Supplemental Material

A. Computer Graphics in Video Games

Table 1 contains a list of game intelligence systems and techniques, sorted in application year in video games. Note that the following list is by no means exhaustive to cover all the type of computer graphics. Moreover, the selection includes all virtual world types and game genres.

Table 1. List of computer graphics techniques in video games.

Year	Technique	Description	Example
1960	Text-based		Lunar Lander
1972	Pixel rendering		Pong
1977	Colored overlay	change the color of background image	Boot Hill
1979	Full color display		Galaxian
1979	Sprite scaling	Integrating a 2D-bitmap into a large scene as part of a graphics display	Rader Scope
1979	Scrolling	Slide video across a monitor or display, vertically or horizontally, for game content and game play progression	Super Speed Race
1979	Vector graphics	Wireframe-based game object image display	Asteroids
1982	Raster graphics	Pixel-based game object image display	Dig Dug
1982	Parallax scrolling	Split the foreground or background into a number of layers which moves at different rates	Moon Patrol
1982	Isometric	Isometric scrolling, 2:1 diametric projection	Zaxxon
1983	Flat shading	3D, 2D versions of its characters in the 3D game	I, Robot
1985	Super scaler	Combine smooth sprite scaling with blistering frame rates	Hang-on
1987	Active shutter 3D	Stereo graphics	The 3-D Battles of WorldRunner
1992	Mode 7	2.5D, a display system effect allowed for a 3D effect while moving in any direction without any actual 3D models	Super Mario Kart
1992	VGA graphics	3D objects blended with bitmap painted environment	Alone in the Dark
1992	FPS	First-person perspective 3 dimension with a dynamic camera	Ultima Underworld
1993	Ray casting (through Doom engine)	Hidden surface removal in FPS 3D games	Doom
1993	Multimedia technology	Pre-rendered content (backdrops) and full motion video	Myst
1993	Super FX	3D objects blended with 2D sprite environments	Star Fox
1996	True 3D graphics (through Quake engine)	True texture mapping to 3D polygonal models	Quake
1998	Voxels (through Voxel Space engine)	Draw 3D models with 3D pixels instead of polygons	Delta Force
2000	Cel Shading	Give 3D images a cartoon-like appearance	Jet Set Radio
2003	GPU for 3D acceleration (through Unreal Engine 2, already have physics support)	GPU for 3D acceleration in FPS 3D games	Unreal II: The Awakening
2004	Physics engine (through Source engine)	Advanced physics simulation support to provide simulation to assist animators to produce realistic motion	Half-life 2

Year	Technique	Description	Game
2004	Unified lighting & shadowing (through Doom 3 engine)	Allow lights to cast shadows even on non-static objects	Doom 3
2004	Bloom (through LithTech Jupiter)	Produces fringes (or feathers) of light extending from the borders of bright areas in an image, contributing to the illusion of an extremely bright light overwhelming the camera or eye capturing the scene.	Tron 2.0
2005	Brown (through IW engine v2)	De-saturate colors for realism	Call of Duty 2
2005	Motion blur	For camera to realistically capture a discrete moment in time to make nature motion more continuous	Shadow of the Colossue
2006	Specular mapping (through Gamebryo engine)	For specular reflection on mirror-like surfaces	The Elder Scrolls IV: Oblivion
2006	High-dynamic-range rendering (HDRR)	Preserve details that may be lost due to limiting contrast ratios to create more realistic scenes	The Elder Scrolls IV: Oblivion
2007	Direct3D 10 support (through CryEngine 2)	Geometry shaders, texture arrays, predicated rendering, and geometry instancing	Crysis
2007	Soft-body dynamics (through Unreal engine 3)	Produce visually realistic physical simulations of the motion and properties of deformable objects (or soft bodies, including muscle, fat, hair, cloth,) through spring/mass models.	Mass Effect
2009	Inficolor 3D	Stereo graphics	Batman: Arkham Asylum
2009	HDR Audio (through Frostbit 1 engine)	Allow differing sound levels to be perceived by the player.	Battlefield 1943
2011	Parallax barrier	Show a stereoscopic or multi-scopic image without the need for the viewer to wear 3D glasses	Combat of Giants: Dinosaurs 3D
2012	Bloom 2.0 (Global illumination, image-based lighting, Ambient occlusion)	To achieve realistic massive light effect	Halo 4
2012	Motion capture	To create realistic physical interactions in animations	Halo 4
2013	Tessellation	To produce smoother surfaces	BioShock Infinite
2013	Soft light	To create the effect that the sunlight seeps in through spaces and reflects off surfaces	The Last of Us
2013	4K support (through RAGE engine)	Higher resolution support	Grand Theft Auto V
2013	Levolution (through Frostbite 3 engine)	Allow all networked players in the game to see the same wave at the same time by destroying a dam	Battlefield 4
2013	Photo-realistic environment		ARMA 3
2013	Checkboard rendering (through Decima engine)[1]	Assist GPU with rendering images at high resolutions to achieve cinematic-realistic effect	Killzone Shadow Fall
2013	Verisimilitude (through 4A Engine)	Encapsulate many cutting-edge rendering, physics, and sound techniques to produce immersive effects	Metro: Last Light
2014	Chromatic aberration	Simulate the divergence of different light wavelengths to the perimeter ofthe screen	Destiny
2014	Depth of field	Object distance visual-perception	COD: Advanced Warfare
2015	High Definition Ambient Occlusion (HDAO) (through REDengine 3)	A shading and rendering technique to calculate how exposed each point in a scene is to ambient lighting	The Witcher 3: Wild Hunt
2017	Advanced lighting & AA (including GGX spherical area lights, height fog model,	To produce physically-based light and fog rendering and photorealism	Horizon Zero Dawn

	and FXAA+TAA, Enhanced Decima engine)[1]		

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B. Mulsemedia Rendering Devices

Table 2 contains a list of rendering devices, categorized by function and type and sorted in release year. Note that the following list of devices is by no means exhaustive to provide various rendering function.

Table 2. List of Mulsemedia Rendering devices.

Product	Year	Sensation Type	Notation
Glove			
GloveOne[6]	2014	Vibrotactile feedback	
Mood Glove[1]	2016	Vibrotactile feedback	
Senso Glove[2]	2016	Haptic display	Include vibration and temperature fluctuation
Manus VR[5]	2016	Vibrotactile feedback	
Avatar VR[7]	2017	Vibrotactile feedback	
Hi5 VR Glove[3]	2018	Vibrotactile feedback	
Plexus[4]	2018	Vibrotactile feedback	
Cynteract[9]	2018	Force feedback	
Hands Omni[8]	Under development	Force feedback	
Exoskeleton			
Dexmo[10]	2016	Force feedback	
HGlove[11]	2017	Force feedback	
HaptX[12]	2017	Haptic display	Include realistic touch and force feedback
VRgluv[13]	2017	Force feedback	
SenseGlove[14]	2018	Force feedback	
CyberGlove[15]	2009	Force feedback	
Thimble			
VRTouch[16]	2017	Force feedback	
Tactai Touch[17]	2017	Force feedback	
Chair			
Emoti-chair[19]	2009	Haptic display	
MMOne VR Chair[21]	2015	Haptic display	
Telepod[22]	2016	Vibrotactile	
Roto VR Chair[18]	2017	Haptic display	Provide sense of weightlessness
Voyage[20]	2017	Haptic display	Provide sense of weightlessness
Yaw VR Motion Simulator[23]	2018	Haptic display	Include locomotion and vibrotactile
Feel Three[24]	Under development	Haptic display	Include locomotion and vibrotactile
Vest			
Interactor Vest[26]	1994	Vibrotactile feedback	
3RD Space Vest[27]	2007	Vibrotactile feedback	
Tactile Gaming Vest[28]	2010	Vibrotactile feedback	
ARAIG[29]	2013	Vibrotactile feedback	

Product	Year	Sensation Type	Notation
KOR-FX[30]	2014	Vibrotactile feedback	
HAPTIKA[32]	2016	Vibrotactile feedback	
Rapture Vest[33]	2016	Vibrotactile feedback	
Synesthesia Suit[25]	2016	Vibrotactile feedback	Functioned as interactive skin
Teslasuit DK1[31]	2017	Vibrotactile feedback	
NullSpace VR[34]	2017	Vibrotactile feedback	
bHaptics TactSuit[35]	2017	Vibrotactile feedback	
Woojer ryg[36]	2017	Vibrotactile feedback	
NeoSensory Exoskin[37]	2018	Vibrotactile feedback	
Fan			
VirWind[39]	2015	Non-contact haptic display	Implemented through air blowing
ZephVR[38]	2017	Non-contact haptic display	Implemented through air blowing
The Ambiotherm[41]	2017	Non-contact haptic display	Implemented through air blowing and temperature change
VortX[40]	2018	Non-contact haptic display	Implemented through air blowing blow
Wind-Blaster[42]	2018	Non-contact haptic display	Implemented through air blowing
Other Haptic Device			
Novint Falcon[43]	2007	Force feedback	
Aireal[44]	2013	Non-contact haptic display	Implemented through airflow
AirWave[45]	2013	Non-contact haptic display	Implemented through airflow
Olfactory Devices			
Smell-O-Vision[48]	1959	Olfactory display	
AromaRama[48]	1959	Olfactory display	
iSmell[48]	1999	Olfactory display	
Pinoke[48]	2000	Olfactory display	
Scent Dome[48]	2003	Olfactory display	
Kaori Web[48]	2004	Olfactory display	
Aroma Generator[48]	2005	Olfactory display	
Aroma Shooter[46]	2012	Olfactory display	
Smelling Screen[47]	2013	Olfactory display	
Olorama[50]	2013	Olfactory display	
Scentasia[51]	2013	Olfactory display	
Aroma Shooter Mini[52]	2016	Olfactory display	
Nosulus Rift[53]	2016	Olfactory display	
Scentcom[49]	2017	Olfactory display	
OhRoma[54]	2017	Olfactory display	
Gustatory Device			
Meta Cookie[56]	2010	Gustatory display	
Digital Lollipop[58]	2013	Gustatory display	
Planet Licker[55]	2016	Gustatory display	
Vocktail[57]	2017	Gustatory display	
Virtual Lemonade[59]	2017	Gustatory display	
TastyFloats[60]	2017	Gustatory display	
Thermal Taste Machine[61]	2018	Gustatory display	
Multisensory Device			
Feelreal Sensory Mask[63]	2015	Contact haptic display Non-contact haptic display Olfactory display	Contact haptic display include: water mist, vibrotactile feedback, Non-contact haptic display includes: wind display, thermal display
Virtual Cocoon[62]	Under Development	Haptic display, Olfactory display,	

Product	Year	Sensation Type	Notation
		Gustatory display	

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C. Artificial Intelligence in Video Games

Table 3 contains a list of game intelligence systems and techniques, sorted in release year. Note that the following list of games is by no means exhaustive to cover all the type of artificial games. Moreover, the selection mainly includes the games with virtual world features, i.e., players incarnated by avatars. Thus, artificial intelligent techniques in other genres, such as real-time strategy and board game, are not included.

Table 3. List of game intelligence systems or techniques.

Game	Year	Genre	System or technique	Description
Space Invaders[1]	1978	Arcade	Stored pattern	Simulating random movements of the aliens that were actually pre-programmed into the game.
Pac-Man[1]	1980	Arcade	Complex Stored pattern	Different colorful enemies exhibit different personality traits
Rogue[17]	1980	Role-playing	PCG on game space	Provide changing play experiment with dynamic game environment generation.
Metal Gear[3]	1987	Action-adventure	Artificial behavior	NPCs are capable of hearing player movement, noticing gunshots, and behaving based on a lot more variables
Mortal Kombat[1]	1992	Fighting	FSM	Prompt enemy action in each single state
Civilization II[4,5]	1996	Turn-based strategy	MCST	To create a competitive opponent
Creatures[11]	1996	Life Simulation	Artificial life model, Neural network	Simulate real life functions, such a mutation and decision making
Half-Life[3]	1998	First-person shooter	FSM, Squad AI	Enable members of a squad of NPCs to coordinate their behaviors, allowing them to see their colleagues and notice if they are killed through sense simulation
The Sims[1]	2000	Simulation	Artificial life, Terrain analysis	Create realistic, lifelike behaviors in game characters with rule-based system, genetic algorithms, flocking algorithms, and decision-making hierarchy; Make the pathfinding problem more flexible and location-based
Halo[3]	2001	First-person shooter	Decision-tree, Squad AI	Decision-tree creates dynamic enemy behaviors, such as cover-based behavior
Black and White[6]	2001	Simulation	Belief-desire-intention model, Decision tree, Perceptron neural network	For sophisticate task selection
EVE Online[17]	2003	MMORPG	PCG on game system	Create the entire solar system
.kkrieger[17]	2004	First-person shooter	PCG on game bits	Create texture, meshes, and sounds

Halo 2[7]	2004	First-person shooter	Behavior tree	It is a hierarchical finite state machine to create complex tasks for control in different granularity
F.E.A.R.[3]	2005	First-person shooter	GOAP	The architecture is for NPC to extremely varied behavior that was perceived as intelligent, and to adapt to new situations.
Façade[15]	2005	Interactive drama	Computational narrative	Through artificial intelligence to bring interactive storytelling experience
Diablo II[17]	2008	Action-adventure	PCG on game scenarios	Create quests
GTA4[3]	2008	Action-adventure	Emotion-response, Squad AI, Decision-tree	Emotion-response enable NPCs to react in a realistic way
Left 4 Dead[13,16]	2008	First-person shooter	AI Director, Pathfinding	A PCG mechanism to provide players a dynamic experience based on their performance; A* algorithm is applied to move NPCs to a certain location
Killzone 2[8]	2009	First-person shooter	HTN planning, Squad AI	NTN planning is based on visual perception to create believable NPCs,
Silent Hill: Shattered Memories[9]	2009	Survival horror	Psychological profiling	A PCG mechanism to adjust gameplay elements based on the player's personality determined by the interaction with the game
Heavy Rain[15]	2010	Interactive drama	Computational narrative, Virtual camera	Improve immersion in storytelling
The Elder Scrolls V: Skyrim[14]	2011	Open world	Radiant AI	Allow NPCs to dynamically react to and interact with the world
Hitman: Absolution[10]	2012	Action-adventure	Reinforcement learning	For animation to generate realistic locomotion for NPC crowd
République[12]	2012	Action-adventure	Tactical Pathfinding, GOAP, Point of interest (POI)	POI allows NPCs to randomly utilize the nearby items to create great variety behaviors
GTA5[1,2]	2013	Action-adventure	Pathfinding, Artificial life, NPC-to-NPC interaction, Computer vision	Computer vision is applied to learn distance to stop signs in a race
The Last of Us[3]	2013	Action-adventure	Companion AI	For NPC to coordinate with player character.
Alien: Isolation	2014	Survival horror	Adaptive behavior	NPC behavior is adapted with each decision made by players
Forza Horizon 2[3]	2014	Open world	Drivatar system	Use Neural networks to learn about driving of each player of the game for emulation
Metal Gear Solid 5[1]	2015	Open world	Smart opponent	NPC can hunt players, improve health levels, reload ammo or seek cover during battle
No Man's Sky[18]	2016	Open world	Extreme PCG	Everything in the world is procedurally-generated

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D. Full List of Sample Virtual Worlds

Table 4 lists 180 virtual world products in the market. This list focuses on the identifying virtual world architectures their scalability. This is by no means an exhaustive list. But it covers all typical architectures which are used in all past, current, and developing virtual worlds.

All samples are classified into: game worlds, social worlds, and child's worlds. The proportion of different classes of virtual worlds can truly reflect their respective proportion in the market, as investigated.

Most virtual worlds are investigated through the experience of play. A few virtual worlds have already been out of operation. For those virtual worlds which cannot be directly investigated through play, their architectures are explored by watching user replays on YouTube, reading official game Wikipedia, and collecting the traces from news and forums.

In summary, 6 types of scalability approaches are discovered:

1) Shard,
2) Shard + Zone + Instance,
3) Shard + Instance,
4) Zone,
5) Instance,

Some virtual worlds of the same type may show slight differences. For example, RuneScape and Wizard101 allow users to freely switch accounts among several shards, while other sharded worlds do not allow it. The description of each type and differences are detailed in the Description field.

The data of Peak User Base are also collected from various sources. The values in this column are only reported peak values during the operation of worlds. Due to different virtual world types, consumption models (fix fee change, monthly subscription, pay-as-you-go, and free-to-play), and business considerations, user bases of different virtual worlds are disclosed in different ways by their respective operators:

1) Created Accounts (CA) – active & in-active users of non-monthly subscribed virtual worlds,

2) Subscriptions (SS) – active users of monthly subscribed virtual worlds,
3) Active Accounts (AA) – active users of non-monthly subscribed virtual worlds,
4) Unique Visitor (UV) – active users & potential users of Web-page virtual worlds only,
5) Concurrent Users (CU) – active users of any virtual worlds, concurrently online.

As observed, some virtual worlds have only a few concurrent users online for a long period. This may result in wrongly identified architecture. If user population is low on a server, the way of scaling may be veiled (if it is not documented and released). For example, a non-zoning world might show zoning characteristic if a region were fully populated. It can be observed that all single-seamless worlds only have a very small number of concurrent users. Thus, they are too small to show their real scalability. The best index to validate the architecture of a virtual world is the number of concurrent users. Unfortunately, not all operators disclosed this figure.

Some collections of user population are divided into different regions, e.g., global, North America, and Korea. If the users of a virtual world are mainly from one region, e.g., Asian developed games mainly played by eastern users, only the data of that region is displayed. If the users are evenly distributed in different regions, the data from all regions are displayed, e.g., World of Warcraft. The values ended with (Steam) are the data collected from Steam DB, on Jan. 23, 2016.

Each virtual world links to its (global/regional) official Web site. Please be noted that the URL may change with the change of domain/sub-domain name, leading to access fail. For those virtual worlds out of operation, their landing page points to the Wikipedia page.

Table 4. List of investigated sample virtual worlds.

No.	Name	Scalability Approach	Population[1,2,3]	Release Date	Description on Architecture
Game Worlds					
1	Never Winter Nights (AOL)	Shard	115,000 CA[4]	1991-01-01	The game world of Never Winter Night (AOL) is copied into several parallel servers. On each server, regions do not restrict the number of users. User accounts switching between servers are restricted. Instance system is not found.
2	Nexus: The Kingdom of the Winds	Shard + Instance	12,263 CU in a single shard[85]	1996-01-01	Same as Asheron's Call
3	The Realm Online	Shard + Instance	25,896 SS	1996-01-01	Same as Asheron's Call
4	Furcadia		4500 CU	1996-12-16	Furcadia seems to be run on only one server with no restriction in each zone. But, the user population of this world is too small to show its scalability.
5	Tibia	Shard + Instance	113,299 SS; 64,000 CU	1997-01-07	Same as Asheron's Call
6	Ultima Online	Shard	250,000 SS	1997-09-24	Same as Never Winter Nights
7	Underlight		Few CU	1998-03-01	Underlight seems to be run on only one server with no restriction in each zone. But, the user population of this world is too small to show its scalability.

No.	Name	Scalability Approach	Population[1,2,3]	Release Date	Description on Architecture
8	Lineage	Shard + Instance	3,000,000 SS	1998-10-03	Same as Asheron's Call
9	EverQuest	Shard + Zone + Instance	550,000 SS	1999-03-16	The game world is copied into several parallel servers. On each server, each zone only allows limited number of users. Some zones are instanced.
10	Clan Lord	Shard	100 CU	1999-10-18	Same as Never Winter Nights
11	Asheron's Call	Shard + Instance	120,000SS	1999-11-02	Asheron's Call is run on several parallel shards. On each shard, the game maintains a seamless world with dynamic load balancing technology. It dynamically assigns computing load to different servers for each region according to the player population in that region. Some regions do not restrict the number of users, while others do but they are copied into many instances for different groups. User accounts switching between servers are restricted.
12	Aces High	Instance		2000-05-08	Same as Guild Wars
13	RuneScape	Shard + Instance	1,200,000 SS; 250,000 CU	2001-01-04	Same as Asheron's Call except that users are free to switch between all available servers.
14	Anarchy Online	Shard + Instance	1,100,000 SS; 60,000 AA	2001-06-27	Same as Asheron's Call
15	Dark Age of Camelot	Shard + Instance	250,000 SS	2001-10-09	Same as Asheron's Call
16	The Legend of Mir 2	Shard + Instance	1,000,000 CU;	2001-10-19	Same as Asheron's Call
17	Final Fantasy XI	Shard	550,000 SS	2002-05-16	Same as Never Winter Nights
18	Westward Journey Online II (大话西游 Online II)	Shard + Instance	1,190,000 CU	2002-08-02	Same as Asheron's Call
19	Ragnarok Online	Shard + Instance	750,000 CU	2002-08-31	Same as Asheron's Call
20	Ashen Empires	Shard		2002-09-01	Same as Never Winter Nights
21	Neocron 2	Shard + Instance	6,000 SS; Few CU	2002-09-09	Neocron 2 is supposed to be run on several servers in parallel. (Due to the small number of players for the time being, there is one serve, called Vedeena, for the time being.) Neocron dungeons are not instanced. Neocron uses only one instance zone, Area MC5. In other places, players can meet others.
22	Earth & Beyond	Shard	38,000 SS	2002-09-24	Same as Never Winter Nights
23	Asheron's Call 2	Shard + Instance		2002-11-22	Same as Asheron's Call
24	EUDemons Online	Shard + Instance	570,000 CU	2003-01-01	Same as Asheron's Call
25	Gekkeiju Online	Shard + Instance		2003-01-01	Same as Asheron's Call

No.	Name	Scalability Approach	Population[1,2,3]	Release Date	Description on Architecture
26	Entropia Universe	Zone	500,000 CA[29]	2003-01-30	Same as EVE Online
27	A Tale in the Desert	Shard	2,089 SS	2003-02-15	Same as Never Winter Nights
28	Shadowbane	Shard	50,000 SS	2003-03-25	Same as Never Winter Nights
29	MapleStory	Shard + Instance	250,000 CU (Korea)	2003-04-29	
30	Eve Online	Zone	500,000 SS	2003-05-06	Eve Online is run on single-server mode. In the game world, each zone only allows limited number of users. If a zone is full, newly coming users have to queue.
31	PlanetSide	Shard	60,000 SS	2003-05-20	Same as Asheron's Call
32	Star War Galaxies	Shard + Instance	300,000 SS	2003-06-25	Star War Galaxies is copied into several parallel servers. On each server, some regions do not restrict the number of users, while others do but they are copied into many instances for different groups.
33	World of Legend	Shard + Instance	50,000 CU	2003-07-18	Same as Asheron's Call
34	Istaria: Chronicles of the Gifted	Shard + Instance	36,000 SS	2003-09-09	Same as Asheron's Call
35	Lineage II	Shard + Instance	2,000,000 SS; 14,000,000 CA[87]	2003-10-01	Same as Asheron's Call
36	MU Online (奇迹)	Shard + Instance	400,000 CU	2003-10-06	Same as Asheron's Call
37	Puzzle Pirates	Shard + Instance	4,000,000 CA[35]	2003-12-08	Same as Asheron's Call, multiplayer puzzles are instances to players in Puzzle Pirates
38	Fantasy Westward Journey (梦幻西游)	Shard + Instance	1,000,000 CU[80] 1,330,000 CU[81] 1,500,000 CU[30] 2,320,000 CU[83] 2,560,000 CU[84] 2,600,000 CU[77]	2003-12-18	Same as Asheron's Call
39	Red Stone	Shard + Instance		2004-01-01	Same as Asheron's Call
40	Ran Online	Shard		2004-04-20	Same as Never Winter Nights
41	City of Heroes	Shard + Instance	194,000 SS[17]	2004-04-27	Same as Asheron's Call
42	Mabinogi	Shard + Instance	397,526 ± 13,681 CA (Steam); 1,229 CU (Steam)	2004-06-24	Same as Asheron's Call
43	The First Myth (封神榜 Online)	Shard + Instance	203,480	2004-08-01	Same as Asheron's Call

No.	Name	Scalability Approach	Population[1,2,3]	Release Date	Description on Architecture
44	Knight Online	Shard + Instance	4,000,000 CA[88]	2004-08-17	Same as Asheron's Call
45	Dofus	Shard + Instance	3,000,000 CA[20]; 450,000 AA; 250,000 CU	2004-09-01	Same as Asheron's Call
46	Pardus	Shard		2004-09-14	Same as Never Winter Nights
47	Ryzom	Shard		2004-09-19	Same as Never Winter Nights
48	The Legend of Mir 3	Shard + Instance	750,000 CU[89]	2004-10-01	Same as Asheron's Call
49	Uncharted Waters Online: Gran Atlas (大航海时代 Online)	Shard + Instance	196,907 ± 9,632 CA (Steam); 462 CU (Steam)	2004-10-30	Same as Asheron's Call
50	Vendetta Online		Few CU	2004-11-01	Vendetta Online seems to be run on only one server with no restriction in each zone. But, the user population of this world is too small to show its scalability.
51	EverQuest II	Shard + Instance	330,000 SS; 303,325 ± 12,128 SS (Steam)	2004-11-09	Same as Asheron's Call
52	Conquer Online (征服 Online)	Shard + Instance	92,000 CU	2004-11-14	Same as Asheron's Call
53	World of Warcraft	Shard +Instance	10,000,000 SS; 1,010,395 CU (West); 1,000,000 CU (East); 600,000 CU (China)	2004-11-23	Same as Asheron's Call
54	PlaneShift	Shard		2004-12-24	Same as Never Winter Nights
55	The Matrix Online	Shard	48,000 SS	2005-03-22	Same as Never Winter Nights
56	Zhen Feng Shen (真封神 Online)	Shard + Instance	100,000 CU	2005-04-01	Same as Asheron's Call
57	Guild Wars	Instance	6,000,000 CA[5]	2005-04-26	Guild Wars is not entirely run on multiple parallel shards. Instead, the world will assign each user a unique instance for play. Users can join others' instance to form groups, while group size is limited, except the hub zone (i.e., the town).
58	Shot-Online	Shard + Instance		2005-06-28	Same as Fiesta Online
59	Dungeon and Fighter (地下城与勇士)	Shard + Instance	2,600,000 CU[78] 3,000,000 CU[79]	2005-08	Same as Asheron's Call
60	Cabal Online	Shard + Instance	480,000 CU[16]	2005-10-01	Same as Asheron's Call
61	Silkroad Online	Shard	7,200,000 CA; 100,000 CU[38]	2005-10-01	Same as Never Winter Nights

No.	Name	Scalability Approach	Population[1,2,3]	Release Date	Description on Architecture
62	Perfect World (完美世界)	Shard + Instance	300,000 CU[33]	2005-11-25	Same as Asheron's Call
63	Minions of Mirth	Instance		2005-12-01	Same as Guild Wars
64	Flyff	Shard + Instance	30,000,000 CA	2005-12-25	Same as Asheron's Call
65	Ask Tao	Shard + instance	1,010,000 CU	2006-01-01	Same as Asheron's Call
66	Hero Online	Shard		2006-01-01	Same as Never Winter Nights
67	Granado Espada	Shard + Instance	30,817 ± 3,812 CA (Steam); 265 CU (Steam)	2006-02-14	Same as Asheron's Call
68	RF Online	Shard + Instance		2006-02-21	Same as Asheron's Call
69	Dungeons & Dragons Online	Shard + Instance	109,000 AA; 1,569,448 CA[24]	2006-02-28	Same as Asheron's Call
70	Dynasty Warriors Online (真·三国无双 Online)	Shard + Instance		2006-03-01	Same as Asheron's Call
71	Auto Assault	Shard + Instance	34,000 SS	2006-04-11	Same as Asheron's Call
72	Zhengtu (征途)	Shard + Instance	2,000,000 CU	2006-04-21	Same as Asheron's Call
73	Shaiya	Shard + Instance	520,000 CU	2006-06-18	Same as Asheron's Call
74	Scions of Fate (热血江湖)	Shard + Instance	600,000 CU[46]	2006-11-13	Same as Asheron's Call
75	Dragon Oath (天龙八部)	Shard + Instance	80,000 CU[90]; 50,000,000 CA[91]	2007-01-01	Same as Asheron's Call
76	Vanguard: Saga of Heroes	Shard + Instance	120,000 SS	2007-01-30	Same as Fiesta Online
77	Puppet Guardian	Shard		2007-04-01	Same as Never Winter Nights
78	The Lord of the Rings Online	Shard + Instance	564,000 SS	2007-04-24	Same as Asheron's Call
79	Champions of Regnum	Shard + Instance	500,000 SS	2007-05-24	Same as Asheron's Call
80	Giant Online (巨人)	Shard + Instance	344,005 CU	2007-06-15	Same as Asheron's Call
81	Empire of Sports	Shard + Instance		2007-08-01	Same as Asheron's Call
82	Twelve Sky	Shard + Instance		2007-10-12	Same as Asheron's Call

No.	Name	Scalability Approach	Population[1,2,3]	Release Date	Description on Architecture
83	Fiesta Online	Shard + Instance	$270,545 \pm 11,289$ CA (North America, Steam); 117 CU (North America, Steam); $226,857 \pm 10,338$ (Global, Steam); 135 CU (Global, Steam)	2007-11-07	Fiesta Online is run on several parallel servers. On each server, the game opens an instance for each player. Players can also form group in dungeons (i.e., group instances)
84	Tabula Rasa	Shard + Instance	125,000 SS	2007-12-02	In Tabula Rasa, there will be different 'versions' of each zone and each 'version' has a limited player capacity. When a version of the zone hits its player limit, a new version of the zone is created for any new players that enter.
85	Elsword	Shard + Instance	$853,839 \pm 20,034$ CA (Steam); 50,000 CU[28]; 1,834 CU (Steam)	2007-12-27	Same as Asheron's Call
86	Atlantica Online	Shard + Instance	$190,100 \pm 9,465$ CA (Steam); 52 CU (Steam)	2008-01-01	Same as Asheron's Call
87	Fragoria	Shard + Instance		2008-01-01	Same as Asheron's Call
88	Pirates of the Burning Sea	Shard + Instance	100,000 SS	2008-01-22	Same as Asheron's Call
89	R.O.H.A.N.: Blood Feud	Shard + Instance		2008-03-28	Same as Asheron's Call
90	Wonderland Online	Shard + Instance	$50,000 - 60,000$ CU[45]	2008-04-09	Same as Asheron's Call
91	Age of Conan: Hyborian Adventures	Shard	159,000 SS[10]	2008-05-20	Same as Never Winter Nights
92	AdventureQuest Worlds (AQ Worlds)	Shard + Zone	10,000,000 CA[9]	2008-06-02	The game world of AQ is copied into several parallel servers. On each server, each zone only allows limited number of users. Instance system is not found.in this game.
93	Twelve Sky 2	Shard + Instance	80,000 CU[40]	2008-07-18	Same as Asheron's Call
94	Dead Frontier	Shard + Instance		2008-08-21	Same as Drakensang Online
95	Yu Yan 预言 (Online)	Shard + Instance	380,000 CU	2008-08-28	Same as Asheron's Call
96	Warhammer Online	Shard + Instance	800,000 SS	2008-09-18	Same as Asheron's Call
97	Parallel Kingdom	Instance	1,000,000 CA	2008-11-04	Same as Guild Wars

No.	Name	Scalability Approach	Population[1,2,3]	Release Date	Description on Architecture
98	Aion: The Tower of Eternity	Shard + Instance	4,077,000 SS; 530,000 CU	2008-11-25	Same as Asheron's Call
99	Wizard101	Shard + Instance	50,000,000 CA[44]	2008-12-02	Same as Asheron's Call except that shards (or realms and areas) are free to switch
100	AIKA Online	Shard + Instance		2009-01-01	Same as Asheron's Call
101	Shou Xue Fei Teng (兽血沸腾)	Shard + Instance	400,000 CU	2009-01-01	Same as Asheron's Call
102	Runes of Magic	Shard + Instance	2,000,000 CA[36]	2009-03-19	Same as Asheron's Call
103	Requiem	Shard + Instance	181,436 ± 9,246 CA (Steam); 305 CU (Steam)	2009-06-19	Same as Asheron's Call
104	Hello Kitty Online	Shard	3,300,000 CA[32]	2009-07-01	Same as Never Winter Nights
105	Champions Online	Instance	586,388 ± 16,610 CA (Steam); 986 CU (Steam)	2009-09-01	Same as Guild Wars
106	Fallen Earth	Shard + Instance	1,612,133 ± 27,488 CA (Steam); 930 CU (Steam)	2009-09-22	Same as Asheron's Call
107	Journey to the West (西游记 Online)	Shard + Instance	300,000 CU	2010-01-15	Same as Asheron's Call
108	Vindictus (Mabinogi Heroes)	Shard + Instance	100,000 CU[41]	2010-01-21	Same as Fiesta Online
109	Star Trek Online	Shard + Instance	14,800 AA	2010-02-02	Same as Asheron's Call
110	Dragonica	Shard + Zone + Instance		2010-02-20	Same as EverQuest
111	Dragon Nest	Shard + Zone + instance	200,000,000 CA[21]; 900,000 CU[22]	2010-05-01	Same as EverQuest
112	Final Fantasy XIV	Shard + Instance	800,000−1,200,000 SS[8]	2010-09-30	Same as Asheron's Call
113	Lego Universe	Shard + Instance	90,000 SS	2010-10-26	Same as Asheron's Call
114	Perpetuum	Zone	6016 SS	2010-11-25	Same as EVE Online
115	DC Universe Online	Shard + Instance	18,000,000 SS[19]	2011-01-11	Same as Asheron's Call
116	TERA	Shard + Instance	1,400,000 CA[86]; 160,000 CU (Korea)	2011-01-25	Same as Asheron's Call
117	Battlestar Galactica Online	Shard	10,000,000 CA[13]	2011-02-08	Same as Never Winter Nights
118	Rift	Shard + Instance	600,000 SS	2011-03-01	Same as Asheron's Call

No.	Name	Scalability Approach	Population[1,2,3]	Release Date	Description on Architecture
119	Xsyon	Zoned		2011-03-15	Same as Wurm Online
120	Spiral Knights	Instance	3,000,000 CA[39]	2011-04-04	Same as Guild Wars
121	Realm of the Mad God	Shard	2,276,244 $\pm$ 32,621 CA (Steam); 2,831 CU (Steam)	2011-06-20	Same as Never Winter Nights
122	Drakensang Online	Shard + Instance	3,000,000 CA[18]	2011-08-01	Drakensang Online is run on multiple parallel shards. On each shard, the game will assign each user a unique instance for play. Users can join others' instance to form groups, while group size is limited, except the hub zone.
123	9Dragons	Shard + Instance		2011-09-17	Same as Asheron's Call
124	Digimon Masters	Shard + Instance		2011-10-20	
125	Star Wars: The Old Republic	Shard + Instance	1,700,000 SS	2011-12-03	Same as Asheron's Call
126	Wakfu	Shard + Instance	916,834 $\pm$ 20,757 CA (Steam); 4,026 CU (Steam)	2012-02-29	Tactical turn-based MMORPG
127	Ragnarok Online 2	Shard + Instance	1,047,652 $\pm$ 22,183 CA (Steam); 528 CU (Steam)	2012-03-26	Same as Asheron's Call
128	Phantasy Star Online 2	Shard + Instance	3,500,000 CA[34]	2012-06-04	Same as Asheron's Call
129	Blade & Soul	Shard + Instance	1,000,000 AA[15]	2012-06-30	Same as Asheron's Call
130	The Secret World	Shard + Instance	1,000,000 CA[37]	2012-07-03	Same as Asheron's Call
131	Dragon Quest X	Shard + Instance	300,000 AA (Daily)[23]	2012-08-02	Same as Asheron's Call
132	Guild Wars 2	Shard + Instance	3,000,000 CA[6]; 400,000 CU[7]	2012-08-28	Same as Asheron's Call
133	Wurm Online	Zone	18,936 $\pm$ 2,988 CA (Steam); 1,958 CU (Steam)	2012-12-12	Sandbox MMORPG; Each land in Wurm is run by one sever. All servers (i.e., lands) are connected, forming a complete map. The number of users on each land is limited.
134	ArcheAge	Shard + Instance	17,332 SS[12]	2013-01-25	Sandbox MMORPG; Same as Asheron's Call
135	Marvel Heroes	Instance	3,613,748 $\pm$ 40,996 CA (Steam); 8,759 CU (Steam)	2013-06-04	Same as Guild Wars
136	Neverwinter	Shard + Instance		2013-06-20	Same as
137	Age of Wulin	Shard + Instance	28,880,000 CA[11]	2013-07-18	Same as Asheron's Call

No.	Name	Scalability Approach	Population[1,2,3]	Release Date	Description on Architecture
138	Defiance	Shard + Zone + Instance	2,851,741 ± 36,472 CA (Steam); 11,263 CU (Steam)	2013-08-02	Same as EverQuest, Story mode +multi-team
139	Darkfall Unholy Wars	Shard + Instance		2013-08-16	Same as Asheron's Call
140	Echo of Soul	Shard + Instance	433,541 ± 14,287 CA (Steam); 2,730 CU (Steam)	2013-09-11	Same as Asheron's Call
141	Aura Kingdom	Shard + Instance	1,791,670 ± 29,393 CA (Steam); 2,165 CU (Steam)	2013-12-23	Same as Asheron's Call
142	Black Desert	Shard + Instance	1,500,000 CA[14]	2014-01-01	Same as Asheron's Call
143	The Elder Scrolls Online	Instance	772,374 SS[25]	2014-04-04	The Elder Scrolls Online adopts MeagServer technology[26,27] to realize dynamic switch between single and instance mode. When the player population is small, the game presents a single, seamless world. When some region servers are overloaded, copies of the region will be dynamically created and merged, with the fluctuation of player population.
144	WildStar	Shard + Instance	40,000–50,000 CU[42,43]	2014-06-03	Same as Asheron's Call
145	Firefall	Shard + Instance	2,686,023 ± 35,408 CA (Steam); 13,397 CU (Steam)	2014-07-29	Same as Asheron's Call
146	Elite: Dangerous	Zone	694,297 ± 18,336 SS (Steam)	2014-12-16	Same as EVE Online
147	H1Z1	Shard	2,151,748 CA[31]	2015-01-15	Same as Never Winter Nights
148	Trove	Instance	4,604,593 ± 46,188 CA (Steam); 58,949 CU (Steam)	2015-07-09	Away from the hub, players in Trove will enter their own instanced world zones or join other's dungeon play. Clubs also have their respective Club world.
149	Shroud of the Avatar: Forsaken Virtues	Instance		2016-01-01	Same as Guild Wars
Social Worlds					
150	Moove	Zone	1,546,464 CA[55]	1994-01-01	Same as Asheron's Calltive Worlds
151	Active Worlds	Zone	1,000,000 AA[47]	1995-06-28	In Active worlds, each world (i.e., a region) is run by a world server. The number of concurrent users a world can support depends on the capacity of that particular world server, mainly on CPU power, memory, and bandwidth. If a world is full of users, others must queue and wait.

No.	Name	Scalability Approach	Population[1,2,3]	Release Date	Description on Architecture
152	Habbo Hotel	Shard + Zone	178,000,000 CA; 15,000,000 UV[48]; 100,000 CU[49]	2001-09-26	Habbo Hotel shards are geographically distributed all over the world. On each regional shard, the world is divided into many zones (i.e., rooms) which only allow limited number concurrent access.
153	WeeWorld	Zone	60,000,000 CA[65]; 2,100,000 UV (Monthly)[66]	2002-01-01	Same as Asheron's Calltive Worlds
154	The Sims Online	Zone	105,000 SS	2002-12-17	Same as Asheron's Calltive Worlds
155	There	Zone	170,000 AA	2003-01-09	Same as Asheron's Calltive Worlds
156	Second Life	Zone	800,000 AA	2003-06-23	Same as Asheron's Calltive Worlds
157	Kaneva	Zone	5,000,000 CA; 300 CU[53]	2004-01-01	Same as Asheron's Calltive Worlds
158	IMUV	Zone	20,000,000 CA[56]; 800,000 AA (Monthly)[57]	2004-04-15	Same as Asheron's Calltive Worlds
159	Rise: The Vieneo Province		Few CU	2006-01-01	Rise seems to be run on only one server with no restriction in each zone. But, the user population of this world is too small to show its scalability.
160	Utherverse	Instance	1,500,000 CA[59]	2006-01-01	Same as Onverse
161	Meez	Zone	3,000,000 UV (Monthly)[54]	2006-03-28	Same as Asheron's Calltive Worlds
162	vSide	Zone	150,000 SS[58]	2006-05-15	Same as Asheron's Calltive Worlds
163	Onverse	Instance	600,000 SS[51]	2007-06-15	Onverse' world is not entirely copied and run on multiple parallel shards. But each region of the world has multiple copies, in case a large number of users want to access to the same region.
164	SmallWorlds	Zone	25,000,000 CA[62]; 101,335 UV (Daily)[63]	2007-12-01	Same as Asheron's Calltive Worlds
165	Club Cooee	Zone		2008-01-01	Same as Asheron's Calltive Worlds
166	Twinity	Zone		2008-09-05	Same as Asheron's Calltive Worlds
167	Free Realms	Shard + Instance	20,000,000 CA[52]	2009-04-28	Same as Asheron's Call
168	WoozWorld	Zone	8,500,000 CA[60]; 2,673,173 UV (Monthly)[61]	2010-01-01	Same as Asheron's Calltive Worlds
169	Chit Chat City		Few CU; 22,610 UV (Daily)[64]	2010-01-01	Chit Chat City seems to be run on only one server with no restriction in each zone. But, the user population of this world is too small to show its scalability.
170	Play-town Game	Instance	Few CU	2014-01-20	Same as Onverse

No.	Name	Scalability Approach	Population[1,2,3]	Release Date	Description on Architecture
171	Zanpo		Few CU; 47 UV (Daily)[67]		Zanpo seems to be run on only one server with no restriction in each zone. But, the user population of this world is too small to show its scalability. Beside, no player interaction is designed.
172	OpenSim	Zone	496,344 CA; 34,160 AA[55]	N.A.	OpenSim includes all public virtual worlds which are constructed with the OpenSim platform. On this platform, many virtual worlds are operated and connected to each other through Hypergrid protocol, including InWorldz, Kitely, OSGrid, etc.
Child's Worlds					
173	Whyville	Zone + Instance	4,000,000 CA[71]; 750,000 UV (Monthly)[72]	1999-02-01	Whyville is run only on one shard. The entire world is divided on many zones each of which limits the number of concurrent user access. Some rooms have multiple copies.
174	Toontown Online	Shard + Zone	110,000 AA	2003-06-02	The Toontown world is copied into several parallel servers. On each server, each zone only allows limited number of users.
175	Club Penguin	Shard + Zone	200,000,000 CA[68]	2005-10-24	Same as Toontown Online
176	Roblox	Instance	100,000 CU[69]	2006-01-01	Roblox is not run on multiple parallel shards. Each region of the world has multiple copies
177.	Space Heroes Universe!		2,000,000 CA[70]	2007-01-01	Little Space Heroes is run only on one shard. The entire world is divided on many zones, each of which limits the number of concurrent user access.
178	Poptropica	Instance	500,000,000 CA	2007-09-01	As many instanced virtual worlds, the game assigns each user a unique instance to play. Some regions contain common rooms for user meet, chat, and interaction.
179	Fantage	Shard + Instance	30,000,000 CA[74]; 3,300,000 UV (Monthly)[75]	2008-04-01	The shards of Fantage are deployed in United States, Span, and Japan[76]. On each shard, users play in the same world. Regions do not have population restriction. Some regions have instanced rooms.
180	MovieStarPlanet	Instance	200,000,000 CA[73]	2009-01-01	Same as Roblox

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