

Individual Project

APPLE- M1 Ultra

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1. Introduction

Processor in Mac

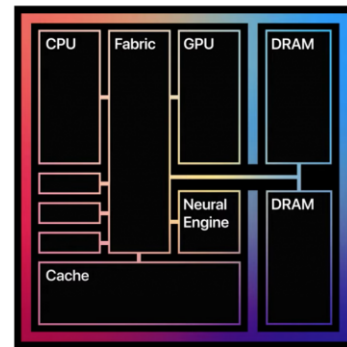
- Apple Silicon from 2020~
- M1, the first SoC in Mac



First of all, I will introduce the central processing unit used in Apple's personal computer product "Mac". Macintosh computer (Mac) has changed the use of instruction set architecture 3 times in history. Motorola 68000 series processor (CISC) was applied before 1994. IBM PowerPC processor (RISC) was applied from 1994 to 2006. Intel x86 series processor (CISC) was applied from 2006 to 2020. From 2020 to present, Apple creates its first-generation M-series processor-M1. M1 is based on ARM cortex architecture (RISC) and this is the first time for Apple to put a SoC (System on Chip) architecture in PC such as iPhone.

Apple's SoC

- CPU
- GPU
- IPU: Image Processing Unit
- DSP: Digital Signal Processor
- NPU: Neural processing Unit
- Video encoder/decoder
- Memory: Unified Memory for Apple
- Secure Enclave: encryption, authentication, security

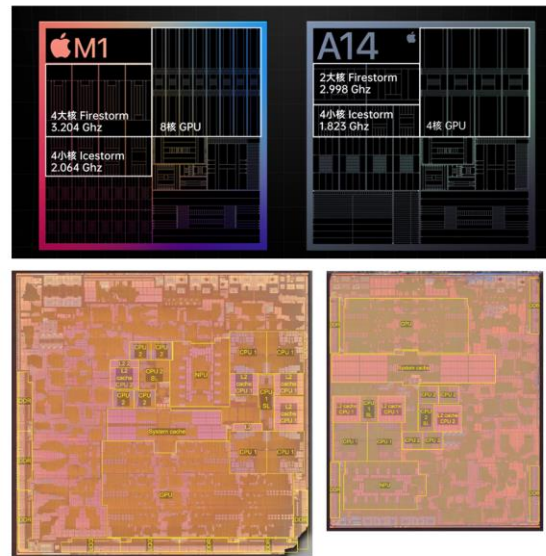


There is a lot of basic components with various functions in Apple's SoC, including CPU, GPU, IPU, DSP, NPU, video encoder/decoder, memory, secure enclave. All these elements are combined together as a single chip and they all have their own task to deal with. Hence, the single chip has the ability to act like a fully functional system in a computer or phone. Specially, the reason of placing the memory in the SoC is that all the functional units could decrease the time of getting data from memory and exchanging data between the units. The ability of sharing use of memory with all units in the SoC is attributed to the interesting unified memory architecture (UMA) for Apple.

A14 to M1

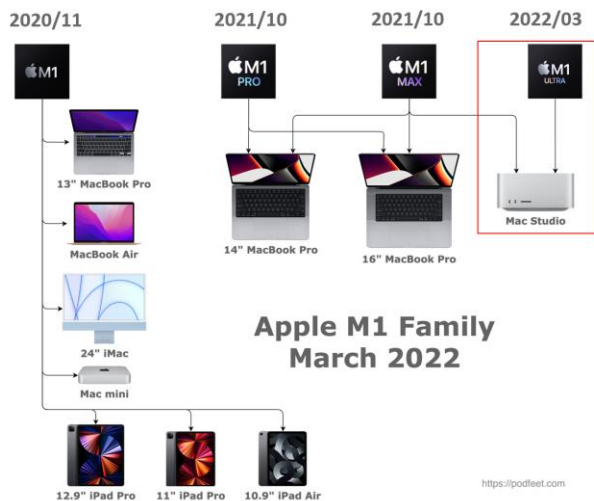
Mobile chip→ PC chip

- 2 more performance CPU cores (Firestorm)
- Higher single core frequency
- 4 more GPU cores
- Doubles the DDR interface (4 -> 8)
- Area 37% larger
- Largest ARM SoC



M1 is quite similar with A14 - the SoC of iPhone 12. M1 is such an upgraded version of A14. To build M1 with outstanding performance, Apple strengthens A14 by placing 2 more performance CPU cores – Firestorm, 4 more GPU cores, doubling the DDR interfaces from 4 to 8 and also heightening the CPU frequency about 10 percent. Due to the strengthening of performance, the chip area also has great increasing about 37 percent larger than the area of A14. Also, M1 was the largest and strongest ARM chip when it was first announced at 2020.

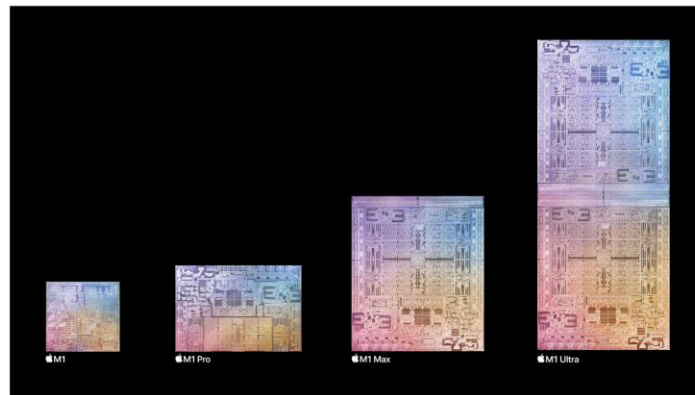
M1 series



M1 series include 4 members – M1, M1 pro, M1 max, M1 ultra. M1 pro, M1 max, M1 ultra are the upgraded version of M1. They all have more CPU cores and much more transistors in the chips. M1 pro and M1 max were both announced in 2021. M1 ultra was later announced in 2022. M1 is widely used in Apple's product including MacBook, iMac, iPad and M1 pro, M1 max are mainly used in MacBook pro. Moreover, M1 ultra is only used in Mac studio.

M1 series

- Area & Performance keep increasing



As you can see, the area of the M1 series has become greater and greater from M1 to M1 ultra and the performance keep increasing as well. M1 ultra is almost 8 times larger of M1, so its performance is elevated to an unprecedented level.

M1 Ultra

- Combine **two M1 Max** (high performance version of M1) by UltraFusion architecture (Chiplet)

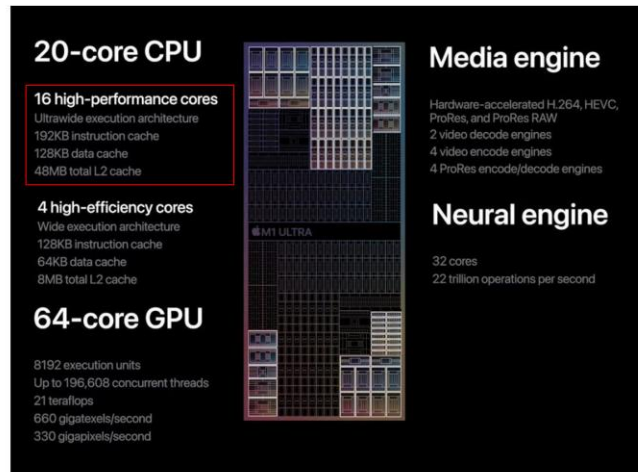


In my report, M1 ultra is the main character that I am going to introduce. The reason why I choose M1 Ultra is due to the amazing technique which combines two M1 max into a piece of chip. The amazing technique is called “UltraFusion architecture” by Apple silicon. UltraFusion is based on the trending chiplet architecture that integrates many small IPs or chips to a large SoC system by advanced IC packaging and processing technology. As you can see, the actual size of M1 ultra compared to the hands in the picture is quite large. Besides the size, M1 ultra also has lots of industry leading techniques inside the system and I will introduce them in the later section.

2. System SPECS & Performance

SPECS

- 20 - core/threads CPU
- 16 high performance 'Firestorm' cores clocked at 3.20 GHz
- 4 high efficiency 'Icestorm' cores clocked at 2.06 GHz
- Maximum power up to 120 W
- TSMC 5nm
- Chiplet Architecture



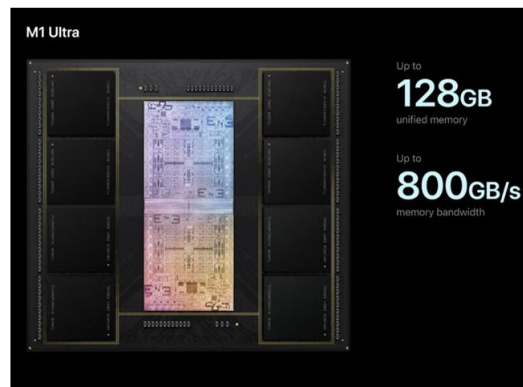
The introduction of the SPECS of M1 ultra will focus on CPU and memory and its performance analysis with the comparison to other CPU based on x86 architecture.

M1 ultra has 20 CPU cores and threads including 16 high performance cores - Firestorm and 4 high efficiency cores - Icestorm. Firestorm has the maximum frequency at 3.20 GHz and Icestorm has the maximum frequency at 2.06 GHz. Furthermore, the CPU core in M1 ultra with the ultrawide execution architecture and large capacity of caches are contributed to the enhancement of instruction throughput. This is also why M1 ultra is able to reach high level performance and lower the maximum power below 120W at the same time.

TSMC 5nm technology is applied to manufacture M1 ultra. Also, the chiplet architecture production is one of the technologies of TSMC.

SPECs

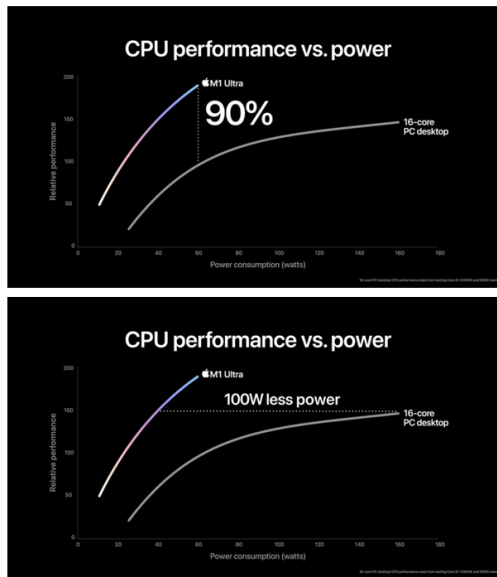
- 128GB storage
- 256-bit LPDDR5 interface
- 800 GB/s bandwidth



Internal memory is one of the most important unit associated to CPU performance. So, size of storage and bandwidth of memory is an essential issue needed to be well designed. Otherwise, memory might become the bottleneck of the performance. M1 ultra has great capacity up to 128GB and super wide bandwidth up to 800GB/s with 256-bit LPDDR5 interface. All the memory blocks are integrated on the SoC to decrease the distance between memory and functional units.

Performance (CPU)

- vs. **intel i9-12900K** with DDR5 memory
- 90% higher performance in the same power envelope
- Similar multi-thread CPU performance while using 100W less power
- **Best performance per watt (PPW) in industry**



The performance of M1 ultra (ARM) is compared to intel i9-12900k (x86) with DDR5 memory. In the same power envelope, M1 ultra reach 90 percent higher relative performance than i9-12900k. Moreover, M1 ultra could deliver similar multi-thread performance as i9-12900k while using 100W less power than i9-12900k.

Thanks to ARM cortex, M1 ultra has the ability to achieve high performance and low power at the same time. Even more, M1 ultra accomplishes the industry leading performance per watt (PPW).

Performance (Memory)

- vs. **intel i9-12900K** with DDR5 memory

Memory Specifications

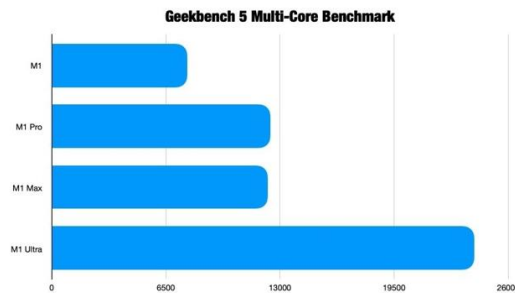
Max Memory Size (dependent on memory type) ?	128 GB
Memory Types ?	Up to DDR5 4800 MT/s Up to DDR4 3200 MT/s
Max # of Memory Channels ?	2
Max Memory Bandwidth ?	76.8 GB/s

Memory in M1 ultra plays a key role on the accomplishment of the outstanding performance. As you can see in the table, i9-12900k supports the same max memory size as M1 ultra, however, the max memory bandwidth of i9-12900k is only 76.8GB/s with two channels. So, the maximum bandwidth of i9-12900k is less than half of M1 ultra's bandwidth.

3. Technology Analysis

How?

- High performance & Low power
- $1 + 1 = 2?$ (CPU)



Now to the technology analysis, I will introduce the technology applied in M1 ultra through two questions.

The first question is how can M1 ultra simultaneously reach high performance and low power consumption?

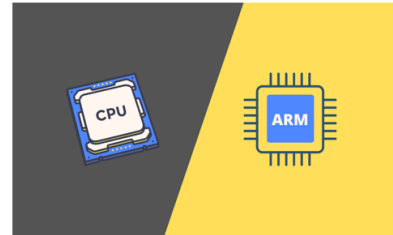
The picture below is the performance test of Geekbench 5 multi-core benchmark (CPU). As you can see, M1 ultra gets two times scores of M1 max's scores.

So, the second question is how can M1 ultra have two times of M1 max's performance just by connecting two chips?

ARM

1. RISC instructions are smaller and faster to process
2. less complicated instructions & architecture
3. less effort to translate instruction
4. ability to share workloads across high- and low-performance CPU
5. more advanced technique can be applied to develop (both designing & manufacturing)
6. don't need to support 32-bit operations

As the result: **high power efficient**



To answer the first question, ARM's advantages in comparison with x86 are going to be discussed. The six points listed on the top explain why M1 ultra based on ARM architecture can have high performance with great power. One of the most important points is that ARM instructions and architecture are much simpler than x86. So, the main reason why M1 ultra simultaneously reach high performance and low power consumption is due to the ARM architecture.

UltraFusion – Advanced Packaging

- 2.5D packaging of two SoC
- x2 the **connection density** of any technology available
- x4 the **bandwidth** of the leading multi-chip interconnection technology
- connect over 10000 signals
- **behaves like a single chip to software**



To answer the second question, Apple's UltraFusion technology is the main reason that makes $1+1=2$ become true. UltraFusion technology perfectly solve the problem of the most important issue of the chips' combination – signal transmission rate. In attributed to advanced 2.5D packaging technique by manufacturer, Apple is able to connect two chips with super large bandwidth - 2.5TB/s making two chips transfer data with super low delay and accomplish the co-working. Therefore, UltraFusion actually makes $1+1=2$.

Moreover, UltraFusion is an industry leading technology that its connection density is two times of any technology available and its bandwidth is more times of the leading multi-chip interconnection technology.

UltraFusion – InFO_LI technique by TSMC

- **Silicon interposer** as silicon bridge between two M1 max
- Area, Power drastically decreasing
- lower the cost

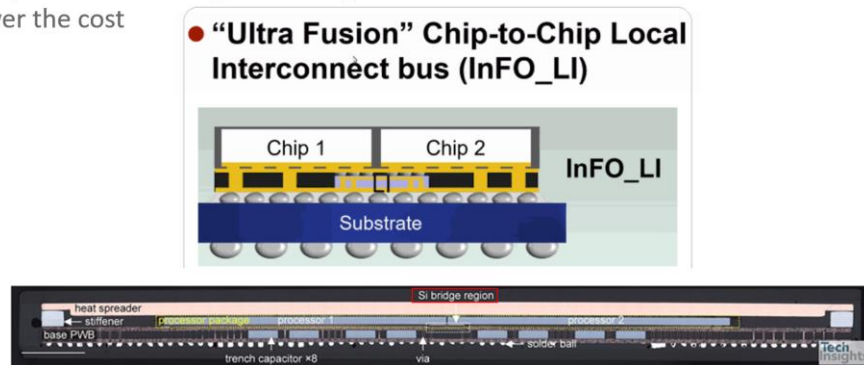
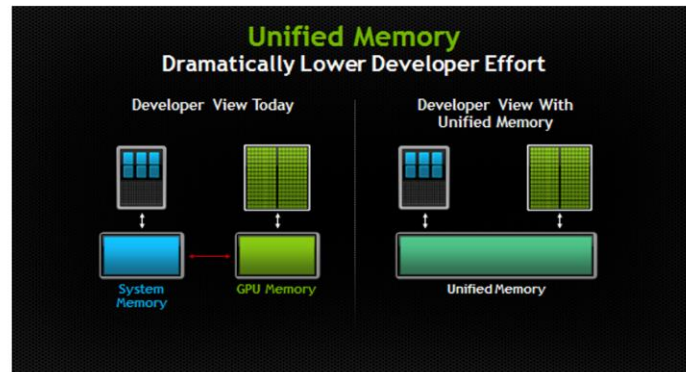


Figure 3. Apple M1 Ultra package (cross-sectional view)

UltraFusion isn't only developed by Apple itself, its manufacturer – TSMC also occupies a pivotal position of the chiplet design. Actually, UltraFusion applies InFO_LI technology by TSMC. InFO_LI is based on the connection through a silicon interposer locating under two chips. The interposer not only achieves high density of connection, but also drastically reduces the area and power produced while transmission. Furthermore, InFO_LI is a cheaper choice of advanced packaging technologies nowadays.

Unified Memory Architecture (UMA)

- Simplify the memory architecture
- Reduce the processing steps of data exchanging
- 800 GB/s bandwidth

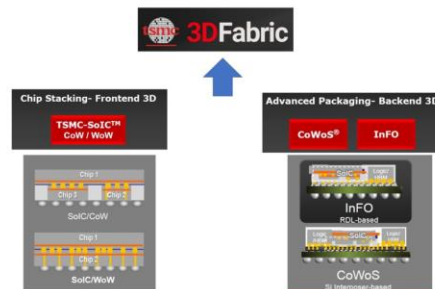
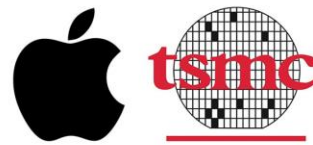
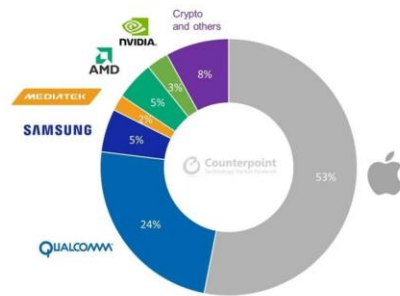


Despite the technologies mentioned above, Apple also applies a special memory architecture different from most of computers. In most of computers, CPU and GPU aren't located in the same place and have their own memory. But, M1 ultra is a SoC architecture, both CPU, GPU and other functional units are combined in single chip. They locate very close to each other, so Apple is able to apply a special memory architecture called "Unified Memory Architecture". UMA does a great job on reducing the complexity and processing steps of data exchange between functional units. It also delivers super large bandwidth up to 800 GB/s. Apple smartly strengthens M1 ultra through the advantage and characteristic of the SoC architecture.

4. Industry Analysis

Industrial Chain - TSMC

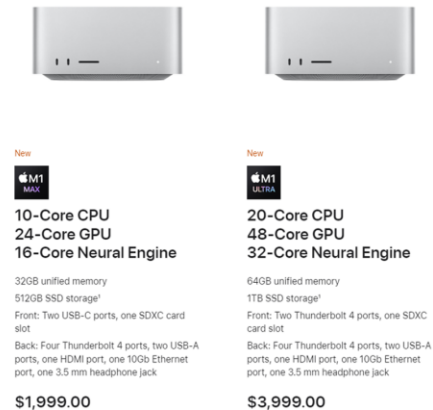
- Designer & Manufacturer
- Apple to account for 53% of **TSMC 5nm chips** production in 2021



The most related job to IC designer is IC manufacturer. So, a large part of M1 ultra's excellent performance is contributed by TSMC's technology. Besides, Apple accounted for 53 percent of TSMC 5nm chips production in 2021. The fact indicates that Apple and TSMC have very close cooperation to build up new designs.

Market

- Product: mac studio
- For professional designer
(Videographers , Musicians, 3D artists)
- High price



M1 ultra is applied in the professional product – Mac Studio. Apple makes this computer mainly for designers, videographers, musicians, artists. To fulfill the performance requirement, Apple uses the strongest chip in M1 series. However, the high price isn't seeming to be a great choice for the normal user. Sadly, there aren't many people having chance to enjoy the great performance of M1 ultra.

SWOT Analysis



Strength

1. Best performance per watt
2. High compatibility between SW & HW
3. Apple ecosystem



Weakness

1. Maximum performance (maximum CLK rate lower than x86)
2. High price
3. ARM software supports



Opportunity

1. Attract more user
2. More advanced technique can be applied because of ARM architecture
3. Development of ARM ecosystem



Threat

1. Intel - x86
2. AMD - x86
3. Qualcomm - ARM

Listed on the top.

5. Conclusion

M1 Ultra Feature:

- Best performance per watt in industry
- Last & Strongest member in M1 series
- UltraFusion technique

Future Trending:

- ARM might become more popular in PC architecture
- Advanced packaging will occupy an important position beyond Moore's law

Listed on the top.

6. Reference

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