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Analysis of performance and energy efficiency of processors with hybrid architecture

Analiza wydajności i energooszczędności procesorów w architekturze hybrydowej

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Abstract

This study presents a comprehensive comparison of the performance and energy efficiency of performance (P) cores and efficiency (E) cores in Intel's 12th and 13th generation processors, including both desktop and mobile variants. The results demonstrate that P-cores are 1.3 to 3.2 times faster than E-cores, with the largest performance gaps observed in floating-point intensive tasks. E-cores show up to 17% better energy efficiency compared to P-cores in memory-intensive tasks, while P-cores demonstrate up to 2.1 times better energy efficiency in floating-point intensive calculations.

Keywords: CPU; hybrid architectures; energy efficiency

Streszczenie

Niniejsze badanie przedstawia kompleksowe porównanie wydajności i efektywności energetycznej rdzeni wydajnościowych (P) i efektywnościowych (E) w procesorach Intela 12. i 13. generacji, obejmujące zarówno procesory stacjonarne, jak i mobilne. Wyniki pokazują, że rdzenie P są od 1,3 do 3,2 razy szybsze niż rdzenie E, przy czym największe różnice w wydajności zaobserwowano w zadaniach intensywnie wykorzystujących obliczenia zmiennoprzecinkowe. Rdzenie E wykazują do 17% lepszą efektywność energetyczną w porównaniu do rdzeni P w zadaniach intensywnie wykorzystujących pamięć, podczas gdy rdzenie P demonstrują do 2,1 razy lepszą efektywność energetyczną w obliczeniach intensywnie wykorzystujących operacje zmiennoprzecinkowe.

Słowa kluczowe: CPU; architektura hybrydowa; wydajność energetyczna

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1. Introduction

In the rapidly evolving landscape of computer technology, hybrid architectures in processors stand as key determinants of performance and energy efficiency. This study focuses on Intel's 12th, 13th, and 14th generation desktop processors, which exemplify these advanced architectures. Integrating various types of processor cores, they are crucial in addressing the diverse computational needs of modern applications.

This article diverges from the majority of current research, which typically targets specific use cases like certain neural networks or algorithms. Instead, it offers a comprehensive comparison of cores within these Intel generations across both artificial and realistic benchmarks. The former involves intense computation with minimal data movement, while the latter considers performance limitations due to factors like cache efficiency. Notably, existing comparative research in this field has primarily focused on contrasting different computing en s, such as CPUs, GPUs, and FPGAs. However, the detailed comparison of cores within a single CPU, particularly within Intel's latest generations, remains an uncharted territory in academic literature. This study aims to fill this gap, providing a thorough examination of the performance and energy efficiency of various cores within a single CPU using a robust methodological approach.

By utilizing a blend of artificial and realistic benchmarks, the aim is to deliver a comprehensive understanding of how different cores perform under various computational scenarios. The findings of this study are poised to have significant implications for processor design and the optimization of applications to leverage the strengths of hybrid architectures.

2. Related works

This study addresses a notable gap in processor technology research: the direct comparison of cores within the same CPU for performance and energy efficiency. Existing literature, such as the study comparing energy efficiency across different platforms like CPUs, GPUs, and FPGAs [1], primarily focuses on broad platform comparisons without delving into intra-CPU core analysis.

Additionally, research on CPU performance and energy efficiency often concentrates on specific tasks or configurations [2], rather than examining the varied performance of individual cores within a single processor. Even benchmarking studies, critical for assessing CPU performance, typically overlook the performance distinctions between different cores within the same CPU [3, 4].

Recent studies have begun to address this gap. For instance, work by Rathijit Sen (2024) [5] analyzed performance, power, and thermal profiles for database workloads on hybrid processors with P and E cores. This study found that E-cores operate at lower temperatures, consume less power, and are more energy-efficient, but require over three times as many cores compared to P-cores to achieve equivalent performance in multi-threaded analytical tasks.

In conclusion, while existing research offers a comprehensive view of processor performance and energy efficiency at a broader level, it leaves a distinct void in the comparative analysis of cores within the same CPU. This study seeks to fill this void by establishing a dedicated methodology in this area.

3. Method

A robust methodology was developed to conduct a comprehensive analysis of the performance and energy efficiency characteristics of processors with hybrid architectures. This approach addresses the unique challenges presented by these modern CPUs, encompassing careful test configuration, diverse test platforms, and a selection of benchmarks designed to stress different aspects of processor performance.

3.1. Test configuration

In consumer CPUs, directly measuring the energy usage of individual cores is complex, as standard metrics typically reflect the entire CPU's consumption. This challenge is compounded by the potential interference from background OS tasks. To address this, the methodology incorporates several key steps.

The study of performance and energy efficiency in hybrid CPU architectures presents unique challenges, particularly in isolating the behaviour of specific core types. To address these challenges, a comprehensive testing methodology was developed.

The Linux tool 'taskset' [6] was employed to bind test programs to specific CPU cores. This approach ensures that the benchmark runs exclusively on the designated core type (P or E). However, it's important to note that taskset does not prevent other programs or system processes from utilizing the same core. To mitigate this, all unnecessary programs and services were closed prior to testing, minimizing the impact of background processes on the results.

Energy consumption measurements were conducted using the 'perf' [7] tool, which is part of the Linux kernel's performance analysis toolkit. Perf offers a wide range of performance monitoring capabilities, utilizing hardware counters available in modern processors.

To account for the performance disparity between P-cores and E-cores, which often results in different execution times for the same benchmark, a normalization process was implemented. This process involves measuring the baseline energy consumption of the system for a duration equal to the benchmark's execution time. This baseline measurement is then subtracted from the total energy consumption measured during the test, resulting in a value that represents the energy consumption directly related to the benchmark execution.

3.2. Test platforms

To conduct a comprehensive analysis of the performance and energy efficiency characteristics of processors with hybrid architectures, three distinct test platforms were selected. Each platform features an Intel processor with a combination of performance (P) cores and efficiency (E) cores. All platforms run Ubuntu 22.04 as the operating system to ensure a consistent testing environment.

Table 1: Platform 1 specification

Specification	Details
Processor	Intel Core i5-13600KF
Performance Cores (P-cores)	6 cores, 12 threads, up to 5.1 GHz
Efficiency Cores (E-cores)	8 cores, 8 threads, up to 3.9 GHz
RAM	32 GB DDR5 @ 5600 MHz

Table 2: Platform 2 specification

Specification	Details
Processor	Intel Core i5-1230U
Performance Cores (P-cores)	2 cores, 4 threads, up to 4.4 GHz
Efficiency Cores (E-cores)	8 cores, 8 threads, up to 3.3 GHz
RAM	16 GB DDR4 @ 4800 MHz

Table 3: Platform 3 specification

Specification	Details
Processor	Intel Core i9-13900
Performance Cores (P-cores)	8 cores, 16 threads, up to 5.6 GHz
Efficiency Cores (E-cores)	16 cores, 16 threads, up to 4.2 GHz
RAM	32 GB DDR5 @ 5200 MHz

3.3. Benchmarks

To evaluate the performance and energy efficiency of the hybrid processors, four benchmarks were selected, each focusing on different aspects of the system. These benchmarks include a synthetic test, realistic workloads, and tests that utilize specific hardware features. The chosen benchmarks are:

3.3.1.Pi digits calculation

The Pi digits calculation benchmark is a highly synthetic test that primarily stresses the processor's computational capabilities. This benchmark calculates a large number of Pi digits, which is a CPU-intensive task. As the calculation does not heavily rely on RAM, memory bandwidth is not a limiting factor in this benchmark.

3.3.2.Linux kernel compilation

The Linux kernel compilation benchmark represents a realistic workload that is commonly encountered in software development and system administration. This benchmark involves compiling the Linux kernel source code. It stresses the processor's ability to handle real-world computational tasks and tests the system's overall performance. The Linux kernel compilation benchmark is sensitive to both CPU and RAM performance. Additionally, cache performance plays a significant role in this benchmark, as the compilation process involves frequent access to small files and header files, making efficient cache utilization crucial for optimal performance.

3.3.3.File compression using deflate algorithm

File compression is a common task in various computing scenarios, and the Deflate algorithm is widely used for this purpose. This benchmark evaluates the processors' performance in handling data compression workloads. The Deflate algorithm is computationally intensive and benefits from efficient memory access. By measuring the time taken to compress a large file using the Deflate algorithm, this benchmark assesses the processors' ability to handle data-intensive tasks efficiently.

3.3.4.File encryption using AES algorithm

The file encryption benchmark using the Advanced Encryption Standard (AES) algorithm tests the processors' performance in cryptographic operations, which are increasingly important in secure computing environments. AES is a widely-used symmetric encryption algorithm that is known for its security and efficiency. This benchmark leverages the cryptographic hardware acceleration features present in modern processors, such as Intel's AVX-512 VAES instruction set. By measuring the time taken to encrypt a large file using the AES algorithm, this test evaluates the processors' efficiency in handling cryptographic workloads and the effectiveness of their hardware acceleration capabilities.

4. Results

The results obtained from these experiments are presented in Tables 4, 5, and 6, corresponding to the three test platforms. Each table showcases the mean execution time, standard deviation of execution time, energy consumption, and standard deviation of energy consumption for each benchmark and core type combination.

Table 4: Platform 1 results

Benchmark	Core	Mean time (s)	Stdev time (s)	Energy (J)	Energy stdev (J)
PI	P	207	0.05	3974	44
	E	658	0.11	6511	81
Kernel	P	7076	9.83	124990	6200
	E	11900	27.86	129166	11438
Deflate	P	151	0.86	2714	165
	E	227	0.94	2307	153
Crypto	P	190	1.15	1701	70
	E	350	2.35	1689	120

Table 5: Platform 2 results

Benchmark	Core	Mean time (s)	Stdev time (s)	Energy (J)	Energy stdev (J)
PI	P	192	7.91	4969	80
	E	616	0.94	8484	193
Kernel	P	6410	19.45	139740	5353
	E	10760	49.1	135148	9917
Deflate	P	135	5.19	3389	30.09
	E	210	0.62	3032	45.49
Crypto	P	162	3.66	2145	22.65
	E	295	14.12	2070	39.53

Table 6: Platform 3 results

Benchmark	Core	Mean time (s)	Stdev time (s)	Energy (J)	Energy stdev (J)
PI	P	240	0.09	2871	50
	E	787	0.12	6198	112
Kernel	P	10208	8.5	109936	6822
	E	14562	25.19	111992	12001
Deflate	P	211	0.76	2394	206
	E	272	0.88	2270	202
Crypto	P	235	1.02	1325	88
	E	425	1.98	1305	145

4.1. Performance comparison

4.1.1.Linux kernel compilation

The Linux kernel compilation test revealed significant performance differences between P-cores and E-cores across all tested processors. For the desktop platforms (i9-13900, i5-13600KF), P-cores demonstrated a 68% speed advantage over E-cores. The mobile platform (i5-1230U) showed a smaller but still substantial difference, with P-cores being 43% faster than E-cores.

Analysing the performance differences of E-cores between processors, it was observed that they were proportional to the clock frequencies. The performance difference between i5-1230U and i5-13600K was 20%, while between i9-13900 and i5-13600K it was 10%, corresponding to the differences in clock speeds of these processors.

An interesting observation was made regarding the P-core performance of the i5-13600K, which was 44% better than the i5-1230U, despite only a 16% higher clock speed. This suggests a significant impact of other factors such as architecture or optimizations on performance in this test (Figure 1).

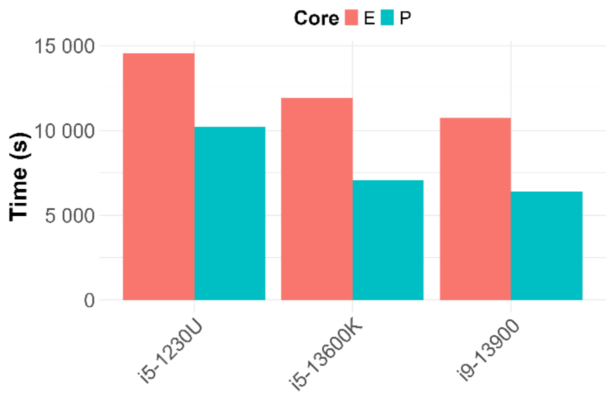

Figure 1: Kernel compilation benchmark execution times.

4.1.2.File compression using deflate algorithm

The file compression and decompression test showed smaller performance gaps between P-cores and E-cores compared to the kernel compilation test. For i5-13600K, the difference was 50%, for i9-13900 it was 56%, and for the mobile i5-1230U, it was 29%.

Similar to the kernel compilation test, the performance differences of E-cores between i5-13600K and i5-1230U were proportional to clock frequencies, while the P-core performance of i5-13600K relative to i5-1230U was better than the clock speed difference would suggest (Figure 2).

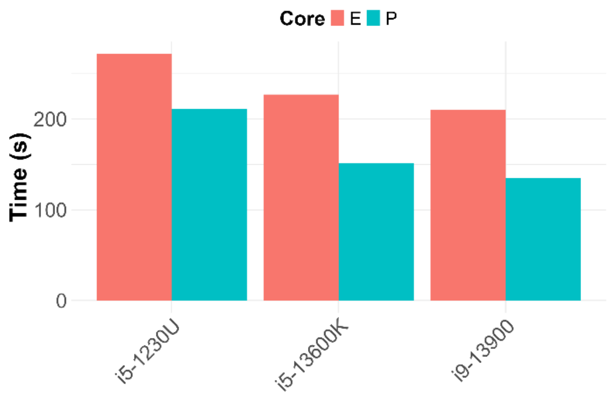

Figure 2: File compression benchmark execution times.

4.1.3.File encryption using AES algorithm

The AES encryption and decryption test revealed larger differences between P-cores and E-cores compared to the previous tests. The performance gaps ranged from 82% to 85%, suggesting better support for cryptographic operations in P-cores.

Analyzing the performance differences between processors, it was observed that they closely matched the ratios of their clock frequencies, indicating a smaller influence of other factors in this test (Figure 3).

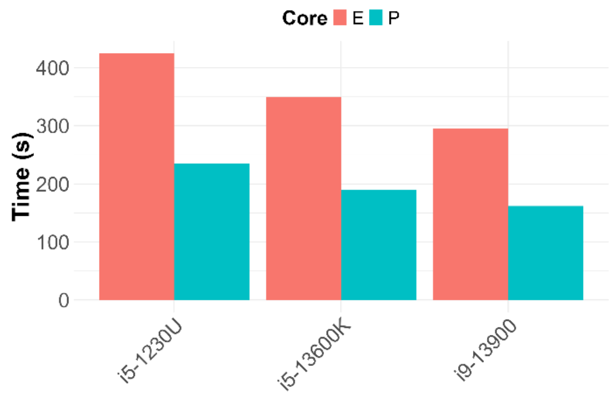

Figure 3:AES encryption benchmark execution times.

4.1.4.Pi digits calculation

The Pi calculation test demonstrated the largest difference between P-cores and E-cores among all conducted tests. For all tested processors, P-cores were approximately 3.2 times faster than E-cores.

This significant difference suggests that in other tests, P-core performance might have been limited by other factors such as memory access. The result also indicates much better support for floating-point operations in P-cores.

Smaller differences between E-cores were observed in this test compared to others, and the differences between processors were proportional to the differences in clock frequencies (Figure 4).

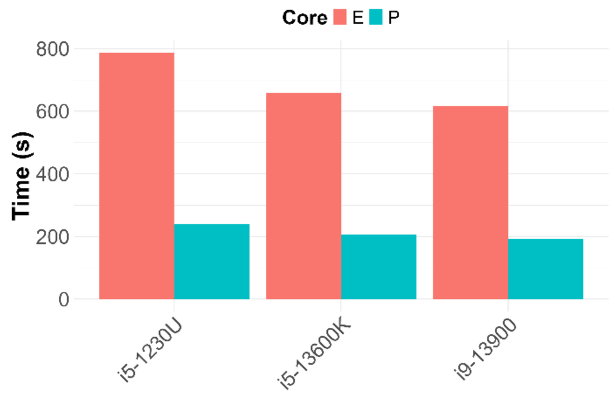

Figure 4: Pi calculation benchmark execution times.

4.2. Energy efficiency comparison

4.2.1.Linux kernel compilation

In the Linux kernel compilation test, P-cores and E-cores showed very similar energy efficiency across all tested processors.

For i5-1230U and i5-13600K processors, E-cores were marginally less energy-efficient, consuming about 2% more energy than P-cores. Conversely, for the i9-13900 processor, E-cores were 2% more energy-efficient than P-cores.

Comparing energy efficiency between processors, the i5-1230U proved to be the most energy-efficient, being 15% more efficient than i5-13600K for both core types.

Between desktop processors, i5-13600K demonstrated better energy efficiency than i9-13900, with P-cores being 12% more efficient and E-cores 5% more efficient (Figure 5).

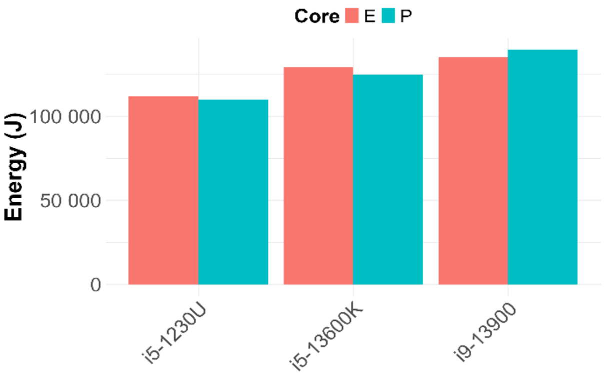

Figure 5: Kernel compilation benchmark energy usage.

4.2.2.File compression using deflate algorithm

The file compression and decompression test revealed significant differences in energy efficiency between P-cores and E-cores.

In all tested processors, E-cores proved to be more energy-efficient than P-cores. For i5-1230U, the difference was 5%, for i5-13600K it was 17%, and for i9-13900 it was 12%.

Comparing energy efficiency between processors, notable differences were observed, especially between desktop processors. The i5-13600K demonstrated significantly better energy efficiency than i9-13900, with P-cores being 25% more energy-efficient and E-cores 31% more energy-efficient (Figure 6).

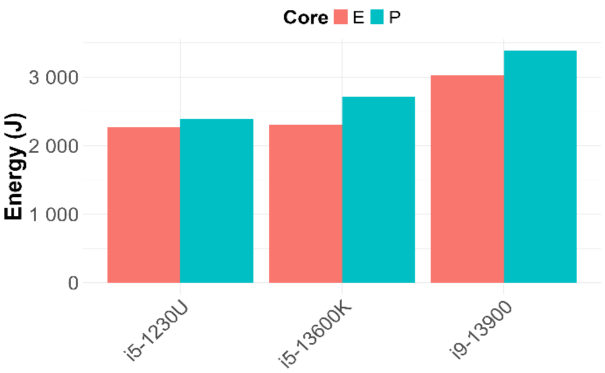

Figure 6: File compression benchmark energy usage.

4.2.3.File encryption using AES algorithm

The AES encryption and decryption test results were similar to the Linux kernel compilation test in terms of energy efficiency between P-cores and E-cores.

In this test, P-cores and E-cores showed comparable energy efficiency, with P-cores having a slight 3% advantage over E-cores.

The i5-1230U processor proved to be the most energy-efficient, being 50% more efficient than i5-13600K for both core types. Among desktop processors, i5-13600K demonstrated significantly better energy efficiency than i9-13900, being 30% more energy-efficient for both P-cores and E-cores (Figure 7).

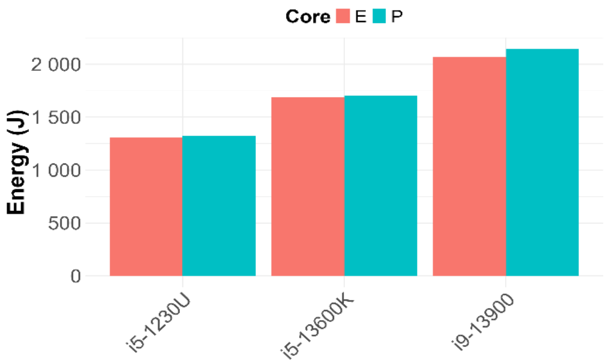

Figure 7: AES encryption benchmark energy usage.

4.2.4.Pi digits calculation

The Pi calculation test showed the largest differences in energy efficiency between P-cores and E-cores among all conducted tests.

[Figure 8: Average energy consumption for Pi calculation test]

In this case, P-cores proved to be significantly more energy-efficient than E-cores, with differences exceeding twofold. For the i5-1230U processor, P-cores were 2.2 times more energy-efficient than E-cores. For i5-13600K, the difference was 1.64 times, and for i9-13900, it was 1.71 times.

Comparing energy efficiency between processors, trends similar to those observed in other tests were revealed. The i5-13600K processor was 30% more energy-efficient than i9-13900 for both P-cores and E-cores. The mobile i5-1230U again demonstrated high energy efficiency, particularly for P-cores, being 38% more energy-efficient than i5-13600K for P-cores. However, for E-cores, this difference was much smaller, with i5-1230U being only 5% more efficient than i5-13600K.

These results highlight the complex relationship between performance and energy efficiency in hybrid CPU architectures, with the relative advantages of P and E cores varying significantly depending on the nature of the computational task (Figure 8).

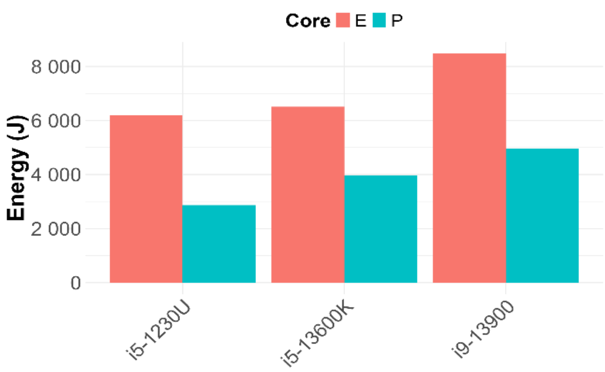

Figure 8: Pi calculation benchmark energy usage.

5. Conclusions

The study consistently demonstrated that P-cores outperformed E-cores across all benchmarks, with speed advantages ranging from 1.3 to 3.2 times faster, depending on the nature of the task. The most substantial performance gaps were observed in floating-point intensive operations, such as the Pi calculation test, where P-cores demonstrated a 3.2-fold speed advantage.

However, the energy efficiency comparison between P-cores and E-cores revealed a more nuanced picture. In memory-intensive tasks, such as file compression, E-cores demonstrated superior energy efficiency, consuming up to 17% less energy than P-cores to complete the same task. Conversely, for compute-bound operations with minimal memory interaction, such as the Pi calculation, P-cores proved to be up to 2.1 times more energy-efficient. This indicates that the energy efficiency advantage of each core type is highly dependent on the specific characteristics of the workload.

The study also highlighted a clear trade-off between computational power and energy efficiency. The i9-13900, while offering the highest raw performance, consistently showed lower energy efficiency compared to the i5-13600K. This suggests that pursuing maximum performance comes at the cost of reduced energy efficiency, an important consideration for system designers and users alike. The mobile-oriented i5-1230U demonstrated superior energy efficiency in most tests, particularly for its P-cores. This highlights the effectiveness of mobile-oriented optimizations.

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