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The Original 45nm Intel Core™ Microarchitecture

Greater Mobility Through Lower Power

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ABSTRACT

Mobile Original Equipment Manufacturers (OEMs) place great emphasis on creating unique system designs to differentiate themselves in the mobile market. Intel Corporation's introduction of low-power, high-performance Intel® processors based on original 45nm Intel® Core^{TM} microarchitecture, originally referred to by the codename Penryn, brings a new level of opportunity for differentiation into the mainstream segment without sacrificing performance. The Mobile Penryn family of processors offer mainstream performance at 25 watts (W) Thermal Design Power (TDP), 10 W less than previous-generation processors. This paper focuses on those attributes of design that are enhanced by the Penryn family of processors: thickness, temperature, and noise level. These processors allow thinner, cooler, and quieter systems, and they offer the end-user a more satisfying mobile computing experience.

In this paper we discuss the fundamentals of system cooling capabilities in any given form factor and look at how power relates to the thinner, cooler, and quieter systems. In the end, both Intel and OEMs 'win' when Intel provides the options to allow OEMs to enhance their overall system designs without sacrificing performance and thereby enhance their brand in more systems.

INTRODUCTION

In the extremely diverse world of mobile platform design, the focus of Original Equipment Manufacturers (OEMs) is on "look & feel" (commonly referred to as Industrial Design). Mobile OEMs place great emphasis on creating unique system designs to differentiate themselves in the mobile market [1,2]. Differentiation results in systems that come in all shapes and sizes, or form-factors, as well as systems that emphasize different aspects of mobility such as size, weight, and features. This differentiation makes the specific industrial design of many notebook computers unique to their designer, and that uniqueness becomes associated with their brand. Therefore, components that make it easier for OEMs to implement unique designs allows them to achieve their brand goals.

Additionally, in order to build on the brand equity of a particular industrial design, OEMs frequently maintain the same mechanical design "skin" of the previous platform for two to three generations. This implementation choice also forces them to maintain the same thermal design characteristics as the previous design. Therefore, there is little room for an OEM to innovate when no other parameter is changed.

Although industrial design is a predominant OEM consideration, another major consideration is ergonomics. Ergonomics includes, but is not limited to, user touch-temperatures and audible system noise levels. An uncomfortable touch-temperature (also called chassis or "skin" temperature) or exhaust temperature, or an annoying system noise level distracts from the user experience, even for the sleekest systems. Given the highly integrated nature of notebook system designs, often the vectors of performance, noise, and comfort can be divergent, and each may constrain the other as OEMs seek to innovate and differentiate. OEMs spend substantial design effort to balance performance, chassis temperatures, and or quiet systems, as well as differentiating along one or more of these vectors.

Intel's introduction of lower-power, high-performance Intel® processors based on original 45nm Intel Core^{TM} microarchitecture, originally referred to by the codename Penryn, to the mainstream mobile market brings a new level of opportunity for differentiation. The mainstream Penryn mobile processor draws 25 watts (W), 10 W less than its 35-W predecessor. In this paper we focus on those attributes of the design that are enhanced by lower power Penryn family mobile processors: (1) thickness, (2) temperature, and (3) noise level. We concentrate on the mainstream Penryn family of mobile processors and do not describe the benefits of utilizing the even lower power, small-form-factor family of Penryn mobile processors.

In the following sections, we show form-factor trends and summarize fundamental limits of cooling under ergonomic constraints and other boundary conditions. We then relate these limits to form factor, noise, system temperatures, opportunities for feature additions, and design flexibility.

Current Platform Thermal Challenges

Mobile OEMs design notebook cooling solutions with challenging form-factor limits, component temperature limits, and the primary ergonomic boundary conditions of noise level and chassis "skin" temperatures. A representative system layout is illustrated in Figure 1.

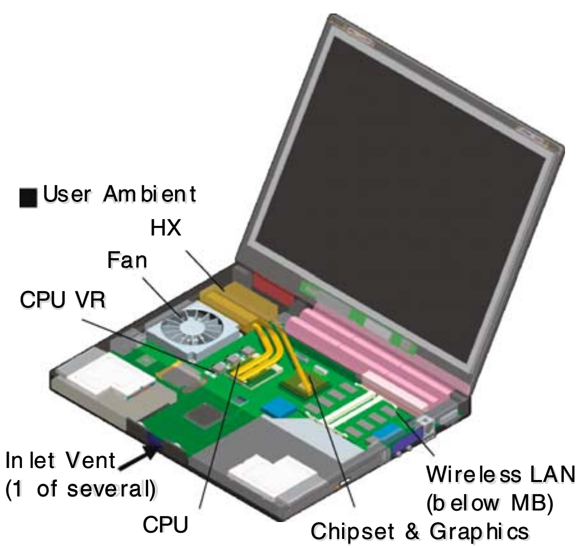

Figure 1: ***Representative notebook iso-view with transparent chassis.***

The numerous subsystems and components compete with each other for motherboard and notebook perimeter real estate for connectors and user interfaces. The result is little unused space, leaving marginal room for adequate air flow. As a consequence, systems are highly integrated mechanically and thermally; they are interdependent for balancing the limited cooling available. The major cooling components, the heat pipe, fan, and heat exchanger, are often referred to as the thermal solution. However, in reality, the solution is the total system design itself, as careful consideration is given to the placement of the air inlet and exhaust vents, the placement of components in primary air flow paths, air flow paths themselves, the fan and heat exchanger, as well as conduction interfaces such as spreaders and even insulators. Change in any of these parameters impacts the cooling of components and the system as a whole, which can make or break a successful design.

Within this competitive landscape, the higher power components vie for good air flow paths, and in the best case, a direct attach to the active solution (the fan and heat sink assembly). Since these good air flow paths and the placement options of the active solution are limited, the higher the power of the component, the more restrictions it places on the system design, whether in the location of the device itself, or in limiting the ability to attend to other components.

Thermodynamic limits

In any given system there is a maximum sustainable level of cooling that is established by the thermodynamic limit. This limit includes theoretical passive limits and the capacity of the available air flow to absorb heat between the ambient air (input) temperature and any given maximum allowable exhaust (output) temperature.

Most of the powered components reside in the base of the system, and the base represents the primary cooling challenge in mobile systems. An energy balance about the base of the system in steady-state conditions is

$$P_{\text{base}} = Q_{\text{passive}} + Q_{\text{active}} \qquad (1)$$

where P_{base} is the allowable total power of components in the base of the system; that is, excluding power to the display. Q_{passive} is the combined passive heat transfer mechanism for energy dissipation; that is, radiation and natural convection, represented by a form of Fourier's Law.

$$Q_{\text{passive}} = hA(T_{\text{chassis}} - T_{\text{ambient}}) \qquad (1)$$

h is a combined effective heat transfer coefficient including natural convection and an approximation of radiation; a typical value may be 8 W/m^2-K. Considering Equation 2, once the system form factor, and thus A (area), is fixed, and once the ambient temperature and the allowable maximum skin cooling temperature (an ergonomic limit) are defined, the passive cooling is established.

Q_{active} is the active cooling level, and its maximum capability is determined by the thermal capacity of the air flowing through the system as in

$$Q_{\text{active}} = \rho \dot{V} C_p (T_{\text{exhaust}} - T_{\text{ambient}}) \qquad (3)$$

Equation 3 illustrates how, in a given ambient temperature, and a maximum allowable exhaust air temperature, the maximum active cooling capability is defined wholly by the amount of air that can be passed through the system. The relation is linear. Figure 2 shows this relationship with the thermodynamic limit for a 1.1″-thick, 14″-display system with nominal boundary conditions of 35°C ambient, an average chassis temperature of 50°C, and assuming a maximum exhaust air temperature of 70°C.

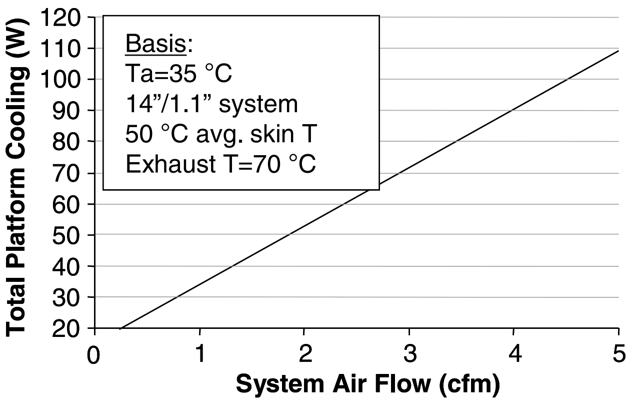

Figure 2: ***Maximum sustainable system cooling—thermodynamic limit.***

Air flow then is the most critical determinant of the total cooling capability of the system; it carries the primary burden for cooling the system. How much air flow can be passed through the system, of course, relies more on the performance of the fan. This capability is primarily characterized by the allowable space for the fan and air flow paths around the fan. There is limited area on the motherboard as well as limited available chassis perimeter space for the fan exhaust, so the only remaining major parameter to examine is the available internal height for the fan and air flow around it.

Thermal stack-up

In mobile systems, the amount of internal height available for the fan and air flow approaching it is limited to, and roughly characterized by, the vertical distance z-height between the bottom of the keyboard and the inside bottom chassis surface. This space is a fraction of the total stack-up as shown in Figure 3. For example, in a typical 14"-display and a 1.1″-thick system, the internal z-height available is 15 mm, which is broken down roughly to 12 mm for the fan itself and 3 mm for air flow paths about the inlet(s). For a system of this size, a typical maximum air flow rate may be 3.3 cfm (1.6e-3 m^3/s); of course, actual air flow depends on the specific design, particularly on system flow paths and corresponding flow resistances.

Several of the system stack-up components at any given time are virtually fixed, such as the display, the keyboard, the motherboard, and the chassis skin. Consequently, if an approximate 10-percent or 0.1" (2.5 mm) reduction in total system thickness is desired, it is effectively a reduction in the vertical space available for the fan and air flow paths at the inlet, or approximately 20 percent for the fan itself (2.5 mm out of 12 mm) assuming the space for the air flow inlet is retained.

Thermal technology limits

Cooling technologies are focused on increasing efficiency in component cooling interfaces and on air flow, whether it's the fan itself or some other means. These technologies have resulted in roughly only a 5-percent additional total system cooling capability year-over-year. Moreover, this progression is prone to tapering off over time with diminishing returns on incremental improvements. Therefore, cooling technology alone cannot keep up with a desire for progressively thinner systems. The power of the components themselves must therefore be reduced to realize thinner systems.

INTEL PROCESSORS BASED ON ORIGINAL 45NM INTEL CORE™ MICROARCHITECTURE

With the introduction of the Intel Penryn processors, Intel Corporation is providing a solution to realize

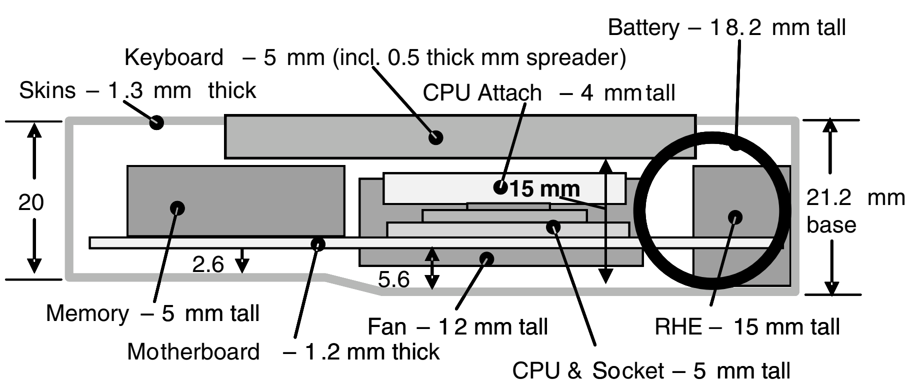

Figure 3: ***Side-view cutaway of vertical stack-up (base only) for a nominal 1.1″ system.***

thinner, cooler, and quieter systems. The Mobile Penryn family of processors provides an option for a full-performance component, but with a 10-W reduction in TDP from 35 W to 25 W. These parts were optimized to 25W TDP in order to address the increasing focus on thermally constrained notebook designs.

Application to mobile systems

These new processors also bring a new level of opportunity for differentiation in the mainstream mobile market segment without sacrificing performance. The 10-W reduction in TDP that they provide as an option can be utilized at the system design level in one of four different ways:

- Thinner systems
- Cooler systems
- Quieter systems
- More feature-rich systems

Thinner systems

One of the primary directions in the mainstream mobile market is to build thinner systems. Figure 4 illustrates this trend of notebook system thickness over time. As is shown with the dotted line in Figure 4, there is a somewhat linear relationship to this decrease in system thickness over time, and OEMs continue to look for opportunities to achieve thinner systems.

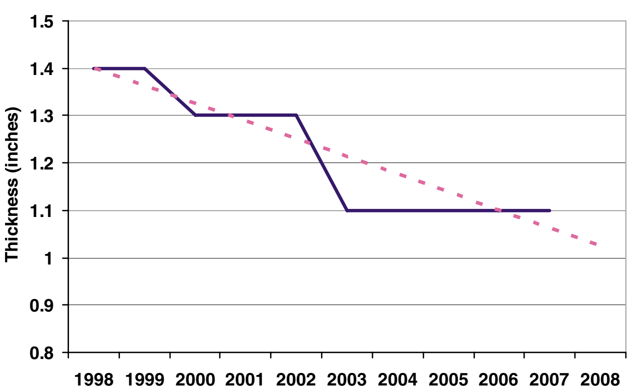

Figure 4: ***Notebook system thickness variation over time.***

However, as stated earlier, the thermodynamic limit for a particular system design is dependent on the air that flows through the system. In a horizontal fan configuration, also called blower fans, the volumetric air flow rate at a given speed is roughly proportional to the z-height of the fan and or blades.

$$\dot{V} \propto z \quad \text{or} \quad V_2 = \frac{z_2}{z_1} V_1 \tag{4}$$

This is an approximation, but it generally holds true for the horizontal fans in mobile systems. For a low-flow loss system, this applies roughly to the air flow rate associated with the operating point in the system. Therefore a reduction in available z-height results in a proportional reduction in air flow through the system.

In the example noted earlier, a 0.1″ (2.5 mm) reduction in total system thickness from 1.1″ to 1″ applies directly to the internal height available for the fan. Thus, a 2.5-mm reduction in the available fan height of a 12 mm thick fan, results in a 20-percent reduction in air flow. For the nominal 3.3 cfm of the original system airflow, this translates to 0.6 cfm. From Equation 2, this translates into approximately a 10 W effective system cooling capability.

Conversely then, if the required platform (base) power is reduced by 10 W, then the opportunity arises to make that system 0.1″ (2.5 mm) thinner.

The new lower-power Penryn family of mobile processors provides the OEM the ability to achieve this amount of reduction in z-height by providing an option for a TDP of 25 W, reduced from 35 W. This allows the mainstream market to more confidently target a new notebook thickness design point of 1″ (14″ display).

Cooler systems

An alternate use of the headroom provided by the new lower-power Penryn family of mobile processors is to make an existing industrial design cooler, whether by prescription or user choice. To evaluate the temperature reduction of a 10-W reduction in power provided by the Penryn family of mobile processors, we perform numerical simulations on the same nominal 14″ display and 1.1″-thick system. The design features are summarized in Table 1, along with typical component TDP design powers, where TDP is representative of the highest power an individual component can go to under any realistic condition.

The simulation is performed using a Flotherm* model of the system. The grid varies in resolution in z and x-y, according to the proximity of component edges and air gaps. Most components are modeled as blocks with simple resistance planes between component and motherboard. Substantial validation has been performed on such models at Intel to establish a reasonable degree of confidence in the results for purposes of comparison.

When assessing how to design a cooler system, a stacked TDP methodology is not employed; rather, a system design power scenario is applied where the concurrent powers of each component are utilized.

For purposes of comparison, consider a usage scenario in which the user is multitasking, stressing the processor and the platform as a whole with various concurrent activity (applications). The powers that we assume for such a scenario are summarized in Table 1. To evaluate the effect of the 10 W power reduction of the processor, the processor power is simply reduced from 35 W to 25 W, keeping all other TDPs at the same level, as denoted in Case 1 and 2, respectively.

Table 1: System features and power scenarios.

Concept	TDP (W)	Case 1 power (W)	Case 2 power (W)
Processor	35	35	25
Chipset & Graphics	10.5	9.5	9.5
I/O controller Hub	2.5	2.1	2.1
Memory	5.6	5	5
Non voltile memory	0.6	0.6	0.6
Wired network, LAN	0.9	0.1	0.1
Wireless network, WLAN	1.8	1.4	1.4
Hard disk drive	4	22	22
Optical disk drive	5.5	29	29
Battery (self-heating)	1.5	1.5	1.5
Voltage regulator CPU (85%eff.)	6.2	6.2	6.2
System VR (87%eff.)	4.8	4.8	4.8
Rest of base power	4.5	4.4	4.4
CPU	35	35	25
Non-CPU	48.4	40.7	40.7
Platform total	83.4	75.7	65.7

Temperature results for the bottom surface are shown qualitatively in Figure 5, which illustrates a substantial reduction in warm area. Keep in mind that the scenario assumed is relatively stressful, and thus, warm. Some specific bottom surface ("skin") temperatures are summarized in Table 2.

From Table 2, a 10 W reduction in system power translates to approximately a 2°C reduction in skin temperature in the vicinity of the processor and its voltage regulator, and a 5.6°C reduction in exhaust air temperatures. Although these differences may not seem large, they can mean the difference between uncomfortable and unacceptable and make or break a design. Internal testing of various systems yielded similar results to the simulation.

Table 2: Simulation results—selected bottom surface ("skin") and exhaust air temperatures.

Location	Case 1 (°C)	Case 2 (°C)
Bottom Skin, Processor	59	57
Bottom Skin, Processor VR	60	58
Bottom Skin, Chipset	44	43
Bottom Skin, Memory	53	53
Exhaust Ait	63	58.4

Quieter systems

Another use of the additional thermal headroom provided by the 25-W version of the Penryn mobile processor is to allow for reduced maximum noise levels in a system.

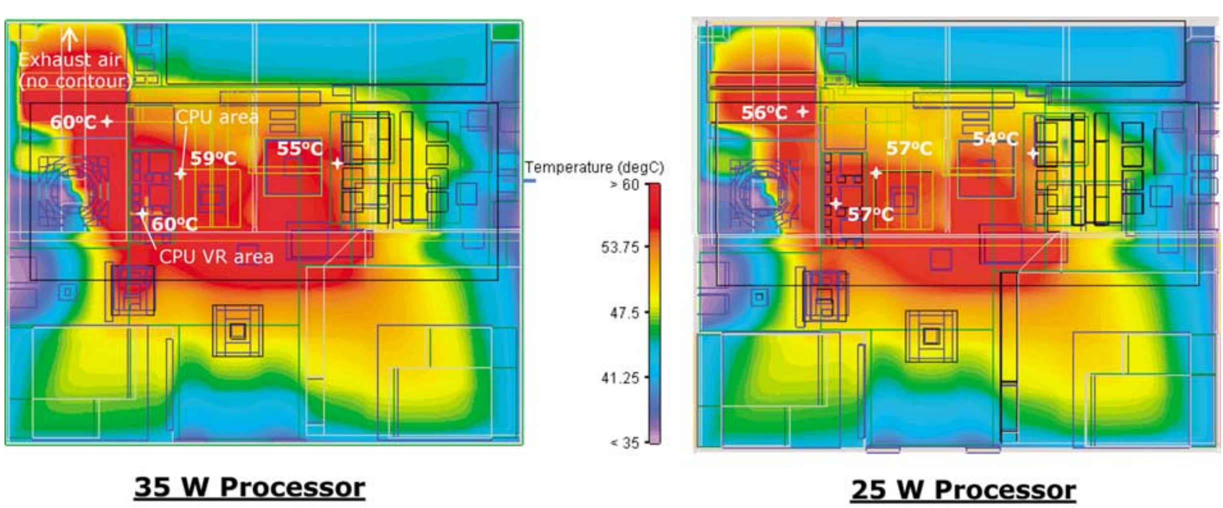

Figure 5: ***Simulation results–bottom surface ("skin") temperature contours.***

Fans are usually turned on or their speed is increased when they are needed to support a high-power application or scenario (alternatively, to reduce the temperatures as discussed above). To evaluate the impact of the 10 W reduction in processor power, consider again the nominal system design in Figure 1, where you have a 14"-display and a 1.1″ system thickness, with a corresponding maximum air flow rate of 3.3 cfm in a user ambient temperature of 35°C and a maximum exhaust air temperature of 70°C.

Intel has internally tested many systems and the noise level associated with their flow rate under standard fan component test conditions [3]. Different flow rates are set by changing fan speed via the fan voltage. The resulting sensitivity of noise measured by sound pressure level is shown in Figure 6. A single fan result is shown by the dashed line in Figure 6. The boxed region indicates a range of system performance, roughly parallel to the single fan result shown. Figure 6 further shows that a 1-cfm reduction in flow rate results in approximately a 10-dBA reduction in noise level.

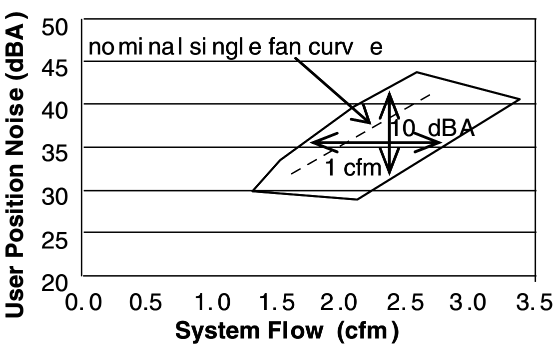

Figure 6: ***Fan noise level sensitivity to flow-rate.***

Using Equation 3 for active cooling, we calculate that the air flow rate associated with the 10 W power reduction of the Penryn mobile processor is approximately 0.6 cfm. Therefore, using the ~10 dBA cfm result from above, a 10 W reduction in power results in roughly a 6-dBA reduction in fan noise level. This is a noticeable reduction in noise to the user position, equivalent to moving the user position twice as far from the noise source [4]. Again, the actual noise level differences will depend upon the specific system design and the usage condition being considered.

More feature-rich systems

One interesting potential use of the TDP headroom provided by the new lower-power mobile Penryn family of processors is to allow other features in the platform to use this cooling capability. Some recipients of this power headroom could be better graphics performance, additional mini-card support (for more wireless cards), higher/hotter system memory capabilities, etc. None of these expanded features could previously be attained within a predefined system design without one of the boundary conditions changing (that is, making the system larger or thicker).

The reduction in the use of power in this processor allows the remaining 10 W to be applied to these other features. For example, current notebook system designs devote approximately 5 W to cooling the system memory. This power limit of system memory prevents mobile platforms from being able to use the fastest (and therefore highest-temperature) memory technology. This is one of the reasons why mobile platforms do not support the same maximum system memory frequencies as desktop platforms. Applying the TDP delta to system memory would allow the OEM to add more features to the notebook system and help bridge some of the feature differences between desktop and mobile platforms.

Platforms based on those ingredients. Each of these opportunities further enhances the user experience of mobile computing and allows the mobile OEMs the ability to provide further innovations to enhance their own brand equity and thereby create a 'win' for both Intel and the OEM.

SUMMARY AND CONCLUSION

The introduction of lower-power, high-performance Intel processors based on the original 45nm Intel Core microarchitecture provides mobile OEMs with an excellent opportunity to create the next great mobile platform design.

Although the results presented in this paper are specific to the conditions analyzed herein and will change based on the specific system design, the opportunities presented for enhancing the mobile platform user experience are compelling. Only time will tell which of the presented opportunities was most highly valued and therefore most utilized. However, one thing is certain: all of these opportunities are directly tied to the Intel processors based on original 45nm Intel Core microarchitecture and the Intel Centrino™ Mobile Platforms based on those ingredients. Each of these opportunities further enhances the user experience of mobile computing and allows the mobile OEMs the ability to provide further innovations to enhance their own brand equity and thereby create a 'win' for both Intel and the OEM.

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APPENDIX: NOMENCLATURE

ρ	density of air, kg/m^3
A	effective heat transfer surface area, m^2
C_p	heat capacity (of air), J/kg-K
h	heat transfer coefficient, W/m^2-K
P	power (or cooling), W
Q	heat, W
T	temperature, °C
T_{chasis}	chassis surface ("skin") temperature, °C
$T_{ambient}$	user ambient air temperature, °C
$T_{exhaust}$	system exhaust air temperature, °C
$\dot{V}$	volumetric air flow rate (of air), m^3/s

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