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Optical Architectures for Displays and Sensing in Augmented, Virtual, and Mixed Reality (AR, VR, MR)

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Introduction to the SPIE proceeding of AR/VR/MR 2020 conference
"Optical Architectures for Display and Sensing in Augmented, Virtual and Mixed Reality"

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1. Abstract

This is an introduction paper to the 2020 SPIEW AR/VR/MR conference held in San Francisco, at Moscone Center, co-located with the 2020 SPIE Photonics West main symposium. The subject of this conference is to share the world state of the art in optical architectures for AR/VR/MR headsets and smart glasses. A heavier than usual industry participation has been present since the inception of this conference in 2018.

The 2020 version of the SPIE AR/VR/MR conference includes a list of invited industry talks, and a list of conference papers which are edited in this proceeding.

In addition to these papers, a list of student papers attempting at solving industry challenges in AR/VRMR hardware have also been presented. The challenges include those of

- wearable comfort (weight, size, center of gravity, thermals)
- visual comfort (angular resolution, optical foveation, vergence accommodation conflict, pixel occlusion, peripheral displays, low latency sensors,…)
- social comfort (unobstructed eye contact, high transparency of combiner optics, low profile optics,…)
- immersion (audio, display and see-through field of view, gesture sensing and eye tracking, spatial scanning,…)

The invited industry papers are mostly discussing existing new product architecture integrations, and are not listed in this proceeding, but are available as videos on the SPIE web site.

In addition to the industry talks, conference papers and optical design challenge papers, a large demo room has been set-up at the conference location to allow participants to experience the latest headsets available in 2020.

This proceeding is a good source of information about new optical architectures targeting entire headset systems, or rather specific building blocks either on the display side, the optical combiners side or the optical sensors side.

The industry talks available as videos are a good companion to this proceeding list.

This introduction paper review the current market position for AR/VR/MR, and lists the various products that have been discussed throughout the conference and have been shown to the attendance as demo headsets.

2. Introduction

Defense has been the first application sector for augmented reality (AR) and virtual reality (VR), as far back as the 1950s.[1] Based on such early developments, the first consumer VR/AR boom expanded in the early 1990s and contracted considerably throughout that decade, a poster child of a technology ahead of its time and also ahead of its markets.[2] However, due to the lack of available consumer display technologies and related sensors, novel optical display concepts were introduced throughout the 90s[3,4] that are still considered as state of the art, such as the "Private Eye" smart glass from Reflection Technology (1989) and the "Virtual Boy" from Nintendo (1995)—both based on scanning displays rather than flat panel displays. Although such display technologies were well ahead of their time,[5–7] the lack of consumer-grade IMU sensors, low-power 3D-rendering GPUs, and wireless data transfer technologies contributed to the end of this first VR boom. The other reason was the lack of digital content, or rather the lack of a clear vision of adapted VR/AR content for enterprise or consumer spaces.[8,9]

This is very similar to the demise of the early iPod developments at General Magic Corp. in the late 90s, which provided an initial hardware concept but without wireless connectivity or an online music store. Once all three conditions were met at Apple 10 years later (hardware, WIFI connectivity, online music store), the iPod concept resonated with a strong consumer market as a music-experience ecosystem, not solely as a desirable music-playing product, no matter how excellent it might have been designed and produced.

The only AR/VR sector that saw sustained efforts and developments throughout the next decade was the defense industry (flight simulation and training, helmet-mounted displays (HMDs) for rotary-wing and head-up displays (HUDs) for fixed-wing aircraft).[10] The only effective consumer efforts during the 00s was in the field of automotive HUDs and personal binocular headset video players.

Today's engineers, exposed at an early age to ever-present flat panel display technologies, tend to act as creatures of habit much more than their peers 20 years ago, who had to invent novel immersive display technologies from scratch. We have therefore seen since 2012 the initial implementations of immersive AR/VR HMDs based on readily available smartphone display panels (LTPS-LCD, IPS-LCD, AMOLED) and pico-projector micro-display panels (HTPS-LCD, mu-OLED, DLP, LCoS), IMUs, and camera and depth map sensors (structured light time of flight (TOF)). Currently, HMD display architectures are evolving slowly to more specific technologies, which might be a better fit for immersive requirements than flat panels were, resembling the display technologies invented throughout the first AR/VR boom two decades earlier (inorganic mu-LED panels, 1D scanned arrays, 2D laser/VCSEL MEMS scanners, etc.).

The smartphone technology ecosystem, including the associated display, connectivity, and sensor systems, shaped the emergence of the second VR/AR boom and formed the first building blocks used by early product integrators. Such traditional display technologies will serve as an initial catalyst for what is coming next.

The immersive display experience in AR/VR is, however, a paradigm shift from the traditional panel display experiences that have existed for more than half a century, going from CRT TVs, to LCD computer monitors and laptop screens, to OLED tablets and smartphones, to LCoS, DLP, and MEMS scanner digital projectors, to iLED smartwatches (see Figure 1).

When flat panel display technologies and architectures (smartphone or micro-display panels) are used to implement immersive near-to-eye (NTE) display devices, factors such as etendue, fixed focus, and low brightness become severe limitations. Alternative display technologies are required to address the needs of NTE immersive displays to match the specifics of the human visual system.

The second emergence of the VR/AR/smart-glasses boom in the early 2010s introduced new naming trends, more inclusive than AR or VR: mixed (or merged) reality (MR), more generally known today as “XR,” a generic acronym for “extended reality.” The phrase “smart eyewear” (including both digital information display and prescription eyewear) tends to replace the initial “smart glasses” naming convention.

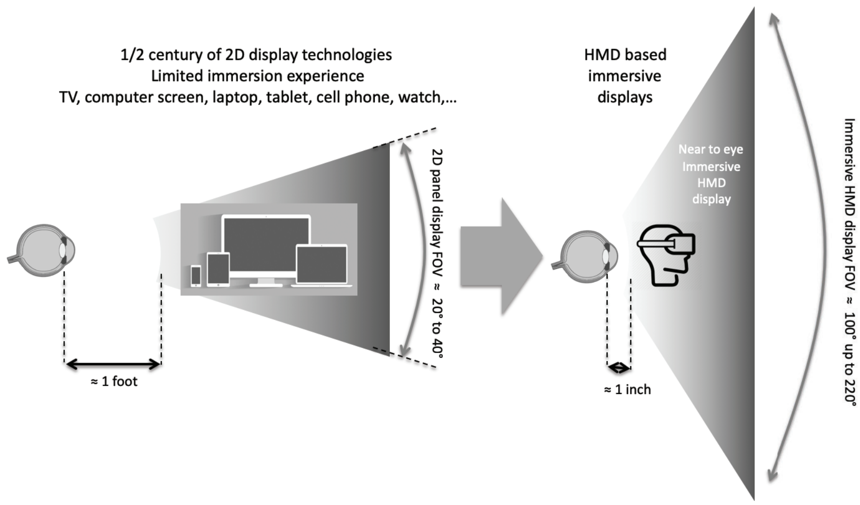

Figure 1: Immersive NTE displays: a paradigm shift in personal information display.

3. Current AR/VR/MR market positions

Unlike in the previous AR/VR boom, contemporary investors, market analysts, and AR/VR/MR system integrators, as well as enterprise users, expect to see a real return on investment (ROI) for these unique technologies in the next five years, as underlined by the Gartner Hype Cycles for Emerging Technologies (see Figure 2). This figure represents 9 graphs over more than a decade, dating back to 2006 up to 2019. For sake of clarity, we chose to leave on the graphs only technologies related to AR/VR/MR. These graphs represent emerging technologies that are poised to become commodities changing the life of millions of users worldwide. Getting pushed off that cycle either indicates an achievement (such as for the smart phone tech disappearing off the graph in 2006) or rather a failure (such as for the 3D flat screen TV tech appearing on the graph in 2008 and disappearing just one year later).

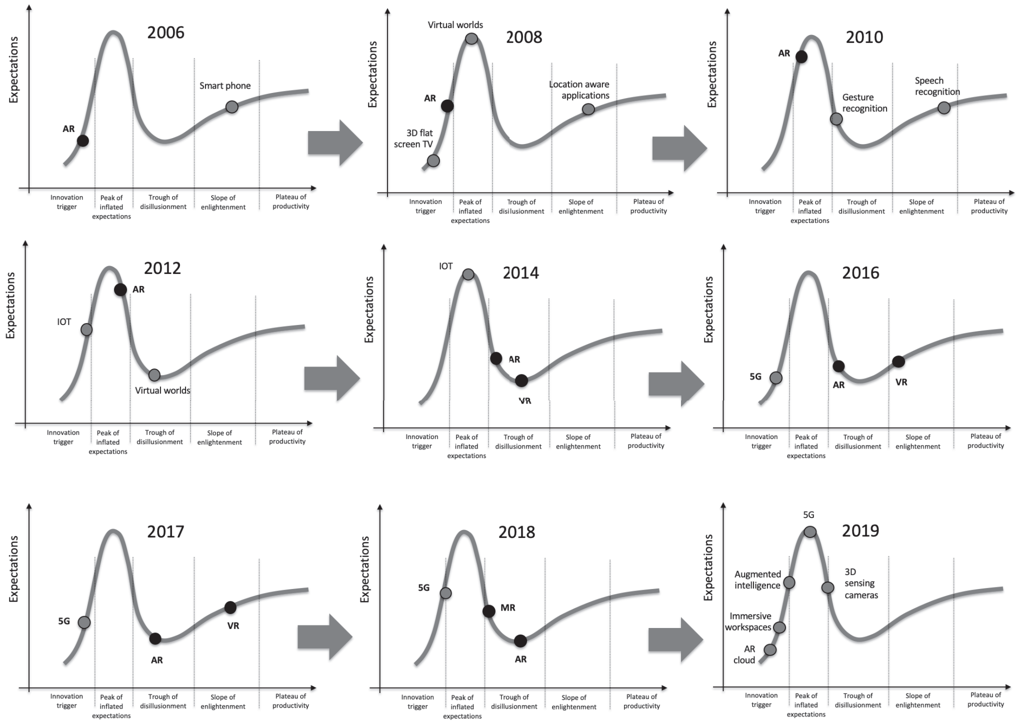

Figure 2: Gartner Hype Cycles for emerging technologies (2006-2019) for AR/VR/MR.

AR has been introduced to the Gartner hype cycle for emerging technologies all the way back in 2006, the same year the Smart Phone dropped out with the iPhone introduction by Apple.

AR is the longest living technology on the Gartner cycle spanning more than one decade. Not many technologies can boast such a long and steady path along this twisted hype cycle. Remaining on the cycle for so long is neither a token of exception nor a token of failure. It relates to the maturity of the underlying market (which is based on the existence - or not - of a use case) rather than the maturity of the technology itself (hardware and software). Gartner chose to keep AR on the cycle for over 12 years, dropping it only in 2019, as market analysts kept expecting year after year the emergence of a huge AR market, first for enterprise (which happened) and second for consumer (which has not happened yet).

The 2008 - 2010 span has introduced on the cycle several technologies that are now critical pillars to AR experience, such as location aware applications, gesture recognition and speech recognition. Gesture recognition has had a tremendous boost with the Kinect technology development for Xbox through 2009-2015 (structured illumination and then TOF), as well as speech recognition for personal assistants in smart phones.

IOT technologies appeared on the graph in 2012, culminated in hype in 2014 and dropped promptly the next year, becoming a real product used by millions, in consumer and enterprise fields. Many IOT core technologies share functionality with AR hardware.

AR culminated at its hype from 2010 to 2012, the years when Google Glass was introduced, along with many other smart glass devices (Lumus, Optinvent, Reconjet, Epson Moverio, Sony, ODG, and many others…).

VR appeared on the graph in 2014, the year Oculus was bought by Facebook for $3B, and coincided also with the first large round of investment by Magic Leap Corp. ($1/2B by Google and Qualcomm), which was followed by many similar rounds (a round E continuing this trend even today, 7 years after its creation and 2 years after its first product introduction).

AR spent also a long time in the through of disillusionment, from 2013 to 2018), without managing to drop off the curve.

The 2017 Gartner graph showed AR and VR poised to reach the plateau of productivity within 2–10 years, with VR preceding AR by a few years.

VR has dropped off the graph in 2018. Instead, MR has been introduced on the graph as departing from the peak of inflated expectations. VR appeared in 2018 to analysists to be at a mature stage, even becoming a commodity, moving it out of the emerging-technology class of innovation profiles.

The 2019 hype cycle dropped both MR and AR (finally after 13 years of the cycle), and introduced AR Cloud, as well the concepts of immersive workspaces and augmented intelligence. The initial AR tech might have also dropped from the graph due to many market readjustments that happened in 2018-2019, leading the way to various companies closing down (ODG, Meta, Cast-AR, Daqri, Google DayDream, etc…) or reducing drastically their workforce (Avegant, North,…).

AR cloud is the major ROI vehicle for AR/MR: it makes therefore much sense to replace AR (more related to hardware) by AR Cloud (more related to services). AR cloud will also be enabled by 5G and WiGig. Mobile 5G technology (low latency and large bandwidth), appeared on the graph in 2016, culminating in hype in 2019, and expecting to make it as a commodity next year in 2020. Major telecom companies developing 5G technology have invested heavily in AR/MR related technologies in 2019, such as ATT and NTT ($280M) for Magic Leap, Deutsche Telekom for Tooz/Zeiss and Verizon for Lytro.

Market expectations come with a word of caution: the only market sector that has proven to be sustainable is MR for enterprise, where the ROI is mainly cost avoidance:

- faster learning curves for new employees, fewer errors, higher yields, higher productivity and efficiency;
- lower downtime and waste, lower operational costs
- collaborative design, remote expert guidance, better servicing, enhanced monitoring;
- higher quality assurance in manufacturing; and
- enhanced product display and demos, and better end-user experiences.

Moreover, experienced workers are retiring, and finding skilled labor for many specialized industry sectors is becoming more difficult than ever, while at the same time operations are expanding globally and products are becoming increasingly customized. Traditional methods for training and upskilling workers are also falling short. AR and MR can provide new tools and technologies to overcome these challenges.

Enterprise sectors that have already shown a tangible MR ROI are concentrated in manufacturing (automotive, avionics, heavy industrial products), power, energy, mining and utilities, technology, media and telecom, healthcare and surgery, financial services, and retail/hospitality/leisure fields.

Proof of an existing consumer market for smart glasses/AR/MR is less obvious; hardware experiments have yielded mixed results for smart glasses (Google Glass, Snap Spectacles, Intel Vaunt, and North "Focals"). VR headset developments have also slowed down recently (Oculus/Facebook VR, Sony Playstation VR). The hyped VR project at Google "DayDream" was terminated in October 2019, mainly because developers were not sufficiently enticed to develop quality apps for Google's Pixel phone series. Other VR efforts have been halted, such as the video see-through (or video pass-through) project Alloy from Intel and the ACER/StarVR wide-FOV VR headset. However, the potential of video see-through MR remains strong in the long term, with technology reducing the video latency and providing optical foveation over wide FOV VR.

2018 saw many medium-sized AR headset companies closing down, such as MetaVision Corp. (Meta2 MR headset), CastAR Corp., ODG Corp. (ODG R8 and R9 glasses) and, more recently, Daqri Corp., even after all four companies had strong initial product introductions and strong VC capital support. Such companies were championing very exciting international AR shows as AWE (Augmented World Expo) from 2014 to 2018. Others went through major re-structuring, such as Avegant Corp. (multifocal AR headset). MetaVision and CastAR saw a partial return in mid-2019, showing that the field is still uncertain and full of surprises. Others (Vuzix Corp.) saw continuous growth as well as continuous VC backing (Digilens Corp.) throughout 2019.

On the smart-glasses front, audio-only smart eyewear has made a strong return. Audio smart glasses, which provide audio immersion as well as world-locked audio (based on IMU solely), is not a new concept, but it has received recent upgrades such as surround sound leaving the ear free (no bone conduction) and external noise-cancelling (such as the Bose Frames). They can provide essential input and commands for consumer and enterprise products and are an essential part of the augmented-world experience. Major companies such as Huawei and Amazon have introduced their own version of audio-augmented-reality smart glasses (Gentle Monster and Amazon Echo Frames, respectively). Camera glasses such as the Snap Spectacles (1st, 2nd, and 3rd generation) have had a difficult time with consumer acceptance, as did the Google Glass Explorer version back in 2014, after a hyped 2012–2013 period.

In addition to spatial world locked audio, if an IMU is present (as in the Bose AR Frames and Amazon Echo Frame), a number of different head and body gestures can also be detected, including push-ups, squats, nod, shake, double tap, look up, look down, spin around, and roll head around.

Figure 3 shows a historical timeline for VR, AR and MR, with their ups and downs from 2012 up to 2019.

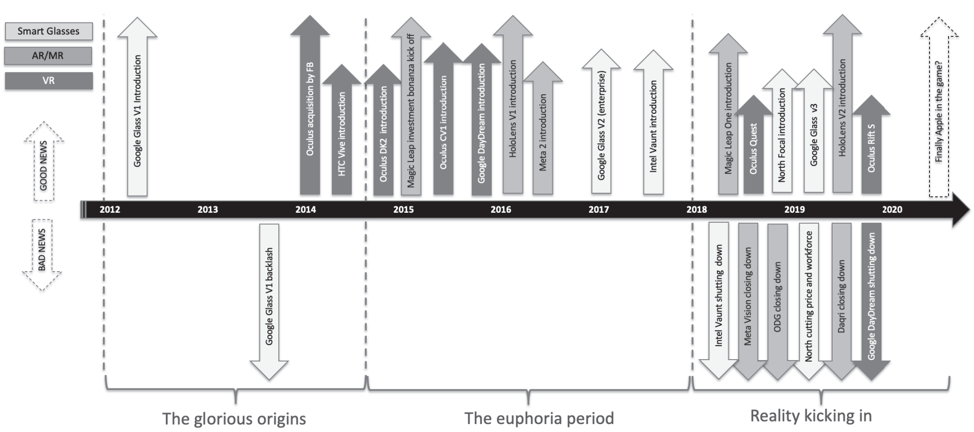

Figure 3: Ups and downs in AR,VR,MR industry (2012 to 2019).

Figure 3 shows three consecutive periods spanning from 2012 to today, starting with the "glorious origins" which include the introduction of Google Glass in 2012 and the purchase of Oculus by Facebook in 2014 for $3B (officially $2B).

Then comes the euphoria period starting mid 2014, where venture capital was ramping up wildly, lots of AR/VR/MR start-ups created, including Magic Leap, and MR product introductions such as HoloLens V1 and Meta2 MR headsets, HTC Vive, Oculus DK2 and CV1 VR headsets, Google Glass V2 enterprise edition and Intel Vaunt smart glasses.

From 2018 on, as it happens in many hyped technology cycles, reality starts to kick in, many start-ups created during the euphoria period are closing, while new products are introduced specifically for the enterprise sector (HoloLens V2, Google Glass V3,…). This is a healthy development, paving to path to a strong potential XR market relying on industries which are able to develop not only the required hardware but also the development platforms and the software/cloud ecosystem to sustain a durable MR effort in industry providing real ROI for such industries.

Table 1 summarizes the current hardware offerings targeting consumer/enterprise/defense sectors for the different types of smart glasses/AR/VR/MR headsets available today.

Small-form-factor smart glasses that included minimal displays (around 10-deg-FOV monocular) and prescription correction saw a renewal in 2018 (after the 2014 Google Glass failure in the consumer market) with the hyped project Vaunt at Intel. However, this project was halted later that year, as Intel invested instead in a very similar architecture the “Focals” developed by North Inc. in Kitchener, Canada. But after a price drop of nearly 50% in early 2019 and a significant workforce layoff by North, the short-term outlook for consumer smart glasses remains uncertain. Other smart glass concepts targeted solely to enterprise sectors have had quiet but steady growth, such as the rugged RealWear headsets (Vancouver, Canada) and the more stylish Google Glass Enterprise V2 glasses.

			Consumer		Enterprise			Medical		Defense	
		Product examples	Daylong usage	Occasional indoor usage	Factory floor usage (shifts)	Heavy outdoor industry	R&D	Non surgical usage	Surgical usage	Training usage	Battlefield usage
Smart glasses	Audio only smart eyewear w prescription correction	Bose Frames Huawei/Gentle Monster, Amazon Echo Frames	+++	+++	++	+++	+	++	++	+	+
	Rugged Smart Glasses, monocular, opaque	RealWear HMT-1 Vuzix m300	+	+	++	+++	++	+	---	---	++
	Smart Glasses, monocular, see-through	Vuzix Blade Digilens Mono HUD Optinvent ORA	+	++	++	++	++	+++	+	+	++
	Smart eyewear w display and prescription correction	Google Glass North Focals Lumus DK32	+++	+	+	---	---	+++	+	+	---
VR	Standalone VR without video see through (3DOF)	Oculus GO Google DayDream VR Samsung Gear VR	---	+++	---	---	+	---	---	+++	---
	Standalone VR with video see through	Oculus Quest NTC Vive Focus 2.0 Pico Neo	---	+++	+++	+	+++	+	+++	+++	---
	PC tethered VR with inside out sensors (6DOF)	Oculus Rift “s” HTC Vive Pro Windows MR 3rd party	---	+++	-	---		---	+	+++	---
	Large FOV PC tethered VR headsets	Varjo VR Foveated PiMax 8k Acer Star VR	---	+	-	---	+++	---	+	+++	---
AR and entry level MR	Tethered AR headsets to PC	Meta 2 DreamWorld Glasses	-	+	++	---	++	--	+++	++	---
	Standalone AR headsets	Epson Moverio Lumus DK50 / Vision Digilens Cristal	-	+++	++	++	++	++	+	+	++
	Standalone AR headsets w 6DOF and gesture sensing	ODG R9 nReal AR glasses Daqri, Atheer Labs,	--	++	+++	+++	++	+++	+	++	+++
High end MR	High end see through untethered MR	HoloLens V1 / V2	---	+	+++	++	+++	+	+++	+++	+++
	Pod-tethered high end see through MR	Magic Leap One Lenovo ThinkReality	---	++	++	+	+	+	++	+	+

Table 1: Current product offerings in consumer, enterprise, and defense markets.

On the other hand, the current VC investment hype fueling frenetic single start-ups such as Magic Leap, Inc. (totaling >$3B VC investment pushing up a >$7B company valuation before seeing any revenues) is a harsh reminder of the ever-present “fear of missing out” behavior from late-stage investors (Alibaba, Singapore Temasek, and Saudi funds) eager to jump on the bandwagon fueled by the early investment decisions from major tech VC firms (Google ventures, Amazon, Qualcomm). The two last VC investments in Magic Leap (late 2018 and mid-2019) were by major communication companies (ATT/USA in 2018 for an unknown amount, and NTT/Docomo-Japan in 2019 for $280M), indicating that large-bandwidth communication channels (5G, WiGig, etc.) will be fueled in the future by demanding AR markets, which will also allow sustained ROI over MR cloud services (AR/MR hardware returns being razor thin). This is also the case with the Carl Zeiss spin-off “Tooz,” which is developing small-form-factor smart glasses in a joint venture with Deutsche Telekom (2018). The telecom company Verizon in the US acquired also the VR company Jaunt in 2019 for similar reasons.

No matter the investment hype, it might take a major consumer electronics company to simultaneously create the ultimate consumer headset architecture (addressing visual/wearable comfort and immersion experience) and the necessary consumer market. Unlike for the enterprise market, where the content is provided by each individual enterprise through the development of custom applications for specific needs, the consumer market relies solely on the entire MR ecosystem development, from generic hardware to generic content and applications.

The smartphone revolution spurred the creation of successful developers in various parts of the world who organically created brand-new apps that took unique advantage of the phone form factor. Today, numerous small companies are trying to replicate such developments for AR and VR, with limited success.

Even though Q3 2018 saw for the first time a worldwide decline in both smartphone and tablet sales (hinting at Apple’s

Q4 2018 30% stock fallout), it is unclear whether MR consumer hardware has the potential (or even the will) to replace existing smartphone/tablets or, alternatively, be the ultimate companion to a smartphone, providing an immersive experience that is out of reach for any other traditional display screen concept.

Apart from consumer and enterprise markets discussed here, there remains a considerable defense market for MR headsets. Microsoft has secured in Q4/18 a $480M defense contract to develop and provide the U.S. Army special versions of HoloLens, dubbed IVAS (Integrated Visual Augmentation System). An additional budget multiple times the initial one will secure the delivery of the headsets to the US Army. This being the largest contract ever in AR/VR/MR—consumer, enterprise, and defense combined—this deal will boost the entire MR ecosystem worldwide.

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