The Procedural Sounds and Music of *ECHO::Canyon*

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ABSTRACT

In the live game-based performance work *ECHO::Canyon*, the procedural generation of sound and music is used to create tight crossmodal couplings between mechanics in the visual modality, such as avatar motion, gesture and state, and attributes such as timbre, amplitude and frequency from the auditory modality. Real-time data streams representing user-controlled and AI driven avatar parameters of motion, including speed, rotation and coordinate location act as the primary drivers for *ECHO::Canyon*'s fully-procedural music and sound synthesis systems. More intimate gestural controls are also explored through the paradigms of avian flight, biologically-inspired kinesthetic motion and manually-controlled avatar skeletal mesh components. These kinds of crossmodal mapping schemata were instrumental in the design and creation of *ECHO::Canyon*'s multi-user multi-channel dynamic performance environment using techniques such as *composed interaction*, *compositional mapping* and entirely procedurally-generated sound and music.

1. INTRODUCTION

From a creative musical standpoint, the relationship between physical motion and action in space and the production and manipulation of musical sound have been one of necessity as for most pre-digital musical systems, physical gesture was an inherent component of instrumental performance practice. From the sweep of a bow across strings, to the swing of a drumstick, to the arc of a conductor's baton, action and motion in space were directly coupled as physical or intentional drivers to the mechanical production of sound and music [1].

The introduction of computer-based musical systems has removed the necessity for such direct couplings, allowing abstract data-analysis or algorithmic process to both instigate and manipulate parameters driving musical output. However artists seeking to retain some level of human-directed control within the digital context often develop and employ mapping schemata linking control data to musical form and function. Such mappings provide interfaces between human intention and digital process that range from the simple to the complex, from the distinct to the abstract.

Choreographies of music and action found in dance and film commonly make use of a reactive association between gesture and sound: dancers' reactions - spontaneous or choreographed - to a musical event or sequence of events often form physical motions or gestures with direct temporal correspondence to the onset, duration or contour of a sounding event [2]. In the same way, events in static visual media such as film, music video and some computer games are often punctuated by the synchronization of visual elements with auditory or musical cues, linking the audio and visual in our perception of the event without any causal relationship existing between the two modalities.

Interactive virtual environments and the tracking of actor motion and action within those environments affords composers and sound designers another approach to the mapping of physiological gesture to parameters of sound and music for multimodal presentation. As avatars within three-dimensional space are wholly-digital constructs, there exists a massive amount of data readily available that represents their internal and external state, their ongoing relationship to other objects in the surrounding environment, and the state of the environment itself. This data can drive complex dynamic musical and sound-generating systems while preserving a causal link between the visual gesture and the resultant audio gesture.

With virtual actors, the contours of motion in virtual space - both macro, such as a three-dimensional Cartesian vector, or micro, such as the relative articulation of individual bones within an avatar skeletal mesh - can be tracked and used as control data for computer-based musical systems. In this manner, gesture or motion drives and controls the sound-generating process, an inversion of a more common reactive model and very much in line with traditional models of instrumental performance. By pairing macro and micro avatar motions with real-time musical sonification, composers and designers can repurpose elements of model physiology and structure, as well as the topographies of virtual space itself, into components of musical gesture. Multiple modalities of interaction can thusly be combined to create performance works wherein the interactions between virtual actor and virtual environment drive any number of parameters of computer mediated musical sound, structure and space.

Figure 1. In *ECHO::Canyon* interactions between avatars and the environment itself drive procedural sound and music generation using UDKOSC.

2. *ECHO::CANYON*

ECHO::Canyon (2013) by Robert Hamilton and Chris Platz is an interactive musical performance piece built within UDKOSC [3], a modified version of the Unreal Development Kit (UDK), a free-to-use version of the commercial Unreal 3 gaming engine [1]. Premiered on April 25, 2013 at Stanford University's Center for Computer Research in Music and Acoustics, *ECHO::Canyon* creates a reactive musical environment within which the idiomatic gestures and motions of avian flight and biologically-based creature motion are mapped to musical sound-producing processes. As such, action and motion of player and AI controlled avatars drives dynamic musical synthesis processes by passing parameterized data streams back and forth between the game environment and a sound-generating software server. Data generated in the *ECHO::Canyon* environment drives a multi-channel sound server written in Supercollider [4] featuring software-based Ambisonic encoding and decoding [5] to spatialize sound around a multichannel speaker environment. Individual actors and sound generating events in the game environment are spatialized throughout the sound field at locations representative of their position in the rendered environment itself, creating a correlated spatial mapping between virtual action and real-world sound. Audiences in a traditional concert setting watch the performance on one or more projector screens showing camera views from a unique camera operator, moving throughout the environment.

[1] UDK by Epic Software. `http://www.udk.com`

3. PRIOR WORK

The use of video game engines for music and sound generation has become increasingly common as generations of musicians who have grown up with readily accessible home video game systems, internet access and personal computers seek to bring together visually immersive graphical game-worlds, wide-area networks, interactive control methodologies and musical performance systems.

Though its graphical display is rendered in 2-dimensions, *small_fish* by Furukawa, Fujihata and Muench [6] is a game-like musical interface which allows players to create musical tapestries based on the interaction of dynamic components within the environment. Similarly playful in scope, *LUSH* by Choi and Wang uses models of organic interaction and gameplay within an OpenGL framework to represent and control sound generating and organizing processes [7].

Commercial gaming environments have been repurposed as dynamic music-producing systems in *Soundcraft* [8], *q3apd* [9], *q3osc* [10] and *OSCCraft* [11]. Multi-modal musical performances built within an earlier version of UDKOSC, as well as within a customized implementation of the open-source Sirikata [12] virtual environment produced a series of immersive and interactive musical works [13]. And the mapping of game-play interactions to real-time sound generating process has been pursued as a prototyping methodology by sound designers [14], and as an immersive creative interface and display [15].

4. SYSTEM OVERVIEW

As the UDK game engine is designed to support multiple performers across WAN or LAN networks, *ECHO::Canyon* currently supports up to 16 human-controlled users, allowing ensembles to choreograph evocative group gestures and motion sequences. At the same time, computer controlled characters, either driven by in-game AI (artificial intelligence) processes or using OSC data generated by external algorithmic processes, can also exist and create sound and music. The combination of human and algorithmically controlled characters creates a dynamic sound and visual environment that allows for and encourages novel interactions with each performance.

To produce musical works such as *ECHO::Canyon*, multiple software and hardware systems must efficiently share large amounts of real-time data with low latency and a high success-rate of packet delivery. At the same time, the sound generation and three-dimensional graphics rendering are extremely taxing for even higher-end personal computer systems. To optimize both sound and video production, multiple machines are used in any one performance, connected over a local gigabit ethernet network. A sound server running SuperCollider typically runs on one computer (OS X, Linux or Windows) while the UDKOSC game-server and individual game-clients each run on their own Windows machine.

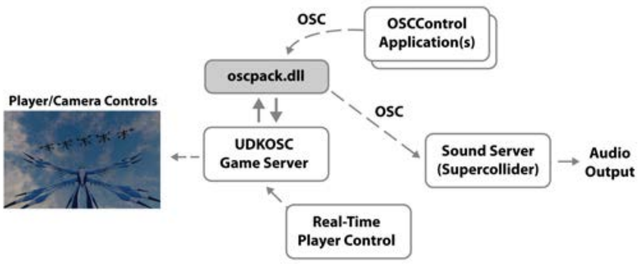

Figure 2. UDKOSC processes OSC input to control avatar and camera motion while generating OSC output representing avatar and skeletal mesh location, rotation and action/state data.

4.1 UDKOSC

UDKOSC was designed to bring together real-time procedural sound synthesis, spatialization and processing techniques from the realm of computer music with the visually immersive networked multi-player environments of commercial-grade gaming engines. Gestures, motions and actions generated by actors in game-space are analyzed and transformed in real-time into control messages for complex audio and musical software systems. UDKOSC was developed to support the creation of immersive mixed-reality performance spaces as well as to serve as a rapid prototyping tool for procedural game audio professionals [16]. A detailed description of UDKOSC's functionality and prior uses can be found in [3] and [13].

4.2 Music and Sound Server.

On the receiving end of the UDKOSC output stream is a music and sound server capable of interpreting OSC messages and mapping game parameters to musical generation and control processes. While any OSC-capable system can be used as the interpreter for UDKOSC output, for most UDKOSC projects, our preference has been to use Supercollider running numerous synthesis processes and spatialized across multiple channels using Ambisonics.

Within Supercollider, data representing avatar positioning, rotation and action is mapped to specific parameters within instances of synthesized instruments. In *ECHO::Canyon*, the flight of a player-controlled Valkordia pawn through the environment is sonified in real-time. At any given moment of the piece each pawn's speed, rotation, absolute Z-location, height relative to the "ground", side proximity to solid environment structures and a Euclidean distance to a series of "crystal" objects in the environment all serve as parameters driving real-time synthesis. Alongside one or multiple human-controlled pawns, flocks of OSC-controlled Valkordia bots, themselves driving separate synthesis processes, are controlled with precomposed OSC-emitting scripts. During flight as well as during a specially-designed "posing state", the location of bones in the bird-skeleton's wings are tracked and mapped to their own synthesis algorithms.

Musical output for *ECHO::Canyon* is currently spatialized across multi-channel speaker systems by a Supercollider sound server making use of stereo output, simple 4-channel panning or first-order ambisonics as the performance space allows. When ambisonic output is used events are placed in the soundfield in a mapping schema uncommon in standard video-game audio where coordinate locations in the environment are mapped to static corrolary locations within the listeners' soundfield. When stereo or simple 4-channel panning is employed, location-based sound events are placed in a more conventional actor-centric perspective, with their amplitudes scaled proportionally to the distance between actor and sound-emitting location.

5. ENVIRONMENT

The world of *ECHO::Canyon* is situated in a fantastical open-air virtual environment featuring rich flora, jagged volcanic rock outcroppings and various species of megafauna. Isolated on all sides from outside interference by a massive ocean, ECHO::Canyon exists as a bizarre island oasis wherein biological evolution has progressed in novel directions, unaffected by the rest of the world. Musical sound has similarly evolved, facilitating communication not only between creatures on the island but between creatures and the island itself, specifically through the use of massive energy crystals situated at key locations around the environment.

5.1 Crystals

As seen in Figure 1, jutting out from high-peaks towering above the ECHO::Canyon environment are sound-generating clusters of crystal, capable of resonating at various pitches when a creature approaches. These crystals form the harmonic structure of *ECHO::Canyon* and draw their resonating frequencies and filter coefficients from a combination of avatar location and randomly generated seed pitches established at the launch of the piece. Each crystal is positioned to break the large environment down into regions, within which performers can congregate, to interact with one another, or across which performers can spread to create an immersive sound field sounding around and throughout the audience.

Musically, each crystal cluster generates a polyphonic wash of pitches scaled in part based on the coordinate location of the crystal itself and in part based on a randomly value,

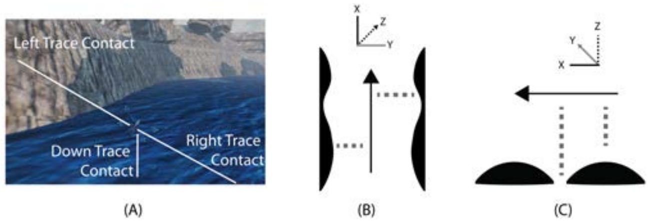

Figure 3. Ray traces visualized as vertical and horizontal lines in (A) track the distance between the Skeletal Mesh and objects and contours of the environment, both to its right and left sides (B), as well as directly below (C).

created and seeded with each launching of the game engine. In Supercollider, each crystal location drives a separate instance of the Gendy1 dynamic stochastic synthesis UGen. An actor's distance from each of these crystals controls both the Gendy1's amplitude as well as the frequency of a ResonZ two pole filter.

When multiple actors approach a single crystal instance, each of their loactions is used to modulate a different aspect of the instrument, creating a group interaction schema which differs signficantly from the individual user schema. This results in a collaborative control system in which each member of an ensemble can directly control one or more attributes of the synthesis process.

5.2 Canyons

Spiraling outwards from a central peak lie a series of low-lying canyons with sharply sloping walls. For creatures moving quickly through these canyons, a variety of musical sounds can be produced by skimming horizontally close to the canyon walls. Ridges carved into the terrain and outcroppings of rock and crystal create composed variations of amplitude and timbre as performers move past them. By sculpting repeated patterns into canyon walls, the designers are able to "compose" rhythmic elements with which the performers can choose to engage.

The relation of a flying Valkordia actor to the environment was a key gestural component in the shaping of *ECHO::Canyon* both literally and figuratively. Valleys, mountains and caves were sculpted with articulated shapes to accentuate specific features of synthesis processes. Fig. 3 shows vertical and horizontal ray traces tracking the relative distance between a flying actor, the ground, and the walls of a valley. In this example, the ray trace distances were used to control amplitude and filter frequencies of separate synthesis processes, as well as panning for the horizontal traces.

6. CHARACTERS

The island of ECHO::Canyon is populated by three races of creatures, each capable of generating unique musical sounds through gesture and interaction with aspects of the environment, as well as with other creatures. Each creature type can be controlled by performers of the piece, allowing for variety in performance and weighting in orchestration.

6.1 Valkordia

The Valkordia are a race of four-winged birdlike creatures with a unique bone structure that creates a variably pitched sound when air passes over and through specialized openings on each wing. Valkordia are highly agile and speedy creatures which generate unique polyphonic vocal cries to communicate. As part of their mating or fighting rituals, males and females alike will often adopt a vertical pose, keeping themselves aloft by rapidly beating their lower/rear wings. While posing, each Valkordia can generate musical phrases, both challenging and enticive, using their beating wings and voices alike.

6.1.1 Flight-based Gesture.

For *ECHO::Canyon*, the theme of avian flight is a central component to the musical sonification, animation and control schemata created and used for the piece. The Valkordia character model fuses physical characteristics and idiomatic movements from both bird and insect-like creatures. Bones found in the model's front right wing were tracked to drive a noise-generating process when the avatar was in flight.

6.1.2 Flocking Pawns.

Our cognitive abilities to group and associate like motions of active objects into single cohesive units can bring disparate dynamic elements together into one unified mass gesture [17]. The sonification of such behaviors with simple sound sources can create dynamic musical textures through similar motion and position of each source [18]. *ECHO::Canyon* makes use of flocks of OSC-controlled Valkordia pawns with a relatively simple mapping of their Z-coordinate to a simple oscillator and their distance from the player actor to the oscillator's amplitude. Each bird in the flock tracks a target position which is moved in pre-composed patterns through the game-space by an OSC-generating script. The sonic result is a shifting grain-like cloud of pitched oscillators.

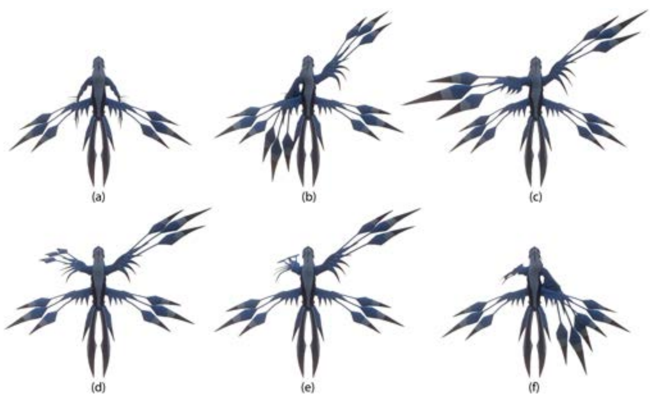

Figure 4. Valkordia model with manual wing positioning during "Posing" state

6.1.3 Posing State.

With the intention of drawing audience and performer attention to the actor itself and away from the environment, micro-scale gestures are comprised of motions and articulations of a given avatar's virtual physiology. By mapping the subtle motions of bones within an actor's skeletal mesh to both dynamic control systems and evocative musical processes, the micro-scale gestures within *ECHO::Canyon* provide a vastly different viewing and listening experience than the work's macro-scale gestures.

Performers in *ECHO::Canyon* enter the posing state by toggling a key on the game-pad or computer keyboard. Upon entering the state, actors no longer fly through the environment; instead their Valkordia avatar interpolates into a nearly vertical pose and control over the actor's front two wings are directly mapped to each of the gamepad's two two-dimensional analog joystick controls. Users control the forward, side and back rotation of each wing independently by rolling the analog joysticks around in circular patterns, mimicking the rotation of arms or wings in shoulder sockets. A series of wing poses can be seen in Fig. 4, examples (A) through (F).

Rather than mapping pre-composed wing animations to output from the joystick controllers, each wing instead tracks an end effector, using inverse kinematics [19]. The location of each effector is itself controlled in 3D space by the joystick output, scaled and acting upon a Cyclic-Coordinate Descent or CCD Skeletal Controller, itself a component of the UDK. The effectors for each wing can be visualized as points in space towards which the chain of bones from the tip of each wing to the shoulder socket are reaching.

6.1.4 Tracking Bone Location.

The tracking of individual bone locations relative to a central point on the actor's skeletal mesh changes the focus and scale of gestures to reside firmly in the micro-scale. In this manner, the extension of a wing to its full length can be mapped to a "larger" sounding sonic response than a "smaller" gesture, closer to the central point. Each bone that comprises a model's skeletal mesh can be tracked in UDKOSC, though due to the high number of individual bones used in many well-articulated skeletal meshes, it is generally a good idea to track a few key bones to reduce the amount of data tracked and output in real-time.

6.2 Trumbruticus

The Trumbruts are a race of elephant-like megafauna that roam freely around the ECHO::Canyon environment. Equipped with a musical prehensile trunk, as well as two posterior-facing rear trumpet horns, herds of Trumbruticus communicate using musical blasts from their three main horns, and are capable of producing loud and low tones, as well as higher harmonic whistling clusters.

Users controlling a Trumbruticus model can independently move each creatures head and trunk using inverse kinematic mappings. Similarly to the Valkordia, each Trumbruticus is capable of producing a complex call as well as a more persistent low frequency tone.

6.3 Shelltapper

The Shelltappers are an ancient race of dinosaur-like creatures sporting a thick carapace and a mane of antenna-like

Figure 5. Trumbruticus avatar posing in *ECHO::Canyon*.

”tappers”. The scales that make up the Shelltapper's thick shell are tuned to musical notes and resonate with a sound reminiscent of a stuck modal bar when struck with the creature's tappers. As they walk through ECHO::Canyon foraging for food, these creatures create pitched rhythmic patterns, modulated by their speed of motion and distance from a batch of crystals. The further Shelltappers are from any crystal, the less pitched their shells are, resulting in a timbral range from flat percussive sounds to highly resonant bell-like timbres.

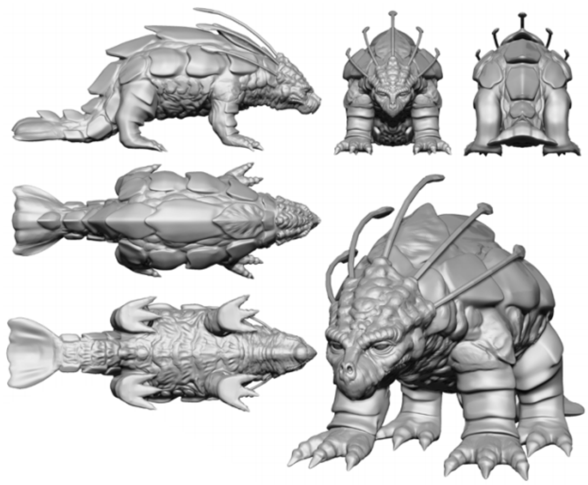

Figure 6. Shelltapper avatar.

As users in the environment control Shelltappers, they can take manual control over the tapper appendages, playing their own rhythms on the creatures backs.

7. MUSICAL SONIFICATION IN *ECHO::CANYON*

During *ECHO::Canyon* performers control virtual actors moving through a fully-rendered outdoor landscape using a computer keyboard and mouse or commercial game-pad controller. Each actors' location and rotation in game-space, as well as other parameters describing their interactions with objects within the environment are streamed in real-time to sound-servers using the Open Sound Control (OSC) protocol [20]. The environment itself is sculpted in such a way as to allow performers the freedom to perform musical interactions by moving above, around and through the topography. In this way the process of environment design takes on the role of composition, with sections of virtual hills, canyons and valleys acting as musical pathways through the environment.

While *ECHO::Canyon* is built within a gaming engine, unlike many commercial games where audio and music play a supporting role to displays of rich visual content [21], the role of music and sound within the work are intended to occupy a perceptual role equal to the presented visual modality. Sonifications used in *ECHO::Canyon* are designed to be musical and performative in nature, and are fundamentally presented as foreground constructs, rather than as background or more associative "sound-effect" constructs. To that end traditional approaches for game sound design are replaced instead by sets of composed interactions.

The following list defines an example set of control events and actions that have been explored within *ECHO::Canyon* and a description of their musical analogues:

7.1 Actor Proximity.

An actor's relative distance to objects in the environment is determined through the use of horizontal and downward ray traces. The distance between the center of an actor's bounding-box and an object with which the ray trace collides is output over OSC. From a design standpoint, traces are used to drive musical processes when an actor moves through a space such as a tunnel, cave or chasm, or simply swoops down above some part of the terrain.

- In Supercollider, horizontal ray trace distance and global location is used to modulate the amplitude, central frequency and grain count of a cloud of granulated SinOsc bursts.
- Amplitude is scaled inversely to horizontal trace distance, while grain count and central frequency are both modulated by the actor's current height, or Z-location.
- Vertical trace distance shapes both the amplitude and the chaotic oscillations of a "screetch"-like sine feedback FM oscillator with phase modulation feedback using the SinOscFB UGen.

7.2 Actor Speed and Motion.

As user avatars move through three-dimensional coordinate space, each avatar's X, Y and Z location data is streamed over OSC to a sound-server. The speed of motion is calculated and used to scale the speed of the flight animation, itself driving parameters of a noise-based synthesis instrument.

- Actor speed is indirectly sonified as the speed of oscillation of the right and left wing bones drives each bone's position in the Z-plane (relative to the actor's central coordinate location).
- Location data controls simple amplitude and ambisonic spatialization of continuous sound-sources for each osc-controlled Valkordia flocking pawn.
- Actor speed also modulates the frequency of a filter shaping the output from each actor's downward trace SinOscFB process.

7.3 Actor Bone Motion.

The structural core of each actor's character model is a skeletal mesh comprised of numerous virtual bones, each one with a coordinate location and rotation accessible via OSC. By tracking motion of each bone within the skeletal mesh, complex control signals can be generated through the use of simple avatar motions.

- During flight, the relative z-location of each wing bone is sonified with a simple sine oscillator, with subtle beating frequencies made audible through a slight freqency offset between each wing's synth.
- During the manual posing state, the same mapping continues, however the manual extension of each wing causes the pitch of each oscillator to modulate within a range of approximately four-semitones.
- The frequency of an actor's manually-triggered "call" sound is mapped to the combined distance between right and left wing tip bones.

7.4 Actor-Group Motion and Density.

While individual actor avatars each communicate their positions through individual OSC streams, actors moving in concert together – in flocks, swarms or herds - can be tracked and sonified as a group. For fast moving particle-based objects, like projectiles generated by an actor or actors, granular synthesis-based instruments have proven an interesting mapping. Similarly, flocks of flying avatars tracked as simple sine-waves have been used to create a shifting field of additive signals.

- Flocks of OSC or AI controlled Valkordia pawns are represented with simple sine oscillators which are spatialized across an ambisonic soundfield.

7.5 Spatio-centric spatialization.

In contrast to traditional gaming concepts of user-centric audio, a spatio-centric presentation superimposes a virtual space onto a physical multi-channel listening space, spatializing sound events around a physical space to correlated coordinates in the virtual space. The goal of such presentations are to immerse an audience in an imposed sound world, creating a perceptual superimposition of virtual and physical environments.

- When ambisonic spatialization is used, each sound generated is positioned in the soundfield according to its position in game-space. Unlike traditional gaming presentations, where sounds are generally positioned relative to the player's head location, such a presentation can represent the location of multiple users and objects to an audience watching without a decidedly "first-person" viewpoint.

8. ONGOING WORK

Additional works set in the ECHO::Canyon environment are being composed and designed as part of a series entitled *ECHO*, combining disparate performance scenes - including an underwater sequence and a mechanical "steampunk" instrument/building - into an evening-length concert experience. Research into the perception of gesture and motion in game space is also being carried out using the UDKOSC codebase. In [22], user studies assessing the perceived coherence between avatar motion and musical sonification of that motion were used to determine which component features of gesture and generated sound were perceived as being the most coherent. In turn, results from these studies are being factored into the design of control and sonification schemata for each new creative work.

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