ULTRA-FAST TEMPERATURE ESTIMATION METHODS FOR ARCHITECTURE-LEVEL THERMAL MODELING

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Certificate

This is to certify that the thesis titled **ULTRA-FAST TEMPERATURE ESTIMATION METHODS FOR ARCHITECTURE-LEVEL THERMAL MODELING** being submitted by **Ms. Hameedah Sultan** for the award of **Doctor of Philosophy** in Information Technology is a record of bona fide work carried out by her under my guidance and supervision at the Amar Nath and Shashi Khosla School of Information Technology, Indian Institute of Technology Delhi. The work presented in this thesis has not been submitted elsewhere, either in part or full, for the award of any other degree or diploma.

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> One can never pay in gratitude: one can only pay 'in kind' somewhere else in life.
>
> — Anne Morrow Lindbergh

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Abstract

As the power density of modern-day chips has increased, the chip temperature, too, has increased steadily. High temperature causes several adverse effects, affecting the chip's performance and reliability. It also increases the leakage power, which further increases the on-chip temperature, resulting in a feedback effect. In order to carry out temperature-aware design optimization, it is often necessary to conduct thousands of temperature simulations at various stages of the design cycle, and thus the speed of simulation without a concomitant loss in accuracy is essential.

State-of-the-art works in thermal estimation have serious limitations in modeling some important aspects of thermal modeling. Additionally, these methods are slow. We overcome the limitations of these works by developing fast Green's function-based analytical methods.

Green's function-based methods have been shown to be faster than the traditional finite difference and finite element methods, but their use has been limited to simple problems in the past. In this thesis, we develop Green's function-based methods for a wide range of complex thermal problems and demonstrate their superior efficiency compared to existing works.

In the first work, we developed a fast and analytical leakage-aware thermal simulator for 3D chips using Green's functions (impulse response of a unit power source). We use several novel algebraic techniques and transforms to arrive at a closed-form expression for the Green's function. Next, we extend this work to compute the thermal profile for 3D chips with microchannels by taking care of the anisotropicity in the thermal profile of such chips.

After that, we proceed to model the effects of process variation on the temperature since process variation is increasingly becoming important as the device dimensions are decreasing. We propose an analytical thermal simulator that considers the effects of process variation, temperature-dependent conductivity, and temperature-dependent leakage power altogether.

However, an analytical process variation-aware method cannot be extended to complex geome-

tries. So in our final work, we propose a convolutional neural network architecture for thermal estimation in the presence of variability that leverages the physics of the heat transfer. This approach is capable of modeling modern-day 3D chips with microchannels and incorporates accurate leakage power models.

In summary, by using a combination of rare mathematical transforms, algebraic manipulations, and numerical and machine learning-based methods, we not only solve these complex problems but also achieve greater than $100\times$ speedup over the state-of-the-art simulators in all of our works. Thus, the work presented in this thesis significantly advances the state-of-the-art in ultra-fast thermal estimation.

सार

जैसे-जैसे आधुनिक चिप्स की शक्ति घनत्व में वृद्धि हुई है, चिप के तापमान में भी लगातार वृद्धि हुई है। उच्च तापमान चिप के प्रदर्शन और विश्वसनीयता को प्रभावित करते हुए कई प्रतिकूल प्रभाव डालता है। यह रिसाव शक्ति (leakage power) को भी बढ़ाता है, जो आगे ऑन-चिप तापमान बढ़ाता है, जिसके परिणामस्वरूप प्रतिक्रिया प्रभावित होती है।
तापमान-जागरूक डिज़ाइन अनुकूलन करने के लिए अक्सर डिजाइन चक्र के विभिन्न चरणों में हजारों तापमान सिमुलेशन करना आवश्यक होता है। इस लिए अनुकरण की गति बिना सहवर्ती सटीकता नुकसान के अत्यन्त आवश्यक है।

तापमान प्रतिमान में अत्याधुनिक कार्यों की कुछ गंभीर सीमाएं हैं। इसके साथ ही ये तरीके धीमे हैं। हम अत्याधुनिक कार्यों की सीमाओं पर काबू पाने के लिए अत्यन्त-तेज ग्रीन फंक्शन पर आधारित विश्लेषणात्मक तरीकों को विकसित करते हैं। ग्रीन-फ़ंक्शन-आधारित तरीकों को पारंपरिक परिमित-अंतर (finite-difference) तथा परिमित-तत्व विधियों (finite-element) की तुलना में तेज़ दिखाया जा चूका है, लेकिन उनका उपयोग अतीत में साधारण समस्याओं तक ही सीमित रहा है।

इस थीसिस (thesis) में हम जटिल तापमान प्रतिमान की विस्तृत श्रेणी के लिए ग्रीन-फ़ंक्शन-आधारित तरीकों का विकास करते हैं। साथ ही हम मौजूदा कार्यों की तुलना में उनकी बेहतर दक्षता का प्रदर्शन करते हैं। पहले काम में हमने 3D चिप्स के लिए ग्रीन फंक्शन (एक इकाई शक्ति स्रोत की आवेग प्रतिक्रिया) का उपयोग कर एक तेज़ और विश्लेषणात्मक लीकेज-जागरूक थर्मल सिम्युलेटर विकसित किया। हम ग्रीन-फंक्शन के लिए एक बंद-रूप अभिव्यक्ति पर पहुंचने के लिए कई नवीन बीजगणितीय तकनीक और परिवर्तन का उपयोग करते हैं।

इसके बाद हम इस काम का माइक्रोचैनल-सहित 3D चिप्स के तापमान-प्रतिमान के लिए एनाइसोट्रोपिसिटी (anisotropicity) का ख्याल रखते हुए अधिक विस्तार करते हैं।

जैसे-जैसे डिवाइस के आयाम कम होते जा रहे हैं, प्रक्रिया भिन्नता (process variation) तेजी से महत्वपूर्ण होती जा रही है। इस लिए अपने दूसरे काम में हम तापमान पर प्रक्रिया भिन्नता के प्रभावों को मॉडल करते हैं। हम एक विश्लेषणात्मक थर्मल सिम्युलेटर प्रस्तावित करते हैं जो तापमान-निर्भर प्रक्रिया भिन्नता, तापमान-निर्भर प्रवाहकत्त्व (conductivity) तथा तापमान-निर्भर रिसाव शक्ति के प्रभावों को पूरी तरह से ध्यान में रखते हुए तापमान प्रतिमान करता है।

हमारी प्रस्तावित विश्लेषणात्मक प्रक्रिया भिन्नता-जागरूक पद्धति को जटिल ज्यामिति तक नहीं बढ़ाया जा सकता है। इसलिए अपने अंतिम कार्य में, हम प्रक्रिया भिन्नता-जागरूक तापमान प्रतिमान के लिए एक कोंवोलुशनल न्यूरल नेटवर्क (convolutional neural network) का प्रस्ताव करते हैं जो इस समस्या के समाधान के लिए गर्मी हस्तांतरण (heat transfer) के भौतिकी का लाभ उठाता है। यह विधि आधुनिक समय के माइक्रोचैनल वाली 3D चिप्स में सटीक रिसाव शक्ति मॉडल सहित तापमान अनुमान में करने में सक्षम है।

संक्षेप में, दुर्लभ गणितीय परिवर्तनों के संयोजन का उपयोग करके, बीजीय जोड़तोड़ और संख्यात्मक और मशीन लर्निंग-आधारित विधियों का इस्तेमाल कर, हम न केवल इन जटिल समस्याओं को हल करते हैं बल्कि अपने सभी कार्यों में हम अत्याधुनिक सिमुलेटर पर 100× से अधिक स्पीडअप भी प्राप्त करते हैं। इस प्रकार इस थीसिस में प्रस्तुत कार्य अत्यंत-तेज़ तापमान प्रतिमान की अत्याधुनिक विधियों को महत्वपूर्ण रूप से आगे बढ़ाता है।

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