Paper Review: **Requirements, Bottlenecks, and Good Fortune: Agents for Microprocessor Evolution**

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**Introduction:**

In this paper, the author, Professor Yale Patt, provided us with a synoptic introduction to the history of microprocessors’ development from the very first invention of microprocessor since 1971 to their status and functionality in 2001. He also pointed out that the rapid evolution and development of microprocessors industry is a process of making tradeoffs, which has been achieved and prompted by three major contributing forces (agents): new requirements, bottlenecks, and good fortune.

This paper was extended into three parts: the basic framework of microprocessors, the important development landmarks within the 30-year development since the invention of microprocessors, and some expectations and predictions of the directions under which the microprocessors would evolve in the next few years. In this work, we will briefly summarize the paper with respect to the three focus as well.

**I. Framework of computer architecture, microarchitecture, microprocessor, and microprocessor design.**

*A. Experience accumulation and tradeoffs.*

The development of computer, especially the microprocessor, is a process of retrospection and refinement. The experience of computer architects from the past design and manufacturing provides invaluable reference for designing the next generation’s architectures. Besides experience, another term that prevails the development of microprocessors is tradeoffs. When we encounter a situation where two or more factors are equally important but they are mutually incompatible, often we need to make compromises so that each factor concedes and the maximum performance is achieved from them. In the evolution of microprocessors, we will meet a lot situations where tradeoffs are inevitable, and thus propel new models to be invented.

*B. Hierarchy of microprocessor*

Simply put, the microprocessors are composed of millions of transistors and switches. We invent and develop microprocessors so that we could use them to solve problems and we can solve them fast. The process of a microprocessor addressing a problem goes through a hierarchal way: when we encounter a problem, we first need to select the proper algorithm to simulate the problem and sort out the unnecessary features of the problem, we then code the problem into programs with languages that the microprocessors could understand, and send the program to the specific part of the microprocessor, called the instruction set architecture (ISA). The ISA is a collections of the microprocessor’s microarchitecture that could be regarded as an interface such that the program tells the microprocessor what to do and the microprocessor knows what it needs to do for the program. From ISA the program is further allocated to different portions of circuits and eventually carried out by the electronics.

For each level of the hierarchy, we could choose from multiple options, each has advantages and shortcomings, in order to achieve better performance to some aspects, we need to sacrifice other aspects, and namely, we need to make compromises, which is often the case of the design and development of microprocessors.

*C. Considerations in designs*

When designing a microprocessors, there are many factors that need to be taken into consideration besides performance, such as cost, stability, power consumption, which are all critical to a successful version of microprocessor.

To choose which aspects need to be enhanced and which aspects need to be compromised is usually determined by the problems we address. Some problems, such as scientific research, may require extremely fast and accurate computations of results and are less concerned with other factors, in these case, we could enhance the performance and sacrifice power consumption, among others. Other problems, such as those run in embedded computers and portable mobile devices (PMDs), are more concerned about the power efficiency, and are willing to sacrifice some performance in order to achieve more power sustainability.

*D. Application Space*

The problems we encounter and want to use computers and microprocessors to solve is collectively called the application space. It is a concept with a wide range. With the rapid development of computer industry and the increasing power of computers, the scope of application space continue to expand rapidly to an even wider range. Today, we could see the computers are utilized in almost everywhere from scientific applications to home-used software. The expansion of the application space also demands more different tradeoffs for the specific applications.

*E. Processing*

After the program has been sent to the microprocessor as instructions, it will do the following three in order to solve the problem: 1. Supply the instructions to the specific part of the processor, 2. Supply data used by the instructions, and 3. Perform the operations. For each of the three tasks, different technology are required to achieve the best performance for the microprocessor’s computing, and we also need to consider the situations that could prevent them from achieving their full potential.

1. Instruction supply:

The efficiency of instruction allocation has evolved from 1 fetch at one time to 4, and soon will grow to 6 or even 8, which greatly enhance the computation speed of microprocessors. However, situations such as instruction cache misses, fetch breaks, and conditional branch mispredictions could impede the supplying of instruction.

1. Data supply

Instructions need data to provide the solutions, and thus the supplying of data correctly and efficiently is critical to the overall performance. Ideally, we want infinite supply of needed data which could be supplied in zero time at reasonable cost. In reality it would be impossible, thus we invented a storage hierarchy to help store data. Since the larger portion of data is stored in media such as hard disk and could be accessed with over 10 cycles, a microprocessor could likely to be fallen into the situation that it needs to supply data from those sections that need long time to access.

1. Instruction processing

One the processor procures the data, it is expected to perform operations on those data fast enough to provide correct solutions in a short span of time. Henceforth, the microprocessor needs not only sufficient amount of operations units to perform the operations, but also interconnections between them to supply the results from one unit to the other in order to complete the operations succession fast enough. Unfortunately, with the increased amount of units in one chip and the enhanced speed of operations, the lag of forwarding results from one part to the other will inevitably get worse.

**II. Factors that prompts the evolution of microprocessors**

The evolution of microprocessors has been propelled by many factors, and Professor Patt attributed three of them as the forcing functions (AKA: agents for evolution): new requirements, bottlenecks, and good fortune.

1. *New requirements*

We invented computers and microprocessors because we need them to solve problems for us, and since our problems continue to grow bigger and more complicated, we will keep having more requirements for microprocessors so that it could be faster, more stable, and more power efficient.

When the microprocessors were firstly invented, they could fetch, encode, and forward only one instruction at a time. That soon fell in short in practice, and thus prompt the invention of wide-issue microprocessors, which allow multiple instructions to be fetched, encoded and forwarded at one time.

Besides that, we also want more operations to be performed at one time, and that urged the advent of multiple functional units which could achieve that goal.

Since we enter the post-PC era, the requirement for power efficiency became eminent, we want the same performance for a microprocessor, but with less power consumption. Improvements are working toward to achieving and perfecting this goal, among others, such as better HCI effects.

1. *Bottlenecks*

From the first introduction we have already knew that in each steps of microprocessor processing there are situations that prevent them from functioning, those situations are also referred as bottlenecks. Many great breakthroughs in the development of microprocessors were aimed to eliminate bottlenecks. Examples include the inventions of instruction cache for solving the bottleneck of the slow fetching of instruction from memory, the invention of trace cache to store the instruction in the order of execution to ensure the full fetch of instructions, and the invention of branch predictor to eliminate the uncertainty caused by branching.

1. *Good Fortune*

Sometimes, an unexpected result from practices could lead to a revolution in microprocessor evolution. Such is a case that the shrinking technology allows microprocessors to occupy a very little portion of a chip, and thus the remaining part of the chip could be implemented with other useful modules, such as floating point accelerator.

**III. Microprocessor Evolution from 1971 to 2001**

The microprocessor experience an evolution from the first generation with 2,300 transistors in 1971 to 200 million transistors in 2001, and the growth continues until today, with the largest transistor counts to 80 billion in 2018[1]. Aside from transistor counts, the speed and scope of the microprocessor evolution is unparalleled. A number of exciting invention and new concepts were introduced during this period of evolution, including:

1. Pipelining: invented to satisfy the request of performing multiple instructions within one clock cycle.
2. On-chip caches: invented to solve the time delay caused by the slow access speed of off-chip memory.
3. Branch prediction: invented to solve the loss of efficiency caused by conditional branches.
4. On-chip floating point unit: as mentioned earlier, this invention was due to the technology shrinking to make microprocessors small enough to occupy only a small portions of chip, thus sparing space for other units such as the floating point unit, which out beat the microprocessors that rely on off-chip floating point units with respect to the speed of operations.
5. Additional specialized functional units: more tailored units were added to chips so that the functions of the microprocessors became more powerful.
6. Out-of-order processing: a distinction between instruction execution and instruction retirement were established so that the results of computation are presented in correct order.
7. Clusters: a concept to implement cores into cluster in a chip to prevent the traversal of computational values throughout the whole chip.
8. Chip multiprocessors: to implement multiple microprocessors into one chip, so that with proper interprocessor communication, the computation will be enhanced greatly.
9. Simultaneous multithreading: invented and implemented so that the microprocessor could use the resources and time in a clock cycle to perform other operations if a cache miss occurs for one operation.
10. Fast core: a conception to make the execution part of a microprocessor much faster than the other parts so that the overall speed would be increased, since the major portion of time used in computation would be for execution.

**IV. Future of microprocessor evolution**

Written in 2001, Professor made a series of predictions about the evolutional process of the microprocessors, by that time the microprocessors was expected to grow to contain 1 billion transistors and operate at a frequency of 6 to 10GHz within 5 years. He delineated a few prospective, including:

1. A new type of microprocessor that with special purpose algorithms embedded so that the efficiency of processing operations and data would be even further improved.
2. A new set of data path that will travel and transmit data with shorter wire length.
3. A fault-autocorrection mechanism within the microprocessor to automatically detect and correct internal errors.
4. New microprocessors that unite asynchronous operations and synchronous operations to increase the functionality of the processor.
5. New microprocessors that could adjust its clock cycle to tailor the need for different types of problems, so that the more resources could be allocated to more important part of a problem, and thus increase the performance.
6. New materials to provide better performances for chips.
7. More use for microcode to exploit the plenty of on-chip bandwidth.
8. A microprocessor that could reconfigure the logic functions to suit different kinds of problems.

It has been 17 years since Professor Patt wrote the paper. Take a retrospective investigation, we noticed that the transistors has way passed 1 billion for one microprocessors, and some of the predictions are looking promising to be true[2].

Nevertheless, the evolution continues to grow, so are the challenges, since postPC era, we now need to put more concerns about power consumption, the need for compatibility to run in different situations and type of machines, and so on. The evolution for the next stage now becomes more and more unpredictable, but the progress continues to become a definite happening, to what extent it will lead us in this digital age will rely on the computer scientists, the computer engineer, and every single one of us.

**V. Conclusion**

It is one of the most amazing achievement of mankind to make such a rapid and sensational evolution for microprocessors within such a short span of time. The power of microprocessors, combined with the imagination for solving diverse problem with them, boosted this evolution, it is hard to predict where this evolution would reach to, and no one can tell if the speed of evolution for microprocessors would increase, decrease, or stay.

But one thing is predictable. With different concepts, such as machine learning, artificial intelligence, are brought out to light, more problems are present and we rely on more powerful microprocessors to help us solve them. With that impetus, the urge for the continuation of the microprocessor evolution would keep motivating us to quest the further development of microprocessors.

**Reference**

[1] M. Slater, “The Microprocessor today.” IEEE Micro 1995.

[2] S. Furber, “Microprocessors: the engines of the digital age.” Proc Math Phys Eng Sci. 2017;473(2199):20160893.