were able to maintain an almost

10 degree lower temperature inside the cabinet than the current room temperature.
Since the authors only used the heat pipes to cool the cabinet the processor could still overheat. The cooler heat pipes could have been connected directly to the processor to achieve an even greater cooling potential

Micro channels and Microheat pipes in multichip modules

Micro channels are channels etched into the silicon itself which and mostly have a width ranging from 10 to 1000micrometer. Fluid is allowed to flow at a high rate as to get maximum effect from this technique. Micropipes are highly conductive materials which serve the same the effect but has no fluids running through. These are made from graphite or copper In this paper "High Density Packaging
Enhancement Of Multichip Modules (MCMs) Cooling By Incorporating MicroHeatPipes And Other High Thermal Conductivity Materials Into Microchannel Heat Sinks" the authors discuss about the how micro channels and micro heat pipes and discuss how changing factors like fin material , heat pipe configuration and pumping power effects the overall efficiency[2]. The authors concluded that the incorporating both microchannels and micro heat pipes was the way to go. They theorized that the best way to let micro heat pipes act as a heat sink for the micro channels thereby we can overcome the limiting factor of flow rate. Moreover increasing the core size of micro channels led to lower surface temperatures. The increase was about 10 to 20% over normal plain micro channels.

Cool Chip's Kinetic Cooling Engine

The basic idea behind the standards coolers is that one heat pipe transfers heat to a heat which in turn is cooled by fans. But coolchips technolgies developed a product where all the 3 are combined into 1 . It is made of a base plate which is attached directly above the heat load that is the processor and the fan cum heat sink is placed on top of the base plate. These both plates are connected to each other with interconnecting groves. A thin layer of air still exists, between both these layers but is of little significance on the heat transferring abilities. The end result was that the according to companies claims for a similar product having a same size and and a fan spinnig at a similar RPM their product had a better cooling potential and even better noise levels upto 20dB quieter than its competitors .

Vapor chamber cooling

Vapor chamber is used to cool down the CPU more efficiently than any other traditional cooling techniques. The vapor chamber achieves this due to the reduce weight and height. It helps the CPU to work in safe operating temperatures thereby extending the component and product life. It is made of copper or aluminum container material with its inner wall made of copper mesh and copper powder sintering. The coolant used in the vapor chamber can be distilled water, methanol or acetone. The minimum thickness and maximum size of it can be 1.0mm and 250*250mm respectively. The allowable operating temperature is between -10 °C to 200 °C.

The fig 2 shows the process that take place inside a vapor chamber.

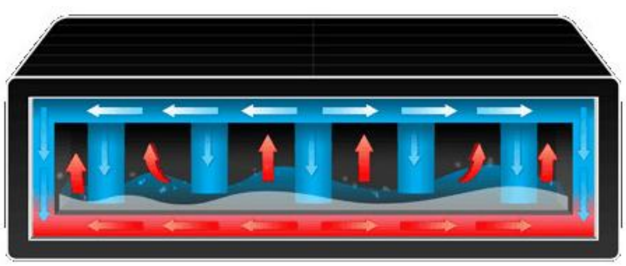


Figure 2: https://www.maketecheasier.com/what-is-vapor-chamber-cooling/. This image depicts the heat flow inside the vapor chamber when heat waves are passed through it.

The process behind vapor chamber cooling technology is that when heat waves are passed through vapor chamber, the coolant liquid molecules present inside the chamber changes its form from liquid state to gaseous state. The coolant then streams down the coolest surface area to dissipate the heat.
This active molecular coolant stream is responsible for the super thermal properties, which spreads temperature evenly on the surfaces and helps to cool down the CPU much more efficiently than any other traditional methods such heat pipes. By this process, the vapor chamber uses its entire body to cool the CPU.

The main advantage of using vapor chamber is that they can be used as a heat flux transformer for cooling a high heat flux from a microprocessor chip or a diode which can be laser to a lower heat flux that can be removed by natural or forced convection.

In the research paper,"Thin Vapor Chamber Heat Sink and Embedded Heat Pipe Heat Sink Performance Evaluations" by Garrett Glover and Herman Chu, it has mentioned about a new generation vapor chamber that maximizes the air side performance by making vapor chamber thickness to 3mm [3].This helps in maximizing heat sink cooling performance while minimizing base thickness for heat spreading and weight.
So basically the vapor chamber became more efficient by lowering weight and thinning its base.

In the research paper,"Overview Latest Technologies Using Heat Pipe And Vapor Chamber For Cooling Of High Heat Generation Notebook Computer" by Vijit Wuttijumnong, Thang Nguyen, Masataka Mochizuki, Koichi Mashiko, Yuji Saito and Tien Nguyen states that as the size of the chip decreased, the heat dissipiation increased year by year[4]. So inorder to cool the CPU, the heat must spread to a larger surface and away from the processor.

So basically the working of the vapor chamber was explained that the one end of the container is heated, causing the liquid to vaporize and the vapor to move to the cold end.
So they came into conclusion that the vapor chamber was more efficient than traditional heat pipes as the heat flow is in two dimension when compared with heat pipes, which is in one dimension. This helps the vapor chamber higher heat transfer and lower thermal resistance. It has higher heat flux capability and uniform temperature distribution, large body surface area so excellent for heat dissipation. Vapor chamber can be directly contact with CPU, eliminating conducting and contacting resistance of the "heat block" which heat pipe attached to. Fins can be attached directly to vapor chamber, having higher surface of contact so thus can reduce contact resistance and increase fin efficiency.

In the research paper," Integrated Vapor Chamber Heat Spreader for High Power Processors", by Thanh-Long Phan , Yuji Saito. , and Masataka Mochizuki presents a newly solution to improve the thermal spreading resistance between processor die and the IHS by using two phase micro channel vapor chamber[5]. The main problem was the shrinking size of the chip which leads to high power densities, thermal hotspots and large temperature variations in the die. As the number of cores in a single die increases , the power consumption also increases which thereby result in high heat dissipiation. The use of vapor chamber instead of heat spreader helps to spread the heat more effectively and can eliminate the hotspot on top of the die, thereby maintaining uniform temperature across the chip.

Liquid Metal Cooling

Principle:

The principle used in a typical liquid cooling system for computers is identical to that used in an automobile's internal combustion engine, with the water being circulated by a water pump through a water block mounted on the CPU and out to a heat exchanger, typically a radiator. The radiator is itself usually cooled additionally by means of a fan. Besides a fan, it could possibly also be cooled by other means A coolant reservoir is often also connected to the system.
Liquid metal is required to evacuate the waste warmth created by segments, to keep them inside passable working temperature limits. Segments that are powerless to brief glitch or changeless disappointment if overheated incorporate coordinated circuits, for example, Central handling units (CPUs), chipset and so on.Liquid cooling is a highly effective method of removing excess heat, with the most common heat transfer fluid in desktop PCs .

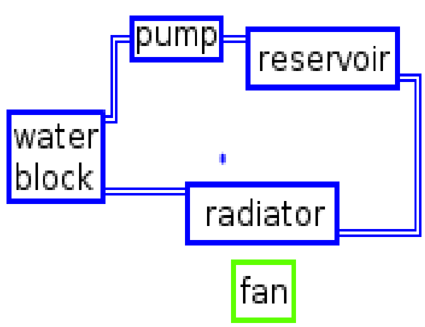


Figure 3: Schematic of a regular liquid cooling setup for PC's.

Advantages:

- The advantages of water cooling over air cooling include water's higher specific heat capacity and thermal conductivity.
-Liquids allow the transfer of more heat from the parts being cooled than air, making liquid cooling suitable for overclocking and high performance computer applications
-It has become a practice largely associated with overclocking in the form of either manufactured kits, or in the form of setups assembled from individually gathered parts.

Disadvantages

-Downsides of these systems however are that they are much less efficient in discarding the heat and thus also need to have much more coolant -and thus a much bigger coolant reservoir thus giving more time to the coolant to cool down.
-Another draw back is because of liquid cooling include high complexity and the potential for a coolant.
-There might be a leak. Leaked water or more importantly any additives added to the water can damage any electronic components with which it comes into contact.

Figure 4: Regular Peltier cooling setup for PC's.

New trends in cooling technique Amount of heat generated is directly proportional to the number of transistors in a microprocessor. As we stick to Moore's Law and number of transistors in a processor rise exponentially, concerns of overheating increases as well. We can see that overheating in a microprocessor is a major issue and must be addressed right away.
In the paper by V Goyal et.al. a novel method for using nanomaterials instead of using general metal heat sinks for Thermal Management of processors is discussed[6]. This is proposed to be much more effective since they can drag heat out much more effectively due to their unique thermal and mechanical properties.
Carbon Nanotubes are lightweight but are still stronger than most of the other materials. They can be either highly conductive or can be made semi-conductive too by adding dopants.
CNT can be metallic or semiconducting defending on chirality. Due to C-C covalent bonding they form a very strong and flexible molecular structure. Also CNT are porous in nature due to which they have a very high surface area to volume ratio. It is this high surface area to volume ratio that makes this technique highly effective. For example if we consider a sphere of Volume = 'V' and surface area = 'S' upon dividing it into a number of smaller spheres the volume remains the same but the surface area increases exponentially.Due to these properties CNT can be used effectively in processors as they can be made into very small shapes and fitted into them also their flexible properties and high resistance to heat.
In the paper by **P.Bhattacharya et.al.** a design for a **fin** is proposed using Carbon Nanotubes[7]. These fins are then used to cool the microprocessors by forced convection
The nanotube fins are mechanically superior compared to other materials being ten times lighter, flexible, and stiff at the same time. These properties accompanied with the relative simplicity of the fabrication makes the nanotube structures fesible for future on-chip thermal management applications.
To fabricate their CNT heat sink, Liu et.al.'s team has first defined the microfin structures by standard photolithography and lift-off processes. They then applied a specially developed CNT transfer technique to position the microfins at the desired position on the chip. Finally, a plastic lid was covered on the top of the CNT microfins to create microchannels through which the coolant could flow.
Another design proposed by R.S. Parasher et.al. CNT are vertically aligned along their longitudinal axes perpendicular to the substrate surface (called Carbon Nano Tube Array) [8]. Doing this, a drop in thermal conductivity of very high magnitude is observed, ranging from 0.1 to 220 W m^{-1} K^{-1}. The main reason for the significant reduction in thermal conductivity, as opposed against a single CNTs, is the relative high porosity of the foam-like CNT arrays and due to the weak thermal coupling between two or more neighbouring nanotubes in the CNT array.

There are many advantages of a foam-like vertically aligned CNT array like: -

- They are one of the few nanoscale materials that can be made from a bottom-up template.
- This is the most important featue for large-scale integration with microprocessors that replaces the need for such as heat sinks and fans.

Combining the nanoporous morphology of vertically aligned CNT's with different nanoscale conformal coatings, we can control the functionality and tune the properties of the respective material.

A Volkov et.al. also discusses experimental discovery that by using thin coatings of only a few nanometers we can achieve high elasticity to the CNT nanofoam[9]. This makes the nanofoam promising for thermal interface material replacing the pastes that are usually used.

Finally, the CNT nanofoam structures are suitable for large-scale integration with microprocessors. We therefore believe that CNT nanofoam structures are suitable for on-chip cooling solutions, like micro-fins, pin arrays and other 3D microarchitectures.

Embedded liquid cooling of multicore microprocessors

A liquid cooled embedded microchannel heat sink is capable of minimizing temperature gradient in the chip in a highly energy efficient manner. Still an experimental design, we will discuss about the performance of this technique under realistic multicore microprocessor operating conditions. An optimized design would distribute the coolant flow without any external flow control devices. The geometry of the coolant supply system to the microprocessor has minimal effect on the performance of this technique.
Most of the research on liquid cooling of chips has focused on maximum temperature (Ts,max) reduction under uniform heat flux dissipation conditions. However, it is also necessary that the chip temperature is spatially as uniform as possible. There are also few studies that focuses on decreasing the temperature non-uniformity of the chips[10]. In modern high-performance chips, the cores can dissipate on an average up to 150 W/cm2 while the rest of the chip dissipates as low as 20 W/cm2.
As cores dissipate more heat than the rest of the chip, they are referred to as 'Hotspots'. The Embedded Liquid Cooling works on a Hotspot-Targeted heat sink concept.
Embedded microchannels enable efficient targeting of hotspots by reducing the overall thermal resistance and heat spreading.

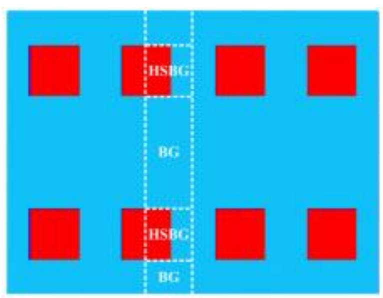


Figure 5: This image shows the heatmap of a conventional multicore microprocessor.The red area are hotspots which are the cores of the microprocessor.
Design proposed in paper 1, the introduction of 'throttling zones' is what makes the design extremely energy efficient. The image above represents the design proposed in the paper. As HSBG region requires more cooling than the BG region, flow rate should be higher.
Finer channels over the hotspot is coupled with a high flow rate which results in a higher heat transfer coefficient over the hotspots compared to the BG region.
The BG zone consists of coarse channels along with throttling zones. Introduction of throttling zone in the BG area is to manipulate the flow rate distribution on the hotspot and background regions. Throttling is achieved by using fine channels and wide channel walls.
This method of hotspot targeted embedded cooling stands out as the best method because, introduction of throttling zones helps to maintain the overall pressure in the microprocessor thereby, minimizing the temperature difference between the core and the rest of the processor.
The entire objective of this design is to achieve a higher second law of thermodynamics efficiency. The authors have taken a reference from paper 2 for further increasing the efficiency of the embedded microchannel system. As proposed by the authors of paper [11], using hot water through the inlet pipes will reduce the heat transfer component of entropy generation significantly which leads to higher 2nd law efficiency[12].

Electro Osmotic flow based cooling system for microprocessor

A when a potential difference is applied across a solution are charged the the liquid itself can physically move if the channel is a porous membrane, capillary tubes or microchannels . A cooling system can be designed within the processor where micro channels are places through the hotspots of the material and the water can be made to flow by applying a potential difference applied by electrodes embedded within the chip itself. The fluid used inside them is usually a dielectric. The flowrates such setups were found to be in excess of pump reported by Yao at el[13] up to 1.3 atm of pressure and flow rates greater than 33ml/min, using a porous sintered-glass cylinder with a 40 mm diameter and 1mm thickness to support cooling heat load of 100W. The solution is Silanol which has Si-OH when dissolved in water to form Si-O- ions having a net negative charge . These ions attract the positive charges inside the walls to form a electrical double layer.

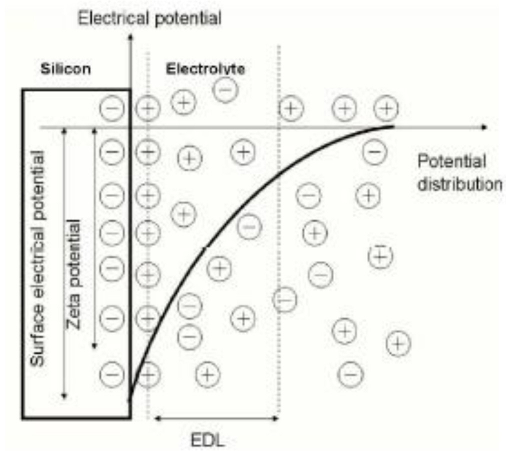


Figure 6: Electric double layer (EDL) by the wall

So the bulk of liquid inside is positively charges and flows towards the negative electrode. By using the above technique S. Yao, and D.E. Hertzog were able to the present system[14], with 150V applied voltage to the pump, removes 38 W from a 1cm x 1 cm chip and keeps the chip temperature rise below 100 degree Celsius , with reasonable stability and reliability. A Stanford research team is using MEMS technology were able to minimize the above technology to quite small levels . The technology combines two-phase convection in silicon microchannels with an electroosmotic pump to achieve minimal heat sink volume at the chip backside[15]. They were also able to achieve a respectable heat exchange values of chip removed a peak heat flux exceeding 100 W/cm^2 and a total heat load exceeding 130 W. so the above experiments serve as a proof of comcept that this technique works and it is useful.

DYNAMIC THERMAL MANAGEMENT TECHNIQUES FOR MICROPROCESSORS

Multi-core designs are being adopted by major microprocessor manufacturers to take advantage of hardware parallelism and large scale integration. In large-scale systems, the processor temperatures can can exceed to over 95 degree Celsius. These high temperatures have an adverse effect on the performance of these systems.

Implementing hybrid schemes that uses a combination of both hardware and software based thermal management techniques in a synergetic fashion is a better and efficient way to tackle thermal emergencies. Temperature aware scheduling and hot/cool rank organizations will be discussed in detail in this paper.

Thermal impact of every processor in a multi-processor system can be determined by using support from the Operating System and minimal overhead. If a particular workload operates above an average-case thermal value for sustained periods, a DTM response will work to reduce the microprocessor temperature. DTM allows designers to focus on average rather than worst-case thermal conditions in their designs. This is especially important in modern day devices that are being used on a daily basis, where thermal management for average cases are more important than worst case scenarios.

The key goals of DTM can be stated as follows: (i) to provide inexpensive hardware or software responses, (ii) that reliably reduce power, (iii) while impacting performance as little as possible

Temperature aware scheduling is an effective DTM technique but has limited cooling capacity and reduces performance for the most demanding jobs. Hot processes are identified based on their activity and is slowed down. As it has no hardware overhead, the hotspots are identified by intensity of the processor's access to the register files. This is especially helpful in multithreading processors where multiple processors are sending simultaneous threads. This is a basic function that is present in most of today's systems.

Wattch Power Model

Wattch is an architectural power model for DTM which is proposed in David Brooks et.al[16]. It is based on parameterized power models of common structures present in modern superscalar microprocessors. This dynamic model uses a combination 5 hardware and software response techniques. Three of these are microarchitectural responses: I-cache toggling, speculation control, and decode bandwidth throttling. The two software response techniques used are: Clock Frequency scaling Voltage/Frequency Scaling.

Clock Frequency Scaling

A basic OS functionality present across almost every system today, clock frequency scaling trades performance loss for power savings. Communication has to be actively done with synchronous devices on the system bus.

Voltage and Frequency Scaling

Dynamic voltage scaling along with clock frequency scaling is done to reduce power dissipation when necessary. A lot of attention has to be done to circuit design and a careful timing analysis has to be done. Furthermore, as future process technologies scale to lower base supply voltages, dynamic voltage scaling may become more difficult. This is especially true when standby leakage currents become important. Leakage currents are directly related to the supply voltage; lowering the supply voltage to dynamically reduce dynamic power would have a corresponding increase in the standby leakage current.

Decode Throttling

Clock gating is used to restrict the flow of instructions into the processor to reduce power dissipation.

Speculation Control

Amount of speculation is arbitrarily restricted in the pipeline whenever a thermal trigger level is reached. To implement this, a counter is incremented whenever a branch is decoded and decremented whenever a branch resolves. If the counter exceeds a software-set limit, the decode stage stalls until enough branches have been resolved.

Instruction Cache Toggling

This response involves disabling the instruction fetch unit and using the instruction fetch queue to feed the pipeline. Using this technique, instruction cache is throttled to reduce the flow of instruction to the microprocessor.

WATTCH model uses a combination of the above response mechanisms that is programmed into the system which allows system designers to design a system that uses DTM to increase the efficiency of the systems.

Hybrid DTM THERMAL AWARE PROCESS SCHEDULING

This method proposed in Amit Kumar et.al. is a hybrid DTM technique[17]. Like the earlier process explained this method also uses hardware and software mechanisms in a synergistic fashion. It provides predictions of overall processor temperature directly from hardware performance counters. The thermal -characterization model is trained periodically using online temperature readings from the hardware. The coordinated hardware/software DTM framework is triggered when a thermal emergency occurs. Appropriate action is then taken to manage the chip temperature.
The combination of hardware and software response techniques used in this model re:

Online Thermal Characterization

Performance counters are used to gather processor usage patterns which is used to train the characterization model developed by the authors. Using this information, thermal profiles of individual processes as well as the entire microprocessor can be designed.

Proactive Software DTM

Timeslice management and process priority management are performed using this technique. IN the algorithm proposed by the authors, If the Process Temperature(TP) of a process, exceeds the Software Trigger temperature, (TSW), that Process is marked as a 'Hot Process'. Processes whose TP is less than TSW, the rank of that process is boosted. Processes with higher ranks are given higher priorities[18]. Authors of the paper have also implemented a Timeslice adjustment in addition to the priority adjustment. As a result, time allocated for each process is controlled.

Reactive Hardware

Upon the occurrence of thermal emergency, hardware-based processor clock gating is employed in incremental steps to manage the processor temperature. This is only used in case of thermal emergencies where software response techniques become useless.

CONCLUSION

When Moores law is slowly drawing to a close, and the concentration of transistors in a chip not increasing as expected the computing performance improvement that powered the major advances of last half a century is slowing down. We cannot go on increasing the number of chips for outright performance increase in the near future. This is where better cooling comes into play to increase the performance of processors. By implementing proper cooling techniques even the processors currently available can perform much better. In the above report we analysed some of the current technologies and some of the upcoming ones. Some of these if implemented properly has the ability to greatly influence the computing world. But the question remains if the industry will continue to push for further increases in processing power or making the current technologies more power efficient quiet and cooler by sacrificing processing power. But under any case we can be sure that there will be a crowd who is interested in squeezing the last bit of performance from the processors and for them all developments in cooling technologies will be music to their ears

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