

Ancient Art, Modern Tech:
Experiencing the Digital Reinvention of the Mogao Grottoes

by

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ABSTRACT

Built from the 4th to 14th century, the Mogao Grottoes in the deserts of northwestern China is the greatest repository of Buddhist art in the world. It has long faced a range of threats from natural disasters to imperialistic plunder. But now it must confront the greatest challenge to its continued existence: modern-day tourism. The sheer volume of visitors seeking a direct experience of this unique but delicate site has resulted in an increasingly rapid process of destruction in the 21st century.

Its guardian institution, the Dunhuang Academy (DA), has thus embarked on an ambitious, decades-long undertaking that puts technology at the core of its mission to protect, research, and promote the site. Today, digital resources, replicas, and exhibitions have redefined what it means to experience the caves. Together, they have also expanded Mogao's reach far beyond its physical boundaries.

Against all odds, this middle-of-nowhere desert outpost has emerged as a global pioneer of digital conservation and restoration. It's a model that can be exported to other fragile sites across the world. This thesis compiles a comprehensive history of Dunhuang's journey and raises questions about what it means to "authentically experience" such cultural heritage today.

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I. INTRODUCTION



*The famous nine-story pagoda of the Mogao Grottoes, an archaeological site of world significance located outside Dunhuang, China.
Image by Celina Zhao.*

At 8 am on a Tuesday, I'm standing in a desert, in the middle-back section of a line of at least two hundred tourists, getting pelted by snowflakes. They're falling hard and fast, a rare January snowstorm for this typically dry climate. But what awaits us is worth the minus 15-degree Celsius chill. In just a few hours, we'll be able to see the greatest treasure trove of Buddhist art in the world: the Mogao Grottoes.

The 492 surviving caves of the Mogao Grottoes are carved into a sheer cliff face in the far west of China, just outside the city of Dunhuang in Gansu Province. Inside the caves, the monochrome gray beige of the desert dunes transforms into an extravagance of color and motion. Royal blues of lapis lazuli, earthy reds of cinnabar, and metallic highlights of gold are just a few shades in this kaleidoscopic

explosion of hues. Mountains and animals and gods and heavenly apsaras soar across the walls, while thousands of tiny Buddhas smile gracefully from the ceilings. Together, they total more than 450,000 square meters of art.

Built from the 4th to 14th century, the caves form an account of 1,000 years of Pan-Asian civilization and history. In the 21st century, they have become one of the most sought-after tourist destinations in China.

To be standing here at this very moment, those in line with me must have snatched up entrance tickets that sold out in a matter of seconds when they were released four weeks ago. Dunhuang is not yet easily accessible from China's high-speed rail network, so just getting here is no easy feat either. It took the father and his 11-year-old son in line in front of me two days and three flights to get here from Fujian, some 3,000 kilometers away. And yet, even after all that, they — and all of us in the queue — will have to wait just a bit longer to enter the caves.

That's because every person here represents what is perhaps the greatest peril the caves have faced across their entire existence. They have persevered through a millennium of sandstorms, floods, and earthquakes. But now, modern-day tourists are slowly loving them to death. Every breath a visitor takes is filled with CO₂ and humidity, which are relentlessly damaging within the interior of the caves. And the presence of too many people greatly accelerates the oxidation of the pigments, changing the once-pink face of an apsara to an inky black. Worse, humidity also weakens the very foundation of the paintings, making them more prone to flaking off the rock walls in chunks.

The numbers of visitors seeking access to the grottos now threaten irreversible consequences. By some estimates, certain paintings may not exist to be seen in just another few decades.

It's a tricky predicament faced by the Dunhuang Academy (DA), the official guardian institute of the Mogao Grottoes. On one hand, the unending assault of human interest and pressure poses enormous risks to the fundamental existence of the caves. Simultaneously, opening access is crucial to understanding the site's historical and cultural significance — and it is the general public who can mobilize the greatest support and awareness. It's a challenge that an increasing number of unique and vulnerable cultural heritage sites across the world are grappling with.

So I'll be experiencing the DA's ambitious, decades-long effort to balancing these conflicting objectives. The result is a new approach to tourism that puts technology at the core of the academy's conservation efforts — and thus at the core of everything we'll see. Because that's the best way, and perhaps only way, to protect the caves: by physically restricting how much each person can interact with the fragile, precious site. Instead, technology has created new visual and interactive mediums through which we will experience the grottoes.

That's why we're all in line here. We can't go to the caves just yet. Rather, our first stop is a sprawling digital visitor complex 15 kilometers away from the site. This \$50 million building was built in 2014 to act as a firewall. Its purpose is to slash the time each visitor spends inside the caves by half. That time is instead spent outside the caves, learning about the evolution of the caves and their resulting fragility, through a duo of high-tech films.



*The lobby of the \$50 million Digital Visitor Center.
Image by Celina Zhao.*

And by 9:30 am, the theater for the first movie is already at full capacity. I'm sitting elbow-to-elbow with my neighbors as the lights are dimmed. As the movie begins telling the story of how the caves came to be, the audience and I are transported back to the past.

Once considered deep in China's wild west, the city of Dunhuang in northwestern China was one of the stops monk Yue Zun made along his journey to the Western Paradise in 366 BC. As he crested the dune of Mount Sanwei, he suddenly saw the light of a thousand golden Buddhas. Inspired, he chiseled the first cave into a sandstone cliff along the Daquan River.

Many of the initial caves that followed were no larger than coffins or small bedrooms. But over the next centuries, Dunhuang emerged as a cultural crossroads on the east-west artery of the Silk Road.

This desert oasis welcomed merchants from Central Asia, monks from India, and travelers and artisans from everywhere in between. With them, ideas flowed.

One of the most influential was Buddhism. In the centuries following Yue Zun's vision, Mogao flourished with activity. Temples and monastic lecture halls were fashioned out of larger and larger excavations, as interiors were carved with sweeping architectural features like beams, eaves, and coffered ceilings. And on top of every available surface, sponsors financed magnificently detailed artwork worshiping Buddha and his various forms. The art reflected the desires of those living in or passing through the city: to safely cross the dreaded Taklamakan desert, or to be reborn in paradise.

The caves thus form a developmental timeline of Buddhism's transformation into a Chinese faith, an encyclopedic archive of wishes and styles and beliefs.

Then, we all shuffle into the second theater. This one is in the shape of a giant dome. Through the spherical screen stretching high above our seats, the caves come to life in stunning 8k visuals. Four times the resolution of a typical movie theater, the clarity of detail is incredible – it's like my eyesight has been enhanced to new heights. This is the level of technical sophistication the guardians of the grottoes are trying to build as the hallmark of their digitization strategy.

The film introduces seven caves of high artistic value that are usually closed off to the public: we learn everything from when they were created to the various stories depicted within. No matter which direction I crane my head — forward, left, right, upwards — every inch of my vision is filled with undulating images. When I twist backward to look behind me, I can even see the source of the “sunlight” illuminating it all, as well as the endless expanse of blue sky and desert beyond the cave's door. The sheer expanse of detail is nearly an information overload.

Only after these two films are completed are we deemed sufficiently primed to be taken to the caves on DA-sanctioned buses. At long last, two hours after arriving, the first grottoes finally begin to appear.



*The first grottoes that we see on our bus ride.
Image by Celina Zhao.*

Because human activity is so detrimental to the site, no tourist is allowed to go inside any of the caves by themselves. Instead, everyone is handed a headset and sorted into docent-led groups of twenty-five. Since I'm the only person who bought an English ticket, however, I end up getting a private tour. "Are you pretending like you can't speak Chinese to bypass the lines?" my guide, Song Hang, jokes as she leads us up the steps to our first cave, number 249.

She's a Gansu native who's been interested in the caves for nearly her whole life. And though not much older than me, she is already a walking Chinese, English, and French textbook rolled into one. That's thanks to her time spent studying in France, where many Mogao relics are located today. It's an international path of education common to many docents here.

After returning to China, she's been giving tours for about two years. "Even in this time, I've witnessed big changes," she says. "A few of the caves that were still open to the public when I first started are now permanently closed because of preservation concerns."

Using the key linked to a chain around her waist, she unlocks a thick metal door. We step into frigid darkness. As my eyes adjust to the dim interior, Song reaches for a flashlight. Once the stream of light hits the walls, the paintings emerge.

I'd seen the artwork: printed in books, magnified in high-definition images on my laptop, and just an hour ago on the dome screen. But nothing could compare to the full majesty of being there in person. Being physically enveloped on all sides with wall-to-ceiling art, seeing the intricate detail, breathing the cool, musky air, hearing the faint reverberations of our voices — it was a transformative experience.

And a constrained one. Song is careful to spend no more than five minutes inside each cave. She chooses just a few highlights to point out. One is a famous sketch of a group of wild boars: a stout sow leading its piglets to forage in the mountain grass. Squinting under the dim lighting at the faint lines, I can just barely make out the shape of three small piglets.

We've barely skimmed the puzzling triangular pattern of three rabbits with three interlinked ears when another docent appears. She apologetically tells Song that her group needs to come in too. As

twenty-five more people crowd into the cramped space, I squeeze myself against a glass-covered wall. It's in vain; I get an unceremonious elbow to the back from an older man, and a kid trips across my foot. So Song and I give up. Every additional second we dwell here only increases the harm.

Over the next hour, Song takes me into eleven more caves. But even with an open door, some of the caves remained too dark to see clearly. Most of the time, Song's flashlight illuminates only the specific details of the sutra or jataka stories she's narrating. For the rest of the time, I am left in the dark, unable to grasp the overall composition and majesty of the paintings.

In addition, signs of the danger humans bring to the caves are obvious throughout. Positioned at the center of each cave is a small white device that measures temperature, CO2 levels, and humidity. These data are reported in real-time back to an office at the DA. If any levels exceed what's safe for the cave, an alarm at the door will start blaring.

Over the winter, Song tells me, the risk is low. It's only during the summer, when daily crowds reach a crushing 18,000, that these alarms can easily go off. Afterward, the cave needs to reset for about a day.

"It can be hard to even breathe normally when crowds get packed," she says.

But right afterward, she gets a call. It turns out that she's needed at the entrance to lead another tour. They're overwhelmed with the number of visitors; today's number is projected to reach over 1,000. It seems like a harbinger of what's to come this summer. Continuing a several-year trend (barring the pandemic years), the DA is expecting a record number of visitors yet again this summer.

Mid-January is usually classified as the off-season. Daily numbers should be in the low hundreds. It's supposed to be a break for the docents to train, reviewing facts about the caves and learning about the latest research — “But the last time we were able to have our full lessons was in the fall, when we discussed the effects of severe oxidation on a few select murals,” Song says.

So we hastily conclude the tour of the twelfth and final cave — Cave 96, which features a behemoth of a 35.5-meter-tall Buddha — and she rushes off. I linger around the outside area of the grottoes for a bit longer. Next to many of the closed doors are QR codes. After I scan them with the built-in camera from WeChat, China's one app for quite literally everything, they lead to webpages describing the cave within in greater detail. It's a surprising amount of information, and much more than what Song was able to narrate given the five-minute time constraints. A few even link to embedded panoramas.

Today's events perfectly encapsulate the central question that the DA faces. For a remote, immovable cultural treasure like the Mogao Grottoes, how do you strike a sustainable balance between access and preservation?

II. THE CENTRAL CONSERVATION QUESTION

Although inscribed as one of China's first batch of World Heritage sites in 1987, the Mogao Grottoes do not have the same international renown as its counterparts like the Great Wall, Forbidden City, or Terracotta Warriors. Until a few decades ago, Dunhuang was still a remote place without a modern airport. But as China's population of 1.4 billion has grown in size and economic power, coupled with a domestic explosion of nationalism and interest in Chinese history, Dunhuang has emerged as a top destination for those looking for a peek into the nation's storied past.

The grottoes are not alone in facing a range of threats from human actions. Most World Heritage sites fundamentally face numerous challenges to their survival. For those not already desecrated by history, the number of threats has only increased: globalization, climate change and extreme weather, surprise disasters, and war, to name a few. The guardians of such irreplaceable sites must figure out how to protect themselves if they are to guarantee survival for even a few more decades. Many are arriving at this conclusion now. But even now is often too late.

Dunhuang is not one of them. This set of desert caves in the middle of nowhere has created an alternative to traditional cultural tourism that many of its peers may soon be forced to adopt. Early on, the leaders of the DA recognized the power of technology in not just dealing with physical challenges to conservation, but also digitization through technology for preservation — dating all the way back to when digitization was still a new term.

As a pioneer, the Mogao Grottoes must also confront undefined uncertainties. A significant component of the charm of ancient heritage sites is the process of traveling to and experiencing it firsthand. Can a digital experience ever be satisfactory in replicating that process of discovery and appreciation? For the sake of Mogao's survival, the DA has spared no effort in trying to make that answer a clear yes.

Today, digitization is inseparable from the fabric of everything in the caves. The effect is the entire visitor experience at Mogao is distanced, yet simultaneously intensified. By building a comprehensive photo archive since the 1990s and adopting increasingly advanced ways to store and promote that data, Dunhuang has transformed what it means to experience, research, and learn from the site.

This strategy is multifold. Of course, there is the technology omnipresent everywhere at the grottoes and visitor center. But researchers and prospective visitors don't even have to travel to Dunhuang anymore. Virtual pieces of Dunhuang have traveled across the globe, in the form of evocative digital exhibitions shared in collaboration with other museums. In 2024, all sorts of Dunhuang online programs that are comparatively rich in detail, if not better, can even be run from the comfort of home. Could all of this comprise what it means to preserve culture in the 21st century?

For Mogao to have become a leader in this path is remarkable, but not necessarily surprising. Several aspects to Mogao's circumstances have forced its transformation from a direct, materially-experienceable one, to one that must be supplemented by virtual aids.

It began with two decades of imperialistic exploration and plunder.

III. A HISTORY OF TRAGEDY

In the years following the Silk Road's collapse in the 15th century, Dunhuang was abandoned by its inhabitants. The once prosperous and sacred Mogao Grottoes were left to the swirling sandstorms. Yet its desert location is also what offered it the greatest protection. The dry and cool climate, along with the site's isolation from the empire's border skirmishes, largely slowed the degradation of the treasures within for over half a millennium.

By the start of the 20th century, however, the caves were in poor condition. Original wooden doors had rotted or been blown away, leaving the insides vulnerable to the natural elements and harsh winds. Some caves had collapsed, and massive sand deposits were piled everywhere. In the face of this decay, a local Taoist monk, Wang Yuanlu appointed himself the caretaker of the caves. One day, he was sweeping mounds of sand that had accumulated in a large hall. That's when he noticed something odd.

Smoke from his candle wafted into the recesses of a wall crack and seemed to disappear. When he knocked away the top layer, he discovered a secret room.

Inside was a mountain of bundled documents, piled nearly ten feet high and written in at least seventeen languages and twenty-four scripts — some of them which had been presumed lost for centuries. These scrolls, ranging from religious writings to legal documents like contracts and statements of divorce, reflected the extraordinary diversity coming out of a crossroads like Dunhuang. They included the earliest complete star chart in the world and a letter written in Judeo-Persian by a merchant duped into buying bad sheep. One standout gem was the Diamond Sutra, a copy of a Chinese translation thought to be a conversation between the Buddha and a disciple. Produced in 868, it was the oldest printed book in the world. Taken together, the Library Cave was one of the greatest archaeological finds of the century.

Abbot Wang contacted local officials and offered to send the materials to the provincial capital. But the faltering Qing government was too preoccupied with maintaining their collapsing dynasty to pay any attention. Word spread further — to the wrong ears.

The first outsider to come knocking was Hungarian-born British explorer Marc Aurel Stein. He immediately recognized the immense value overlooked by the Qing. By the end of his negotiations with Wang, Stein got the deal of a lifetime — over nine thousand documents, painted scrolls, and artifacts for one hundred and thirty pounds — and was knighted to boot.

News of his haul set off a race. One of the world's most brilliant Sinologists, Paul Pelliot, followed on Stein's heels. Furiously reading through stacks and stacks of documents by candlelight, in three weeks he viewed between 15,000 and 20,000 scrolls. From those, he picked the cream to take back to France. Expeditions from Japan and Russia came next, each carting off thousands more manuscripts of immeasurable value.

The explorer who left the most damage was American Langdon Warner, who inspired the character Indiana Jones. Upon seeing the Library Cave, he famously wrote, “There was nothing to do but gasp.” Ironically and tragically, Warner did much more than gasp. He wasn’t satisfied with just movable documents. He also used a harsh chemical solution to peel off select murals, to bring them back home to Cambridge, Massachusetts, in the name of protecting them. Instead, the solution froze, leaving ghostly scars on the pale rock surface. He even lugged off a four-foot-tall bodhisattva from Cave 328 wrapped in his underwear. When Song led me into the cave, its absence was obvious: an unbalanced line of statues that were once four complete pairs.

In 1941, the great painting master Zhang Daqian arrived in Dunhuang in search of the origins of Chinese paintings. Completely awestruck by what he saw, Zhang began the process of comprehensive inventory and replication of the murals. The beauty of these copies, which were disseminated around the country, finally sounded patriotic alarms. In 1944, the National Dunhuang Art Research Institute was established to prevent further destruction of the caves, preceding even the 1949 formation of the People’s Republic of China.

It was too late to rescue 80% of the artifacts from the Library Cave. Some 40,000 documents were scattered in more than a dozen countries around the world. It was also too late to ward the caves against Russians on the run from the Bolsheviks, who lit smoky indoor cooking fires inside several that scorched off countless valuable paintings. But it was not too late to embark on a huge restoration and conservation effort to safeguard the Mogao Grottoes once and for all.

So the institute, later renamed the Dunhuang Academy, was charged with the mission: Protect, Research, Promote. Every task force and objective implemented by the DA was aimed at least one of these ideals.

IV. PROTECT

Living as a researcher in Dunhuang was not easy. During the first few decades of the academy's formation, the town was a backwater, no bigger than a few struggling farms. Many of the scientists had grown up and gotten their education in large cities like Beijing and Shanghai before being relegated to this rural outskirt. It essentially meant committing to career above personal life.

Fan Jinshi was one of these migrants. In 1963, the fresh Peking University graduate was tasked to Dunhuang following part of Premiere Zhou Enlai's allocation of national capital towards the site. She recalls the living conditions of these early days being nothing short of squalid. Staff members were emaciated with sallow complexions, and they wore faded clothes that had been washed too many times. Candlelight was the only source of lighting, and large mice often fell from ceilings. Electricity was nowhere to be found, let alone any sort of conservation technology. It was a huge adjustment from urban life, and an even taller task to begin cave restoration.

The most immediate challenges first came from the environment. Early renovation efforts focused on basic site stabilization, like clearing thousands of tons of sand, installing protective doors in the major caves, and re-erecting fallen statues. Once the fundamental issues had been addressed, in 1979, the caves at long last reopened their riches to the public. Over 26,000 visitors made the trek that first year.



*A Dunhuang Academy vehicle parked in the desert area above the sandstone cliffs from which the Mogao Grottoes are carved. Wind carried thousands of tons of sand into the caves in their years of neglect.
Image by Celina Zhao.*

But the physical demand of keeping the grottoes physically safe was unending. Constant sand intrusion meant sweeping was never done. And the occasional flood could be disastrous. When snow melted from the neighboring Qinling Mountains, the neighboring Daquan River's normal salty trickle could transform into a raging flood.

Left to fix these challenges was the workforce of less than a hundred employees, who lived in rickety communal housing a stone's throw away from the caves. Wu Jun, a senior researcher who has worked at the DA for nearly fifty years, recalls waking up to blaring alarms in the middle of the night that the river had flooded into the caves. "We would haul ourselves up from bed and spend the night passing bucket after bucket of water to each other, trying to keep the water levels down in the first-floor caves."

At the same time, Mogao was quickly becoming a tourist hotspot: within six years, the site was already dealing with over 100,000 annual visitors. Toting bulky backpacks, scribbling “I was here” on the walls, and bringing sweat and damp breaths, the toll they wrought upon the delicate grottoes was obvious.

It was evident to the academy’s director at the time, Duan Wenjie, that relying solely on the DA’s brain and manpower would not be enough to save the caves. Collaborative efforts, specifically international ones, would be integral to establishing the technological solutions needed.

Yet allowing for foreign intervention in Chinese cultural heritage was a deeply sensitive issue. China had just suffered decades of humiliation from European and American imperialism and deception. And no one at the DA needed to look far away from home to see what had just happened to the Library Cave. By this point, the Mogao Grottoes had well and truly become a national treasure. Even rampaging Red Guards who had laid waste to Buddhist temples, cultural artifacts, and foreign emblems across China, agreed not to touch Mogao.

Simultaneously, perhaps it was fitting that Mogao could once again welcome cross-cultural international expertise: the heart of what the caves represented.

As such, the DA began establishing partnerships with organizations and universities across national borders. Among the most fruitful was one with the Los Angeles-based Getty Institute that launched in 1989, a partnership that would stretch for nearly three decades.

With collaborators from the Getty, the academy set up a system of sand nets to capture sand at the top and erected protective barriers against water flow. But by far the most vital resulting project was a pilot monitoring program within one of Mogao’s larger caves, number 85. Completed in 1987, Cave 85

was resplendent with some of the highest-quality frescoes from the Late Tang. Beyond depicting rare religious sutras, the paintings also gave peeks into daily life, featuring a butcher shop, circus acrobats, weddings, and women applying makeup. Collectively, it was a rich pictorial encyclopedia of the period.

It also was an excellent case study for the type of mural deterioration occurring across many other caves. Although the DA had implemented numerous prior strategies to address flaking paint or water damage, none of the fixes were permanent. The goal of Cave 85 was to thoroughly investigate the causes and mechanisms of deterioration. That way, future solutions could be much more long-term, shifting the approach from pure rescue protection to scientific protection. Put simply, don't focus on the symptoms; look for the causes.

The paintings at Mogao present distinct challenges because they aren't directly on the rock surface. Instead, each mural has three layers. The base is the soft rock out of which each cave temple was hewn. Next is a mixture of clay, sand, and plant fiber that acts as a canvas. Finally, bright mineral pigments and some organic dyes are used to create colorful paintings on top.

Sand erosion and flooding are obvious ways that the paintings are degraded. An increase in humidity, whether from human breath or rain, can be immensely dangerous. That's when soluble salts in the rock and plaster layers begin to dissolve and move. Frequent changes in humidity cause the salts to repeatedly crystallize, contract, redissolve, and recrystallize. Together, this cycle causes the paint to become porous, powdery plasters that become even more sensitive to moisture.

Early changes are invisible to the human eye. But the damage can be disastrous once too many iterations of the cycle lead to the mural's breaking point. That's when whole sections of murals will detach and fall off, splintering into tiny pieces and becoming lost.

Normal desert humidity hovers at around 10%-20% in the summer and 20%-50% in the winter and remains low other than the rare period of rain. However, flooding at the base of the caves leads to periods of sustained high humidity. This meant that salt-related deterioration was likely a slow, cumulative process, occurring over a time scale of centuries, that could be suddenly activated by environmental conditions.

Once salt accumulates, it's impossible to remove from the painting. To prevent more damage, controlling humidity in the caves was imperative. The key question was: at what level would it become dangerous for the caves? To find out, the team installed devices that reported real-time data on ambient and wall temperatures and relative humidity. It was the first time such tech had been deployed in a historical site in China.

Results indicated an upper limit of 62% for relative humidity, or the ratio of the amount of water vapor in the air to the maximum saturation amount that the air can hold. This number can easily spike when doors are opened to let tourists in and out of the caves. From these benchmarks, they calculated that the daily number of tourists should be capped at 3,000.

But the waves of tourists were unending. By 2001, the yearly number of visitors was already exceeding 300,000. Since most visitors came during May and October, the daily number of visitors could easily shoot over the 3,000 cap. And this tourism revenue is not something that Dunhuang can easily pass up. The DA gets tens of millions of yuan every year from visitors, the academy's bread and butter. The Mogao Grottoes have literally lifted the city out of poverty.

But the ongoing threats to the caves could not be hidden. By the 1970s, changes in the paintings were already evident. European explorers like Pelliot had documented their Dunhuang tours at the turn of the century in photographs. When DA researchers compared Pelliot's photographs from 1908 to ones

from 1978, the murals seemed to be disappearing in front of their eyes. No solution could ward against the natural elements forever. Every day was a race against time. But a possible answer to the seemingly inevitable deterioration emerged by chance.

Digital Dunhuang

In 1990, Fan, who had by now been promoted to be the deputy director of the DA, had had a premonition. It was an accidental discovery. And one that would fully transform Dunhuang's fate.

While on a research conference trip in Beijing, she saw a young man using a computer. It was the first time she'd ever seen one. She watched in amazement as once he'd finished up his work, he turned off the device. "Won't you lose all your files?" she asked.

"Of course not," he replied. "They've all been saved digitally."

Immediately, she realized the immense potential this held for Dunhuang. The DA is charged with three pillars: protect, research, promote. But realistically, it would be impossible to perfectly protect the caves while accomplishing the other two. So she proposed a revolutionary idea: to create a digital copy of the caves' murals, colored sculptures, and all other cultural relics. United together, it would be called Digital Dunhuang. Digital Dunhuang would be the key product for research and promotion, and it would allow the original caves could be protected for as long as possible. She wrote up a proposal to suggest adopting the digital approach to the Gansu provincial government and got the green light in 1993.

At first, it was hard to know where to start. For one, the caves came in all sorts of shapes and sizes. The murals were often painted on curved walls, making the already dim lighting even more

complex to deal with. To top it all off, they didn't have enough funding or even access to enough equipment. International collaboration would once again be integral to getting started.

In 1999, the DA launched a partnership with Northwestern University. Northwestern brought some creative techniques and hardware inspired by Hollywood, like using rails like miniature train tracks to stabilize cameras moving over the uneven cave surfaces. Because the caves were so small, each team was usually just a photographer, three assistants, and a quality supervisor. It was often frigid inside, and everyone wore heavy winter coats and thick-soled boots for the eight-hour shooting days.

At first, they used traditional cameras. The resulting exposed but unprocessed film was sent back over to the US to be scanned into a computer. Harlan Wallach, one of the Northwestern team leads, called every cave "an exercise in flexible thinking." The conditions in each cave were so different that there was no way to check if the lighting was consistent or if the photos were coming out clearly. 7,000 miles away from their photographic processing laboratory, the team could only hope for the best.

But camera technology was rapidly progressing, and by 2000, the team got their hands on a digital single-lens reflex (DSLR) camera. Access to a digital camera was a game-changing update. For one, they could now see images instantaneously and fine-tune the set-up for the optimal conditions. In addition, they were no longer limited by the physical constraints of film. Because the murals are so large, they're impossible to capture captured in one frame. Instead, each square meter of mural needs about 60-70 photos, which are then stitched together like a quilt in Photoshop to create a single comprehensive image.

In the 5-year collaboration period, the DA and Northwestern were able to digitize 22 caves in total. These early photos were released on Artstor. The response was overwhelmingly positive. Scholars

no longer needed to travel to Dunhuang, get permission to go into caves, clamber onto tall ladders, hold flashlights, and squint at fading murals. Instead, they could simply go online from their own computers.

The DA was eager to push forward, but major constraints still existed. For one, photo stitching was not yet a streamlined process. Just one 15-square-meter mural in Cave 220 required 812 separate pictures to be combined, a process that took over 50 days. And there was a major backlog, with nearly 200,000 images for 50 caves waiting to be processed in 2007.

In addition, the cameras were limited to 2D photography, when the Mogao Grottoes are anything but two-dimensional. The paintings are layered on curved surfaces, and statues — often located in niches — comprise an integral element of the caves. Many grottoes also had small rooms or pillars that added more complexity.

In 2011, Microsoft Research Asia donated a custom-made camera named Apsara, named after the grottoes' famous flying celestial being paintings. It was a video camera with a resolution of 1.3 billion pixels. In one frame, it could capture the same area as 800 DSLR photos at the same quality. As large as a washing machine, once set up in a cave, it could capture statues in a single frame, or even wall-to-ceiling murals by just tilting the lens upwards. Best of all, it reached a level of detail not far off from 3D. Using Apsara, the 688-square-meter Cave 61 took two and a half months to photograph and about seven months to piece together on the computer. It was a dramatic improvement over prior efforts.

Over the past decade, the digitization department has continued to grow, now involving over a hundred people. This larger workforce means that there can be six teams dedicated to photographing the caves on rotating schedules from March to November. It takes them about two months to photograph a cave, and just one month afterwards to overlay the pictures in post-editing. “It’s a speed that would have

been utterly unimaginable just fifteen or twenty years ago,” says Ding Xiaohong, deputy director of the department.

That pace allows the department to process about ten caves from the Mogao Grottoes each year. If efforts were focused purely on Mogao, that number would increase to thirty or forty, he says. But the success at Mogao has been applied to nearby sites facing similar issues with preservation, such as the Yulin Grottoes, another Buddhist site in Gansu also under the protection of the DA.

By the end of 2022, digital data collection work on 289 caves, and image processing for 178 of them, had been completed. That encompassed all the A-list and B-list caves, a four-tiered ranking system that determines digitization urgency based on measurements like cultural value — though digitization for certain caves can also be rushed if a research team requests data.

It’s not just the pace that has improved. One measure of photo quality is DPI, or dots per inch. In the early days with Northwestern, quality was at about 75 DPI. Today, that number has jumped to 300 DPI: a printing resolution where the human eye can’t perceive any disconnect.

“After 50 years from now, when new equipment comes out, we could start from scratch,” Ding says. “But maybe some things in photos from the 90s are already not visible now. So, digitalization is a consistent and continuous process.”

V. Research

As pressure grew and technology advanced, what started as just physically preserving a record of the caves in their current state shifted in aim. Instead, efforts began expanding to investigating what the caves once were — and creating an alternative for the future.

Because simply taking photos of the caves in their present state doesn't capture the rich history behind each one. Buddhism is a religion that preaches the transience of all things, and the ever-fluctuating form of the Mogao Grottoes is no exception. The caves have been carved, decorated, and shaped by a huge international flow of people through several different dynasties. Each person left a unique mark, as did natural environmental processes during the caves' years of abandonment. To see beyond the surface and into the past, having the right tools was once again imperative.

In 2008, researchers from Wuhan University arrived, armed with some of China's best laser-scanning equipment and strategies. They had a three-pronged approach. First, airborne laser scanning from a transport plane allowed them to get the general terrain and landforms around the area. Then, they used ground laser scanners and close-range photogrammetry instruments to analyze the grotto cliff itself, as well as other ancient buildings around the site. All of these data were integrated using precise control surveys into uniform world coordinates. Finally, they could build a 1:1 3D digital model in a computer. This model was the first comprehensive understanding of each cave's position and size, the distance between each grotto, and even the thickness of the walls.

Within each cave, mysteries abound. Even as Dunhuang was conquered by competing dynasties, local aristocracies, and foreign powers, Mogao's development never halted. If anything, a constant stream of change allowed for an extremely diverse palate of colors — many imported from far-flung foreign lands. Cinnabar, malachite, azurite, ochre, calcite, and lapis lazuli were used to bring life into the murals and statues, coloring them vivid reds, greens, blues, yellows, browns, whites, and bright blues. New rulers did not wipe out the traces of their predecessors. Some financed magnificent new caves to be carved, commissioning artisans to emblazon the donor's family on the walls to show their devotion. Others instructed pre-existing caves to be repainted or restored.

This constant stream of updates through different eras can make the murals difficult to analyze, particularly as many have faded from harsh sunlight and exposure to air. In addition, any pigments containing lead have oxidized to black, rendering the original shades unrecognizable.

However, noninvasive multispectral photography has been a transformational technology to visualize faded murals or artwork. One technique uses ultraviolet radiation, which is invisible to the naked eye. However, when emitted from an ultraviolet lamp and directed at an object's surface, UV radiation can be transformed into visible colors. This technique is called ultraviolet-induced visible fluorescence (UVL) photography.

Not only does it help determine colors, but UVL technology can also reveal details otherwise hidden from modern eyes. One of Mogao's most famous murals, "Sattva Sacrifice for the Tigress," is in Cave 254 from the Northern Wei Dynasty. The painting combines Indian and West Asian Buddhism with the traditional Chinese style and narrates a five-scene story of a past Buddha's life. The UVL images revealed scenes that are otherwise invisible, such as blood spurting out of the prince's throat when he commits suicide in Scene 2 and coming out of the tigers' mouths when they bite into the prince's body in Scene 3.

Seeing these now-hidden details offered a privileged view — perhaps in a way, sharing the view of those who originally created them. And all of these findings were recorded by the DA into their ever-evolving understanding of the caves.

In 2016, the culmination of two decades of digitization work was released to the public. The long-awaited Digital Dunhuang resource library was launched in both Chinese and English versions. This was an online platform sharing high-definition images and panoramic views of thirty classic caves. Within the first year, it had recorded over 8 million visits; by 2022, over 16.8 million collective visits.

International Dunhuang Project

Even as more and more of the Mogao images became available to people all over the world, the Library Cave relics remained hidden away in archives around the globe, thousands of miles away from home. They were held by dozens of collections, thoroughly scattered across several continents.

The field of Dunhuangology was also blossoming, a discipline dedicated to unpacking the grottoes' thousand-year record of Chinese arts, music and architecture, science and technology, politics and law, and economic and military conditions. But the Library Cave artifacts remained almost completely out of view.

In 1993, the British Museum hosted a conference for the major institutions holding Library Cave relics. All parties agreed that it was paramount to make these more accessible and to ensure their long-term preservation. The year after, an ambitious digitization program named the International Dunhuang Project (IDP) was created.

Based at the British Library, the IDP revealed the full scope of the cave's riches to the world through its creation of a comprehensive online cache. Conservators across twelve countries united their efforts in restoring, scanning, and uploading the ancient manuscripts into searchable databases. In 1998, multiple language versions of the IDP were launched, giving anyone with internet access full access to anything within.

Through IDP efforts, the treasures of the Library Cave have been reunited in the digital space. Since 2010, the project website has offered access to over 50,000 paintings, artifacts, historical photographs, and manuscripts. There's broad agreement by experts across the world that this is a useful

endeavor: the IDP has made it possible to digitally unite fragile items that otherwise are separated by thousands of miles, an enormous boon to Silk Road research. But despite the enormous strides the IDP has made, it's still an ongoing effort today. Hundreds of scrolls still lie sealed in storage, waiting to join the virtual sphere.

Langdon Warner's collection is among them. After the explorer returned to his hometown of Cambridge, Massachusetts, he entrusted the paintings, bodhisattva, and various documents to the Harvard Fogg Museum. Some of those now lie in glass display cases on the second floor of the Arthur M. Sackler Museum of the Harvard Art Museums.

The bodhisattva statue faces the entrance to the exhibit, and its presence is particularly striking. Brightly illuminated by the gallery lights and from a sunlit alcove of windows a few steps away, his clay body and brightly-colored clothing are easily visible, unlike those of his seven companions still in the dark alcoves of Cave 328. He clasps his hands in a pose of quiet reverence. But his thin eyes hold an unnervingly sharp glare. The fact that he had been separated from his companions for exactly 100 years in 2024 likely escapes the notice of the average visitor strolling through the Asian Art exhibit.



*The Kneeling Attendant Bodhisattva from Cave 328, today displayed at the Harvard Art Museums.
Image by Celina Zhao.*

The same holds true for five murals on the adjacent wall, all fragments peeled off by Warner. The descriptions often reference their surrounding artwork, which remains intact at Mogao. “In its original context” and “fragmentary elements of the figures to his left and right” are a few of the phrases I read during my visit.

But that's all they are: words. There's no way to visually picture or interpret what they once were in the full grandeur of the grottoes. Their value is thus inevitably diminished.

Sarah Laursen, the Alan J. Dworsky Curator of Chinese Art at the Harvard Art Museums, acknowledges the challenges in curating Harvard's ancient archaeological collections. "A lot of them are highly problematic in the ways that they were removed, and in their lack of context," she says. However, the museum is actively experimenting with ways to ethically address these issues.

One such pilot operation took place during a special exhibition held last fall. Laursen and collaborators wrote to the Dunhuang Academy for high-resolution images of Cave 320. Then, they printed the image of the wall — which clearly showed the ghost outlines — where the once fragments lay in precise 1:1 dimensions. The encased original fragments were then placed directly next to replica.

"People often took a minute to register that they were actually seeing the pieces that had been removed from the wall," Laursen says.



Artifacts from Cave 320 during the exhibit Objects of Addiction: Opium, Empire and the Chinese Art Trade, on display September 15, 2023–January 14, 2024 at the Harvard Art Museums, Cambridge, MA. Image by Caitlin Cunningham Photography; courtesy of the Harvard Art Museums.

Now, the conservation team is also working on digitizing the full collection. Recently, the bodhisattva was removed from its case for high-resolution photogrammetry for the first time. The Harvard Art Museums has also signed an agreement with IDP to include Harvard's collection within the database. Before it could be uploaded, however, catastrophe struck.

In October 2023, the British Library Museum was hit with a massive cyberattack. For four, long months of darkness, no one was able to access the IDP databases. It was like the unification had never occurred. In physical space, it never had.

The IDP finally returned in March 2024, under a new domain and renamed the International Dunhuang Programme. But it was a sharp reminder of the unique perils of online data storage.

As 2024 marks the DA's 80th anniversary and the IDP's 30th, the academy is planning to host a conference with all the IDP's partner institutions in May. One of the major topics of discussion will likely be the future of the IDP and Library Cave artifacts. Notably, the Chinese government is increasingly capitalizing upon ever-heightening nationalism — to use the country's rich cultural traditions to increase its international influence and cultural self-confidence.

And Dunhuang's pioneering success poses a sharp contrast to the viewpoint held by outsiders just a few decades ago: that China wouldn't take the time and trouble, nor have the resources and expertise, to preserve its rich cultural heritage. In fact, the very explorers who came to Dunhuang may argue that without their intervention, the Library Cave treasures may have been destroyed at some point or another. (This suggestion was undermined when World War II ended up damaging European-owned artifacts in Paris, London, and Berlin).

The image of Dunhuang in Chinese public discourse is one deeply tied to the imperialistic trauma the nation collectively suffered during its “century of humiliation.” And China is by far not the only one to face such questions. Past wrongs of a similar nature have occurred all across the world. What does it mean that many of these artifacts still cannot return home today? Is reinvention in cyberspace, no matter how precise of a replica, enough of a repatriation to satisfy past wrongs?

For now, it is difficult to return the dispersed stuff, which is far too fragile to bear international travel. Even moving Library Cave artifacts from a storage site in Somerville to the museum in Cambridge, about a 25-minute drive, “involved a high degree of risk to the stability of the artworks” says Laursen.

For now, the IDP is the best — and perhaps only — solution.



*This Library Cave Exhibition, located directly across from the Nine Story Pagoda, depicts the imperialistic tragedy that occurred here in the early 20th century.
Image by Celina Zhao.*

VI. Promote

Though such efforts have created a lasting record, the core of the problem, overwhelming tourism in Dunhuang, persists still.

Dunhuang is a town of less than 200,000 residents that hosts up to three million tourists a year. In the downtown district, every other building is a hotel, a mix of mom-and-pop bed-and-baths and sleek,

sprawling complexes. The Dunhuang nightmarket is conveniently positioned in the middle of it all, a quintessential tourist epicenter filled with endless stalls of local mutton specialties and Silk Road trinkets. Wandering through the empty, dark rows — most have closed during the off-season — I get lost for nearly twenty minutes in the enormous maze.

Outside downtown, the difference is even more pronounced. The Silk Road Dunhuang Hotel, a behemoth of a building, stands in a brutal show of dominance in front of a landscape of small family farms and faded, two-story concrete homes. Just a few minutes down the road there's a farmer herding a flock of goats through a thicket of dry grass, a stand selling a freshly skinned pig, and old pickup trucks rumbling by.



*The Dunhuang Nightmarket is largely empty in the off-season.
Image by Celina Zhao.*

The Mogao Grottoes have lifted Dunhuang out of poverty while bringing the area into the national spotlight. In China, tourism is a pillar industry bringing economic benefit to poorer Western regions, particularly the Silk Road provinces of Dunhuang's Gansu and Xinjiang. The tourist boom has brought economic and infrastructural mobility to the area. But it is exactly these economic interests that are so eager to exploit Mogao's economic potential that pose the biggest threat to what is most valued about the site.

Since the opening of the grottoes to visitors in 1979, a total of 112 caves have been accessible to the general public or special groups at one point or another. The remainder, over 300 caves, have remained closed — because they're too small, are in poor condition, or are of low significance. At any one time, 70 of the caves are open.

Docents play a significant role in tourist site management, keeping a watchful eye on unruly tourists who reach out to touch murals and stressing the importance of conservation and protection. But there's only so much they can do when numbers surge. October 2012 was one particularly shocking moment as DA employees were overwhelmed by Golden Week visitors, China's most extended holiday. Over 18,000 people came in a single day, six times the maximum daily capacity. However, Dunhuang was unable and reluctant to turn away the visitors — and the income they bring.

In 2014, a key tool in the battle to keep the Dunhuang caves intact emerged with the opening of the Digital Visitor Center. It doubled the daily carrying capacity of the caves to 6,000 people. But the relief it provided did not last long.

That's because that staggering number of 18,000 tourists a day is no longer an exception, but the norm. In 2024, numbers are projected to reach at least 2.8 million total by the end of the year. That means

that in the summer months of July and August, 18,000 visitors will descend upon the site every day: a combination of 6,000 normal tickets and 12,000 emergency tickets.

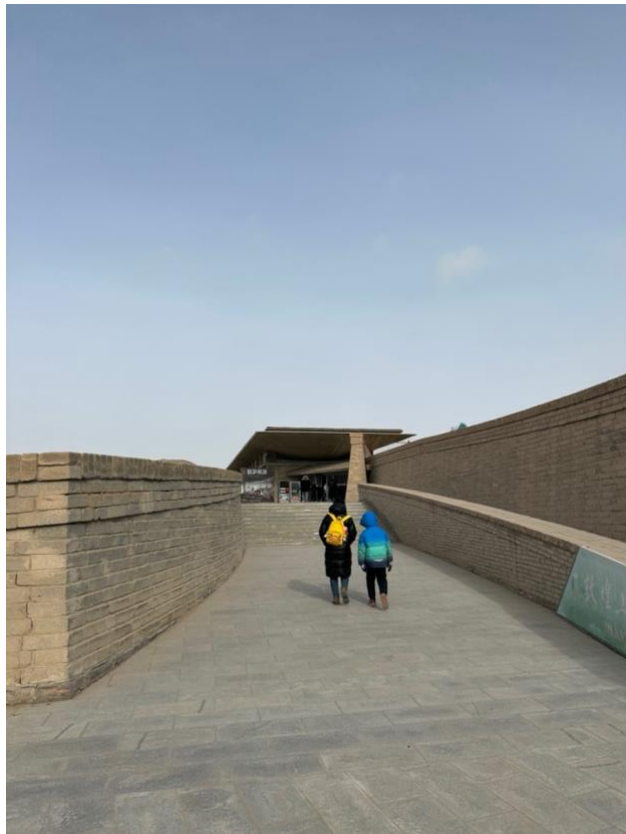


*Tourists line up at the entrance to the caves.
Image by Celina Zhao.*

Reducing the number of caves that each visitor sees on their tour from twelve to six or eight — the privileges of a normal ticket — can only do so much. For those who only snag an emergency ticket, their visit is confined to just four caves. To replace missing out on the real caves, they can head to a large trailer dedicated specifically to VR experiences. Inside, they can get a taste of China’s top-notch digital museology. Online reviews of the experience note that once a visitor dons the VR headset, different elements like texts, pictures, and videos can greatly enhance the educational aspect of experiencing a cave, online reviews say. They can even interact with the figures floating and dancing in the murals.

During my visit in January, the VR station had unfortunately been shut down for the off-season. So after I exited the turnstiles guarding the exit and entrance to the official cave area, it was barren save a few small shops and a café selling ice cream popsicles in the shape of the nine-story pagoda.

The sidewalk eventually curved back over the river and to the Cultural Exhibition Center. The entrance opened to the second floor of the building, where the few movable relics left in Dunhuang were exhibited. (Most of what hadn't been taken by explorers had been transported to Beijing for safekeeping in the 1960s.)



*The entrance to the second floor of the Cultural Exhibition Center.
Image by Celina Zhao.*

The first floor was dedicated to replicas. Massive 3D-printed renditions of Buddhist pagodas and cave pillars stood tall in the glass cases lining the exhibition rooms. But by far the most arresting part of the floor were the eight replica caves dotting the main hallway. Life-sized and precise replicas of their real counterparts, the eight spanned every main dynastic period at Dunhuang.

In Buddhism, the duplication of sacred words and the replication of images was an expression of devotion and a means of gaining merit in the afterlife. This was the premise of the Diamond Sutra: printing was a quick way of earning karmic merit. While no longer done for religious purposes, the tradition of replication and copying was reinstated at Dunhuang as a critical method for artistic training and educating the public. Since the 1940s, teams from the DA have created full-scale, hand-painted cave temple replicas that can be transported and reassembled.

Out of the eight on display, seven hadn't been on my tour. The eighth was Cave 249: one of the twelve I'd just seen in person.

I was skeptical at first. Sure, to my untrained eye, the artwork looked indistinguishable. But how would the whole cave experience compare to the real deal? As I took the time to absorb it all in, enveloped on all sides by murals, however, my doubt waned.

For one, I had all the time in the world to browse; I could step as close to the walls as I wanted to see the murals in detail. The soft, warm lighting illuminated the artwork much better than what I could see in the caves under a thin beam of flashlight. My toes weren't freezing off from the cold. For a few minutes, I was the only one inside the replica cave.

I knew I wasn't in the actual grotto. But did it even matter?

Beyond my unaided eye, another tool enhanced the experience. The information table offered AR glasses, which only became available the previous summer. Each pair of glasses connects to a Wechat mini-program that is paired to the eight caves.

Once I'd put on the white, visor-like glasses and tapped on "Cave 249: Start" on the mini-program, the wall in front of me came to life. A trail of golden sparkles appeared in my periphery, indicating for me to turn my body and eyes that way. The source turned out to be a small pink and white animated deer — derived from the famous nine-color deer mural in Cave 257. In a child-like voice common to many Chinese educational programs, it introduced itself as my guide and soared off to the ceiling's west slope. There, the first set of murals, a collection of the four gods of wind, rain, thunder, and lightning, came to life.

As the deer introduced each god, their figures peeled off the walls, grew bigger, and were illuminated in a golden halo. Once magnified, I could see every last detail, even their fingernails. The rain god's introduction was accompanied by the sound of pitter-pattering raindrops, the thunder god's with booming cracks of thunder.

As the deer continued gliding around the cave, it told me some of the same stories Song had told me but in much greater detail. There were also some new stories that Song hadn't had a chance to mention, like that of Feather Man. This was a man with ears growing on top of his head and feathers growing on his arms, possibly a god who guides the souls of the deceased to heaven.

And when the deer got to the north slope of Cave 249's ceiling, it once again pointed out the sow and her piglets. This time, I easily counted six little pigs — three more than I'd been able to make out in the dark interior of the actual cave on a time crunch.

Altogether, the AR tour had about 15 minutes of programming for Cave 249. It was three times the time and volume of information as the real deal. I'd never experienced anything like it in America.

For Chinese travelers, this partly virtual approach is nothing out of the ordinary. The leading museums in China, such as the Palace Museum in Beijing and Emperor Qinshihuang's Mausoleum Site Museum in Xi'an, have adopted similar technological visitor experiences, giving equal time to artifacts and information technology. If anything, multimedia evocations of sites offer greater insight: how else can you see excavated tombs or precious artifacts too sensitive to be displayed in harsh light and air?

It's a different way of thinking from Western ideas of authenticity, or art as an experience that requires seeing the original. A digital approach loses the charm and romance of "the real thing." But for Mogao, that's exactly the point. The whole point of contemporary conservation at the site is to preserve the integrity of the original. And the best way to do so is to restrict access, substituting a virtual aura to take the place of the actual. Such an approach offers the greatest chance that a site of religious, historical, and cultural significance can be left undisturbed, save for occasional visits by conservators and researchers.

This idea is so at the core of the DA's management of Mogao that visitors don't even have to travel to Dunhuang to get an immersive educational experience. The DA has set up several collaborations outside China geared toward audiences who otherwise may never have the chance to see the site.

"We say that protection is the foundation, research is the core, and promotion is the goal," says Song Shuxia, the deputy director of the cultural promotion department, one of the Big Four departments out of the academy's twelve. "So it's very important to make these cultural relics really come alive. Thanks to digital technology, there are many new ways to do so."

Under Song Shuxia's direction, the academy has brought innovative digital exhibits to audiences who have never seen anything like them before. "Pure Land: Inside the Mogao Grottoes at Dunhuang" was among the earliest, created in collaboration with the City University of Hong Kong. In 2012, the Arthur M. Sackler Gallery of the Smithsonian Institution in Washington D.C. became the first North American audience to experience its hyperrealism.

After stepping into a heated tent in the garden courtyard and putting on 3D glasses, visitors were transported straight into the permanently-closed Cave 220 from the Tang Dynasty. Inside, details faded beyond recognition in the actual cave appeared in their original bright colors. Instruments "played" traditional melodies, and dancers moved to the music. A digital "flashlight" traced the narrative sequences of the murals, and a "magnifying glass" allowed visitors to discover intricacies central to the artwork. An iPad Mini serves as a controller, allowing the user to focus in and highlight details.

"At last we have a virtual reality system that is worthy of inclusion in a museum devoted to the real stuff of art," Pulitzer Prize-winning art and architecture critic Philip Kennicott [wrote](#) after visiting Pure Land.

In 2016, the Getty hosted "Cave Temples of Dunhuang: Buddhist Art on China's Silk Road" in Los Angeles. The exhibition featured three full-size, 1:1 scale cave replicas of Caves 275, 285, and 320. But the jewel of the collaboration was a virtual immersive experience of Cave 45. This was the first time a museum exhibition used spherical projection to create a 3D holographic experience, a technique typically reserved for theme park simulation rides or planetarium presentations. By the end of a three-month showing period, over 120,000 visitors had passed through the Cave 45 experience.

And now, you don't even have to set foot outside your house to experience the caves. In January 2020, the caves were closed at the onset of the Covid-19 pandemic. With no foreseeable end to the

country's shutdown, leaders at DA sought ideas on how to continue promoting its cultural heritage—which led to a collaboration with one of the world's internet giants, Tencent.

In February 2020, Tencent and the DA released the WeChat mini-program Dunhuang E-Tour. Containing over 2700 murals and painted sculptures, the program allowed users to search for Dunhuang's religious works based on various criteria. Within 10 days of its launch, E-Tour had attracted five million visitors. By the end of 2022, this number had risen to 200 million.

The success of this pilot mini-program opened up a new chapter for the Tencent and DA collaboration. As the world's largest video game company, Tencent had even more ideas for how Dunhuang could be experienced.

A month before I set out for China, I'd tried two of the resulting products. "Searching for Dunhuang—Digital Dunhuang Immersive Exhibition" is an online, interactive version of Cave 285 on the Digital Dunhuang website. Advanced visuals and narration first introduced me to the architectural and artistic style of the cave. After following a guided example of how to navigate around the cave's murals, I was then given free rein to click on any of the hundreds of highlighted spots on the murals to explore further.

The second, "Digital Library Cave," is a game also produced with high-definition digital scans that reproduced the grottoes with millimeter-level precision. In caves 16 and 17 alone, more than 30,000 images were rendered to generate a 900-million-sided hyper-realistic digital model.

Here, users can explore five chapters of the Library Cave's history. To proceed through each chapter, the player must engage in conversation with important names through the Library Cave's history, such as Hong Bian, the most eminent religious official in the region when the cave was sealed. At the

same time, the player accomplishes relevant “tasks,” such as hand-copying a chapter of the Diamond Sutra. It serves as an extremely engaging crash course on the tragedy that unfolded here. But the silver lining is that after the adventure, the user is then directed to a virtual exhibition room. Inside, a circling platform of 21 artifacts is displayed. They come from several different IDP institutions, and the exhibit expresses gratitude towards the partner institutions for sharing their collection.

When Song brought me to the entrance of the Library Cave during my tour, I instantly recognized it from the game. For some inexplicable reason, I still held onto a silly little shred of hope that somehow I’d see the reunited artifacts in real life, there in the grottoes.

But all that was left was a mostly empty chamber, devoid of everything except a statue commemorating Hong Bian.

VII. Looking Out and Ahead

On a September day in 1940, a dog fell down a hole in southern France. When a group of boys crawled in afterward to rescue it, they discovered a cave filled with 17,000-year-old paintings of prehistoric animals, people, and abstract patterns.

The Lascaux cave was hailed as a prehistoric wonder, and in 1948, it was opened to the public. Hundreds of thousands of visitors flocked to the site. But the breath and sweat of visitors raised carbon dioxide and humidity levels to unbearable levels. Green mold, white fungus, and later black fungus invaded the space, and the paintings began to show signs of fading and discoloration. Eventually, it was too much for the caves to handle.

In 1963, the caves closed its doors to visitors forever. It became a protected UNESCO World Heritage site, and in the years since, artificial replicas have emerged as the only way to “see” the site. Lascaux II was the first imitation to be released to the public in 1983. The most recent, Lascaux IV of 2016, used 3D digital scanning to create a replica complex of precision down to three millimeters.

At Lascaux, you either see a digital copy, or you see nothing. But can reality ever be rendered through reproduction? Does it need to achieve reality for it to be worthwhile?

Mogao does not yet have to confront these questions. Because of its protective early intervention, technology only supplements and enhances, rather than fully replaces, the real experience. And it is the academy’s paramount goal that it remains this way. Its solution is making a comparable package of interactivity, atmospheric authenticity, and scholarly — one that doesn’t necessarily bank entirely on the “genuineness” of the original.

It’s an attractive solution, and perhaps an increasingly necessary one, for sites far beyond Mogao. “There is a long line at the door asking for our help,” says Chen Quan of the academy’s party committee office. So far, the ideas and technologies employed to protect Mogao have been applied to more than 500 cultural relics protection projects across the nation.

But this is not just a story of a remote northwest corner of China. Nor is it merely a Chinese approach to museology that loses efficacy elsewhere.

Instead, the story of the Mogao Grottoes is a lesson of global significance — one that can be exported, emulated, and applied to a huge number of cultural sites across the globe. Because given all the tumultuous challenges of protecting such treasures today and in the future, digitization is a direct answer

to preparing for the worst, to ensuring as little ancient history as possible is lost. That is the only way to ensure as much of a “real” experience is maintainable.

After the AR tour of the replica Cave 249 in the Cultural Exhibition Center ended, I was stunned by all that I had just seen come alive in front of me. As I lifted my glasses, excited to see what the next cave tour would hold, a woman stopped me.

“What do those glasses do?” she asked. “I heard audio playing from them as you stood there.”

She gestured to the group of kids sitting on the bench outside, swinging their feet and complaining about wanting to go home. “My kids are bored and refuse to keep looking at the museum.”

I directed her over to the desk where I had rented the glasses and moved on, forgetting about the encounter as I became immersed in the AR edition of Cave 220.

But twenty minutes later, she and the kids — now sporting AR glasses of their own — ended up in the same cave as me again. The mom and I made eye contact, and she smiled at me in relieved gratitude.

This time, the kids were all silent. Instead, they were enamored with the tales being spun by the charismatic little deer, and finally lost in the wonder of these ancient caves.

Afterword & Discussion

My family is from Xi'an, formerly Chang'an: the imperial capital of fourteen dynasties, the end of the Silk Road, and home to the Terracotta Warriors. I grew up eating lamb on the streets of Xi'an's famous Muslim quarter, whose residents trace their roots back to ancient Arab and Persian envoys and merchants who braved the Silk Road travels.

Even with these connections, I had never heard of Dunhuang, a key gateway on the journey — much less the Mogao Grottoes — until last summer. Instead, my first time learning about it was due to a flood of coverage on a July 2023 Greenpeace report. The report warned that changing weather patterns in northwest China were putting ancient Silk Road cave art at immense risk. The Mogao Grottoes were named as one of the vulnerable sites.

I was floored. Here was a site of immense archaeological significance, what UNESCO calls “largest, most richly endowed, and longest used treasure house of Buddhist art in the world.” And I'd only learned about it when it was about to be lost to the world.

But after digging a little deeper, I quickly discovered that the problem, while pressing, wasn't hopeless. Instead, researchers at the Dunhuang Academy (DA) had already been working on the problem for decades. And rather than the climate posing the biggest threat, it was instead the sheer level of human interest in visiting such a storied location. Humans were loving the caves to death.

The Dunhuang Academy's solution? Digitization: a way to preserve the caves for far beyond their own lifespan.

The following January, I flew to Dunhuang. During my five-day visit, I stayed at the residence of a former longtime Dunhuang Academy employee. He in turn introduced me to his old colleagues. They were the old guard of the academy, the ones who had witnessed and contributed to the rise of the academy from a desert outpost to a global leader in what it does. Through conversations and dinners with them, I finally began realizing the remarkable scale of the DA's accomplishments.

The Mogao Grottoes, from birth to now, have always been an international wonder. But my ignorance can also be partially attributed to the serious lack of English language coverage of the site in recent years. Since 2016, virtually no American major news organizations have reported on Mogao. Their most descriptive visitor accounts are from prior to 2012. That means that American readers have no idea how much Mogao has evolved since.

In my trips to the grottoes, I experienced a radically different type of tourism. It was one centered around technological replicas, supplements, and pioneering inventions. To say it opened my eyes to how transformative digitization can be when applied to conserving, protecting, and promoting archaeological landmarks would be an understatement.

To write this thesis, I have compiled project reports, news articles, documentaries, and research articles in Chinese and English alike to piece together Mogao's progress. However, there were also many logistical hurdles along the way. The Dunhuang Academy is protective of its intellectual property, and it was difficult to establish communication with department leaders for interviews as just a student. More obviously, Chinese is not my preferred language. This added barrier of language meant I often could not probe to the desired level of detail. But it also opened doors that most other Western journalists have not had access to.

Despite these challenges, this thesis has grown to encompass far larger questions than I had originally anticipated. It deals with questions of authenticity, immersion, ownership, and that are universally applicable to hundreds, if not thousands, more cultural heritage sites around the world.

This work only begins to scratch the surface of it all.

Lastly, I invite readers to explore the digital resources I mentioned within my thesis. They are linked below.

- Digital Dunhuang <https://www.e-dunhuang.com/index.htm>
- Digital Library Cave <https://dlc.e-dunhuang.com/>
- International Dunhuang Programme <https://idp.bl.uk/>
- Searching for Dunhuang—Digital Dunhuang Immersive Exhibition of Cave 285 <https://285.e-dunhuang.com/#/>

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[caves-%e6%95%a6%e7%85%8c%e7%9f%b3%e7%aa%9f%e4%bb%8b%e7%bb%8d/](https://www.dunhuang.ds.lib.uw.edu/dunhuang-caves-%e6%95%a6%e7%85%8c%e7%9f%b3%e7%aa%9f%e4%bb%8b%e7%bb%8d/)

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