ENTERTAINMENT TECHNOLOGY CENTER

WONDER BUFFALO

NEX-GEN TECHNOLOGY EXPLORATION SHORT FILM

WITH A FOCUS ON VR, HDR AND CLOUD-BASED WORKFLOWS

An ETC Innovative Technology Award

WHITE PAPER – DECEMBER 2017

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1. INTRODUCTION

1A. ABSTRACT

Wonder Buffalo is a linear short film and room scale virtual reality (VR) experience produced by the Entertainment Technology Center at the University of Southern California (ETC), directed by Christine Berg. The project was commissioned to test the Cinema Content Creation Cloud (C4) framework, the ACES workflow for end-to-end high dynamic range (HDR), and the VR production workflow in tandem with a linear physical production.

This paper focuses on providing an analysis of *Wonder Buffalo* regarding best practices and opportunities for standardization regarding the Cloud-based workflow employed for the film's production. It will also detail the HDR on-set capture and final deliverables, as well as the process of incorporating a parallel VR pipeline into the linear production workflow.

1B. PROJECT CLOUD

The Entertainment Technology Center's "Project Cloud" led by Erik Weaver aims to clarify the Cloud and its use in media production. The project united senior leaders from the six major studios to develop next generation Cloud standards, support Hollywood organizations and major Cloud vendors, and produce proof of concepts. Project Cloud encompasses many aspects of the Cloud including transport, security, metadata, long-term storage, and the formation of an agnostic framework that unites key vendors and studios.

1C. ETC HISTORY AND MISSION

The Entertainment Technology Center at the University of Southern California (ETC) is a think tank and research center bringing together senior executives, innovators, and thought leaders from the media, entertainment, consumer electronics, technology, and service industries. Along with the academic resources of the University of Southern California, ETC explores and acts upon topics and issues related to entertainment content.

ETC was founded with the help of George Lucas in 1993 with the goal of bringing technology and entertainment visionaries together to collaborate on the future of entertainment technology. ETC was established with the mission to be a neutral research organization devoted to identifying pivotal, emerging entertainment technologies and creating programs to analyze and test them.

As an organization within the USC School of Cinematic Arts, ETC helps drive collaborative projects among its member companies and engages with consumers to understand the impact of emerging technology on the media & entertainment industry. ETC specifically focuses on technology development and implementation, the creative process, business models, and future trends.

ETC helps to identify new technology to address fundamental industry needs. The work supported by ETC is "pre" standardization, which encourages innovation and flexibility in the design and development process. The focus is to create pragmatic solutions focused on real-world products for the business of Media and Entertainment. After validating solutions in the real world, relevant technologies may then be submitted to SMPTE for standardization and industry-wide adoption.

In an effort to be practical and realistic in its evaluations, ETC began a program of regular real-world

production tests. These tests are delivered in the form of short film productions. So far, three films have been produced under this program.

The first film, *Luna*, shot in 2014, focused on quantifying the "state of the art" in Cloud production in order to provide a starting point for understanding the potential and limitations of Cloud technologies. The second film, *The Suitcase*, shot in 2015-2016, added end-to-end HDR capture and deliverables along with live streaming 360 capabilities for behind-the-scenes capture.

With *Wonder Buffalo,* we expanded on our findings for Cloud and HDR production while asking what the future of VR beyond 360 video has in store for the entertainment industry. The *Wonder Buffalo* experience, built as part of a transmedia corpus, seeks to answer that question as well as uncover the challenges involved with integrating virtual reality into a film production pipeline.

2. BACKGROUND

2A. C4 AND THE CLOUD

C4 is a set of open source tools and guidelines created to solve many of the problems that face media production in the Cloud. The phrase, "the Cloud," has been used as a metaphor associated with various Internet-type technologies. However, the Cloud can be clearly differentiated from other things such as the Internet, data centers, or mainframe time-sharing by its economic model.

The Cloud refers to computing resources that are utilized "on demand" resulting in usage-based billing. This allows computing power to be treated like a utility rather than an infrastructure. The utility model of the Cloud means that computing power is not purchased in advance, and the amount of computing power is not fixed. The scalability potential of the Cloud makes it a potentially important resource for modern media production.

To date what has been a significant challenge for the media & entertainment industry is understanding how to add the Cloud to existing workflows. Complex technical issues arise when working with assets in multiple locations, and new factors must be considered when moving large amounts of production data such as bandwidth, latency and egress costs.

Fundamentally, the needs of media production are different from how the web is designed and much of what is offered by the leading Cloud providers is oriented towards web applications and services. These services simply aren't designed or priced for the constant creation and movement of large production assets.

The "web services" business has a relatively light transport requirement as compared to media production. Even high-end HD video on the web is microscopic in size when compared to RAW production assets where 12MB for a single frame is common. In addition, shooting ratios of 100:1 or more, multiple edits, post-production, and visual effects, make it is easy to see that storage requirements in excess of 100TB is not uncommon.

As one example of how different the needs are, consider the example of 'edge caching', where data on the web can be pushed to 'edge' locations that are closer to users, and because the data is accessed often but rarely changes, the data can be cached for faster access. This doesn't have much value during media production however, since the data is constantly changing and accessed by relatively few people.

C4 solves these issues by providing a more reliable way to identify and communicate about large media assets, and a mechanism for relating files to dependencies and metadata. Whereas with URLs and file paths that are bound to locations, C4 identifies files in a way that does not depend on the location. A file in the Cloud is known by the same ID as it is on your computer, or in fact any computer.

This removes all of the complexity of building production tools that work just as well in the Cloud as locally. For example, C4 eliminates the ambiguity caused when making two or more conflicting changes to the same file, which is a common problem with keeping files in sync in the Cloud (a hard problem in computer science known as 'distributed consensus').

While C4 provides many of the resources needed to successfully incorporate the Cloud into production, there still exist many issues. One reason for the difficulty is there appears to be miscommunication between production assets and the Cloud. One instance this appeared in production was when Cloud assets were accessed through general naming conventions, rather than their C4 ID. This caused much of the production staff to search for personal help, rather than follow the chain of IDs. Due to C4's preference for IDs, users who attempt to use other solutions often found themselves lost in the process.

2B. HIGH DYNAMIC RANGE

The term High Dynamic Range (HDR) is used to refer both to the way an on-screen image is represented virtually and the way it is displayed to the eye. By definition it is greater or equal to the contrast ratio derived from 13f stops. When extending dynamic range, it can be extended upwards into the highlights by making the 'brights' much brighter. It can be extended downwards into the lowlights by making the 'darks' much darker. Thus, HDR allows the eye to receive more details in both the shadows and highlights of an image, and greater overall color fidelity.

This document aims to describe consistent methods for the creation and delivery of end-to-end HDR production for film. The goal is to identify best practices within the production workflow to ensure the integrity of the image from on-set capture through final color grade. There will also be specific attention made towards the consistency of aesthetic between the multiple color spaces and deliverables that the film will be displayed in.

2C. PRODUCTION OVERVIEW

Wonder Buffalo mirrors a studio scale professional production while utilizing students, recent graduates, and professional film crew members. *Wonder Buffalo* was captured over 5 days of physical production. The short film was assembled from 372 minutes of production footage resulting in a shooting ratio of 14 to 1. The film was shot on the Sony F55 XOCN codec. Roughly 2TB of data were produced per production day, all of which were transferred nightly to Cloud and local storage, for a total of around 25TB of production assets.

The VR production of *Wonder Buffalo* was captured over 2 days using photogrammetry for the location and 8i volumetric capture for the character performance. The final build size (a Unity build) was 11GB with a .obj room model.

PRODUCTION TEAM
Executive Producer – Erik Weaver
Writer/Director – Christine Berg
Writer – Simon Shterenberg

Producer – Drew Diamond
Editor – Amy Reynolds Reed
Cinematographer – Jon Keng
VFX – Fernando Rabelo
Sound Supervisor – Scott Gershin

VFX TEAM
VR Executive Producer – Lindsey Townley
VR Producer/Lead Developer – Brian Frager
VR Coordinator – Ming Qiu
Developer – Samuel Terry
Developer – Samantha Mosqueda
Developer – Giuseppe Mattiolo

Although the infrastructure components are different between feature film, television, music, broadcast, and other production pipelines – consistent, reliable coordination is the most fundamental challenge. Cloud resources have an inherent set of problems and bottlenecks facing the entertainment industry. As productions turn to the Cloud to automate, store, and facilitate multi-user collaborations, these challenges must be addressed to safeguard assets. It is important that as the usage of the Cloud continues to grow, that productions identify best practices and opportunities to standardize workflows.

Entertainment production brings together experts across a wide spectrum of specialties. These experts bring with them disparate organizational habits, naming conventions, and workflows within their departments. In order to maximize the full potential of Cloud technologies, it is important to identify and address the inherent issues realized in early case studies.

2D. CHALLENGES IN THE CLOUD

The key challenges of working with the Cloud are:

1. Asynchronous, Cross-Organization Data Management.
2. Data Transport Latency, Bandwidth, and Cost.
3. Cloud System Integration and Throughput.
4. Metadata Management.
5. Access Management.
6. Interoperability between Tools and between Organizations.

Asynchronous, Cross-Organization Data Management

The general challenges of data management between organizations are complicated when interactions also happen at different points in time. You might take data from set, deliver to a dailies house, and then a month later manipulate the data in post-production, and so on. These gaps of time allow relationships between things to get lost, and leads to the need for detailed records, data, and communication. Hollywood already has established data management protocols. Each department has standardized production reporting procedures that streamline communication. One issue we have identified is reliable communication of this information to members of a widely distributed team.

Additionally, time lag introduces a subtle yet complex issue regarding consistency. Hypothetically, if two people make a copy of a hard drive in one location, then make independent changes at different points of time and locations, which version should be considered correct? If the file name remains the same how can you tell which is which? This problem doesn't come up on a single computer, or file system with shared access. Across larger distances, and time intervals this becomes a serious challenge to keeping files in sync.

Unlike other industries, such as manufacturing, the work of producing content changes completely from project to project. Hollywood has become expert at handling this unstable environment, but by adding the distributed consensus problem that comes with Cloud computing, Hollywood's existing solutions begin breaking down.

Data Transport Latency, Bandwidth, and Cost

Data transport can be understood as files being moved from location to location. Many Cloud-based workflows are not affected by issues of latency; however, latency was an issue in this production. The issue that came up specifically in *Wonder Buffalo*'s production involved the use of remote desktops. The delay between desktops created issues with communication and understanding between members of the production. Any instances of latency often times would create miscommunication just because of the mere fact that two parties were viewing completely different material.

The Cloud proved incredibly beneficial in terms of bandwidth. When using the Cloud, files can be transported at the speed of the server. The network between the Cloud server and home offices experienced no sort of data bottleneck, so we were not limited by bandwidth. Latency issues did not appear in moving files.

Cloud System Integration and Throughput

This refers to queue management software working in conjunction with the Cloud. The chief problem is there is no universal solve function. Each integration must be individually catered and crafted for each system. This creates an arduous workflow that requires careful collaboration between teams, otherwise the queue will be mismanaged and cause issues with production.

Metadata Management

With the introduction of the Cloud, metadata management is a key factor in collaboration, and with it, naming conventions becomes vital. If you have multiple users collaborating in a Cloud and everyone has their own sets of metadata, how do you share, protect, and organize the different users manipulating the same assets? Synchronization problems within these productions highlight this issue with metadata. Particularly, improperly named datasets create critical problems with synchronization.

This was an issue in *Wonder Buffalo*'s production phase when improper naming conventions between both the sound and camera departments led Technicolor dailies to be unable to automatically sync production footage and audio. This issue occurred in post-production as well, as we had multiple exports from Technicolor dailies following improper aspect ratio protocol. The multiple iterations of shots without metadata to direct to the correct aspect ratio created several instances that required additional work by the editorial team.

Cloud Access Management

This issue arose with federated access to the Cloud. For this project, Avalanche CEO and Cloud architect, Josh Kolden was in charge of granting access to the Cloud for the team members and was the primary intermediary for all Cloud ingest and export. This became a time-consuming task and created unnecessary work for Kolden.

Interoperability between Tools and between Organizations

Interoperability between tools and between organizations refers to the industry push for standardization of language. Specifically, a push that organizations and software speak in the same language. This project illustrated that we still have communication problems even with the workflows that we consider standardized. Editorial edit decision lists (EDLs) sent to Technicolor for EXR conversion for VFX were flawed on multiple instances. We waited until the final cut to get EDL's, but the problem was that they were modified clips without reference to RAW files. As a result, we lost the source of the master file that made various clips. C4 was not used in the EDL. If the EDL's had a standard reference ID, such as through C4, or if editorial could make note of modification citing a standard ID or original assets, we could follow the chain rather than requiring personal help finding the clip. The hope with C4 is to provide a hierarchy of assets. Modifications would automatically be detailed and the chain of assets would be available to reference. In this instance, it would be easy to find appropriate materials.

2E. THE WORKFLOW

For *Wonder Buffalo*, we outlined a number of tests to be conducted over the course of pre-production, production, and post-production project phases. During pre-production, the team evaluated a number of currently available "software as a service" (SaaS) production platforms. These included SyncOnSet, Movie Magic, Scenechronize, and ScriptE. Though many of these tools do not currently have RESTful JSON APIs, as per ETC's recommendations, they are working in that direction.

Production consisted of an on-set workflow through Technicolor's DIT Cart overseen by student volunteers. The F55 was transferred via the on-set cart shortly after capture to the cart's local RAID storage. C4 data was run for the footage after it was backed up. Each evening the footage was sent to the Technicolor Dailies lab where it was transcoded to H.264 and DNxHD 115. The H.264 was transferred to PIX online. The files were then remotely prepped for editorial on the remote desktop editing platform BeBop Services.

During production 5 G-Tech Studio drive systems were used. These were configured in RAID 5 and provided between 4TB to 8TB of storage with 200MB/s of sustained throughput. These drives were backed up daily onto a 24TB master drive at the ETC offices at USC, which acted as the production office. At the ETC offices, the master drive transferred to the Cloud via ETC's connection provided by Sohonet.

The full Sohonet's connection bandwidth is 1GB/s, but ETC is configured to use only 1/3 of the full line capacity. Nevertheless, using C4 optimized data transfer, the data was fully transferred to the Cloud nightly, leaving time for additional tests to be conducted.

To provide enhanced file tracking, each time data was copied from one location to another, C4 was used to identify the files and log transactional metadata. This provided searchable JSON format log files that associated C4 IDs with names, dates, physical location, and drive names. This was a source of unassailable proof of custody that could be used to resolve any missing file issue.

From editorial, we created EDL's for Technicolor to prep VFX pulls in the form of EXR's to deliver to the VFX team. The final edit went to all teams as a reference guide as we simultaneously pulled RAW files from the edit. We then sent them via Aspera to conform for color. Files were extracted from the Cloud and delivered by hard drive until an Aspera link was set up with Technicolor, after which time the Aspera system was used for transferring RAW files back and forth.

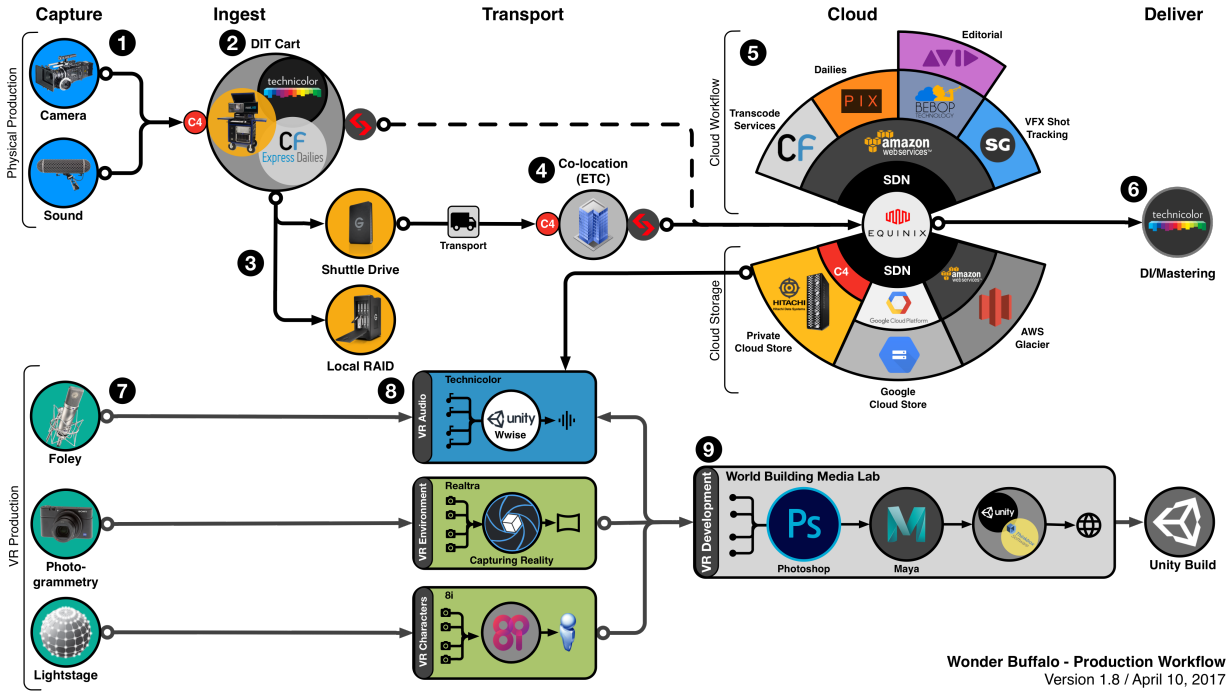


Figure 2.1: ***1)*** *Both picture and sound are captured on set.* ***2)*** *Camera RAW recorded files (Sony X-OCN ST) and sound files are ingested using the DIT cart using C4 to validate the copies.* ***3)*** *Two sets of copies are made, one to Local RAID storage and the other to a Shuttle Drive and sent via either car or Sohonet (when available) to ETC at USC.* ***4)*** *With ETC servicing as the "co-location" the files are C4 validated and then transmitted to Equinix El Segundo via Sohonet.* ***5)*** *At Equinix files are stored on the Hitachi Private Cloud Store with C4 automation used to create corresponding backups on both Google and AWS, transcode files for dailies, editorial, and VFX, and route those files to their appropriate endpoints in the workflow.* ***6)*** *4K ACES EXR files are created for mastering from EDLs and sent to Technicolor for color grade mastering.* ***7)*** *VR assets are captured using the same sets and actors as the physical short production.* ***8)*** *VR audio, environmental, and character assets are processed using their respective pipelines at different locations.* ***9)*** *Rendered VR audio, environmental, and character assets are then brought together to create a Unity build.*

2F. C4 ON SET

Allison Hettinger from On Location Services at Technicolor modified Technicolor's on-set software and workflow to automatically capture the connections between assets. This was done by identifying the C4 IDs of the various assets, and associating them to each other. Furthermore, this included the identification of the source SONY XOCN footage, the H.264, the DNxHD footage, and the audio.

Importantly, the metadata is easy to read and understand using the YAML language, yet it represents a complete and traceable record of the relationships between these files. Finding the C4 ID of any of these files (regardless of any path or file name change), allows one to quickly search the other related files. Prior to the use of C4 IDs, there was no way to do this without a centralized digital asset management solution, and even then, it was prone to user error that could cause this information to be permanently

lost.

We refer to this as “Indelible Metadata.” If you have the metadata in a text file, database, or other searchable form, and you have the asset, then C4 ensures that you can always connect the two together.

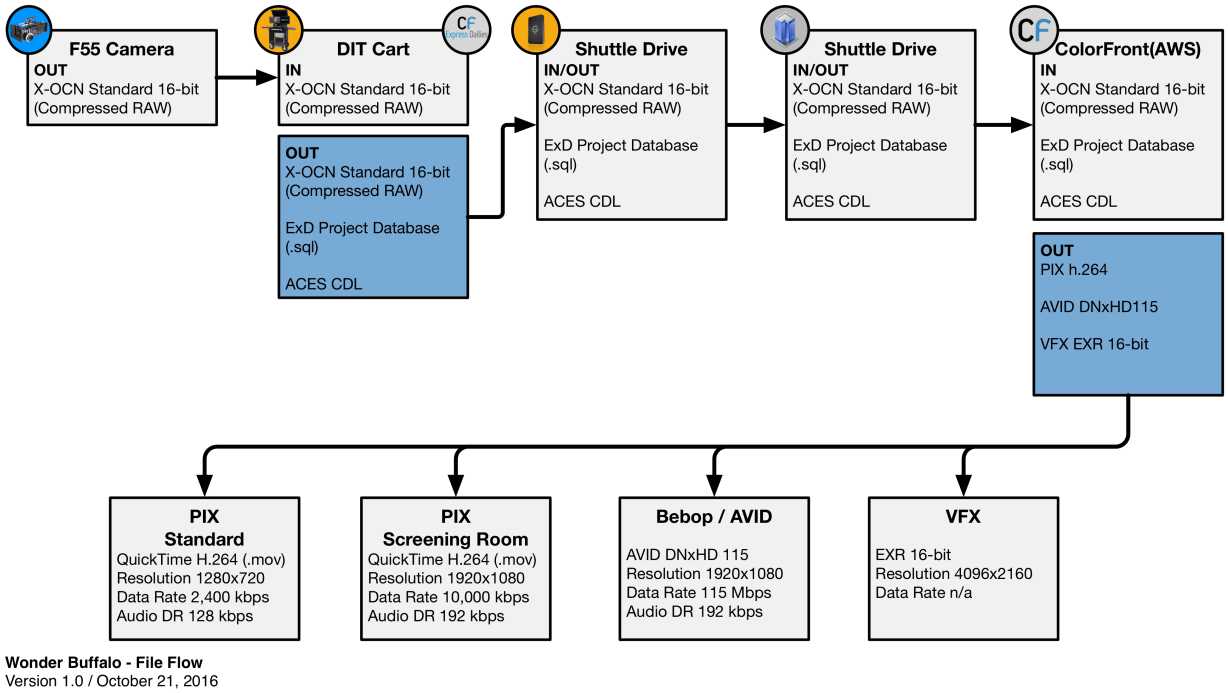


Figure 2.2: *Wonder Buffalo File Flow depicting the file inputs and corresponding outputs at each step of the process.*

3. CLOUD PRODUCTION NOTES/LEARNINGS FROM WONDER BUFFALO

Coming from *The Suitcase* we wanted to test elements that had worked relatively well in the previous production and see what surprises we may encounter which could facilitate new learning regarding Cloud production.

As with the previous production, we had the Cloud. But this time we had a Hitachi + Equinix Media Cloud functioning, so we were able to test media upload/transfers throughout the production workflow.

3A. METADATA MANAGEMENT

The first issue we encountered with the Cloud occurred due to improper naming conventions on set where the sound and camera reports did not align. These highlighted an issue in the Cloud relating to disambiguation. The incorrect information captured on set rippled into naming and synchronization issues that continued through editorial and into post color conform and relinking.

The same issue occurred after dailies were generated by Technicolor with the improper aspect ratio. During editorial, the footage was set up and synced with the improper footage, using the incorrect aspect ratio. This would then relink to the improper footage during relink for VFX editorial and color

grading.

We addressed this issue by redelivering the footage, which means we had two deliverables with the same reference information. You typically erase first deliverables and replace it. When you are replacing it with the second deliverable you usually have no issue, but in the Cloud, it became complicated due to wanting to store all new assets for the purpose of archival. With both versions persisting we had to differentiate between the copies.

This allowed us the opportunity to test how to differentiate and automate the hierarchy within the route folder to house multiple assets while directing to the "proper" one. Since we can unambiguously ID assets, we qualify what is the proper route. In the case of the re-exported dailies, we overrode the original exports by assigning them to the most recent file uploaded. The path still would take you to the two deliverables, but the newest one would automatically be referenced.

C4 supports this, but the issue became how does the Cloud present this to the user before every single file is EDL referenced pathed? Previously, when a new file is generated with a fix, it would name it the same and "replace" it in the project. This way the edit would reflect the latest update.

When we relink footage, it's going back to a folder route. Normally there's only one route, but in the Cloud, there are multiple files so you need to set up a hierarchy. The new default behavior always chooses the "highest one" as the "proper" one. Thus, you can access multiple versions of it, adding ability to the storage system. The user's point of view is that the latest version always supplants the previous, while still archiving all iterations and keeping in the same route location. The file allows us to see an array of the past iterations of the piece without naming conventions.

In its current form, there does not appear to be any solution to this issue identified. Most traditional workflows see new files replacing previous files, however this is not the case in the Cloud. Therefore, a key issue that needs to be ameliorated moving forward is orienting the Cloud to people's expectations. Rather than attempting to break old habits and create a hierarchy of assets, this production believes that the Cloud should adapt.

3B. MORE ON LATENCY

Cloud providers have a tendency to say latency is not an issue. But issues of latency highlight a major issue in Cloud production. In *Wonder Buffalo*, we found lag in the responsive time of tools residing in the Cloud. Human beings work at the speed of immediate latency and we feel sluggishness with any perceived lag. Cloud latency is seemingly very short because it is in milliseconds and is happening nearly at the speed of light. But when working, globally you are experiencing greater latency.

A number of factors can create potential latency issues when working with any Cloud provider, and the biggest culprit is bandwidth. Your choice of Internet Streaming Provider (ISP), the size of your home or work connection, your Wi-Fi set up, and the number of simultaneously connected devices all impact bandwidth. Congestion on any part of the connection path can impact video streaming quality and upload/download speeds, especially at peak times. The average home broadband speed in the United States in 2015 was 50mbps, and many people have significantly faster connections available. While 50mbps is more than enough bandwidth to run most Cloud-based services, this bandwidth is not necessarily consistent bandwidth, because it is being shared with every device and service being used at the same time on the same pipe.

For this production, we worked with BeBop, a Cloud-based post-production platform that enables remote editing by rendering a virtual desktop in the Cloud for playback and editorial duties. All Cloud-based applications require a certain amount of consistent, congestion-free bandwidth to produce a seamless experience, and the amount of consistent bandwidth needed varies by software. Post-production tools require an enormous amount of processing power, and to make this manageable in a Cloud environment, BeBop's approach to virtualization is to in effect move the tools to the content in the Cloud rather than moving the content to the tools. BeBop recommends ensuring that 20-30Mbps of consistent bandwidth be available to create a nearly seamless streaming experience, at which point the company has found that any latency or lag becomes imperceptible to the human eye.

For Wonder Buffalo, BeBop client software was installed on the editor and the assistant editor's individual computers. However, the consistent bandwidth available varied and at times was less than what BeBop recommends, which created an inherent lag when interacting with the remote desktop. In most frameworks, playback and editorial are best done with immediate machine response – editors cannot afford to miss a frame. For that reason, using BeBop for this production presented an interesting task for editors. They had to constantly juggle the benefits of remote collaboration with the challenges of latency. After a slight adjustment curve, the task became much easier and the benefits of Cloud-based collaboration outweighed issues with latency.

It is worth noting that latency with sound sync was also a concern. While working together, the director and editor regularly questioned whether picture and sound were in sync. Discussion with BeBop after the project concluded suggested that Internet speed played a significant factor in latency. When the editor worked from home, for example, latency issues were fairly noticeable. However, when she worked from USC, the latency issues rarely occurred.

For any film, the need to balance project timelines and editing quality is apparent. However, a large takeaway from *Wonder Buffalo* is that challenge is only heightened for Cloud productions. By allowing for remote, cross-team collaboration, BeBop helped make sure the *Wonder Buffalo* project was able to deliver edits in a much more time-sensitive manner.

Latency also poses potential problems for color critical applications. Virtual desktops across wires have perceptual compression (such as jpeg), so not all the data is consistently present. In these formats, the user is only shown what is relevant and prioritized. This is incredibly useful in terms of performance. However, while virtual desktops operate quickly and without perceived data change, in actuality there is less data in the background.

As image and video assets become more intricate, the performance provided by compression becomes indispensable. This is especially important for VR pieces due to the complexity of the footage. To capture in 360, an incredible amount of images needs to be processed all at once. By compressing these images, the editors were able to work on them in a more efficient fashion.

Additionally, the collaborative aspect of BeBop allowed for multiple eyes to be on the same piece. This was not only useful for increasing editing efficiency, but also for maintaining attention to detail. In the context of *Wonder Buffalo*, it was often noticed that the quality of edits produced by multiple editors collaborating frame-to-frame was much higher than those produced by individual efforts.

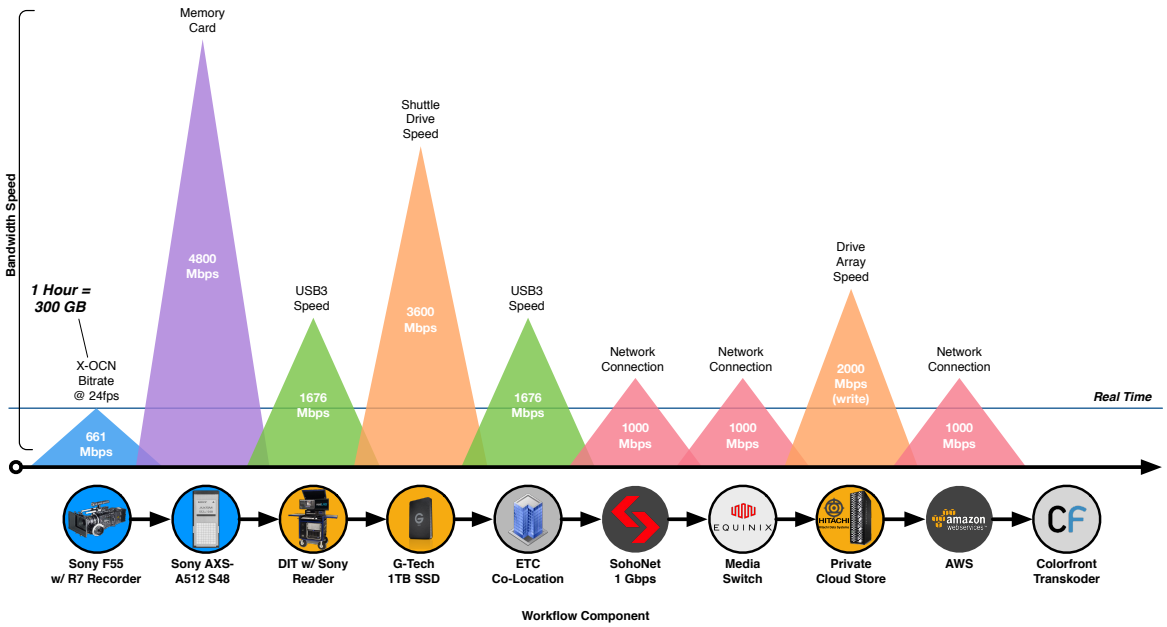
Nonetheless, this project team did wish that problems with latency could be somehow ameliorated. One

possible solution hypothesized during the production is that of a web browser where one would send all information on a webpage to individual users and then the browser would render it. This allows all interactivity to exist locally. All the tools necessary for media production ideally need to be local tools talking to the Cloud rather than tools existing on computers in the Cloud.

"The single biggest challenge for the media and entertainment industry is still understanding how to add the Cloud to existing workflows," stated Josh Kolden. "Traditional Hollywood is spending more now to make films than ever in history. It is the primary revenue generator. They compete directly with YouTube, and Snapchat is based on the cheapest possible model for entertainment production and delivery. They are constantly in a battle to reduce costs and see Cloud as a way to potentially reduce costs. Reducing production costs by scalability is still the biggest hope for Hollywood to maximize revenue." The biggest challenge is figuring out how to complement existing workflows.

3C. DATA BANDWIDTH

For several large deliveries of raw footage, we relied on sending hard drives to ensure we had the same reference for all files a technician might need. An initial concern was the speed of upload and transport between parties as it is directly tied to the speed and stability of the server. When working with the Cloud we had no bottleneck in the bandwidth to transport files. This was due to the network between Amazon and Technicolor, which was large enough so that we were never limited.



Wonder Buffalo - Bandwidth Flow
Version 1.1 / November 2, 2016

4. HIGH DYNAMIC RANGE

4A. ACES

In order to facilitate the HDR workflow process, the Academy Color Encoding Specification (ACES) was

used as the color pipeline for the project. ACES is a framework for motion picture color management with the intent of providing a vendor-agnostic color standard for digital cinematography files. This standard aids in making color pipelines across departments more efficient and future proofing archive files as display technologies progress.

For this project, ACES was used as the underlying format throughout the process including on-set. Much of the viewing was done through ACES using Technicolor's DP lights. Additionally, we used the ColorFront Transkoder with downstream transcodes created through ACES and conducted color grading on 4K ACES EXR files in DaVinci Resolve.

One aspect of ACES not used was ACESclip which provides a standardized "sidecar" XML capable of cataloging all of the relevant ACES components used. This makes sure that proper configuration and viewing can be guaranteed as files move downstream in the workflow process. While not used for the *Wonder Buffalo* production, it is highly recommended for any future productions using the ACES framework.

4B. PRE-PRODUCTION

Prior to principal photography, the production coordinated a test shoot day focused on wardrobe, lenses, and exposure on the F55 camera and Sony HDR monitor. This allowed the production a chance to ensure proper calibration of the HDR monitor, assessment of the Look-Up Table (LUT) for production, and a chance to see in real time how materials aesthetically look on the final display for HDR.

Based on this test shoot, the production sent the monitor to Technicolor to be recalibrated and sent any relevant notes regarding the LUT. Additionally, the team assessed the aesthetic of different materials based on the HDR display as well as the exposure of scenes. An interesting note from cinematographer Jon Keng was that the noise or grain in the image that goes relatively unnoticed when shooting in low lighting situations appeared much more visible in HDR. Additionally, the soft roll-off of highlights that we are accustomed to with theatrical aesthetics did not occur in HDR.

4C. PRODUCTION

The production captured on the Sony X-OCN ST codec ensured a high resolution and wide dynamic range with a smaller file size for storage. While trying to be economic with the size of the data wrangled daily on set, the production had to be sure to capture as much information as possible for the HDR grade. Additionally, there was a large focus on archiving the image for any potential future content grades.

On set, a DIT cart from Technicolor was operated by two student volunteers who would copy all materials to the central hard drive and run C4 ID's for the materials. Afterward, the footage was sent to Technicolor Dailies Services where (2) 3D-LUTs were applied for the outputted dailies to support the on-set ACES workflow. The input LUT was Slog3/SGamut3 to ACEScc (Input Device Transform) and the output LUT was ACEScc to Rec. 709 1000 nit (Output Device Transform).

4D. POST-PRODUCTION

The editorial process was done entirely on files transcoded to DNxHD 115 for editorial. The dailies' LUTs were also applied to it. When exporting the picture locked sequence, the editor submitted an EDL to Technicolor, which was used to pull the raw footage from storage into the color grading session.

4E. COLOR GRADE

Using ACES workflow for HDR production, the footage was first prepped for a Rec.2020 HDR master. While coloring the project, this workflow did present challenges in creating the look in HDR that the director envisioned theatrically. Specifically, the soft roll-off of highlights between the theatrical and standard definition color space was substantially different in HDR. The information in the highlights remained, making the image extremely contrasted when trying to blow them out in the HDR color grade.

Once the HDR master was created, the ACES algorithm adjusted the project into a DCI-P3 color space for the theatrical master. The remapping was near perfectly automated with only special attention needing to be paid toward the highlights that did not translate as well as the other exposures.

Once the theatrical master was completed, the ACES workflow next transitioned the project to a Rec.709 color space for the standard definition master. Again, the image near seamlessly transitioned into the SD color space.

One interesting observation was how editing in the highest resolution possible ultimately produced the best version of the film in SD. For that reason, we found that if you edit HDR first, you will save time because in the long run the optimal version of SD will be produced.

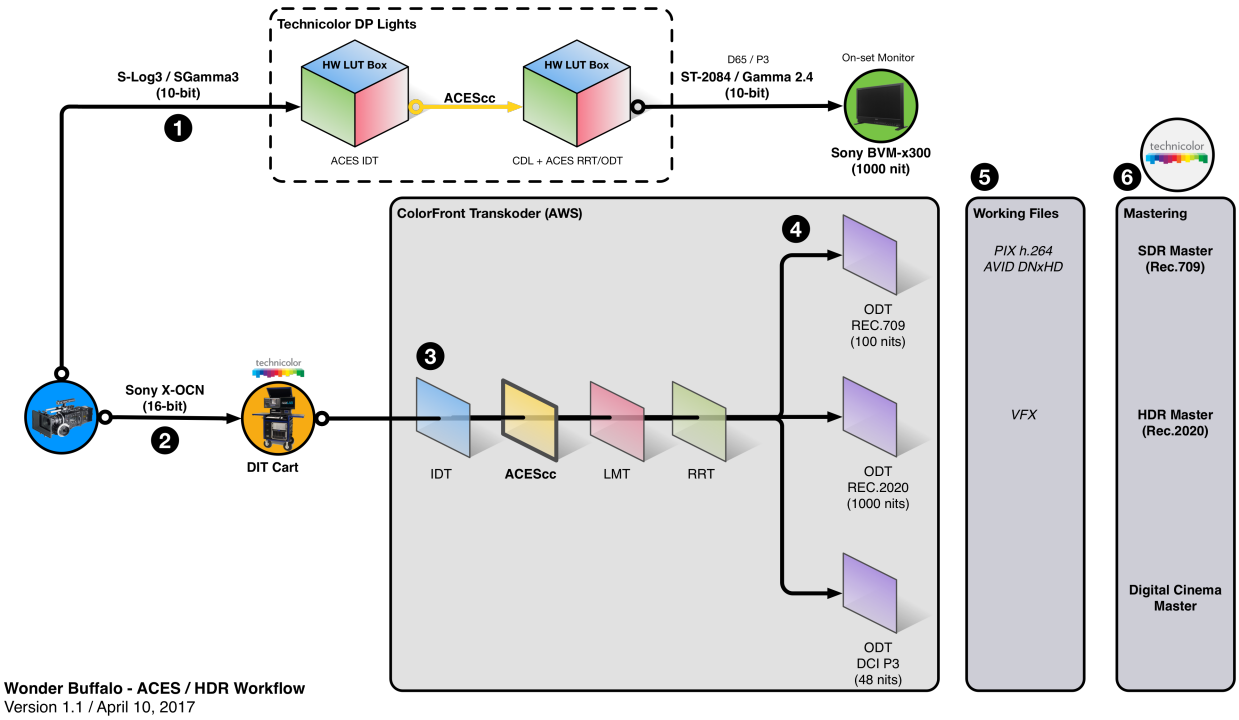


Figure 4.1: **1)** Camera monitor output is routed through Technicolor's DP Lights solution where the Sony S-Log3/SGamma3 signal is converted to ACES and then converted a D65/P3 output signal for on-set monitoring. **2)** Camera RAW recorded files (Sony X-OCN ST) are ingested on the DIT cart. **3)** ColorFront Transkoder applies the ACES process to first convert camera RAW files to ACES and applies any CDLs and/or Looks. **4)** Transkoder then transcoded downstream files in their appropriate color spaces from the ACES "digital negative". **5)** Working files are created in their appropriate format for dailies, editorial, and VFX. **6)** 4K ACES EXR files are created for mastering with the primary grade done in HDR (Rec.2020) and subsequent grades created through ACES with an additional trim color pass.

5. VIRTUAL REALITY

For further reading see WbML White Paper for *Wonder Buffalo*.

5A. STORY DEVELOPMENT COLLABORATION WITH THE USC WORLD BUILDING MEDIA LAB

For the story development of the virtual reality experience, the production partnered with the World Building Media Lab (WbML) at the University of Southern California's School of Cinematic Arts. Building upon principles of cinematic storytelling and game design, the WbML utilizes its own "world building" methodologies to enrich narrative experiences by focusing on the world of those stories. The WbML then uses cutting-edge technologies to create those worlds, often developing new methods of interactivity to enable previously-unseen experiences in spaces beyond movies and games. Through multiple explorations into virtual reality, augmented reality, and mixed reality, the WbML has established itself as a leader at the cutting edge of storytelling.

5B. WORLD BUILDING IN STORY DEVELOPMENT

The WbML was founded in 2012 by Alex McDowell RDI. In addition to being a professor in the Cinema School's Media Arts and Practice division, McDowell is also the celebrated production designer behind such films as *Minority Report, Fight Club, Man of Steel,* and *The Crow.*
In 2016 the WbML began a new research project, code-named "Project Tesseract," that explored how pre-production processes must be reinvented to accommodate VR and AR. These new mediums are more "spherical" than traditional linear filmmaking, and must be treated accordingly.

5C. BUILDING THE WORLD OF WONDER BUFFALO

Wonder Buffalo served as a real-world test for the WbML's reimagined pre-production process, streamlining collaborations between the film production and VR departments.

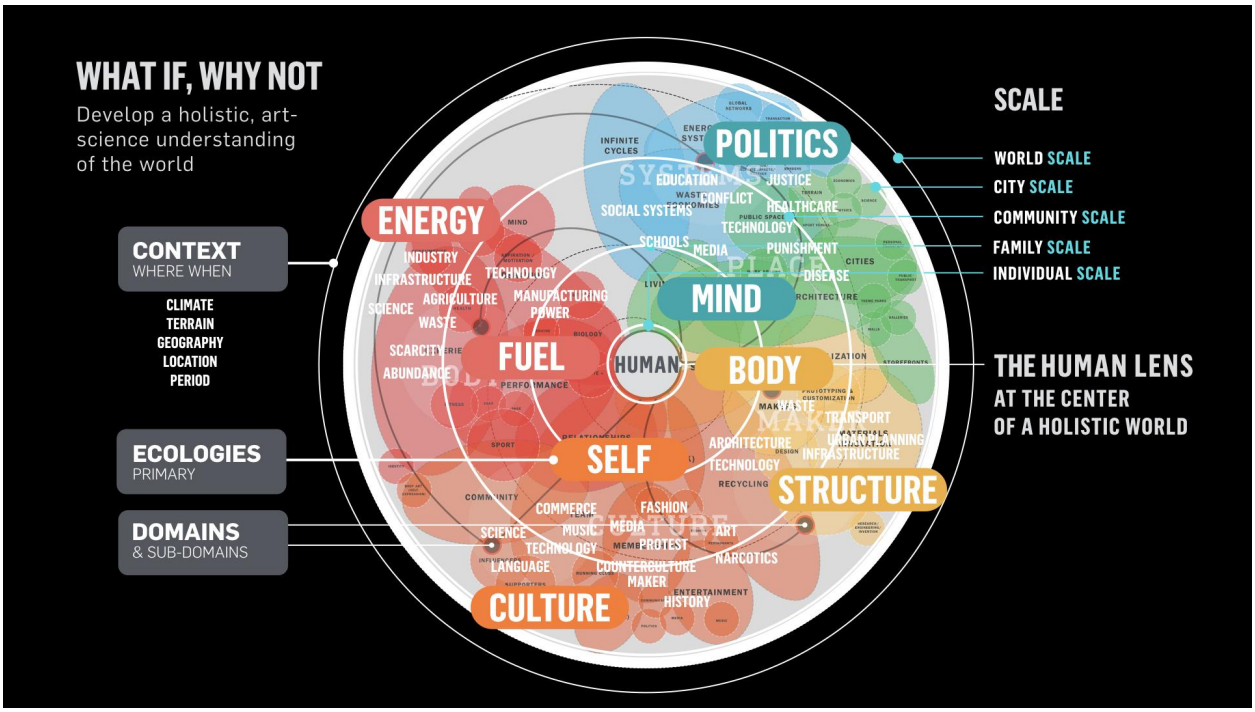
Wonder Buffalo began with an existing script for a short film. However, as the project evolved into a transmedia experience with a virtual reality component, the team applied the WbML's methodology to craft a world bible unifying the tone, rules, and logic of the world across the film and the VR components. The project's world builder, Brandon Cahoon, describes this process as "gathering all the connected knowledge associated with the world being built, developing a holistic art and science understanding of the world through rigorous research."

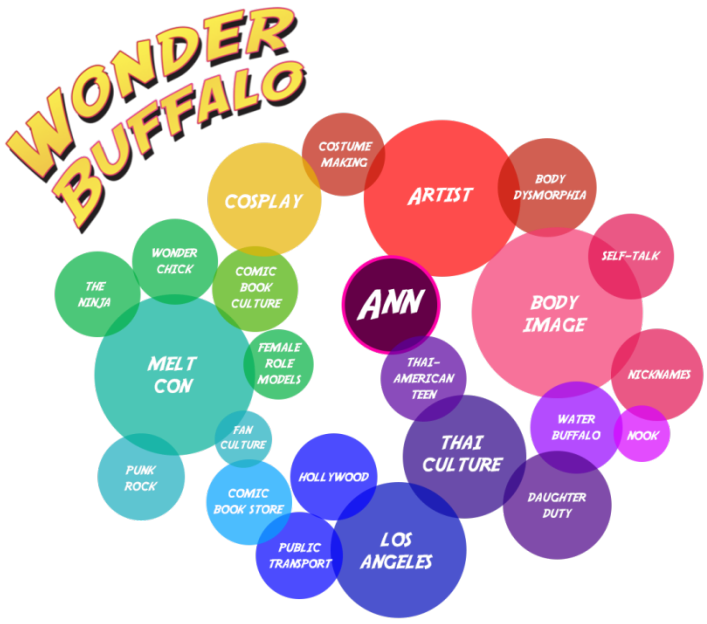
To populate this world bible, Cahoon and director Christine Berg discussed in detail the world of her script and her inspirations, identifying key research topics and domains, creating a world map for the protagonist, and establishing the rules of the world. Keeping the "human lens" of Ann squarely at the center of their exploration, Cahoon and Berg organized the following primary domains and rules for the world of *Wonder Buffalo:*

When: 2016
Where: Thai Town, Los Angeles

- Thai culture clashes with American youth culture
- "Daughter duty" reigns, a cyclical, familial pressure where young Asian girls are expected to marry well so they can support their parents
- Ann is most alive when engaged in comic book fiction, especially featuring empowered female superheroes

- Ann's taste in music and men is wise beyond her years
- Ann's body dysmorphia and weight equates to the amount of love or connection she deserves
- Ann is anti-social, a misfit





Prompted by these discussions, the world building team set about conducting deeper research into:

- LA Teens
- LA Teens + Metro

- LA Teens + Cosplay
- Thai Town + LA
- Body Dysmorphia
- Wonder Woman + Fan Culture
- Los Angeles National Guard

As the world building process continued, it expanded to include members across every part of the creative team, including film production, sound design, computer programming, animation and production design – allowing every crewmember across disciplines to draw from their shared visual references and research of the story and the larger world.

The WbML's world-centric pre-production process aimed to break down departmental barriers, facilitate more constant communication across teams, enable more informed decisions earlier in the production process including changes to the script and clarifications to the story's theme.

An example of this process was utilized in planning the film's opening scene. During a VR meeting, as the director discussed power props with the team, she realized that the water buffalo prop would be a perfect image to begin the film on. Noting that "the symbol's meaning paralleled the protagonist," the director then proceeded to integrate the shot into the schedule with the cinematographer.

5D. STORYTELLING IN VR - NARRATIVE & INTERACTIVITY

When the VR creative team first met, the meeting began by asking: What makes for a good VR experience? Why should a story be in VR? What type of stories resonate in VR? What can VR do with a story that film cannot?

Identifying the VR experience's need for interactivity, room-scale movement, and photogrammetric environments directly impacted the production's technical choices on software and hardware tools for principal photography.

The team decided against utilizing 360 video for the VR complement as this medium has been historically better suited for documentary behind-the-scenes marketing activations for films. The intention of the VR component for *Wonder Buffalo* was to extend the film experience and immerse the viewers into the world of the film and give them the freedom of agency to be a part of the story.

However, there had been a conversation brewing in the industry claiming that interactivity is the enemy of narrative. So the team set out to test this theory by creating a cinematic room-scale VR experience utilizing real-time rendered interactive elements enabling the viewer to create their own narrative within the world of the existing film's story.

With the idea locked to make an immersive room-scale VR experience, the director and VR team went through the script to determine which location would be best for the setting. Ann's bedroom was chosen because the scene that takes place there between Ann and her overbearing mother encompasses the main tension of the film and could serve as a stand-alone experience. For that reason, the production used the scene to set the relationship and dilemma for the protagonist.

From there, the user would engage in a "hunt-and-gather," "acquire-and-activate" experience with several "power objects" each tied to the personality of Ann and the thesis of the director that "art and creativity overcomes negativity".

5E. SCRIPTS IN VR

A major question discovered in the process of the VR development was what exactly a "VR script" looked like. In a traditional script, you use minimal words and rely on action verbs to convey the scene along with dialogue. Yet, in an interactive VR experience a viewer has complete free will to elect the path that they follow within the virtual world. To address this, we created two separate scripts, one that focused on the story beats and interactivity and a second detailing blocking and dialogue for the narrative scene. Go here for the scripts: http://etcusc.co/2CzFgKM

5F. STORYBOARDING FOR VR

Previsualization of the 360 environment was key to getting all departments on the same page regarding the richly imagined world. Three major previsualization steps allowed the cast, production crew, and post-production team to understand how their individual contributions would fit into the final scene:

1. Rough block out of the 3D bedroom environment built to scale in Maya and imported into Unity to allow the viewer to inhabit the space and walk around it at scale. Director Christine Berg used this view to get a sense of the space and the ideal placement of the interactive objects in the scene.
2. Traditional rectangular storyboard frames that showed the key points of interaction.
3. Rough photogrammetry capture of the bedroom set imported into Unity before the day of volumetric character capture, so that the actors could put on the headset and understand their relative position in the space compared to the other characters and key props.

5G. DESIGNING THE PRACTICAL LOCATION FOR VR

How do you tell a large expansive story in a small space? Ann's bedroom is an extension of herself, with every bit of the set's dressing and props telling the audience about who she is and what she values. For that reason, the world builder and director designed questions to clarify for the team the underlying meaning of the experience and interactions within the space:

Experience - What does the user get to do?
Theme - What's the experience about?
Point of View - 1st person or 3rd person? What does the user see, feel, and hear?
Challenge - What kind of challenges does the experience present?
Decision-making - Where does the user make decisions? How does the user make decisions?
Skill, Strategy, and Chance - How much agency does the experience allow the user?
Context - Who is the player? Why are they playing it?
Emotions - What emotions might the experience create in players?

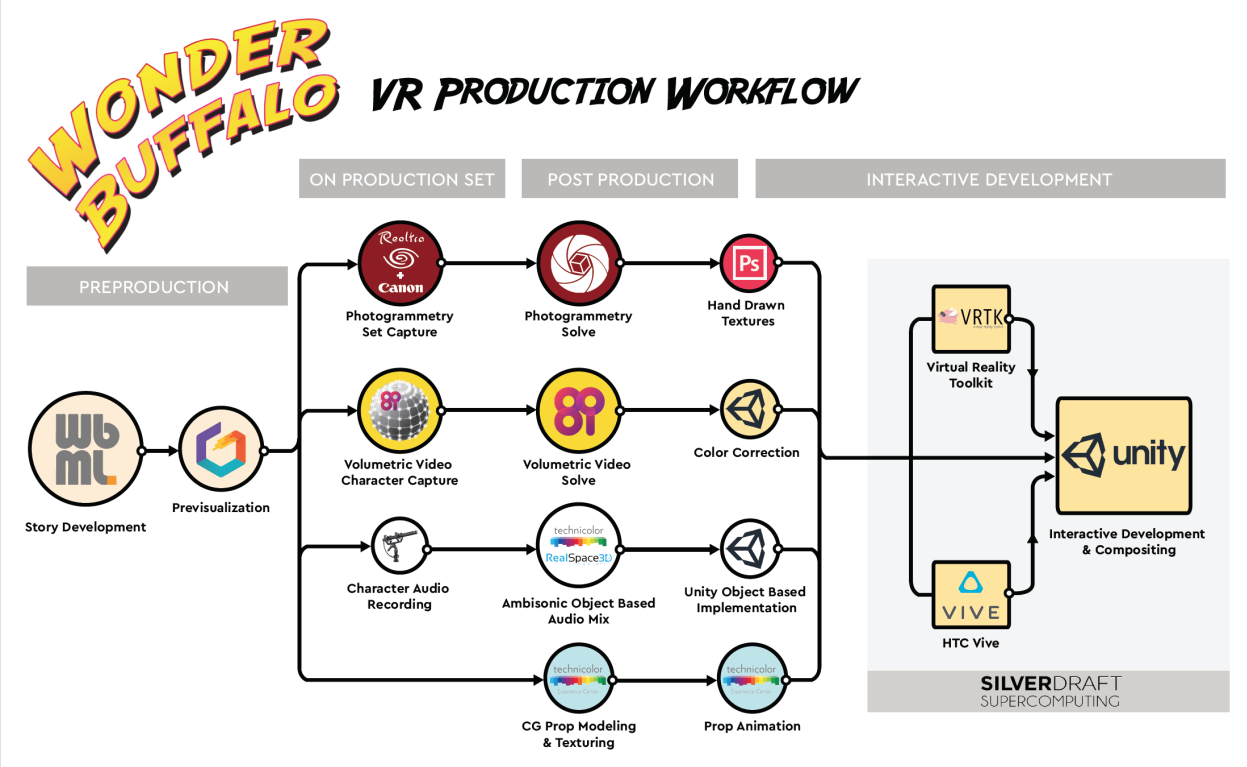
STRENGTH OBJECTS AS CHARACTER STUDY

Every object in Ann's bedroom has its own history and unique meaning. Together, these help the audience to understand the many different sides of Ann. The six strength objects act as metaphors for the most active parts of Ann's personality:

- Magic Marker - Ann's imagination
- Record Player - Ann's spirit
- Poster Art - Ann's creativity
- "KAPOW!" Word Pillow - Ann's will
- Water Buffalo Figurine - Ann's sense of Thai culture
- Handmade *Wonder Buffalo* Costume - Ann's search for freedom

VR PRODUCTION

The goal of *Wonder Buffalo*'s VR production was to combine different photo realistic volumetric capture techniques and bring those results into a game engine to create a fully immersive walk-around experience. This was achieved by incorporating the latest techniques in photogrammetry environment capture, volumetric actor performance capture, and positional VFX. A new workflow was developed to bring all of the assets together in tandem with a traditional 2D short film production.



5H. PHOTOGRAMMETRY

Photogrammetry was determined to be the best approach to capture the bedroom set from the film and recreate it as a virtual environment for the VR experience. The set was captured using over 1,000 individual pictures taken by Realtra volumetric supervisor, Rainer Gombos, with a 50-megapixel digital SLR camera.

The environment was then recreated utilizing a photogrammetry software called Capturing Reality. Capturing Reality was able to produce a "solve" by creating the 3D geometry of the bedroom with high-res textures from the individual photos. The Technicolor Experience Center's modeling team in Bangalore, India then simplified the mesh and polygon count to optimize for real-time performance before the environment was brought into Unity. Porting to Unity produced a virtual environment that allows viewers to walk around within and explore. Given that the environment was a bedroom, its scale worked very well for the HTC Vive room-scale VR system, and felt very natural within the constraints of the play area.

5I. VOLUMETRIC CHARACTER CAPTURE

In order to volumetrically capture the actors' performances, an "outside-in" video-based capture system was required. The 8i capture with its 36 high definition cameras was used for actor performance

capture. Since the capture diameter of the system is limited to about one meter, actors were captured one at time in a technically challenging setup that made rehearsal, previsualization and preparation key to the success of the shoot. Only one actor could be within the 360-degree green screen volume of the stage at a time, so proper eyeline measurements had to be taken from the actual bedroom set ahead of the 8i shoot to ensure the two characters' eyes would meet when they were placed into the final Unity environment. For the first take, one actor stood inside the volume while the other actor stood outside of the stage to feed lines for timing. Once the select take from the first actor was chosen by the director, this take was used for audio playback to the second actor in order to ensure perfect sync between the two performances. This was necessary because any editing of the volumetric captures after the fact would require dropping frames, which would lead to jumps in the character poses in the final environment.

Processing of the video to render out volumetric video assets was performed using 8i's custom rendering pipeline. The resulting solves were then imported into the Unity virtual bedroom environment, where they were color graded to match the bedroom lighting using 8i's color correction plugin. It is important to note that 8i's technology does not (at the time of this writing) allow for real-time lighting of the captured assets, so beyond basic color correction the look of the lighting must be baked in to match the final environment. In our case, since flat, uniform lighting captures best on the 8i stage, we lit the entire bedroom for photogrammetry capture in a way that would match this flat, diffuse look of the 8i characters in the final Unity scene.

5J. INTERACTIVE CG IN VR

Maya was used to create the interactive elements scattered around the bedroom scene, with two teams working in different locations. Modeling, texture, and rigging were created by a team of USC students using Maya. Modeling cleanup, animation and bedroom retopology was done by the new VR/AR-focused Technicolor Experience Center's dedicated team in Bangalore. Once animations of the CG assets were complete, they were exported into a Filmbox (FBX) format for import into Unity.

A custom shader was developed to allow customs transitions between two textures on bedroom walls, starting with the realistic photogrammetry textures and transitioning to stylized artistic textures created by a team of talented 2D artists, including lead artist Kathy Liu and director Christine Berg.

5K. CLOUD WORKFLOW/PIPELINE & ASSET MANAGEMENT IN VR

Various tools both local and Cloud-based were utilized in the creation of the VR portion of *Wonder Buffalo*. The status of the assets that needed to be created by various artists were tracked by our production manager in Shotgun while our main storage repository for those assets resided in a file directory hosted on Google Drive. Our lead VR developer architected the directory for collaborators to upload their assets as they were completed, which could then be downloaded by developers to implement and update into the Unity project. Most feedback demos for updated Unity build versions were done in person except for the progression of the photogrammetry model of the room, which was hosted on Steam app Destinations.

The volumetric supervisor uploaded each version of the photogrammetry .obj solve into destinations for everyone with an HTC Vive headset to download and preview from the Destinations app. Notes were then given and new updated versions were uploaded based on those notes. Once the final .obj photogrammetry background model was approved, it was uploaded to Google Drive by the volumetric supervisor in Beverly Hills and downloaded by the lead VR developer at ETC.

After production, Trello boards allowed us to efficiently track all tasks and progress between the distributed post-production and development teams. After final approvals, all of the elements and various formats were brought together for real-time rendering in the Unity Game Engine.

Git management and source control through a Github Cloud repository was set up early in the Unity project to track changes between developers, but the project file size including the heavy volumetric character capture frames soon caused major issues with this centralized Cloud collaboration on the final project. Despite the integration of Git LFS (large file storage), any pushes or pulls to the remote repository would hang up after the .git file grew beyond several gigabytes and the project grew to over 20 gigabytes. Source control solutions specifically tailored to large game assets such as Perforce or PlasticSCM may provide better solutions for such issues for future projects, but the licensing costs were prohibitive to their implementation on this project.

5L. IMPACT ON PRODUCTION

By locking Ann's bedroom set as the location of the VR experience, we needed to capture a 360 view of the room. Most sets are only partially dressed or even constructed in order to save time, money, and resources. This decision meant that we would either have to build a full room with ceilings to facilitate filming and VR capture, or shoot in a real location. Due to budgetary constraints, we chose to film in a practical location and set dress it for 360 capture.

Once we identified the "power props," the world builder and production designer coordinated with our photogrammetry expert Rainer Gombos to have volumetric captures of the props prior to the on-set photogrammetry capture.

For the volumetric captures of the performance, we initiated discussions with 8i and Uncorporeal, when 8i graciously agreed to come on as a partner and donate stage time and post-processing in order to test the current limits of their technology and showcase the state of volumetric capture to the industry. Since the time of our production, several other players have come out with volumetric capture solutions, and 8i has continued to improve upon its capture technology and features.

5M. SCHEDULING AND BUDGETING

Wonder Buffalo was a 5-day physical production. To include VR into the production window, a second Unit VR team captured the set the day following the shoot. The volumetric performances were captured during an off day for the performers. In total this added 1 full day to the talent and director's schedule as the set capture was overseen entirely by the VR unit. While this was a minimal addition to the physical production, the amount of development time cannot be stressed enough, as the prep for the VR portion was equally time consuming to develop and prep in tandem with the physical production.

Through donations from our sponsors and other affiliated vendors, the team was able to execute the VR piece on a minimal budget.

While there were substantial costs to execute a cinematic VR experience at the level of this production, the ability to execute the VR capture in tandem with the short film saved money by allowing the art department, properties, set dressing, and wardrobe to capture their items in advance. This facilitated their use on the days of photogrammetry and videogrammetry captures without needing any

additional rental days. The most money was saved by choice of location, which had been prepped for 3 days prior to shooting. By adding the VR capture to the end of a location's use, it only required one additional day of location rental.

5N. CROSS MEDIA COLLABORATION

The importance of communication is key in any production, but especially so in a cross-media production. *Wonder Buffalo* had to create new workflows and build onto workflows that have long been cemented in other disciplines such as game design or film. In an effort to streamline communication and engage all departments, we had meetings that involved all creatives from VR production to physical production to maximize our time and brainstorming sessions. This provided unique problems and opportunities to explore and helped organize the sharing of information across all departments.

Wonder Buffalo's production was unique, with VR being developed and executed in parallel with the linear film. In an effort to facilitate communication, we utilized multiple different collaborative sites and apps. Trello and GitHub were used with the developers while Slack was used by the creative teams to share research, location scout images, concept artwork, costume design, art reference, and meetings notes across all departments.

Open, active communication between the director, production designer, and world builder was key to making sound creative decisions. Additionally, we fused meetings and location scouts to have the key creative and tech team members weigh in. For instance, needing a 360 view of the room for VR capture placed constraints on shoot locations and the art department.

The set dressing choices had effects on the VR capture. Wardrobe had to do a camera test for VR prior to the shoot to know what materials captured best at 8i. All of these variables were new to the team, thus constant communication and inclusion in decision making became vital to facilitate departmental needs on a transmedia production.

6. SUPPORTERS and CONTRIBUTORS

This project would not be possible without the help from the following:

Supporters:
Disney/ABC Television Group, Warner Bros. Entertainment, NAGRA Kudelski Group, Technicolor, Sony Electronics, Amazon, Equinix, the Creative Visions Foundation, The World Building Institute, USC School of Cinematic Arts, and Universal Pictures

Contributors: