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Metaverse: A Guide to the Next-Gen Internet

Global TMT Sector

#SALMANQADIR

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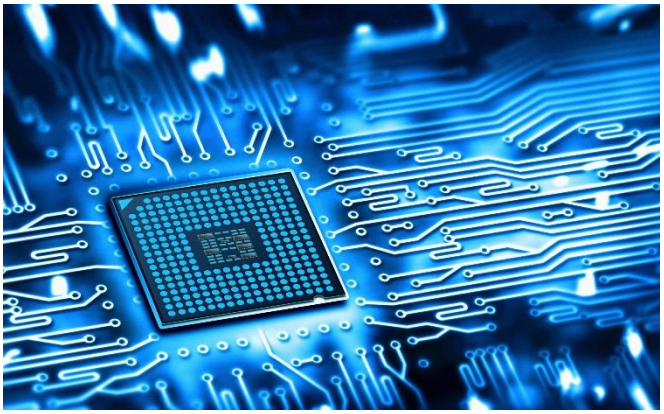

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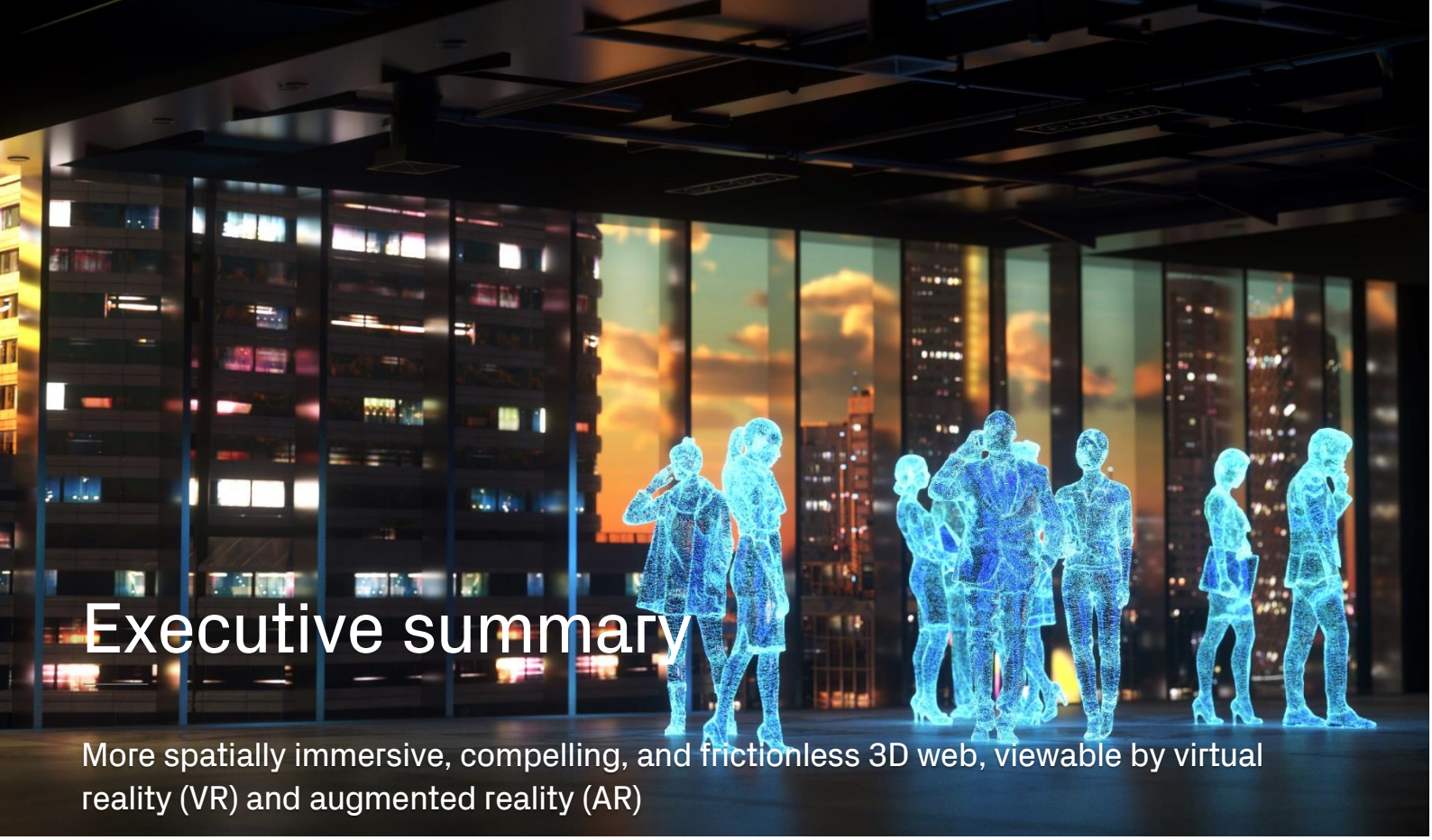


Executive summary

More spatially immersive, compelling, and frictionless 3D web, viewable by virtual reality (VR) and augmented reality (AR)

Understanding the metaverse

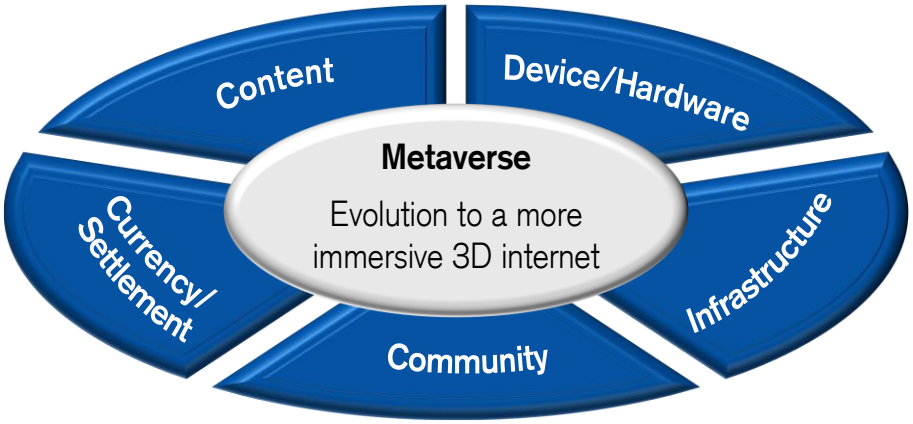
The metaverse is best understood as an evolution of the internet into a more spatially immersive, compelling, and frictionless 3D web, viewable by virtual reality (VR) and augmented reality (AR), along with traditional compute devices, with three key aspects: presence, interoperability and standardisation. There are five key vectors for metaverse advancements, in our view: (1) hardware; (2) infrastructure; (3) content; (4) community; and (5) currency/settlement mechanism.

At this early stage in its emergence, there are of course varying views as to what constitutes the metaverse; in this report we outline how leading companies Meta, Microsoft, Google, Apple, NVIDIA, and Niantic conceptualise the metaverse, as well as perspectives from VCs and industry commentators.

Metaverse use cases are expanding

As is usually the case at the start of most such technology evolutions, some existing applications leverage emerging innovations to deliver a better and/or broader user experience. However, eventually completely new-use cases develop, as the technology evolves and matures and new killer apps can take advantage of the better on-device

Figure 1: Essential components of the Metaverse



Source: Company data, Credit Suisse estimates

processing and sensing, higher data rates, lower latencies and machine learning enabled by AI. At this stage, we see developments across gaming, entertainment, work collaboration, social media, virtual worlds, education and fitness. For businesses, we see advances in collaboration, design, and commerce, with additional sector-specific benefits to healthcare, real estate, and manufacturing.

Hardware: Near-term focus on AR/VR devices

The metaverse should eventually bring profound changes to the entire TMT sector, perhaps none as soon or as extensive as in consumer electronics. In this report we examine the special demands of the metaverse on AR and VR devices where companies are expanding resources and innovation. We also believe the metaverse will drive upgrades to capabilities required on almost all hardware devices involved, and may even lead to some dedicated "killer" hardware products, such as the iPhone was for the 3G (mobile data) era. Key pieces of the technology evolution include better lens and display technologies, sharper on-device sensing and faster processing, higher network data rates and lower latencies allowing cloud compute resources, changes to studio content production, and machine learning.

We expect global AR/VR headset unit sales of 42 mn units (US$12.6 bn revenue) by 2025, representing a 48% shipment CAGR (and 36% revenue CAGR) over 2020-25.

We believe that three factors can drive additional growth in the next few years: (1) a disruptive AR/VR headset maker emerges amid more applications for enterprises and consumers; (2) a better integrated hardware-software platform emerges to drive penetration; and (3) technological improvements such as micro-LED and fast LCD enable a better price-performance product.

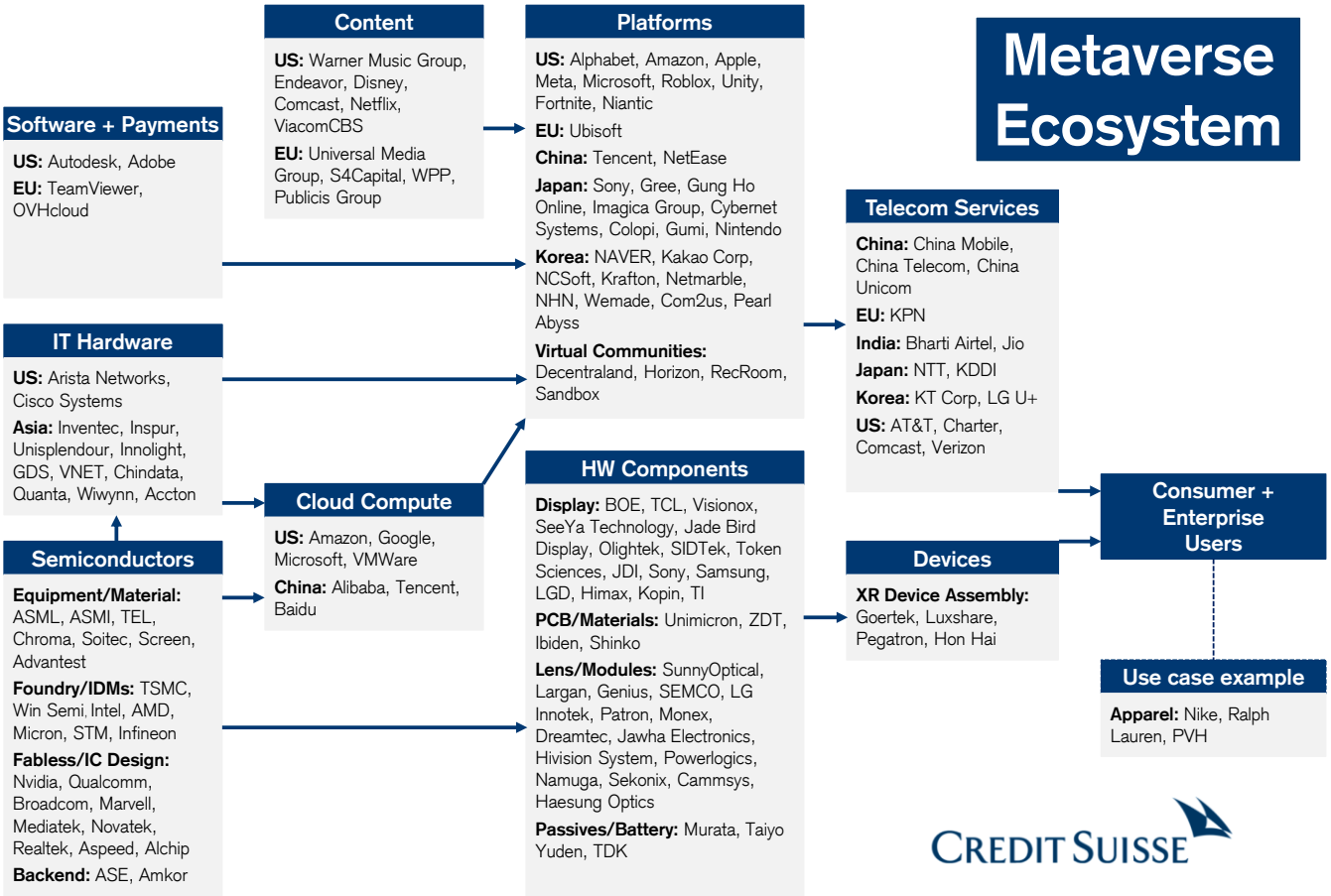
The demanding performance characteristics of metaverse applications have effects up and down TMT beyond consumer electronics makers. Semiconductors are levered to the ever-rising trend to create, store, transmit, and analyze data—we estimate the metaverse will drive a 100-300 bp tailwind to our base 6-8% forward revenue CAGR for the sector. Cloud, infrastructure, and telecom companies look set to benefit too, with a fully immersive metaverse experience challenging servers with a 100x harder compute task than an AAA game server hosting Fortnite today, and telecom access networks facing 24x more traffic in a decade (with more demanding latency requirements to boot, likely demanding edge compute and small cell deployments).

Sector views

We discuss the implications in three sections on the areas of potential for each sector:

(1) **Content:** Includes regional internet sectors (China, Korea, Japan, Europe and the US) and the US media,

Figure 2: The metaverse ecosystem map



Source: Credit Suisse

software, and apparel sectors. New applications are being pioneered to evolve today's experiences in gaming, entertainment, commerce, the monetisation of online property, advertising, and both consumer and enterprise social connectivity. The best-placed companies for the metaverse era have scaled data-centre footprints, deep services and content, existing gaming/video platform businesses, integrated hardware, and/or 3D game engines.

(2) **Hardware and semiconductors:** Includes components, assembly, display, hardware and semiconductors. For semiconductors, the metaverse fits into our data paradigm thesis, with the metaverse permeating the create/capture, store, transmit and analyse view of the data economy and poised to benefit as improvement in power/performance unleashes more data consumption and use cases for silicon. We see silicon content expansion across edge devices (AR/VR and traditional compute), the upgrade of WiFi to 6E/7, increased 5G/6G penetration and broadband fibre transmission, and upgraded cloud infrastructure (both more compute resources, and more diffuse edge compute). For hardware, the metaverse would drive AR/VR opportunities in assembly, display, camera/optics, PCB/substrate, MLCC, connectors and batteries.

(3) **Telecom and infrastructure:** Includes the US, Europe and Asian telcos, US towers, data centres and equipment, and Asia cloud IT infrastructure. The metaverse has enormous potential to further expand or divert screen time (Americans average 10+ hours/day on media, including 3+ hours on TV) and drive more bandwidth consumption. Internet traffic is already 80% video and has been growing at a 30% CAGR. Our team projects even modest metaverse usage could drive a further 37% CAGR over the next decade to 20x current data usage. This will support the value of the best-constructed networks in each region, while also demanding upgrades to data centres and network equipment.

“Metaverse: An evolution into a more immersive 3D internet.

Understanding the metaverse

Immersive 3D internet with upgrades along five key vectors: (1) hardware; (2) infrastructure; (3) content; (4) community; and (5) currency/settlement mechanism

A brief history

Science fiction. The first vision and naming of the metaverse originated in the science fiction novel, *Snow Crash,* by Neal Stephenson in 1992. In it, the metaverse was a shared multiplayer online game made available over the world's fibre optics network and projected onto virtual reality goggles. Users could control avatars that could interact with other avatars and computer-controlled agents. An avatar in that metaverse could gain status through its technical acumen navigating the arena and gaining access to exclusive spaces. *Ready Player One* by Ernest Cline in 2011 and adapted into a film in 2018, followed on with this concept in a future view of the world in 2045 where users escaped the real world by entering a metaverse called Oasis accessed with a VR headset and wired gloves.

Multiplayer games and 'avatars'. The use of avatars has extended even further back from these novels. In the early 1970s, Steve Colley and Howard Palmer invested in a multiplayer game called MazeWar that could be played over ARPANET, a precursor to the internet. The game's first avatar had a graphical eyeball that moved through the maze pointing in the direction it was travelling to shoot other players. In the 1980s, the Commodore 64 computer had a virtual world Habitat with cartoon-like avatars that could walk around and communicate with chat bubbles. As the internet ramped by 1994, WorldsChat created a space-station-themed virtual space for avatars to have social interaction and explore the various rooms. Out of that effort, a more advanced programme, AlphaWorld, featured 700 themed rooms or Active Worlds, with 12 different avatars, more interaction with the game and reaching 250,000 cumulative users. Other services, including Worlds Away, Virtual Places, Comic Chat and The Palace, also offered these virtual rooms.

Communities and services. In 2000, a Finnish company created Habbo (formerly Habbo Hotel), an online community that has accumulated 316 mn avatars since launch and now has 800,000 active users. The main feature in the game is a hotel where users can visit public areas (restaurants, cinemas and clubs) and create guest rooms. The users in this community can create a character, design and build rooms, chat with other players and take care of virtual pets.

The early services formed the building blocks for Second Life, a virtual online world that launched in 2003. By 2013, it had 36 mn accounts created, with 1 mn monthly active users who had spent 217,000 cumulative years online on territory comprising over 700 square miles and spending US$3.2 bn on in-world transactions.

The users in Second Life created avatars to interact with places, objects and other avatars through chat, IM or voice. The avatars could take any form or resemble their real-life form and could travel by walking, vehicle, flying or teleporting. The community allowed a variety of socialising, games, group activities, and opportunities to build, shop, create and trade property and services. The service also used a virtual currency to buy, sell, rent or trade goods and services. The goods could include buildings, vehicles, clothes, art or jewellery, and services could include entertainment, custom content, or business management.

Figure 3: Ready Player One Participants in the world of VR

Source: Industry

Figure 4: Second Life virtual reality world

Source: Industry

Second Life went into decline as it was usurped by other social media platforms and did not adapt well to a mobile platform. Second Life's chief architect, Philip Rosedale, in an iEEE Spectrum interview in November 2021 noted limitations with adults wanting to socialise with strangers online, technical challenges getting more than 100 people together in a copy of a concert space, a need for better toolkits for large numbers of people to build the experiences and content, and a better common currency that can unify the diverse tokens that each platform uses. He also views VR still having issues to solve around comfort, typing speed and communicating comfortably with others.

A reporter from Reuters in a series published from 2007-08 noted issues including limited support to new joiners to make the most of the platform, an overly complicated user interface, IT issues (crashes and unstable IM), and a high weighting towards adult content. They still did note an incredible depth, passion and camaraderie in the community and some interest in being able to buy a grid of space and mould it into something.

The Second Life site still claims 750,000 monthly active users on the platform and US$650 mn in annual transactions, though this is marginal relative to the major social media platforms and never ramped much above 1 mn people. The creators of Second Life followed up with a VR-based virtual world called Project Sansar but it did not ramp up well. The company returned to focussing on Second Life and sold Project Sansar to Wookey Project Group. That group is now focussing on virtual concerts including pre/after parties.

Metaverse: A still-evolving concept

The metaverse has seen a substantial increase in awareness in past months with Facebook's renaming of the company as Meta in October 2021 and a focus on driving all of its efforts towards building out the metaverse, including the most recent renaming of its Oculus Quest VR glasses as Meta Quest. While the renaming of Facebook did bring increased attention to the concept, there isn't really an agreed definition as to what the metaverse is or as to how it will evolve. In this section, we outline how various key technology companies are viewing and defining this opportunity along with providing frameworks from two industry experts/commentators.

CS' summary view of the metaverse

While industry participants hold various views as to what constitutes a metaverse, in our view it essentially boils down to an evolution into a more immersive 3D internet with upgrades along five key vectors (and different commentators' sub-divisions of these vectors):

- **Devices/hardware:** The key interface between the user (humans) and the metaverse. These could be smartphones (which evolve and add functionality over the coming years) and/or could be dedicated or linked AR/VR devices or could be a completely new dedicated hardware.
- **Infrastructure:** The network and devices that connect the hardware device to the content—5G networks, WiFi, edge computing implementations and eventually 6G.
- **Content:** All the various types of software and content, including gaming.
- **Community:** All the various use cases with many (theoretically unlimited) individuals/users who interact and socialise within the platform and also across applications/platforms (use cases).
- **Currency/settlement:** The method used to "settle" transactions for participation, content creation or direct commerce.

Figure 5: The metaverse ecosystem already growing diverse

Source: Building the Metaverse—Jon Radoff

In the following section, we further dig into the definition of and the key concepts around building out the metaverse from various leading companies in the technology world as well as views/definitions of the concept from some prominent industry commentators.

Meta's view: Metaverse as an embodied internet

Metaverse comes from the Greek word "Beyond" and is about creating a next generation of the internet beyond the constraints of screens and physics. The metaverse is expected to be the next platform for the internet with the medium even more immersive—an embodied internet where people are *in* the experience, not just looking at it. Users will be able to do almost anything they can imagine: get together with friends and family, work, learn, play, shop and create, with entirely new categories not available on phones/computers today.

The metaverse will be the successor to the mobile internet, enabling people to be able to feel present and express themselves in new immersive ways. That presence should allow people to feel they are together even if they are apart, whether in a chat with family or playing games and feeling like they are playing together in a different world of that game and conducting meetings as if face to face. The embodied internet would mean, instead of looking at a screen, users would feel they are in a more natural and vivid experience while connecting socially, and during entertainment, games and work, by providing a deep feeling of presence.

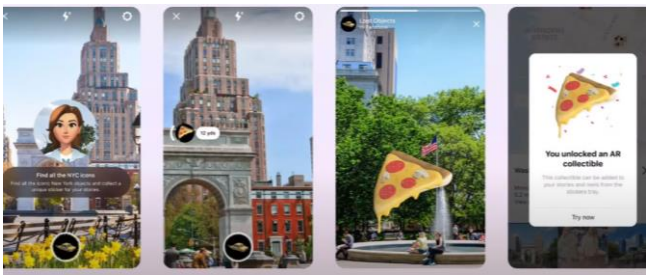
Meta believes several foundational concepts are required for the metaverse:

- **Presence.** The defining quality of the metaverse—this should enable the ability to see people's facial expressions and body language, and feel in the moment by being more immersed.
- **Avatars.** Avatars will be how people represent themselves rather than a static profile picture. The codec avatar is a 360-degree photorealistic avatar that can transform the profile image to a 3D representation with expressions, and realistic gestures that can make interactions richer. The avatar could have a realistic mode but also a mode used for work, socialising, gaming and clothing designed by creators that can be taken across different applications.
- **Home space.** The home space can recreate parts of the physical home virtually, add new parts virtually and add in customised views. The home space can store pictures, videos and purchased digital goods, have people over for games and socialising, and a home office to work.
- **Teleporting.** A user can teleport anywhere around the metaverse to any space just like clicking a link on the internet.
- **Interoperability.** Interoperability would allow someone to buy or create something that is not locked into one platform and can be owned by the individual rather than the platform. Meta is building an API (Application Programming Interface) to allow users to take their avatar and digital items across different apps and experiences. The interoperability would require ecosystem building, norm setting and new governance.
- **Privacy and safety.** The metaverse needs to build in privacy, safety, interoperability and open standards from the start, with features allowing a user choice in who they are with, the ability to be private or to block another user. The metaverse needs easy-to-use safety controls and parental controls, and also to take out the element of unexpected surprises.
- **Virtual goods.** The metaverse would allow the ability to bring items into the metaverse or project those into the physical world. A user can bring any type of media represented digitally (photos, videos, art, music, movies, books and games) into the metaverse. These items can also be projected into the physical world as holograms or AR objects too. Street art could be sent over and paid for. Clothing can also be created that is accurate, realistic and textured, and that can be purchased and bought.
- **Natural interfaces.** All kinds of devices will be supported. The metaverse will have the ability to be used on all types of devices ranging from using virtual reality glasses for full immersion to AR to still be present in the physical world, or through the use of a computer or phone to quickly jump in from existing platforms. Interaction and input can be through typing or tapping, gestures, voice recognition or even thinking about an action. In a future world, the user would not even need a physical screen as they could view a hologram for the images throughout the virtual world.

Figure 6: Meta's Horizon Home, World, and Workroom modes

Source: Meta

Figure 7: Meta developing tools for AR overlays on the World



Source: Meta

Microsoft's view: Bringing people together and fostering collaboration

Microsoft defined the metaverse as a persistent digital world inhabited by a digital representative of people, places, and things. The metaverse can be thought of as a new version of the internet where people can interact as they do in the physical world, and gather to communicate, collaborate and share with personal virtual presence on any device.

The company views the metaverse as no longer a vision, citing already existing-use cases such as the ability to go to a concert and shows with other real people inside a video game, the ability to walk a factory floor from home or to join a meeting remotely but be in the room remotely to collaborate with other workers.

The company believes the metaverse has the ability to stretch us beyond the barriers and limitations of the physical world, which proved to be a larger barrier when COVID-19 prevented work from the office or travelling to visit clients, friends, and family. Microsoft is working on tools to help individuals represent our physical selves better in the digital space and bring that humanity with the person into the virtual world. Some of the capabilities it is enabling is about teammates joining meetings from everywhere and real-time translation allowing people from different cultures to collaborate in real time.

Microsoft is driving big investment into virtual connectivity in gaming. It discussed its view that in gaming, the metaverse would be a collection of communities with individual identities anchored in strong content franchises accessible on every device.

The company also views its Azure offerings for business as well suited for the metaverse as noted from Satya Nadella at the May 2021 Build Developer Conference: (1) with Azure Digital Twins, users can model any asset or place; (2) with Azure IoT, the digital twin can be kept live and up-to-date; (3) Synapse tracks the history of digital twins and finds insights to predict future states; (4) Azure allows its customers to build autonomous systems that continually learn and improve; (5) Power Platform enables domain experts to expand on and interact with digital twin data using low-code/no-code solutions; and (6) Mesh and Hololens bring real-time collaboration.

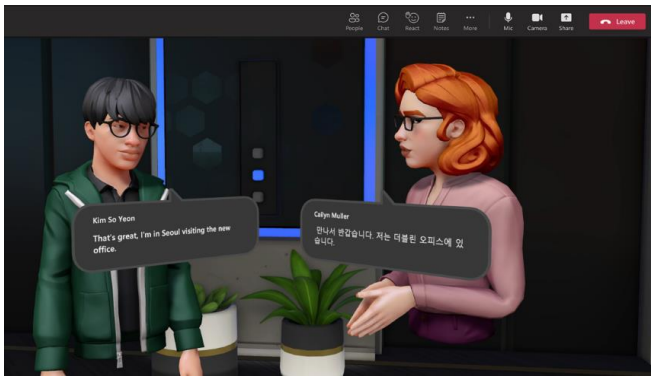
Google: Development of AR/VR could reboot with its ambient computing push

Google has been an early visionary for mixed reality products, having introduced its Google Glass for developers in 2013 and smartphone-driven VR systems in the form of Google cardboard in 2014 and Daydream headset in 2016. The company has a goal of driving ambient computing, which means users can access its services from wherever they are, and they become as reliable and essential as running water. The company's hardware strategy around smartphones/tablets, Nest home devices and potential re-emergence into AR/VR are tied to this ambient compute experience.

Figure 8: Microsoft collaboration in the metaverse

Source: Microsoft

Figure 9: Real time translation can improve communication



Source: Microsoft

Figure 10: Google Glass Enterprise Edition Two

Source: Google

Figure 11: Google Daydream smartphone-based VR

Source: Google

The company recently hired former Oculus GM, Mark Lucovsky, who is now leading Google's operating system (OS) team and experiences delivered on top of the OS for AR. Google in its recruiting posts for AR hardware developers, hardware engineers and software developers indicated it is building the foundations for substantial immersive computing, and building helpful and delightful user experiences to make it accessible to the billions of people through mobile devices. The company also indicated it includes building software components that control and manage the hardware on its AR products.

Apple: Designing its ecosystem already around AR

Apple views AR transforming how people work, learn, play, shop, and connect with the world, and the perfect way to visualise things that would be impossible or impractical to see otherwise. Apple claims it has the world's largest AR platform, with hundreds of millions of AR-enabled devices and thousands of AR apps on its Apps store. CS expects Apple to launch its first mixed reality device in late 2022 manufactured by Pegatron, though the initial projects are for small unit volumes (1-2 mn). The product may be the first stage to unleash more creativity among its develop community to move the AR from phone/tablet viewing to 3D mixed reality viewing.

Nvidia: Omniverse to create and connect worlds within the metaverse

Nvidia defined the metaverse in its August 2021 blog as a shared virtual 3D world, or worlds, that are interactive, immersive and collaborative and as rich as the real world. It views it as going beyond the gaming platforms and video conferencing tools aimed at collaboration. The metaverse would become a platform that is not tied to any one app or any single digital or real place. The virtual places would be persistent, and the objects and identities moving through them can move from one virtual world to another or into the real world with AR.

Niantic's view: Metaverse driven by AR

Niantic, developer of Pokemon Go, which was originally spun out of Google, published a blog in August 2021 building its vision for the metaverse around AR rather than VR. It views the world in science fiction novels such as *Snow*

Figure 12: Apple ARKit 5 effects' overlay

Source: Apple

Figure 13: Apple AR creation to convert models for AR use

Source: Apple

Figure 14: Nvidia's Omniverse industry use cases

Source: Nvidia

Crash and *Ready Player One* as a dystopian future of technology gone wrong where users need to escape a terrible real world with VR glasses to go into the virtual world. The company views VR as a sedentary process slipping into a virtual world and being cut off from everyone around you with an avatar as a poor substitute for the real human-to-human interaction. The company believes VR glasses remove the realistic interactions from the presence that you can sense being with people that are difficult to replicate staring into OLED display goggles.

Niantic is leaning into AR in order to be able to be outside and connect with the physical world with AR as an overlay to enhance those experiences and interactions, and get people back outside and active by learning about their city and community.

The company's view of the metaverse is a world infused with "reality channels", where data, information, services and interactive creations can be overlaid on the real world. The company incorporated these into its products Field Trip, Ingress and Pokemon Go as games that can make the world more interesting. The capability, though, can stretch beyond games and entertainment, as the AR can allow education, guidance, and assistance anywhere from work sites to knowledge work.

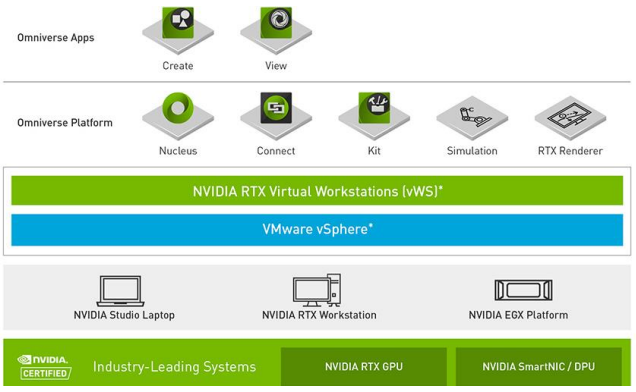
Niantic is also developing a visual positioning system (VPS) that can place virtual objects in a specific location so those objects can persist to be discovered by other people using the same application. With a live production code it has mapped thousands of locations. Niantic is attempting to build a much more in-depth digital map beyond Google Maps which can recognise location and orientation anywhere in the world leveraging on computer vision and deep-learning algorithms, and the leverage of the millions of users playing its games such as Pokemon Go.

The company's vision follows Alan Kay's 1972 Dynabook paper that discussed the trend of continuing to shrink compute (from mainframes now down to smartphones/ wearables) and eventually to compute devices disappearing into the world. Niantic views shifting the primary compute surface from the smartphone to AR glass to remove the demands on hands to make it easier to access data and services, and view overlays on the real world. Niantic has partnered with Qualcomm to invest in a reference design for outdoor-capable AR glasses that can orient themselves using Niantic's map, and render information and virtual worlds on top of the physical world with open platforms allowing many partners to distribute compatible glasses.

Figure 15: Omniverse allows collaboration on a 3D project

Source: Nvidia

Figure 16: Nvidia's Omniverse platform



Source: Nvidia

Figure 17: Niantic's metaverse uses AR to overlay digital objects in the physical world

Source: Company data

Industry commentators' views

Different companies and participants interpret what metaverse means differently. We provide views from some prominent industry commentators, one a venture capitalist and another an entrepreneur, regarding what a metaverse entails.

A. A venture capitalist's definition of the metaverse and its development vectors

Venture capitalist (VC) Matthew Ball defined (here and here) the metaverse as a "massively scaled and interoperable network of real-time rendered 3D virtual worlds which can be experienced synchronously and persistently by an effectively unlimited number of users with an individual sense of presence and with continuity of data, such as identity, history, entitlements, objects, communications and payments".

The metaverse, in his view, should be viewed as a quasi-successor state to the mobile internet as it would not replace the internet but will build on it and transform it just as mobile devices changed the access, companies, products/services and usage of the internet. As with mobile internet, the metaverse is a network of interconnected experiences and applications, devices and products, and tools and infrastructure. The metaverse places everyone in an embodied, virtual or 3D version of the internet on a nearly unending basis.

Some characteristics of the metaverse are that it would be: (1) persistent; (2) synchronous and live; (3) without caps on users and providing each user with an individual sense of presence; (4) a fully functioning economy; (5) an experience that spans digital and physical worlds, private and public networks, and open and closed platforms; (6) offer unprecedented interoperability of data, digital items/assets and content; and (7) populated by content and experiences created and operated by an incredibly wide range of contributors.

The VC is tracking the metaverse around eight core categories:

(1) Hardware: Technologies and devices to access, interact and develop the metaverse (VR, phones, haptic gloves).

(2) Networking: Development of persistent real-time connections, high bandwidth and decentralised data transmission.

(3) Compute: Enablement of compute to handle the demanding functions (physics, rendering, data reconciliation and synchronisation, AI, projection, motion capture and translation).

(4) Virtual platforms: Creation of immersive and 3D environments/worlds to stimulate a wide variety of experiences and activity supported by a large developer and content creator ecosystem.

(5) Interchange tools and standards: Tools, protocols, services and engines to enable the creation, operation and improvements to the metaverse spanning rendering, AI, asset formats, compatibility, updating, tooling and information management.

(6) **Payments:** Support of digital payments including fiat on-ramps to pure-play digital currencies/crypto.

(7) **Metaverse content, services, and assets:** The design, creation, storage and protection of digital assets such as virtual goods and currencies connected to user data and identity.

(8) **User behaviour:** Changes in consumer and business behaviour (spending and investment, time and attention, decision making and capability) associated with the metaverse.

B. An entrepreneur's view: The seven layers of the metaverse

Jon Radoff, CEO of Beamable, a Live Game Services platform, is another prominent industry commentator on the topic of the metaverse and is widely quoted by various articles associated with the concept. His prior work has focussed on online communities, internet media and computer games. Jon sees the metaverse (link) as composed of seven layers:

(1) **Experience:** The experience layer is where users do things in the metaverse including gaming, socialising, shopping, watching a concert or collaborating with co-workers. The metaverse experiences do not need to be 3D or 2D, or even necessarily graphical; it is about the inexorable dematerialisation of physical space, distance and objects. When physical space is dematerialised, formerly scarce experiences may become abundant.

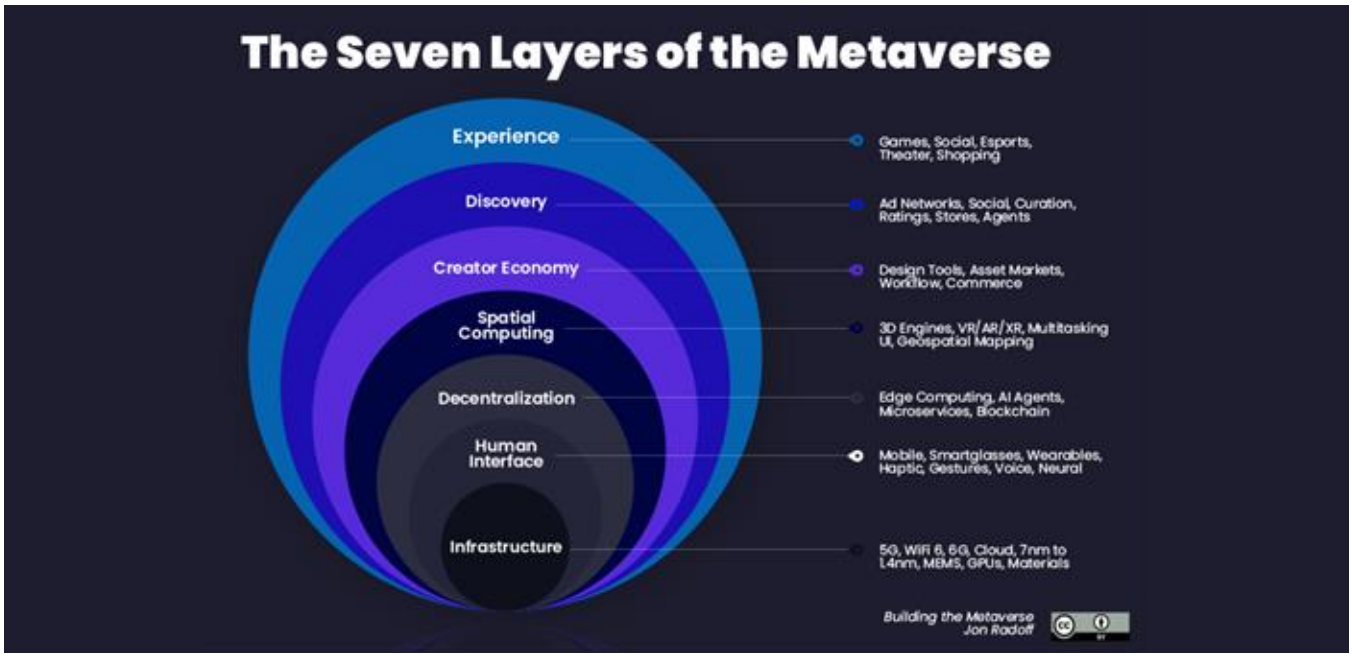
(2) **Discovery:** The discovery layer is about the push and pull that introduces people to new experiences. Broadly speaking, most discovery systems can be classified as either inbound (the person is actively seeking information about an experience) or outbound (marketing that was not specifically requested by the person, even if they opted in). The discovery layer could include the curated portals, online agents, rating systems and advertising networks drawing users to discover different areas.

(3) **Creator economy:** Not only are the experiences of the metaverse becoming increasingly immersive, social, and real-time, but the number of creators who craft them is increasing exponentially. This layer contains all of the technology that creators use daily to craft the experiences that people enjoy.

(4) **Spatial computing:** Spatial computing has exploded into a large category of technology that enables us to enter into and manipulate 3D spaces, and to augment the real world with more information and experience. The key aspects of such software includes: 3D engines to display geometry and animation; geospatial mapping; voice and gesture recognition; data integration from devices and biometrics from people; and next-generation user interfaces.

(5) **Decentralisation:** The ideal structure of the metaverse is full decentralisation. Experimentation and growth increase dramatically when options are maximised, and systems are interoperable and built within competitive markets. Distributed computing powered by cloud servers and microservices provide a scalable ecosystem for developers to tap into online capabilities without needing to focus on building or integrating back-end capabilities. Blockchain technology, which enables value-exchange between software, self-sovereign identity and new ways of unbundling and bundling content and currencies, is a large part of decentralisation (this area of innovation can be called Web 3.0).

Figure 18: The Seven Layers of the Metaverse



Source: medium.com (link)

(6) **Human interface:** Computer devices are moving closer to our bodies, transforming us into cyborgs. Smartphones have evolved significantly from their early days and are now highly portable, always-connected powerful "computers". With further miniaturisation, the right sensors, embedded AI technology and low-latency access to powerful edge computing systems, they will absorb more and more applications and experiences from the metaverse. Dedicated AR/VR hardware is also coming into the market, and in the coming years will likely evolve significantly. Beyond smartglasses, there is a growing industry experimenting with new ways to bring us closer to our machines such as 3D-printed wearables integrated into fashion and clothing.

(7) **Infrastructure:** The infrastructure layer includes the technology that enables our devices, connects them to the network and delivers content. This includes the semiconductors, battery technology, cloud servers and storage, and 5G and Wi-Fi transmission required. The infrastructure upgrades on compute, connectivity and storage supplemented by AI should dramatically improve bandwidth while reducing network contention and latency, with a path to 6G in order to increase speeds by yet another order of magnitude.

Web 3.0 envisions a more decentralised metaverse

Web 3.0 envisions the internet to be based on decentralised blockchains using token-based economics for transactions. The new vision contrasts with Web 2.0 where the large internet platform companies have centralised a lot of the data and content. Web 3.0 was coined in 2014 by Ethereum co-founder Gavin Wood and in the past decade has seen more interest as a concept across tech companies, VCs, start-ups and blockchain advocates. A number of virtual communities in the metaverse are forming with a decentralised concept that may open up the rule making of the community to a collective majority of individuals on the platform and are also adopting the token concept as virtual currency.

While the original "internet" Web1 was built on largely open-source standards, Web 2.0 leveraged those same open and standards-based technologies but ended up creating large and closed communities, often referred to as "walled-garden" ecosystems. As Jon Radoff has argued in one of his posts, walled gardens are successful because they can make things easy to do—and offer access to very large audiences. But walled gardens are permissioned environments that regulate what you can do, and extract high rents in exchange. He argues that there are three key features of Web 3.0 that should change this paradigm of Web 2.0:

- **Value-exchange (rather than simply information exchange).** The enabling technology for value-exchange is smart contracts on blockchains. The blockchain is a shared ledger that allows companies, applications, governments and communities to programmatically and transparently exchange value (assets, currencies and property, etc.) with each other, without requiring custodians, brokers or intermediaries. The ability to programmatically exchange value between parties is a hugely transformative development.
- **Self-sovereignty.** An important part of Web 3.0 is inverting the current model where one uses one's login details for "walled gardens" to interact with several other online applications. Instead of having a company own one's identity and then granting us access to other applications, one would own one's own identity and choose which applications to interact with. This can be accomplished by using certain digital wallets. One's wallet becomes one's identity, which can then allow you to use various decentralised applications on the internet that need to interact with one's currencies and property.
- **The re-decentralisation of the internet.** Currently, there are substantial dependencies across the internet on a small number of highly centralised applications. But with Web3, the power shifts back to individual users, creators and application developers with far fewer centralised authorities to extract rents or ask permission from. This transfer of power and ability for users to monetise their work by certifying efforts on the blockchain and monetising that by exchanging the work for tokens is expected to lead to an explosion of new creativity in the form of applications, algorithms, artwork, music, AI/robots, virtual worlds and metaverse experiences, with more of the rewards staying in the hands of the owners and creators.

Metaverse still has its limitations and risk

We do see significant potential from the latest wave of investments to upgrade to a more immersive internet but also see some limitations and risks in the latest cycle which pose obstacles and may limit its success.

- **AR/VR limitations.** A truly immersive internet would benefit from a 360-degree field of VR or with AR glasses versus access through traditional smartphones, tablets and PCs. VR saw a first wave of hype in 2016 with the launch of VR headsets by many companies and many smartphone-based VR platforms, with every major trade show seeing long lines to experience the concept.

  The first wave failed to live up to the hype with only 2 mn units shipped. A combination of early hardware limitations included tethering to a PC, causing vertigo and discomfort with extended use, a lack of AAA gaming titles and content, and isolation from others while wearing it. The VR technology is improving with better processing and sensors, faster refresh rates, higher resolution and high-speed WiFi eliminating the tethering plus content should improve with the new wave of metaverse funding. Nevertheless, VR would still lead to some discomfort from wearing for an extended time and isolating the user from their surroundings.

- **Mainstream interest in virtual worlds.** The hurdle for virtual worlds is higher as earlier communities faced difficulty keeping up activity 24-7 and it also needs to change user behaviour from still seeking out real-world experiences. The virtual worlds are improving in terms of audio/visual but still fall short on three of the five senses (smell, taste and touch) to be fully immersed in the experience. Some advocates are more aggressively investing in AR technologies which bring elements of the digital world into the real world.
- **Policing the communities.** Social media platforms have continuously faced issues over which content and authors to allow and censure, and also their ability to use AI and human monitors to take down abusive content. A decentralised metaverse, without the scale of the resources major internet providers have, may also struggle to keep up with monitoring abuse on the platform.
- **NFT speculation, fakes, and metaverse asset inflation.** NFTs (non-fungible tokens) represent a unique piece of data on the blockchain that claims to offer a certificate of authenticity or proof of ownership though they do not restrict sharing or copying the digital file or prevent the creation of NFTs with identical associated files. NFTs have been associated with transfers of artwork, in-game assets, music and sports cards, and can be a way to pay a creator for their work. The NFT market, though, is introducing stolen goods, bubbles and the risk of over-saturation as more are created. The metaverse is also drawing headlines for rising real estate prices in some of the digital communities and the high-priced resale of luxury bags carrying no right to carry it into the physical world.

“Potential to transform social interactions, leisure activities, education and work.

Metaverse use cases are expanding

Metaverse would impact gaming, entertainment, work collaboration, social media, virtual worlds, education and fitness in the near term, and will see additional use cases over time.

By moving to a more 3D and immersive form of the internet, the metaverse has the potential to expand opportunities for the current internet. We highlight the use cases and current developments around some of the major areas the metaverse would impact including gaming, entertainment, work collaboration, social media, virtual worlds, education and fitness. While these are some of the current prominent use cases, given that the metaverse is an adaptation and evolution of the internet, use cases are, frankly, endless although we list some additional use cases, notably in the commercial space at the end of this section.

Gaming: Platforms to further leverage 3D immersion

Video games are expected to play a central role in the metaverse as they already build on immersive experiences with 3D graphics, VR-enabled titles, and platforms for user creativity and built-out digital goods for use in gaming. The overall market is exponential and is now at 3 bn users and projected by industry players to reach 4.5 bn by 2030. Gaming platforms can be further unleashed with the metaverse by allowing a gamer to be embodied and moving around in the game or building out further upgrades available to other users. As compute power rises, deeper multi-player gaming can be fully enabled and eventually, a user could turn into a hologram to show up visually with someone in another location.

Entertainment: 3D virtual option opens up for film, television, and music content

The metaverse is stimulating new forms of entertainment, with a likelihood that technology eventually would allow a user to be viewed as a hologram in another place and teleport into a remote concert or party.

During the pandemic, a number of platforms developed the major use case of virtual concerts that took the place of live performances. The advantage of these concerts is they could reach far more users globally than a live venue and could also transform the singer into an avatar or the stage into a virtual environment, with special effects and opportunities for fan interaction. The concerts also formed a good platform to promote merchandising for the event.

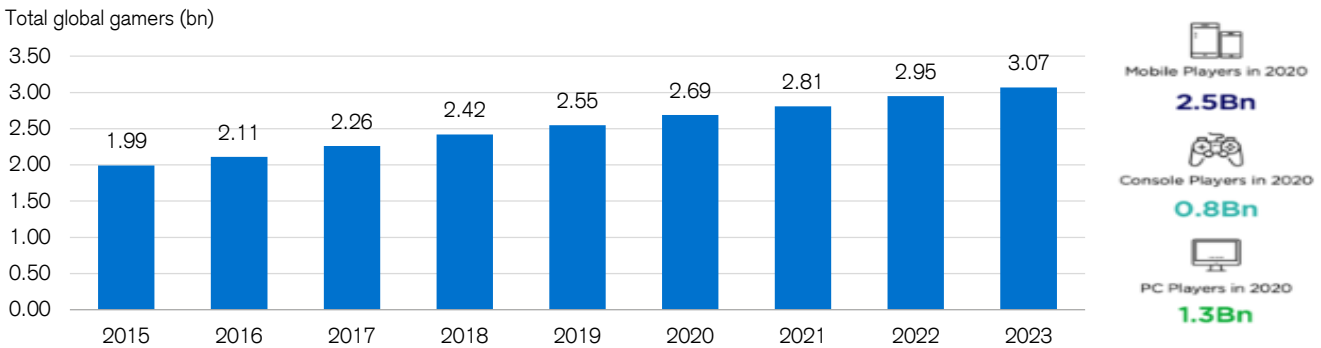
Social: Leveraging AR/VR for connectivity and presence in the metaverse

Social media is embracing the metaverse as a way to expand connectivity with the use of AR/VR. We highlight the efforts of social media platforms as well as some of the early work by dating sites to introduce virtual engagements before meeting in the real world.

Industrial: A solution for collaborative work amid hybrid office evolution

Work in the metaverse would allow a better sense of presence, shared physical spaces, and a productive work set-up in a work-from-home set-up. The work setting can allow collaboration to view a 3D design with others. Companies are investing resources towards various products, including customisable workrooms for meetings, an office space to customise home workspace, and 2D progressive web apps to view applications and social media through VR.

Figure 19: Gamers now approaching 3 bn global players



Source: Newzoo

Commerce: Virtual communities opening up new forms of commerce

The metaverse is also opening up a platform for commerce, with creators making digital objects, offering services and experiences, building worlds, and a place to sell both physical and digital products. The metaverse platform goal is for content that is purchased on one platform to be available on other platforms. For purchases, NFTs can be securely purchased and sold with the data stored on the blockchain.

A number of communities are setting up public spaces that can be accessed through digital means. Most of these networks use avatars to represent the users, though they vary in the digital ownership, centralisation of the platform, rules of engagement with others, ability to build and take ownership on the ecosystem vs being on a platform from one of the major social media companies and the ability to create commerce activities. Some gaming platforms have centralised environments, but several new communities are developing around decentralisation—which places ownership of goods on the blockchain and is opening up ownership and control of the rules toward decentralised policymaking.

Other use cases

The above paragraphs detail use cases across various end-markets and with examples of companies/applications operating within that area. Given that 'metaverse', in some ways, is just an adaptation/evolution of the 'internet', use cases are, frankly, endless.

- **Manufacturing.** Metaverse can help the manufacturing process significantly, particularly in the areas of design and product development, by facilitating an improved relationship and interaction between business owners, suppliers (including design companies) and customers. Such a platform can result in a rapid production process design, increase the number of product designs, lead to more collaborative product development, and potentially reduce the risk to quality control. In addition, customers in the metaverse could have improved visibility into the supply chain process with 3D representations for how products are built, distributed, and sold. There could also be additional opportunities for manufacturers to have add-on digital-products (clothes/fashion, homes, cars) in the metaverse that resemble and mimic the real-world products.
- **Fitness.** VR also gives the chance to transform the living room, similar to how virtual sports gaming products got many off the couch to play their motion-controlled sports games. Fitness games through VR will allow more immersion and interactive training by allowing a user to work out in new worlds, playing against other users or against the machine AI.
- **Education.** Education took a 2D step through online learning during the pandemic but still struggled with student engagement. An upgrade to use 3D features and VR has potential to enhance the experience and engagement by allowing teachers to teleport their students to a different place or time, or into a virtual classroom, library or gymnasium with their fellow students. A headset or glasses could enable much more active exploration of history, biology, a visit to a museum in another location, or an interactive class with fellow students.

  Other online VR educational applications and programmes are now cropping up. One of the companies is offering these experiences by allowing customisation of a virtual classroom and simulation of presence with virtual avatars for more interactive remote learning. The school features presentations and documents, customisable whiteboards, notifications and moveable Post-its, and live video and text. Spatial I/O's collaborative VR platform features iTeacher, which is architecting virtual worlds for high school education to connect on academic topics with its metaverse now having 14 different spaces to simulate different lessons.

“AR/VR devices to be early beneficiaries.

Hardware: Near-term focus on AR/VR devices

We expect AR/VR devices to see strong growth over the next few years, along with advancement in hardware, software and connectivity

While the evolution of metaverse will eventually affect almost all aspects of hardware devices involved, and may even lead to some dedicated 'killer' hardware product—like the iPhone was for the 3G (mobile data) era—in the near future, AR/VR devices is where the companies' and investors' attention is with regard to metaverse devices. With the advancement in optics, chipset, 5G and software, AR/VR is not only used for games but has also seen applications in educational, industrial and medical facilities.

We expect global AR/VR headsets to deliver 42 mn units and revenue to reach US$12.6 bn in 2025, representing 48% shipment CAGR and 36% revenue CAGR over 2020-25.

We believe three factors could drive additional growth of the AR/VR market in the next few years, over and above our forecast growth rate: (1) a disruptive AR/VR headset maker emerges amidst more applications in enterprises and the public; (2) a better integrated hardware-software platform emerges to drive penetration; (3) technological improvements such as micro-LED and fast LCD enable a better price-performance product.

Products from emerging players

In light of AR/VR's ability to enhance gaming experience, other industries like education, healthcare and construction will also benefit from the rise of the headsets. We see an increasing number of start-ups designing headsets for the enterprise and public sector. We expect enterprise application would be another driver for AR/VR devices.

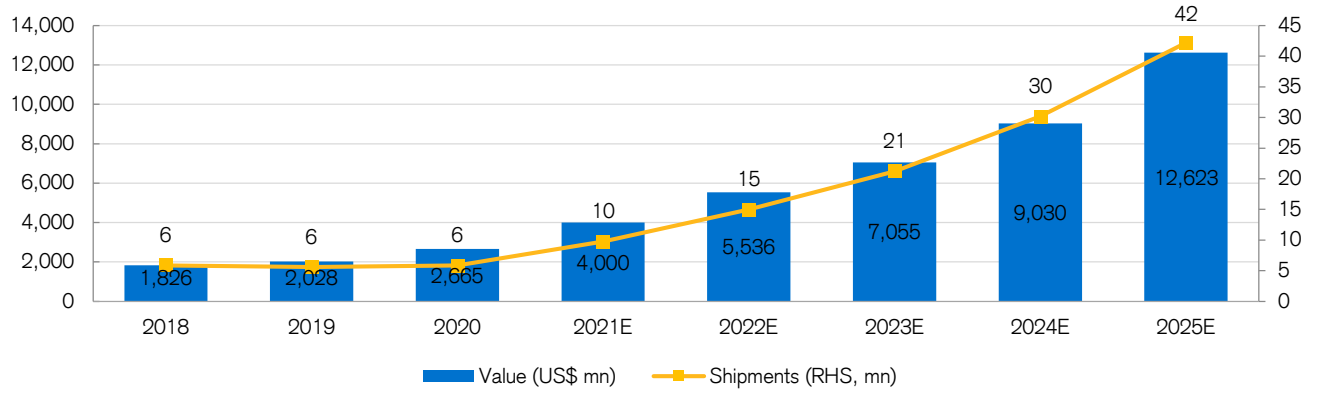
We believe start-ups and emerging headset companies will expand the use of AR/VR devices, and further support the adoption of headsets for commercial use. We expect applications outside gaming/entertainment to be the surprise factor for headsets in the next few years.

Platform will be key in the metaverse

We will pay attention to metaverse content and application development. Facebook renamed itself Meta and declared a commitment to developing a metaverse ecosystem, and launched its virtual social platform Horizon Worlds in Dec-2021. Roblox is already considered a virtual metaverse community with a successful online game creation platform with 31 mn DAUs (daily average users) in 2021. It allows users to build their own areas and play games with other users.

We believe no single company is capable of building a metaverse, and the concept would be closer to a real world society in which everyone plays a role contributing via different tools. Current products of leading companies are platforms providing tools that allow users to build their own spaces. There are many others, which have the potential to become larger with time. Although the platforms are early stage, they will help drive AR/VR headset demand as user generated content (UGC) and applications are created.

Figure 20: AR/VR headset market grows behind "metaverse"



Source: IDC, Credit Suisse estimates

VR technology roadmap

Common complaints against VR were on the motion sickness caused by: (1) the screen door effect (SDE) (visible gaps between pixels); (2) mura (colour inconsistency of each pixel); (3) aliasing (series of square blocks instead of curved lines); (4) latency (low chipset processing and transmission speed); and (5) the weight of headsets. To mitigate these issues, headset makers are advancing the chipset, optics, display, and tracking solution to improve the user experience.

- **Chipset: Qualcomm XR series**

  Qualcomm launched its XR platform Snapdragon Extend Reality (XR) series in 2018 as its first SoC for AR/VR devices. The XR2 5G platform was announced in Dec-2019, which is a derivative of the Snapdragon 865 (7nm). Oculus Quest 2 was the first to deploy the chipset, with a process speed doubling that of Snapdragon 835 in Quest 1. The XR2 enables 2x more video bandwidth, 6x higher resolution, and 11x AI improvement. The strong performance has attracted most of the major headsets makers including HTC, PICO, DPVR, Lenovo, and Microsoft Hololens.

- **Display: Fast-LCD is becoming mainstream**

  The display in the HMD (head-mounted device) for VR is usually one or two pieces of LCD (liquid crystal display) or OLED (organic light-emitting diode) panel, depending on the design of the device, although a dual display system is preferred as human beings have two eyes. Although LCD and OLED are both applicable for VR displays, the majority of recently announced VR models have adopted LCD due to its cost advantage. OLED display was first used on VR devices by Sony's PSVR, Oculus Rift, and HTC Vive due to its fast response time, which reduces motion image blur significantly. However, OLED is limited by its inadequate lifetime and higher cost/lower yield for higher resolution. Normal LCD has the characteristic of high resolution, high brightness, long lifetime and low cost, but its response time is ~100x slower than that of OLED. As a result, LCD usually displays much more severe image blurs than OLED.

- **Optics: Fresnel lenses to replace aspherical lenses**

  Fresnel lenses are advocated by more VR makers due to their lighter weight and thinner centre. HTC was the first to use Fresnel lenses in its high-end product, Vive, followed by Oculus. To reduce the weight of VR devices and enhance the user experience, Fresnel lenses are more likely to be adopted by the majority.

- **Tracking solution: 6DoF and inside-out tracking solution will be the basic feature**

  6 degrees of freedom (6DoF) is an upgrade of 3DoF which adds rotational axes for rolling, yawing and pitching. 3DoF is enough for basic applications such as VR movies, but for a complete immersive experience like gaming, healthcare and training, 6DoF is required. Most of the newly released VR headsets in 2021 employed 6DoF, and we expect the 6DoF function to be a basic feature for VR in the future.

  In inside-out positional tracking, the camera or sensors are located on the headset being tracked (e.g. Oculus); while sensors in the outside-in scenario are placed in a stationary location (e.g. PSVR). We believe inside-out will be used for most VR devices for its mobility and flexibility, whilst outside-in will likely be used in specific scenarios such as healthcare VR and console-powered VR for its accuracy.

Figure 21: Major VR specs

		Best Sellers					New release in 2021				
Brand		Oculus Quest 2	Pico Neo 2	DPVR P1 Pro 4K	HP Reverb G2	Valve Index	Pico Neo 3	Nolo Sonic	HTC Vivo Flow	Huawei 6DoF	DPVR P1 Pro Light
Processor		Qualcomm Snapdragon XR2	Qualcomm Snapdragon 845	Qualcomm Snapdragon XR1			Qualcomm Snapdragon XR2	Qualcomm Snapdragon 845	Qualcomm Snapdragon XR2		Qualcomm Snapdragon 821
Type		Standalone VR	Standalone VR	Standalone VR	PC-powered VR	PC-powered VR	Standalone VR	Standalone VR	Standalone VR	Phone-powered VR	Standalone VR
Display	Display Type	Fast LCD	Fast LCD	Fast LCD	2 x Fast LCD	2 x Fast LCD	Fast LCD	Fast LCD	2 x Fast LCD	2 x Fast LCD	Fast LCD
	Resolution	1832x1920	2048x2160	1920x2160	2160x2160	1440x1600	1832x1920	1920x2160	1600x1600	1600x1600	1280x1440
	Refresh Rate	120 Hz	75 Hz	72 Hz	90 Hz	144 Hz	90 Hz	72 Hz	75 Hz	90 Hz	90 Hz
Optics	Optics	Fresnel lenses	Fresnel lenses		Fresnel lenses	Fresnel lenses	Fresnel lenses				Fresnel lenses
	Field of View	89° horizontal 93° vertical	101° horizontal 101° vertical	100° diagonal	107° diagonal	107° diagonal	98° horizontal 90° vertical	101° horizontal 90° vertical	100° diagonal	90° diagonal	100° diagonal
Tracking	Controllers	6 DoF	6 DoF	3 DoF	6 DoF	6 DoF	6 DoF	6 DoF	6 DoF	6 DoF	3 DoF
	Solutions	Inside-out	Inside-out		Inside-out	Inside-out	Inside-out	Inside-out	Inside-out	Inside-out	
Weight (with headstrap)		503g	670g	340g	498g	809g	620g	502g	189g	188 g	410g
Price (with controllers)		$299	$699	$349	$599	$499	$390	$470	$499	$620	$399

Source: Credit Suisse

AR's Technology Roadmap

Mark Zuckerberg called AR glasses "one of the hardest technical challenges of the decade." Due to the complexity of the architecture, the price of AR glass is still high, which hinders penetration. For example, one of the products from a leading industry player sells for US$3,500 and the majority of the users are enterprises. Unlike VR, in which most components are becoming mainstream specs, AR makers are still exploring different architectures:

- **Display: DLP, LCOS, Si-OLED are mainstream and MicroLED would likely be the ultimate solution**

  AR glasses require compact and power-efficient displays with very high contrast and brightness. We had a leap in AR display technology achieving these objectives, yet there is still room to improve on the yield rate and costs. Organic light emitting diodes on silicon (OLEDoS), digital light processing (DLP), and liquid crystal on silicon (LCOS) are the three main pathways:

  (1) OLEDoS is fabricated on silicon wafers instead of glass substrates and polyimide substrates.

  (2) DLP is a popular solution for projectors, using micro mirrors (DMDs) which are positioned in a semiconductor chip to reflect light, and directs red, green, blue light to the imagers.

  (3) LCOS technology is a variation of LCD technology, separating light into red, green and blue components and reflecting the light off the chip surface to LCD cells. A CMOS chip is under the chip surface to control voltage on square reflective aluminium electrodes.

Figure 22: Popular AR specs

Popluar AR glass											
Brand		**MAD GazeMAD Gaze Glow Plus**	**Rokid Glass 2**	**Magic Leap 1**	**Microsoft HoloLens 2**	**Vuzix 4000**	**Xiaomi Smart Glasses**	**Dream Glass 4K**	**INMO Air**	**Nreal Light**	**Lenovo ThinkReality A3**
Processor			Amlogic S905D3	NVIDIA Parker SOC	Qualcomm Snapdragon 850	Qualcomm Snapdragon XR1	Quad-core ARM CPU	Rockchip Mali T864	Quad-core ARM CPU		Qualcomm Snapdragon XR1
Type		Phone-powered AR	Standalone AR	Standalone AR	Standalone AR	Standalone AR	Standalone AR	Standalone AR	Standalone AR	Phone-powered AR	PC-powered AR
Display	Display Type	2 x OLED	LCOS		2 x Light engine	DLP	2 x Micro LED			2 x OLED	
	Resolution	1920x1080	1280x720	1280x960	1440x936	854x480	640x480	1920x1080		1920x1080	1920x1080
	Refresh Rate			122 Hz	60 Hz		50 Hz	60 Hz		60 Hz	
Optics	Optics	Birdbath optics	Waveguides	Waveguides	Waveguides	Waveguides	Waveguides	Curved mirrors	Waveguides	Birdbath optics	Birdbath optics
	Field of View	53° diagonal	40° diagonal	50° diagonal	52° diagonal	28° diagonal	29° diagonal	46° diagonal		52° diagonal	
Tracking	Controllers	6 DoF Inside-out	3 DoF	6 DoF inside-out	6 DoF inside-out	3 DoF	3 DoF	3 DoF	3 DoF	6 DoF inside-out	6 DoF inside-out
Weight (with headstrap)		80g	96g	316g	556 g		51 g	185g	78g	41g	130g
Price (with controllers)		$599	$3,000	$2,295	$3,500	$2,499		$599	$349	$499	

Source: Credit Suisse

Initially, LCOS was the major technology for AR, for the high brightness, but it was not energy- or cost-efficient. OLED has limitations with brightness; however, breakthroughs in OLED material such as silicon substrate bridged the gap. Therefore OLEDoS (OLED on silicon) is now becoming the most popular technology due to its merits of higher contrast, power efficiency, thickness, wider temperature range, and faster response time. Although there are still many hurdles to achieving mass production, we believe micro-LED would be the ultimate solution for AR glasses due to its super-high brightness and contrast, excellent temperature endurance, fast response time, and low energy consumption.

- **Optics: Waveguide becomes the major architecture**

  The industry is developing two different approaches in waveguide technology:

  (1) Diffractive waveguides are considered the most mature technology, used in HoloLens 2, Magic Leap 1 and Vuzix M4000. A diffractive optical element (DOE) or holographic optical element (HOE) are used to inject the light over a small area into the waveguide and extract it to the user's eyes. The diffractive method disperses wavelengths, so separate waveguides are used. Mainstream products are leaning towards the use of two layers of waveguides for thinner glasses.

  (2) Reflective waveguide designed by the Israeli AR company, Lumus, does not require nano photonics. This methods employs a 1D or 2D semi-transparent mirror along the optical path to guide the light to users' eyes.

Birdbath is another solution for AR optics. It contains a spherical mirror/combiner (part-mirror) and a beam splitter. The method works like a birdbath in which it projects light from the OLED into the beam splitter, at a 45-degree angle with the OLED light source plane. Lenovo Mirage AR and ODG R9 were two examples adopting this method, but it has two major downsides being light loss and double image.

Curved mirror (adopted by DreamWorld and Leap Motion) is the cheapest see-through display technology. It is based on semi-reflective curved mirrors placed in front of the eye. The major advantage was the low cost because it works with LCD, but suffers from a high degree of distortion, low image resolution and less comfort.

Waveguide and micro-LED solutions are at the early stage; it is very difficult for this solution to be mass produced at a low cost, but companies such as Glo, VueReal, BOE, and AUO are investing heavily in micro-LED technology. With the advancement of mirco-LED technology, we expect the solution will be adopted by most of the AR makers in the future.

For AR glasses, Meta has Project Nazare, its first AR glasses that allow augmented reality overlays on the real world. AR requires integration of hologram displays, projectors, batteries, radios, custom silicon, cameras, speakers and sensors to map the world into glasses that are 5mm thick. It also introduced its Ray Ban Stories—which allows taking pictures or phone calls, listening to music, and watching videos—at US$299.

Meta also has a Project Cambria for new high-end glasses. With Project Cambria, Meta would integrate "high-resolution coloured mixed-reality pass-through" glasses, which combine an array of sensors with reconstruction algorithms to represent the physical world in the headset, with a sense of depth and perspective. The representation on the display with these innovations is finally getting closer to representing what the eyes see in the physical world. For optics, the company is developing pancake optics by folding light to achieve a slimmer profile than current lenses.

Vuzix, an AR headset company founded in 1997, recently unveiled its Vuzix Shield which contains battery, computer, cameras and display projector in the temples of the glasses but can be worn all day.

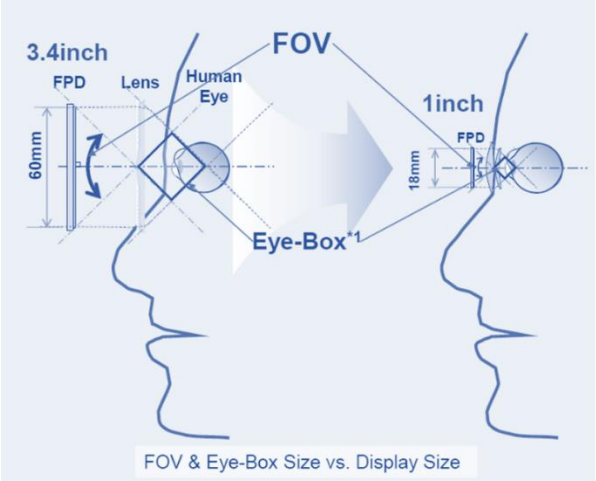
Figure 23: Each display technology excels in different areas

Item	OLED (Glass base)	LCD (Glass base)	Micro Display (Silicon base)
Brightness	★★ ~1000cd/m2	★★ ~1000cd/m2	★★★
Contrast Ratio	★★★ >100,100:1	★*	★★★ >100,100:1
Resolution	★	★★★	★★★
Display Life	★★	★★★	★★★
Cost	★★	★★★	★
Yield rate	★★	★★★	★

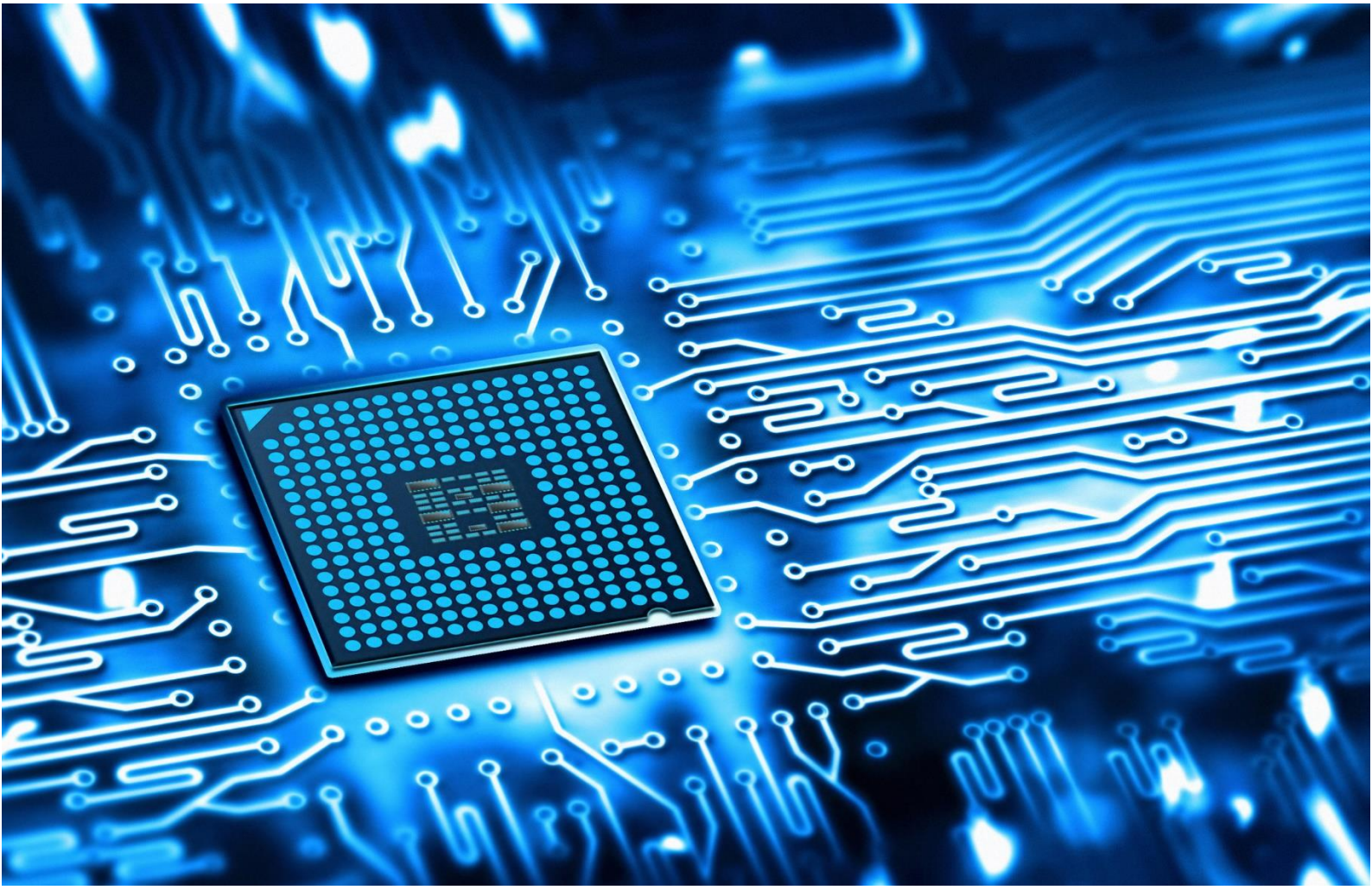
*(can improve to ★★★ using local dimming technology)

Source: JDI, Credit Suisse

Figure 24: LCD is the best technology for 2-3 inch display



Source: JDI



“Semiconductors are becoming the staples of the new data economy.

Semiconductors are a levered metaverse play

Since 1977, the global population has grown 86% from 4.2 bn to 7.9 bn while per capita chip units have grown ~70x from two to 146—a massive accomplishment even before considering the integration of functionality per chip

In addition to rising entry barriers, slowing supply and a better demand mix increasing the global semi revenue CAGR from 3-5% to 6-8%, we see an additional 100-300 bp of potential CAGR upside based on our view that semis are the most levered play on the move to a data-driven economy. Relative to the semiconductor ecosystem, we divided our data thesis into four separate areas:

(1) Data creation/capture;

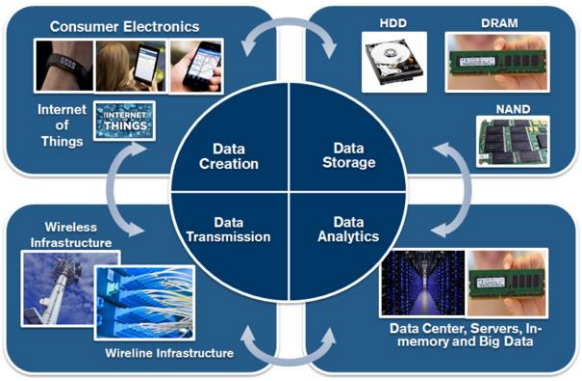
(2) Data storage;

(3) Data transmission; and

(4) Data analytics.

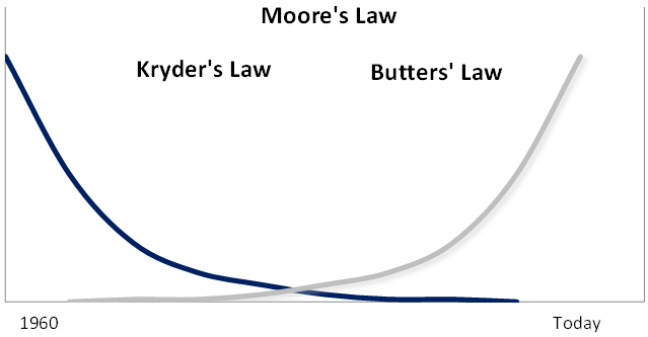
We argue that while data analytics is the most important area—if you can't analyse, you can't monetise—we also argue that each area is self-perpetuating: the more data you can analyse, the more you want, which drives demand for data creation/capture which in turn drives demand for storage and transmission. While our Data Thesis Paradigm is now well understood by investors (we first introduced it in 2010), there is an important subtlety that is still under-recognised. Specifically, the first three areas of Create, Store and Transmit have each benefitted from non-linear cost declines. Moore's Law dictates that each year it is cheaper to create/capture data and there is a Moore's Law equivalent in Storage called Kryder's Law and for

Figure 25: Data paradigm



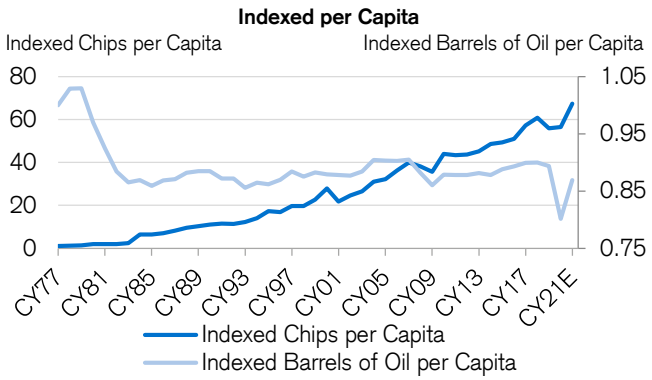
Source: Credit Suisse

Figure 26: Declining cost curves drive application elasticity



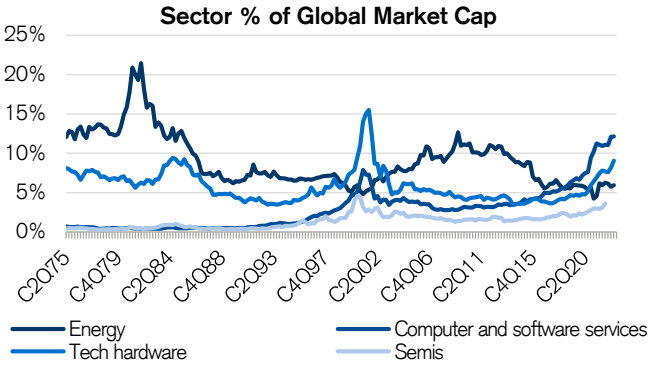
Source: Credit Suisse

Figure 27: Chips per capita accelerating

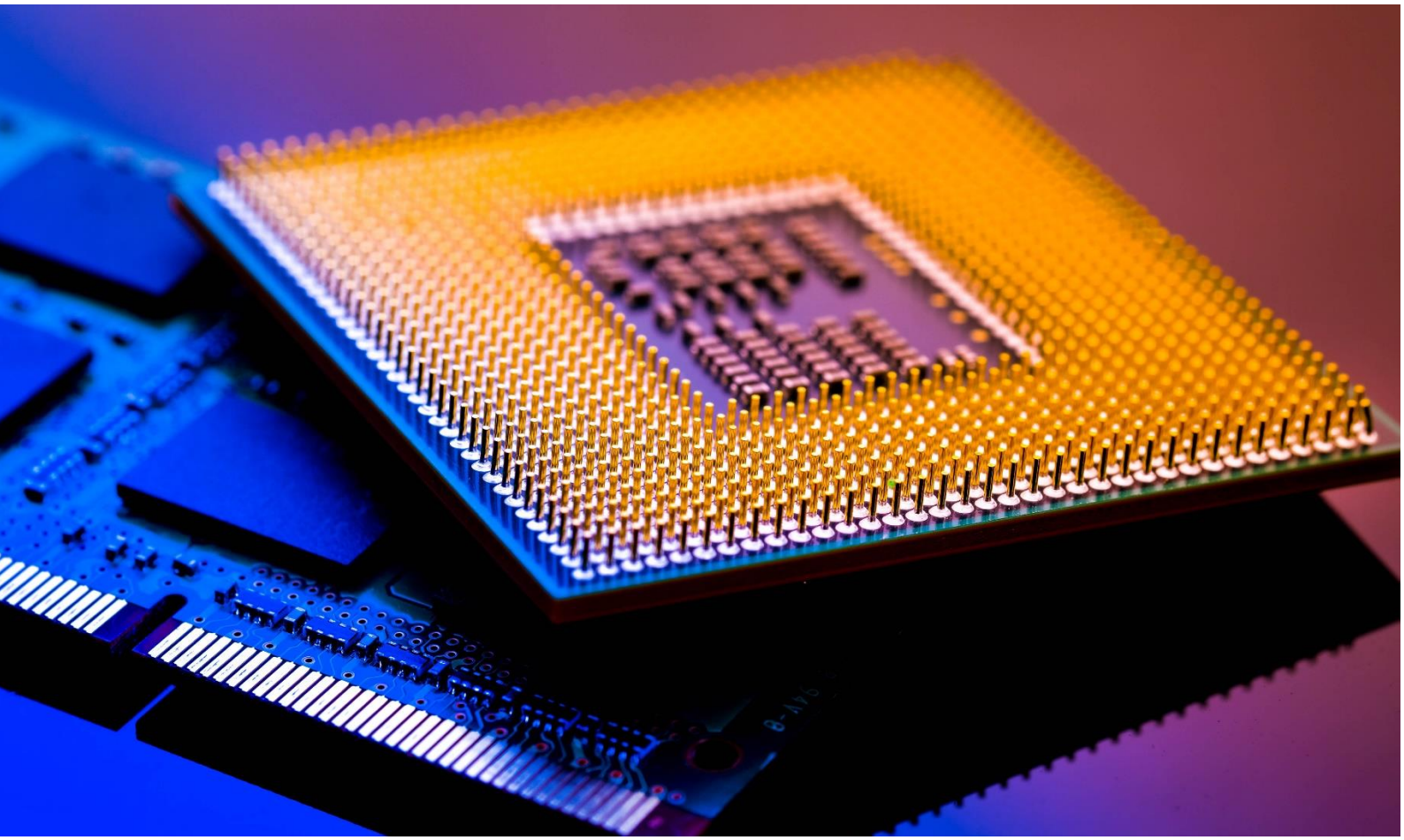


Source: Census.gov, Credit Suisse estimates

Figure 28: Semis have upside to ~8% of global market cap



Source: Company data, the BLOOMBERG PROFESSIONAL™ service, Credit Suisse



Transmission called Butter's Law.

It is our observation that declining cost/function always engenders new application growth and the elasticity of application growth has historically grown TAMs (total addressable markets) to be significantly larger than anyone could imagine at inception. The exception until recently has been analytics, whose cost has mostly only ever increased through the digital age due to the vast majority of data created being unstructured and most analytic models needing clean/structured data. It is for this reason that while data has delivered >50% CAGR for almost 20 years, 98%+ of the data the world creates remains dark.

We see AI as the first technology which holds the promise of lowering the cost of analytics, and if our hypothesis is correct, we see significant elasticity of application driving the TAM for silicon. Defining the TAM for AI is difficult, but AI will be a technology that corporations use in order to drive efficiencies. The three largest spends for corporations are COGS, opex and capex and it is interesting to highlight that global spend in those three areas is ~US$45 tn/year—a 1% value capture by semis would imply US$450 bn in incremental revenue against our CY21 semi revenue forecast of ~US$500 bn.

Equally important, while AI would likely create brand new TAMs for both silicon and software, it has the potential to be disruptive/deflationary to existing TAMs in the economy: i.e., not only is semi absolute growth poised to accelerate, its relative growth profile could be even more attractive. While software stocks seem to embed the AI opportunity, semi stocks do not.

Addressing the world's most consequential challenges is expected to require *more* not *less* silicon, and there are fewer companies with the IP and scale to produce silicon, while those that can, continue to appreciate in value. Simply put, semis are becoming the staples of the new data economy—albeit with higher growth, higher returns and yes, a higher level of cyclicality—but staples nonetheless.

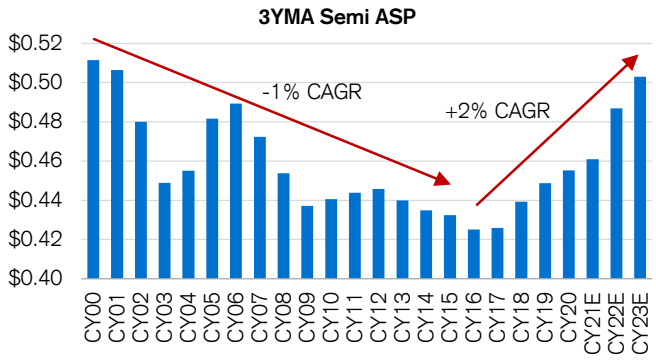
Since 1977, the global population has grown 86% from 4.2 bn to 7.9 bn while during that same time period, per capita chip units have grown ~70x from two to 146—a massive accomplishment even before considering the integration of functionality per chip which is a hallmark of the semi industry. During that same time period, per capita consumption of barrels of oil decreased ~10 pp.

In recent years, semis have increased from 1% of global market cap to ~3%, and we see potential upside to ~8% between now and the end of the decade. Energy is still at ~6% and peaked in 1980 at ~22%.

Forecasts for CY22 and beyond

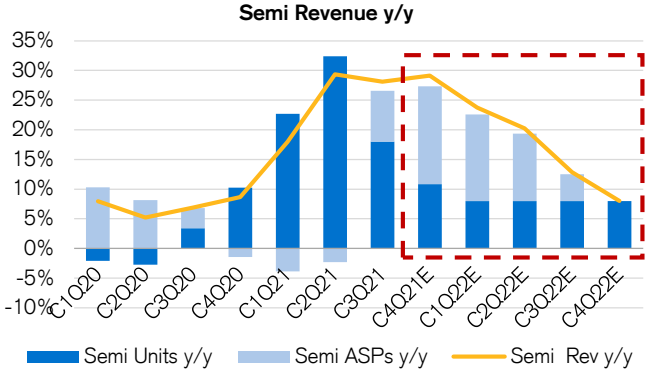
After growing 26% YoY in CY21, we model semi revenue growth of +15% YoY in CY22, well *above* consensus at 8-10% YoY, but supported by ASPs which, even if only flat with CY4Q21, would grow 7% YoY. We model CY23 semi revenue at -5% YoY to reflect an inventory correction and modest ASP decline. We model CY30 semi revenue of US$1 tn, a 5.8% CAGR. After growing 41% YoY in CY21, we expect WFE (wafer fab equipment) to grow 15% in CY22. We model WFE at -14% YoY in CY23 but see CY30 WFE of ~US$150 bn, ~8% CAGR. We model SCE services revenue of ~US$23 bn in CY22, growing to ~US$45 bn by 2030, ~9% CAGR and implying total CY30 SCE TAM approaching US$200 bn, ~2x CY21. Note that these estimates are inclusive of TSMC's CY4Q21 results. By end market, we see the best CY22 growth in data-centre/cloud, auto, enterprise and wireless infrastructure with more modest growth in infrastructure, handsets, and flat-to-down growth in PCs/CE. Longer term, data-centre, auto and industrial, each ~10% of semi consumption, have the potential of doubling as a percentage of revenue by 2030.

Figure 29: Semi ASP leverage remains underappreciated



Source: SIA, Credit Suisse estimates

Figure 30: ASPs flat w/ C4Q21 support ~50% of CY22 rev YoY



Source: SIA, Credit Suisse estimates

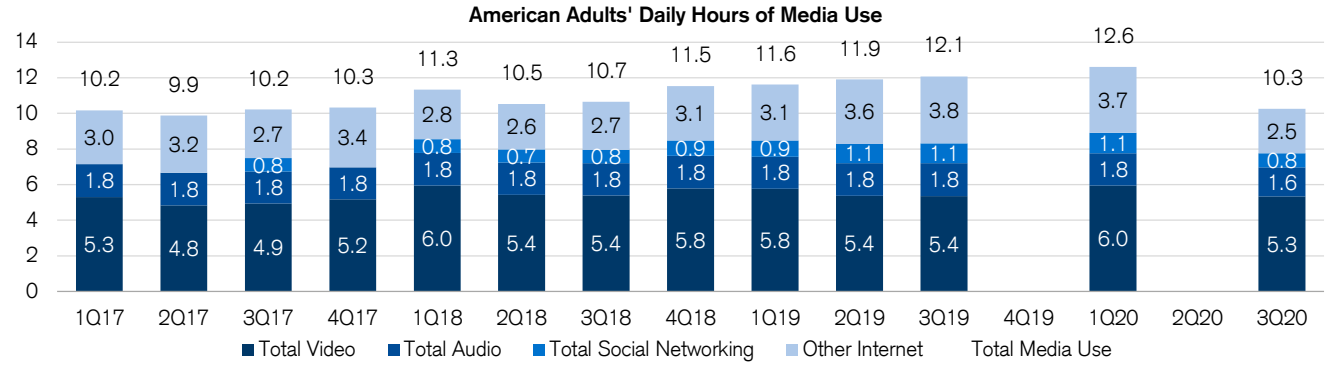
“Telecom infra will provide the backbone to deliver a smooth Metaverse experience.

Metaverse rollout raises demand for bandwidth

Even with modest Metaverse assumptions, data usage could easily expand more than 20x during this decade

Streaming audio and video media are the primary-use cases of the consumer internet today, with consumers in the developing world accustomed to spending a majority of waking hours consuming some sort of media. American adults consume six hours a day of video (whether professionally produced TV and movies, or user-generated content on Youtube or Twitch), just under two hours a day of audio (primarily music, but also a small but growing share of spoken word audio content), more than an hour of social media and nearly four hours of other internet content. Video, with its high bitrate, makes up four-fifths of all consumer internet traffic on its own. (Video games are not specifically measured by Nielsen, but generally use little data and comprise only a mid-single-digit share of consumer internet traffic.)

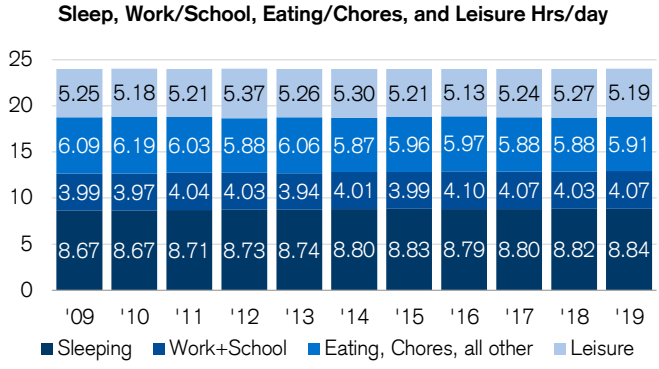
Figure 31: Nielsen's digital metering shows 10+ hours a day of media use by American adults, led by video and followed by audio and browsing

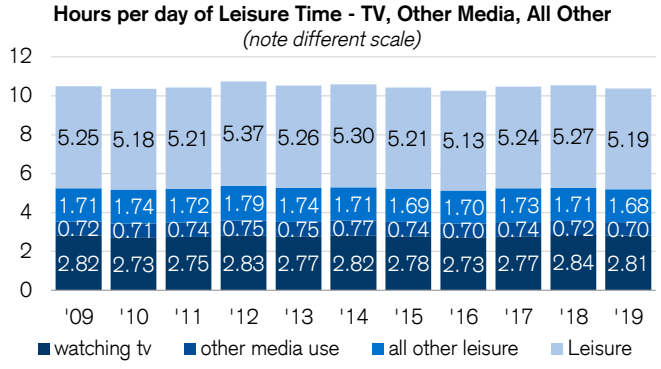


Note: Not all media types available for all periods. Includes simultaneous multi-media usage.

Source: Company data, Nielsen Total Audience Reports (1Q17-3Q20), Credit Suisse estimates

Figure 32: The American Time Use Survey shows media use comprises two-thirds of all leisure time. (The ATUS records primary activities so its lower-than-Nielsen media use is attributable to media use as a secondary activity, such as listening to a show while doing chores.)





Note: (1) All respondents aged 15+, weekdays + weekends. (2) 'Other Media' is reading, playing games, and computer use other than for games.

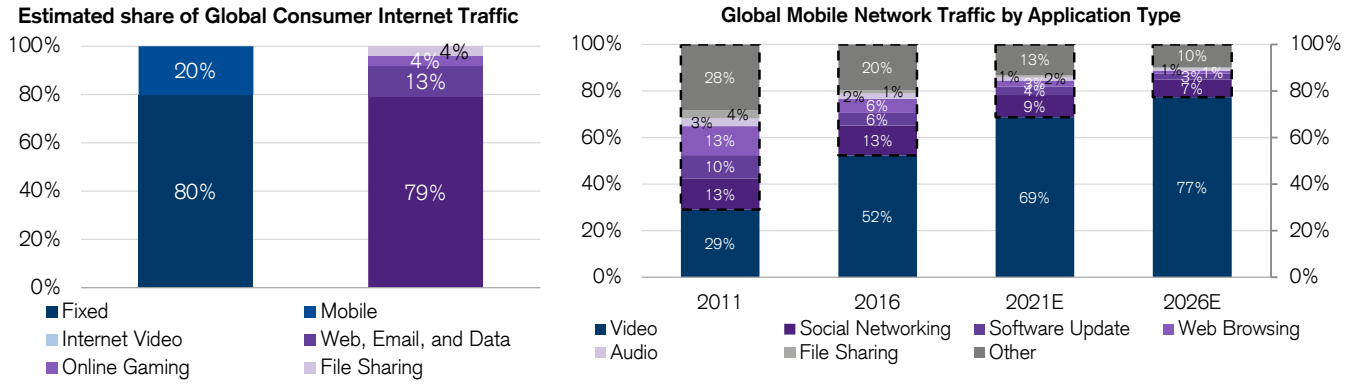
Source: Company data, BLS American Time Use Survey, Credit Suisse estimates

XR places extraordinary demands on networks

Extended reality (XR) technologies are a fundamental building block of the metaverse.

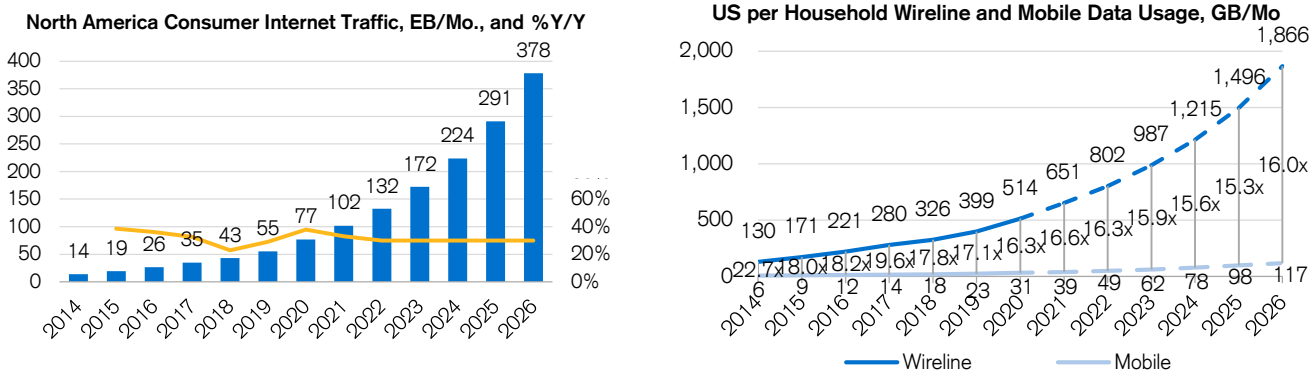
- **Virtual Reality (VR)** combines visual inputs for each eye with positional tracking to present the user with a sense of spatial immersion in the displayed world, perhaps with haptic touch and even environmental feedback. VR experiences are typically currently delivered with a dedicated headset connected to a latest-generation console or high-end PC; they include AAA video games such as Fallout 4 VR and Half-Life: Alyx in which the player is fully immersed in the game world as well as modelling, engineering and architecture programmes such as Enscape. Current efforts such as Oculus by Meta aim to push VR into headsets with onboard computation capability that eliminate console/PC dependency. Apple is widely speculated to be introducing its standalone VR headset in 2022.
- **Augmented Reality (AR)** overlays images onto the real world, such as onto a transparent display surface. AR applications include Niantic's hit 2016 mobile game Pokémon Go and Snapchat's Lenses feature which can modify users' faces, bodies, or backgrounds. AR experiences are becoming widely available.

Figure 33: With high time spent and high bitrates, streaming video has become the primary driver of consumer internet traffic



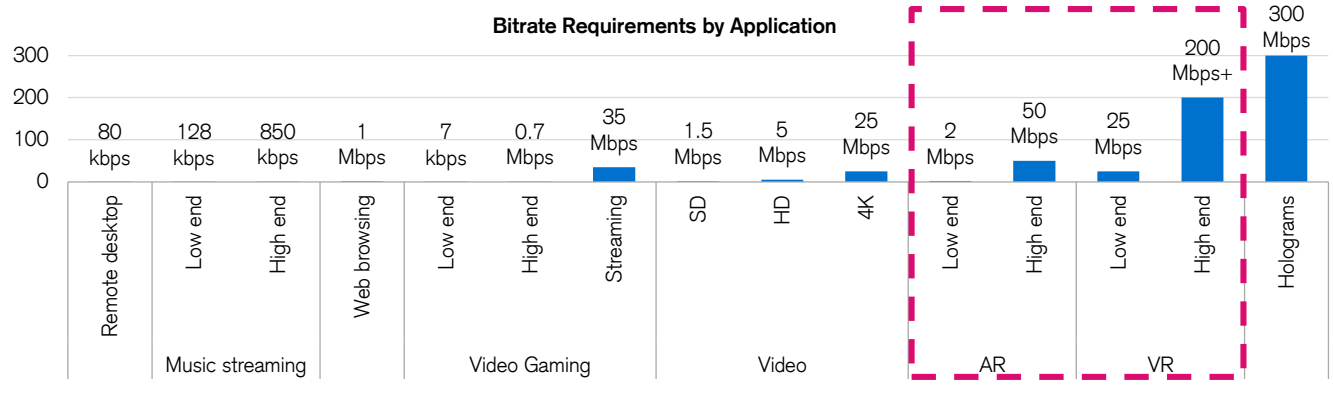
Source: Company data, Cisco VNI 2018, Credit Suisse estimates Source: Company data, Ericsson, Credit Suisse estimates

Figure 34: Streaming video usage growth has driven consistent 30% per annual bandwidth usage growth, but metaverse applications might substantially accelerate traffic needs over time



Source: Company data, Cisco VNI, Ericsson, US Census Bureau, Credit Suisse estimates

Figure 35: XR requires higher speeds and lower latency than browsing and streaming



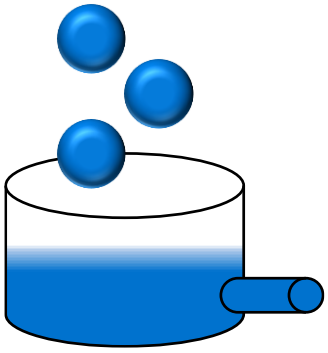
Source: Highspeedinternet.com, Restream.io, Credit Suisse estimates

- **Mixed Reality (MR)** combines features of both VR and AR, with manipulable fully 3D virtual objects anchored in real space, while **hologram** technologies such as the work of Lightfield Labs use a similar fully 3D data structure but a very different display technology to present an actual image in real 3D space rather than merely the illusion of one to a user with a specialised headset.

VR and MR experiences place high demands on both devices and networks. Each eye generally has its own separate display and the displays must be high resolution because they are so close to the eyes. Moreover, the displays generally have a high refresh rate to avoid possible user motion sickness, typically with 72, 90, or 120 frames per second (FPS) compared to the 24 FPS norm for video content. Apple has also been speculated to have a third display to increase immersion, as well as several cameras to gauge the environment and user activity.

Nascent video game streaming services suggest an interesting parallel for XR. Video games' rendering work is traditionally done on-device, so that the best-quality levels require a powerful console or purpose-built PC with gaming-specific hardware. Video game streaming services such as Google Stadia and Nvidia GeForce Now instead offload such rendering tasks to a remote compute cloud—allowing the highest level of quality on weaker devices such as smartphones. Video game streaming has higher download requirements than streaming video (games require a higher frame rate than video content's 24 FPS to give a smooth illusion of motion), and the services are also less latency- and loss-tolerant (to provide satisfying responsiveness to inputs). To an even greater extent than AAA video games, VR and MR are highly computationally intensive. These experiences

Figure 36: Buffering—building a cache as data arrives, then playing it out evenly to provide a smooth stream—hides latency, jitter and packet loss. This means that streaming video/audio user experience is generally little affected by network quality.



Application network demands

	Streaming		Video gaming	Metaverse	
	Video	Audio		On-device	Cloud
Bandwidth needs	High	Low	Low	Moderate	Very High
Latency tolerance	High	High	Low	Low	Low
Loss tolerance	High	High	Low	Low	Low
Device compute	Low	Low	High	High	Moderate
Edge/cloud compute	Low	Low	Moderate	High	Very High

Source: SIA, Credit Suisse estimates

can still be delivered on simpler, lighter, and cheaper end-user devices if computationally intensive tasks can be offloaded to a cloud compute instance. To the extent this is possible, it would drive down the cost of XR devices and allow mass adoption. Verizon has estimated that any more than 20ms of motion-to-photon (total stack) latency causes many users to become nauseated; for comparison, well-built wireline broadband networks today typically have 20ms of network latency alone, and typical LTE latencies are 3x higher.

For metaverse (network) extended-reality compute to be offloaded, the entire process must be shortened so that input from the user device, a network trip, processing by the service, a return network trip and drawing the output on the user device fits in the 20ms time taken by a single network trip today. This would require driving down network latency significantly from the current ~20ms levels with careful network engineering, relying on the capabilities of low-latency DOCSIS and 5G.

Figure 37: Even with modest metaverse assumptions, data usage could easily expand more than 20x during this decade—and metaverse traffic cannot buffer like streaming video

Household data diet: Indicative metaverse data consumption

	Daily usage	Monthly usage	Notes and assumptions
2022			
Video usage (hrs)	15.0	450.0	Indicative 6 hrs/adult/day and 2.5 members per HH
GB/hr	1.4	1.4	SD is 700MB, FHD is 3GB
Video usage, GB	**21.3**	**640.0**	
All other data	5.3	160.0	Web browsing, audio streaming, gaming
Total data usage	**26.7**	**800.0**	
2032			
Metaverse usage, hrs	5.0	150.0	1/4 of all video usage
GB/hr	112.0	112.0	Two streams each 8K 120Hz (8 times higher than 4K 60Hz bitrate)
Metaverse usage, GB	**560.0**	**16800.0**	
Video usage, hrs	10.0	300.0	Conservatively 1:1 substitution (no increase in total media consumption)
GB/hr	7.0	7.0	Assumes average video content consumed is 4K
Video usage, GB	**70.0**	**2100.0**	3.3x, or 13% CAGR
All other data	13.8	415.0	2.6x, or 10% CAGR
Total data usage	**643.8**	**19315.0**	**24.1x, or 37% CAGR**

Source: Company data, Credit Suisse estimates

Figure 38: 6G to perhaps provide wireless networks with greater metaverse capabilities, but deployment timeframes to lag fixed networks

Mobile technology generations

Gen.	Year introduced	Typical DL speed (mbps)	Spectral efficiency (bps/Hz)	Latency (ms)	Use cases
1G	1979	0.002	0.5	1,000	Analog voice
2G	1991	0.1	1.3	600	Digital voice, SMS
3G	2001	8	2.6	65	Email, basic browsing, early IoT
4G	2009	30	4.3	50-60	Streaming video and audio, ride hailing/maps, rich social networking
4.5G (LTE-A)	2014	100	15	30-50 10 (theor.)	Consistent streaming video and audio experience, augmented reality, fixed wireless access
5G	2019	300	30	21-26 1 (theor.)	Better streaming media, virtual reality, massive IoT
6G	**2029?**	**1,000+**	**100+**	**???**	**VR, mobile metaverse, massive digital twinning**

Source: Company data, CTIA, Credit Suisse estimates

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