

Accelerating Your Computing Experience Solid State Drives (SSDs)

What you should know about solid state drives (SSDs)

Envision this rapid start to your day: you boot your laptop, launch an application, and open a large file—all in the blink of an eye. Sound intriguing? Guess which of your computer's components plays a large role in enabling this speed. If you answered, "the solid state drive (SSD)," then you're correct. Even if your processor can handle billions of cycles per second, without fast storage, you might be stuck waiting for data.

Maybe you are in the market for a new laptop. Or maybe your current system is slow. You can accelerate your computing experience with the right SSD. Because SSDs can affect your computing experience in such an impactful way, it pays to learn more about them.

This white paper explains what you need to know about SSDs to experience faster computing. It starts with the basics of computer storage and SSD technology, and it then dives into the details of how to select the right SSD—whether you plan to buy a new computer system or to upgrade your existing system.

Computer storage

SSDs are solid state storage devices. They have no moving parts, in contrast to hard disk drives (HDDs), which have actuator arms and spinning disks. As a result, SSDs deliver a faster experience than HDDs. And because SSDs come without mechanical parts that are prone to failure, they are more reliable. SSDs come in smaller sizes than HDDs (see Figure 1), saving crucial space in systems, and consuming less power. HDDs are generally available at lower price points—depending on capacity—though the gap is closing (see Figure 2).¹

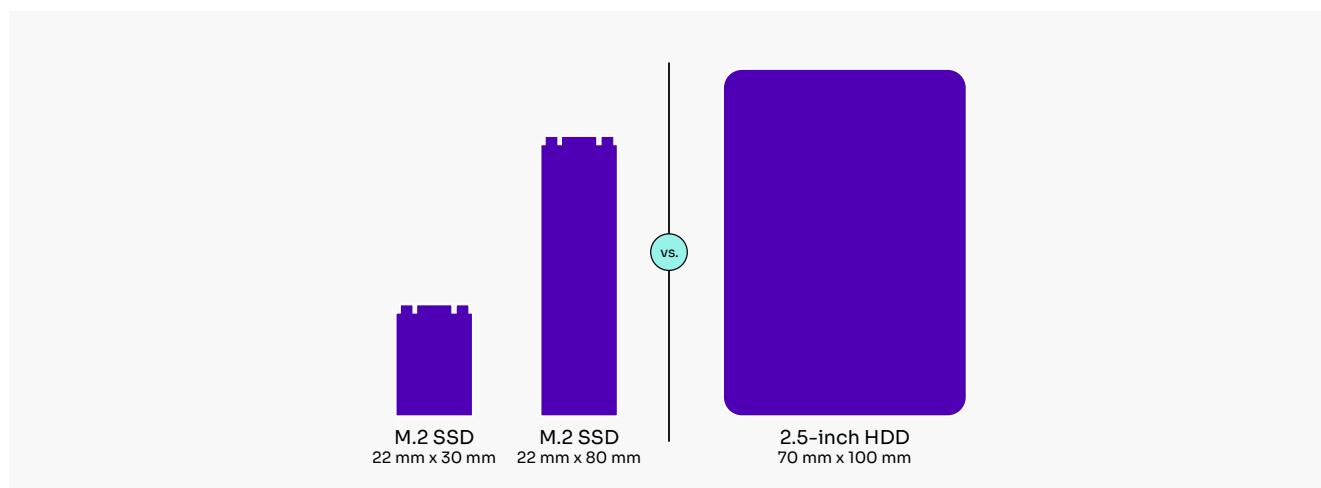


Figure 1. Relative SSD form factors versus HDD form factor

Today's SSDs use NAND flash technology, a type of storage technology that retains data even when the system is turned off. NAND flash features high-density storage with fast read, write, and erase speeds.²

As SSD prices have dropped, OEM computer manufacturers have shifted to using SSDs instead of HDDs as the primary storage drive. Even larger gaming machines now ship with SSDs. In some cases, a desktop computer might come with both: an SSD installed as a boot drive and an HDD installed as a larger-capacity storage medium.³

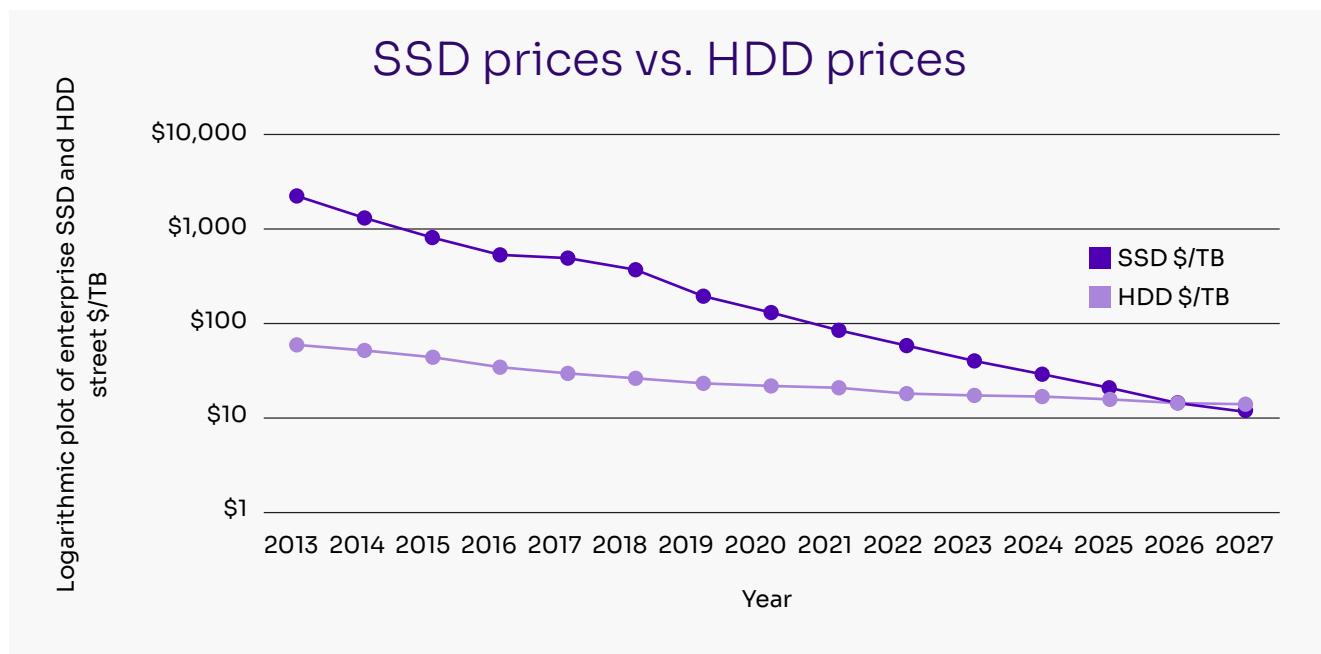


Figure 2. Wikibon forecasts the price of SSDs will drop below the price of HDDs around 2026¹

Solidigm is a leading global provider of innovative NAND flash memory solutions. Born from the combination of Intel's longstanding innovation in memory products and SK hynix's international leadership and scale in the semiconductor industry, Solidigm became a standalone U.S. subsidiary under SK hynix in December 2021.

SSD technology

The NAND flash inside SSDs uses a transistor (also referred to as a cell) to store information as bits in binary form. SSDs are non-volatile—that is, information is retained when the power is off. Launched in the late 1980s, the first non-volatile NAND flash was a single-level cell (SLC): this means there was one bit per cell and two levels of charge, indicating either a one or a zero.⁴

Evolution of NAND

Because the initial cost of NAND flash was high (in 1991, the cost of an SSD was about \$50K/GB, whereas today the cost is as low as \$0.10/GB),^{5,6} and because users need to store ever increasing amounts of data, flash manufacturers have worked to increase the number of charges stored within each NAND flash cell. This led to the development of multi-level cell (MLC) NAND in the late 1990s. Triple-level cell (TLC) NAND and quad-level cell (QLC) NAND came on the market around 2010, delivering higher capacity storage at even lower cost. Historically, denser cells resulted in a slower computing experience and faster wearing out of

the cells. Manufacturer innovation has addressed these two issues so that now the most popular NAND flash technologies for consumer SSDs are the densest: TLC and QLC NAND.⁷

A summary of different flash types is below:

- **SLC:** Stores one bit per cell with two levels of charge.
- **MLC:** Commonly stores two bits per cell with four levels of charge.
- **TLC:** Stores three bits per cell with eight levels of charge.
- **QLC:** Stores four bits per cell with 16 levels of charge.

With the evolution of mobile devices, flash manufacturers were eager to shrink the overall space required for NAND flash: 3D NAND flash started to appear in 2012. This technology achieves higher densities by stacking cells vertically in multiple layers.

Interface technology

The first flash-based SSDs used legacy Parallel Advanced Technology Attachment (PATA), Serial-Attached SCSI (SAS), and Serial ATA (SATA) physical interfaces, protocols, and form factors designed for HDD storage. This approach minimized changes in existing computer systems. But these interfaces and protocols were not designed for high-speed storage media. As the speeds of SSDs increased, these interfaces have become performance bottlenecks.

To enable faster SSDs, manufacturers have switched to PCI Express (PCIe), an interface standard developed specifically for connecting high-speed components. The PCIe standard was introduced in 2003, and by the mid-2000s, most computers were shipping with PCIe slots. Today, most SSDs run on PCIe 3.0 or PCIe 4.0. Note that commercial production lags new standards (see Table 1).⁸

Table 1. PCIe generations and speeds⁹

PCIe generation	Year standard defined	Bandwidth
PCIe 1.0	2003	8 GB/s
PCIe 2.0	2007	16 GB/s
PCIe 3.0	2010	32 GB/s
PCIe 4.0	2017	64 GB/s
PCIe 5.0	2019	128 GB/s

PCIe slots come in different physical configurations: x1, x4, x8, x16, x32. The number after the x communicates how many lanes (how data travels to and from the PCIe card) that a PCIe slot has. For example, PCIe x4 has four lanes. Data is transmitted serially over each lane, but the more lanes that run in parallel, the higher the data-transmission rate. Consumer SSDs typically support either two or four PCIe lanes.

NVM Express (NVMe) is a high-performance protocol that was developed to enable high-speed data transfer over PCIe buses. The NVMe protocol capitalizes on parallel, low-latency PCIe data paths. A PCIe bus running an NVMe protocol is referred to as “PCIe NVMe,” though you might see it written as simply “PCIe” or “NVMe.”

Form factor

In addition to different interfaces, SSDs come in different form factors. If you are replacing an HDD or upgrading your current SSD, consult your computer system manual to confirm the form factor, interface, and data-transfer protocol required by your computer system. Most likely, your SSD form factor is either a 2.5-inch SSD (Figure 3) or an M.2 SSD (Figure 4).



Figure 3. Example of a 2.5-inch SSD



Figure 4. Example of an M.2 form-factor SSD

The most common bus interface for an M.2 SSD is PCIe running the NVMe protocol. However, you might see an M.2 SSD with a SATA interface. A 2.5-inch SSD might have a SATA interface and run the SATA protocol or a PCIe interface and run the NVMe protocol. Table 2 describes form factors and common interfaces and protocols.

Table 2. Common interfaces and form factors

Form factor	Size	Interface	Protocol
2.5-inch SSD	2.5-inch	SATA	SATA
2.5-inch SSD (U.2)	2.5-inch	PCIe	NVMe
M.2 2280	22 mm x 80 mm	PCIe	NVMe
M.2 2230	22 mm x 30 mm	PCIe	NVMe

Endurance

Due to its architecture, NAND flash has an endurance limit. This means that NAND can only be rewritten (or programmed) a given number of times before it becomes difficult to write (or program), resulting in write and read errors. Fortunately, NAND flash technology has evolved so that the odds of a consumer writing enough data to a modern TLC or QLC NAND SSD for reliability to become an issue is low. For example, a 1 TB Solidigm™ 670p SSD with an endurance rating of 370 TBW can be written to the equivalent of more than 200 GB per day over a five-year warranty period before read and write errors become noticeable. This equates to importing more than 33,700 photos (6 MB JPEG each) per day, saving more than 225,000 documents (900 KB in size) per day, or installing the game Dota 2 (15 GB) 13 times per day for five years.¹⁰

SSD manufacturers typically specify terabytes written (TBW) and a warranty period for an SSD. For example, Solidigm specifies its 2 TB Solidigm 670p SSD at 740 TBW with a five-year limited warranty.

Terabytes written (TBW)

TBW is a metric used to characterize SSD write endurance. TBW describes how much data can be written to an SSD over the life of the drive. For example, a 1TB drive with a 370 TBW rating and a five-year warranty will permit a user to write well over 200 GB per day, every day, for five years straight—a number most consumers won't remotely approach.

Reliability

As the cell density of NAND flash increases (the cells are closer together), the number of read or write errors that might occur increases. Error correction code (ECC) software within the SSD works to eliminate these errors. SSD industry standards require that the unrecoverable bit error rate (UBER) be maintained below a very small threshold: less than one in one quadrillion (10^{15}). If you read the UBER specification for the 2 TB Solidigm 670p Series drive, for example, you would see the specified error rate is less than one sector per 10^{15} bits read.

Typically, consumer applications do not reach the endurance write threshold for SSDs, and ECC software manages errors so that endurance and reliability are not issues.

Future of flash

Today, TLC is the SSD front runner for laptops and desktops. However, QLC, now in its fourth generation, is coming on strong. As QLC technology and manufacturing processes have evolved, QLC speed and endurance are approaching those of TLC.

Flash manufacturers are finding innovative ways to increase the performance of SSDs beyond hardware. For example, Solidigm is implementing innovative caching approaches in SSD firmware that result in higher sequential read and write performance. The company is also investing in new storage drivers with queueing, host-managed caching, and prefetching features that increase storage and retrieval speeds.

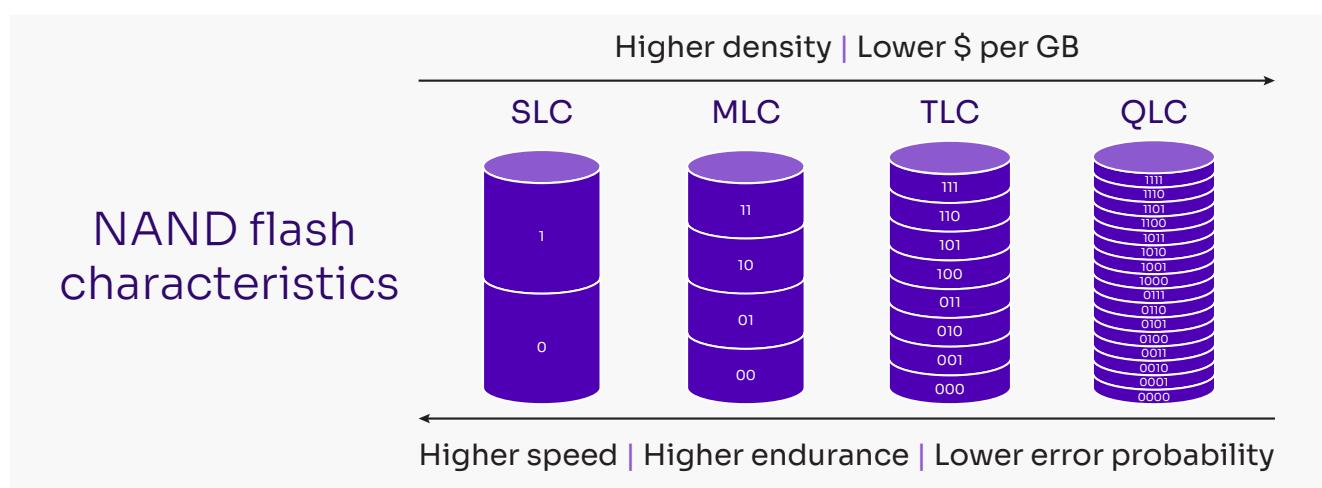


Figure 5. Summary of NAND flash characteristics by technology

Selecting your SSD

Compile the information you need to know to select the right SSD by answering the following questions:

1. What is your computing profile or use case?
2. How should you prioritize SSD features for your use case?
3. If upgrading from an HDD to an SSD, or from one SSD to another, what are your computer's bus interface type, data-transfer protocol, and form factor requirements? (Best found in your computer manual.)
4. Who are your trusted manufacturers?
5. How can you validate your selections through third-party reviews?

What is your computing profile?

Understanding how you plan to use your computer is the first step in determining the best SSD. The following are some typical user personas. Where do you see yourself?

Small business owner

Will you run productivity applications like Microsoft Office or Adobe Creative Suite? Will you open and save large files on your computer system? Do you have regulatory requirements that require encryption to enhance security?

Content creator

Will you be creating content? If you are a photographer, a video editor, or an engineer, do you plan on write-intensive work like saving large files to your storage drive?

Gaming enthusiast

How many games will you save on your system?
How important is performance?

Student

Do you work mostly with small files? Or are you a college student majoring in computer science or engineering, which might need larger files to hold your work?

How should you prioritize SSD features?

After determining your computing profile, the next step is to prioritize SSD features. This section briefly covers the features and attributes (like cost) that you need to consider.

What SSD capacity makes sense for you?

For a consumer computer system, SSDs are available in capacities ranging from 120 GB to 2 TB. The following are some notes on capacity by use case:

- **Small business owner (256 GB or more):** An SSD with a capacity of 256 GB will give a small business owner room to store an operating system (Windows 10 takes up about 20 GB and macOS about 35 GB).¹¹ It will also provide space for frequently used programs and files. To leave room for growth, a 512 GB SSD is recommended.
- **Content creator (1 TB or more):** An SSD with a capacity of at least 1 TB will make workflows easier for video editors and engineers. It will provide space to store programs, project files, and backup images. However, a content creator might consider 2 TB to ensure they have enough space.
- **Gaming enthusiast (1 TB or more):** Many PC games take up about 40 GB to 50 GB in storage. An SSD with a capacity of 1 TB will give a gamer enough room to store the operating system and a variety of games.
- **Student (256 GB or more):** A student's SSD size will depend on what they are studying. An SSD of 256 GB will work for a high school student or a college student majoring in liberal arts (smaller files). An SSD of 1 TB or more might be needed for a college student majoring in science or engineering (larger files).

Selecting the right SSD capacity

Consumer SSDs range in capacity from 120 GB to 2 TB. The following are some rules of thumb for four use cases:

- | | |
|---|--|
| ▪ Small business owner: 256 GB or more | ▪ Gaming enthusiast: 1 TB or more |
| ▪ Content creator: 1 TB or more | ▪ Student: 256 GB or more |

What is your budget?

Consider total cost of ownership (TCO) when determining how much to spend. How much time will faster storage save you? If you're a content creator and you can reduce your import/export times when using software such as Adobe Premiere Pro, Lightroom, or Photoshop, then a high-performance SSD might be a good investment. Similarly, a higher capacity SSD could save you time because you can store more files. Features like high endurance can help increase peace of mind, while hardware encryption can help lower the risk of losing data.

How do you plan to secure data?

Securing your data from theft or exposure due to a lost or stolen computer is important. Users who are looking for enhanced security should consider encryption: either with hardware or with software.

If you prefer hardware encryption, look for an SSD that supports it. These SSDs encrypt data as it is written, and unencrypt data as it is read. The downside of self-encrypting drives is higher cost.¹² Because the drive encrypts the data, and not the computer processor, you won't experience a decrease in performance.¹³

If you prefer software encryption, there are many options. BitLocker Drive Encryption, for example, integrates with the Windows operating system. However, software-based encryption slows performance compared to hardware-based encryption.¹⁴

Whether you use software or hardware encryption to secure your SSD, it is critical to use strong passwords and change them periodically. Cloud-based password managers can help make sure your passwords are hard to crack, stored safely in the cloud (instead of on a sticky note on your desk), and changed regularly.¹⁵ You should also save a backup of your recovery key.¹⁶

If you decide it's time to upgrade or replace an encrypted SSD, you can transfer data and system configurations by cloning your old HDD or SSD to a new SSD. Be sure the new SSD has a higher capacity than the older drive when doing this. You will need to unlock your SSD using the password or encryption key. Third-party software can be used to transfer content from the old disk to your new disk. You can choose from a variety of freeware and paid software offerings for disk cloning.¹⁷

What level of performance are you looking for?

You don't want to wait while your computer boots or opens a large file. But higher performance comes at higher cost. As a result, you want to know what type of performance is right for your use case.

When reviewing the printed specifications of an SSD or system, you might see the following categories of numbers (units in parentheses) displayed as part of the SSD specifications. These are often referred to as the "four corners" of SSD performance:

- Random 4K reads (input/output operations per second, or IOPS)
- Random 4K writes (IOPS)
- Sequential reads (MB/s)
- Sequential writes (MB/s)

Sequential and random read/write performance metrics represent different ways of using storage. Sequential read/write speeds reflect how fast a computer can access or transfer a larger file. A high percentage of sequential reads and writes fits the profile of a content creator. Random read/write speeds reflect how fast a computer reads or writes from smaller files in random locations. A high percentage of random reads/writes fits the profile of a small business owner or student. Each person will have a unique mixed (sequential and random) workload of reads and writes.

What tasks will be faster with a high-performing SSD?

The SSD in your computer system will impact your experience. The right SSD will speed tasks like booting your system, launching applications, or transferring files. Be aware there are some tasks that are not storage-dependent: web browsing or streaming audio or video, for example. Align your expectations with the capabilities of SSDs to increase performance.

To obtain their performance specifications, SSD manufacturers stress drives under various synthetically generated parameters. Though the results are technically accurate, they might not reflect the real-world

experience of a consumer, which typically consists of mixed workloads of reads and writes. Because some manufacturers' published performance data might have been obtained under synthetic conditions only, you might purchase an SSD only to discover it doesn't perform as expected.

To ensure you get the performance you need, look for third-party validation. Seek out third-party validators or reviewers that use real-world workloads that mimic small business owner, content creator, gamer, or student use cases.¹⁸ Be wary of a reviewer that presents a single speed as a reason to purchase. Look for third-party reviewers that take into consideration the nuances of different uses cases: whether they are read-intensive, write-intensive, or a mix of both. Recommended third-party SSD validators include websites such as AnandTech, HotHardware, Legit Reviews, PC Perspective, and Tom's Hardware.

Prioritization wrap-up

Table 3 illustrates how a small business owner, a content creator, a gaming enthusiast, and a student might prioritize capacity, cost, security, and performance. The table also includes endurance/warranty and reliability for completeness, though most modern SSDs offer more than sufficient endurance and reliability for consumer workloads.

In this example, three dots indicate "high priority," two dots indicate "medium priority," and one dot indicates "lowest priority." Create a similar list for yourself. This will help you identify which features or attributes are "must haves" and assist you in making tradeoffs.

Table 3. Sample feature priorities by use case

SSD feature	Small business owner	Content creator	Gaming enthusiast	Student
High capacity	• •	• • •	• • •	• •
High performance	•	• • •	• • •	•
Low cost	• •	• •	• •	• • •
High security	• • •	• •	•	•
High endurance/long warranty	• •	• • •	• •	• •
High reliability	• •	• • •	• •	• •

If upgrading your current system, then check your computer manual to confirm form factor, interface, and protocol.

Prioritization example: small business owner

This section steps through how a small business owner might prioritize features. The small business owner decides he wants an accelerated computing experience, and he also wants hardware-level encryption. His prioritization list is provided in Table 4.

Table 4. Example of how features can be prioritized by use case

Priority	Small business owner
Priority features	Performance
	Security

Reviewing the Solidigm 670p Series spec sheet, as an example, the office worker sees the following:¹⁹

- Sequential reads: Up to 3,500 MB/s
- Sequential writes: Up to 2,700 MB/s
- Random 4 KB reads: Up to 310K IOPS
- Random 4 KB writes: Up to 340K IOPS

The performance looks good. But the small business owner knows that third-party validation is the best way to confirm performance. He finds three third-party validations praising the SSD:²⁰

- AnandTech, “Recommended”
- Legit Review, “Value Award”
- Tom’s Hardware, “Editor’s Choice”

He feels confident the performance is adequate for his needs. Next, the small business owner digs deeper and discovers the SSD offers AES-512 hardware encryption, which is what he wants. As he is buying a new computer, he doesn’t need to be as concerned about matching the form factor, interface, and protocol as if he were upgrading his system, but he does note that the Solidigm drive has a “PCIe 3.0 x4” interface and an “M.2 22 x 80 mm” form factor. The Solidigm 670p Series drive would now be on his short list.

The right SSD for you

Whether you’re in the market for a new laptop or troubleshooting a slow computer, you need to know how the right SSD can accelerate your computing experience. To help you, this paper covers the basics of computer storage and SSD technology. It also steps through key questions to answer before shopping for your new system or SSD.

Start by understanding your computing profile or use case. This will allow you to prioritize the SSD features and attributes that are most important to your experience. Expect to make tradeoffs. Most likely you will be deciding between lower cost and higher performance or higher capacity. Choose an SSD manufacturer with a reputation for technical excellence and good support. Read online reviews of the SSDs published by industry experts to validate manufacturers’ specifications. The result of your due diligence will be an accelerated computing experience that meets, or even surpasses, your needs.

For more information on storage technology and SSDs, visit solidigm.com.

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