EDGE-BLENDING MULTIPLE PROJECTION DISPLAYS ON A DOME SURFACE TO FORM CONTINUOUS WIDE ANGLE FIELDS-OF-VIEW

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Summary

Juxtaposing several projector channels is a viable method of meeting the "wide angle field-of-view" requirement of many training simulators. Blending overlapped images on a dome surface can be done either optically by using lenses and optical filters or electrically by "rolling-off" the video signals at edge boundaries. The quality of edge-blending between projector channels can be evaluated by quantifying parameters like: registration accuracy in the overlap region, color match between adjacent channels, intensity variation across the edge boundary, brightness uniformity across the entire viewing area, and exit-pupil size. In some simulators wide exit-pupils (more than one eyepoint) are required. In these cases the quality of edge-blending is largely determined by the gain characteristics of the screen material used.

Introduction

Wide field-of-view projection systems are used in many of today's training and engineering simulators. As display system technology and CIG (computer image generator) technology rapidly advance, brighter, higher resolution, and more complex images are becoming possible. The contribution of high-quality edge-blending to these images depends on the type of visual simulation required. If training that involves tracking objects across edge boundaries is prevalent, color variations and image distortions across those boundaries will blemish the realism of the simulator. However, if constant and random eye movement is common, edge-blending problems might become less distractive because the trainee's mind is kept "busy" looking at other things. In either case, a high-quality edge-match improves the realism and appearance of a multi channel projection system.

The techniques of edge-blending adjacent projected images on a dome surface need to keep pace with the improving display and CIG technology. In the past, dim, low resolution projector systems displaying simple computer imagery could fare with an edge-match of relatively poor quality. If the projectors displayed background images only, typical scenes were dim, fuzzy, and simple enough that the edge-blending was of little consequence. As scene brightness, resolu-ion, and complexity increase, any color mismatch or geometric discontinuity between juxtaposed projection channels becomes increasingly noticeable and distracting. Since the brighter, higher resolution projector systems available today display CIG scenes that are rich with polygons and busy with complex textured images, better edge blending techniques than were used in the past have become necessary.

Optical Versus Electrical Edge-blending

Quality edge-blending requires that two conditions be met:

(1) Accurate geometric registration across the edge boundary

(2) Careful video-blending (intensity blending) of the overlapped images

These conditions can be satisfied by optical and electrical techniques. Both have advantages and disadvantages. As shown in figure 1a, the amount of distortion correction necessary to geometrically correct and edge-match projected images can be significant. Off-axis and asymmetrical projections on a dome surface typically have keystone, trapezoid, pincushion, linearity and a variety of other types of distortions. Before a quality edge-match can be realized, these distortions must be corrected and the position of these corrected images needs to be adjusted for accurate registration in the edge-blending region.

The edge-blending region is usually not rectangular (figure 1b). Two channels might overlap 48 pixels at the top but only 16 pixels at the bottom depending on the off-axis geometry. This is an important consideration when blending adjacent scenes.

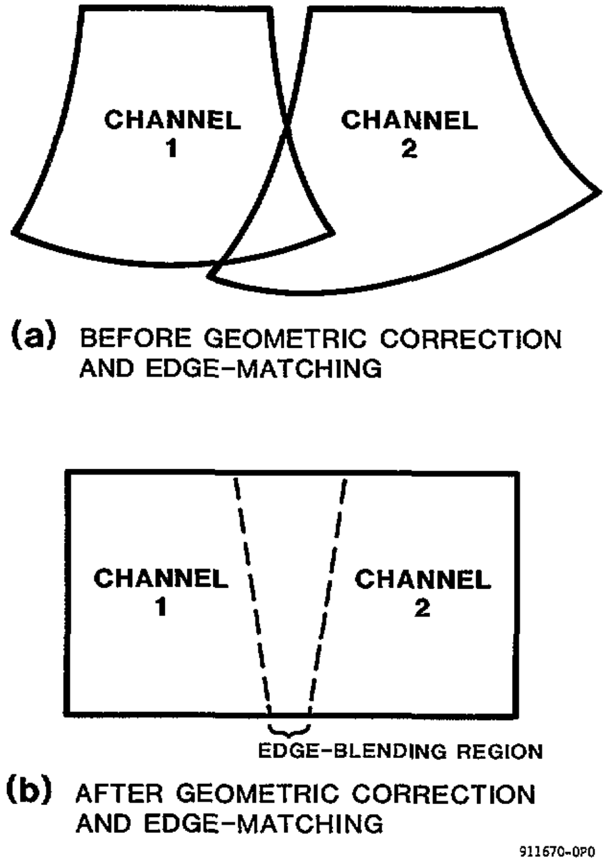

Figure 1. Edge-Matching Can Require Significant Distortion Correction If Off-Axis Images Are Projected On A Dome Surface

A fixed "video roll-off width" referenced to the raster edge would yield an undesireable result. Projected overlapping images should sum to a uniform brightness in the overlap region.

Optical Edge-blending

Edge-blending done entirely in the optical domain implies that the system optics perform both geometric distortion correction and video-blending. Projector systems that employ optical techniques for edge-blending usually do so because system components preclude using the more flexible electronic techniques.

Several drawbacks to optical distortion correction are:

- Customized optical components are expensive
- Optical components are heavy and fragile
- Optical designs can usually accommodate only one system projection configuration
- Channel overlap registration is usually poor due to the inability to fine tune geometry

Even with these drawbacks projection systems using optical correction techniques have performed adequately as low-resolution background projectors when the scene brightness was 1 foot-lambert or lower, especially if the main focus of attention was a brighter, higher resolution target projector or area-of-interest (AOI) projector.

Video-blending can be done optically by using neutral density filters in a real image plane to attenuate the projected light at edge boundaries. This conceptually simple technique is a low cost solution to video-blending if a real image plane is available. These filters are usually customized for a particular system configuration and require mechanical alignment.

Electrical Edge-blending

Electrical edge-blending denotes that: distortion correction is done by predistorting the image before it is focused by the optical system, and video-blending is done by "rolling off" the video signals in the overlap region.

The predistortion or non-linear mapping (NLIM) of the CIG image can be done in the CIG, in the projector, or both. Exactly where it is done is dictated by the CIG and projector capabilities. For instance, most light-valve projectors can not change the shape of their raster so any predistortion must be done in the CIG. The disadvantage of doing NLIM in the CIG is a loss of resolution. If the system distortion requires a compressed image in an area, NLIM done in the CIG would squeeze the information for that area into fewer pixels. However, if predistortion is done in the projector by actually changing the shape of the raster, resolution need not be sacrificed. In a CRT projector, if the amplifiers and phosphor can accommodate the distorted raster without a loss of resolution, then a uniform resolution will result after the image is expanded by the system optics.

Accurate geometric registration in the edge-blending region is critical to achieving a quality edge-match. Electronic control of image distortion is much more flexible and inherently more accurate than any type of optical correction technique. If system distortion correction is done by the projectors, very accurate inter-channel convergence can be realized with real-time interactive alignment procedures. A cathode-ray-tube (CRT) projector has been developed that can achieve sub-pixel registration accuracy of overlapping images via such an interface. A pixel-size light point traversing an edge boundary would have no noticeable image discontinuity as it moves from one channel to the next.

Electronic video-blending is a flexible and potentially accurate means of blending overlapping images. Real-time interactive software control of the blending process permits precise line-to-line adjustment of the video-blending. If the edge-blending region has a trapezoidal shape (figure 1b), either the "blending width" or the "blending start position" must vary line-to-line to achieve a quality edge-match. This kind of real-time computation and software control is easily accommodated by digital circuits and microprocessors.

Besides the "width" and "start position" of the roll-off function, the shape of the roll-off function is important. When blending images, any non-linear video characteristics like "projector gamma" must be calculated into the shape of the roll-off function. If these non-linear characteristics are ignored, the edge-match uniformity will vary for different brightness levels. In a CRT projector, if gamma is handled improperly, a seam might look fine at low light levels but appear as a dark stripe for brighter scenes. Figure 2 shows the effect *gamma has on the shape of roll-off functions.* If the video roll-off is done prior to gamma correction, a simple linear roll-off function can be used (figure 2a). If the CIG does gamma correction prior to video roll-off, an "inverse gamma" shaped roll-off function is needed (figure 2b). If a linear roll-off function is used with a post-gamma video signal, distractive stripes that vary with scene brightness become evident in the edge region (figure 2c).

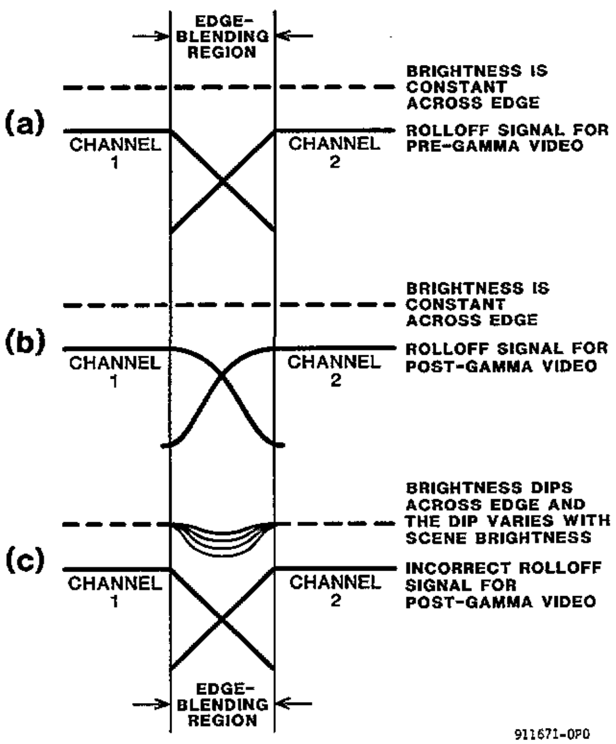

Figure 2. Video Roll-off Function Versus Edge Brightness Uniformity

Incorrect roll-off functions can be partially compensated by increasing the amount of channel overlap. Increased channel overlap seems to lessen the distraction of "misconvergence and stripes" in the edge by lowering mach-banding effects. This technique has the disadvantage of reducing CIG polygon capacity. As channel overlap increases, more and more redundant information is being displayed. A six degree overlap in a sixty degree field-of-view CIG channel equates to a 10% loss of polygon capacity for that channel! It would be more cost effective to attain the proper roll-off function and reduce a six degree channel overlap to a one or a two degree channel overlap.

Hybrid Edge-blending

Hybrid edge-blending implies that either the distortion correction or video-blending is done or enhanced optically. A projector system might use optical distortion correction but do video-blending electronically. Or, a system might use optical distortion correction for gross corrections only and employ electrical techniques for doing fine tuning of the geometry. A hybrid approach makes sense when already purchased system components dictate a mixed solution.

Quantifying Edge-blend Quality

The quality of edge-blending is more a subjective measurement than an objective measurement. Even if exact radiometric equivalence can be achieved across an edge boundary, the perception of edge quality can vary slightly from one person to the next. The quality of edge-blending that satisfies a particular situation is even more subjective. If constant and random eye movement is prevalent in a training situation, slight edge-match aberations might not be noticed. Even so, high quality edge-blending is desirable because it improves the realism of a simulator by making the wide angle field-of-view seem contiguous to the viewer.

Quantifying an edge-match is necessary to compare the quality of edges in different systems. Such quantifying results in a definitive edge-matching specification that enables simulation system users to compare various display system performances. Five parameters that should be quantified to characterize an edge-blend are:

(1) Registration accuracy in the overlap region

(2) Color-match between adjacent channels

(3) Intensity variation across the edge boundary (for both high and low video levels)

(4) Brightness uniformity across the entire viewing area

(5) Exit-pupil size

Each of these parameters has a measurable effect on the quality of edge-blending in a multi-channel projection system.

Registration Accuracy

As mentioned previously, the accurate registration of overlapped images is critical to achieving a quality edge-match. Any noticeable image discontinuities are distracting and decrease the realism. Overlapping images should register at least as accurately as the color convergence specification for a single channel. If the channel convergence requires accuracy to 1/4 pixel, then the registration of overlapped images ought to be accurate to 1/4 of a pixel. Anything less implies the appearance of the edge is less important than the center of a channel. This is not true in a multi-channel projection system with a continuous field-of-view.

Color-match

Figure 3 shows the human eye to be more sensitive to color variations than intensity variations. At 550 nanometers (green), the eye can typically detect a color change of 2.75 nanometers or 0.5 percent (figure 3a) but it can only detect intensity differences of two percent (figure 3b). In a CRT projector system color-hues are determined by the relative intensities of three primary colors (red, green, and blue). If the red intensity in one of two adjacent channels displaying white rasters is adjusted until a color mismatch becomes perceivable, and then if the green and blue components are taken away so only the red rasters are viewed, there would be no observable intensity difference.

As video circuits drift in a multi channel projector system, the first noticeable effect is a color imbalance between channels. Maintaining a constant color temperature between adjacent channels is critical for maintaining a quality edge-match. Color differences should be kept small enough so there is no perceivable color change across an edge boundary.

Intensity Variation

This discussion of intensity variation assumes that perfect color-matching exists between channels and the colors track correctly through gray levels from white to black.

The amount of tolerable intensity variation across an edge boundary is a function of the width of the blending region. A 10% intensity variation might not be observable across a six degree blend but becomes objectionable for a three degree blend. Typically, for every degree of channel overlap, two percent of intensity variation is acceptable.

The intensity variation across an edge ought to be constant for all levels of scene brightness. An improper video roll-off function that does not compensate for non-linearities like "gamma" might result in a 4 percent variation for a night scene and a 20 percent variation for a full daylight scene. All scene brightnesses should conform to the same intensity specification.

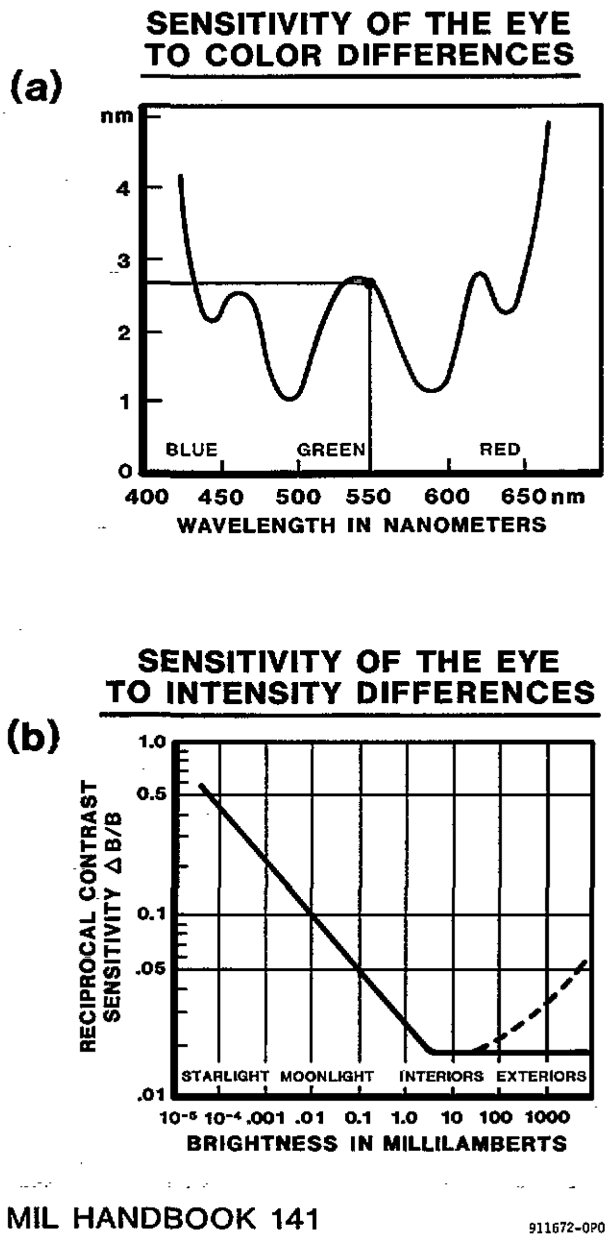

Figure 3. The Sensitivity Of The Eye To Color And Intensity Differences

Brightness Uniformity

As shown in figure 4, optical systems create a "radial brightness gradient" on the projection screen. This gradient is mostly caused by lens roll-off. Typically a channel is brightest in the center (region A) and dimmest at the corners (region C). Region B is called the edge brightness. If this brightness gradient is too steep, the edges are accentuated and become conspicuous. The smaller the "radial brightness gradient" the better brightness uniformity for the entire field-of-view.

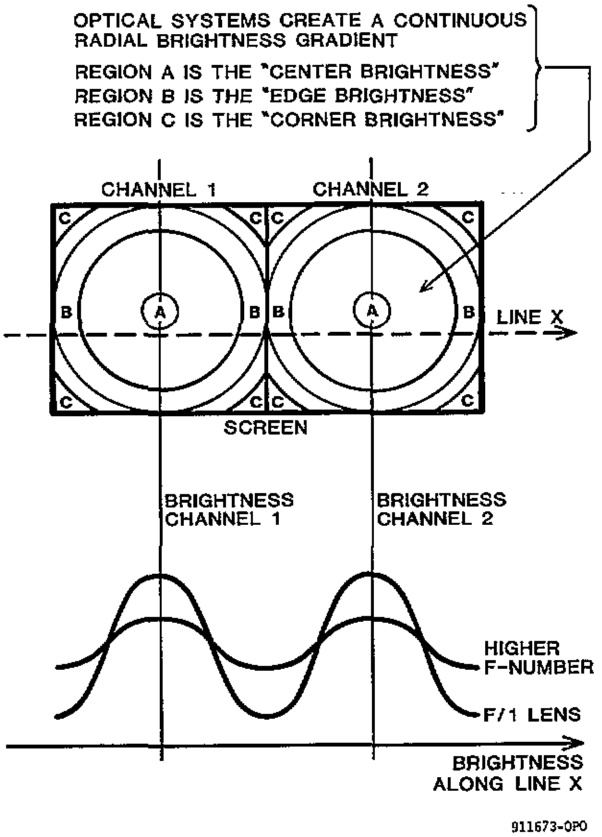

Figure 4. Brightness Uniformity Can Be A Function Of The F-Number Of The Projection Lens

In a multi-channel projector system the brightness in the center of a channel is just as important as the brightness at the edge of a channel. Brightness specifications for multi-channel projector systems can be misleading if only the center brightness is mentioned. The slope of the "radial brightness gradient" can be a function of the F-number for that system. F-numbers greater than one yield systems with more uniform brightness. As the F-number becomes smaller, the center of the channel becomes brighter but the "radial brightness gradient" becomes steeper (figure 4). Therefore, lower F-number optical systems can claim to have a greater brightness due to the increased center brightness but actually have inferior brightness uniformity.

Brightness uniformity is defined as the ratio of the edge brightness to the center brightness. If the edge brightness is 6 foot-lamberts and the center brightness is 10 foot-lamberts the brightness uniformity is 0.6. The brightness uniformity should be better than 0.75 for a multi-channel projection system with edge-blending.

Exit-pupil Size

The exit-pupil in a multi-channel projector system is the area from which quality edge-matching can be viewed. The actual size of the exit-pupil is determined by how the projected light rays are absorbed, reflected, and diffused by the screen surface. These characteristics depend on the screen material and are commonly defined as the "screen gain". If the image is viewed outside this eye envelope, a distinct brightness mismatch becomes apparent across channel boundaries. This is the result of the screen surface reflecting perceivably unequal amounts of light toward the viewer from adjacent projectors channels.

The exit-pupil should be large enough so quality edge-matching is viewed from all expected head positions.

Edge-blending With Wide Exit-pupils

Sometimes wide exit-pupils are necessary when more than one person will be viewing the projected images at the same time. A pilot and a co-pilot side by side in a helicopter simulator, or a driver with passengers in an automobile simulator, require that the exit-pupil be larger than just a few inches.

Simple screen materials with gain, like aluminum paint, have gaussian shaped gain characteristics which make them unsatisfactory for wide uniform exit-pupils. As shown in figure 5a, the "bend angle" is the angle between the spectral ray and the viewing direction. The reflected light for large bend angles varies steeply for materials like aluminum paint (figure 5b). This limits the size of the exit-pupil. The higher the gain of this kind of screen material, the narrower the exit-pupil becomes.

Lambertian screen surfaces are unity gain (or less) and scatter light uniformly in all directions. This is shown as a flat response curve in figure 5b. Lambertian screens yield wide exit-pupils, however, when used in domes the contrast ratio of the projected images is reduced since light is reflected equally in all directions instead of being directed to the exit-pupil. This "wash out" effect which impairs image quality can be less desirable than the narrow exit-pupil caused by an aluminum paint screen.

Ideally, to achieve quality edge blending throughout a wide exit-pupil, a screen material with gain that has a flat gain response over the required viewing angle is needed.

Special Screen Material

A special screen material having a flat gain response curve for wide exit-pupils has been especially developed for dome simulator applications (figure 5b). The bend angles of this screen material can be customized during manufacturing in both the horizontal and vertical directions so the shape and size of the exit-pupil can meet a particular system configuration. Since this material has gain associated with it, projection systems can realize improved brightness capability. The system contrast ratio is also improved because the reflected light is directed into the exit-pupil instead of uniformly scattering about in the dome.

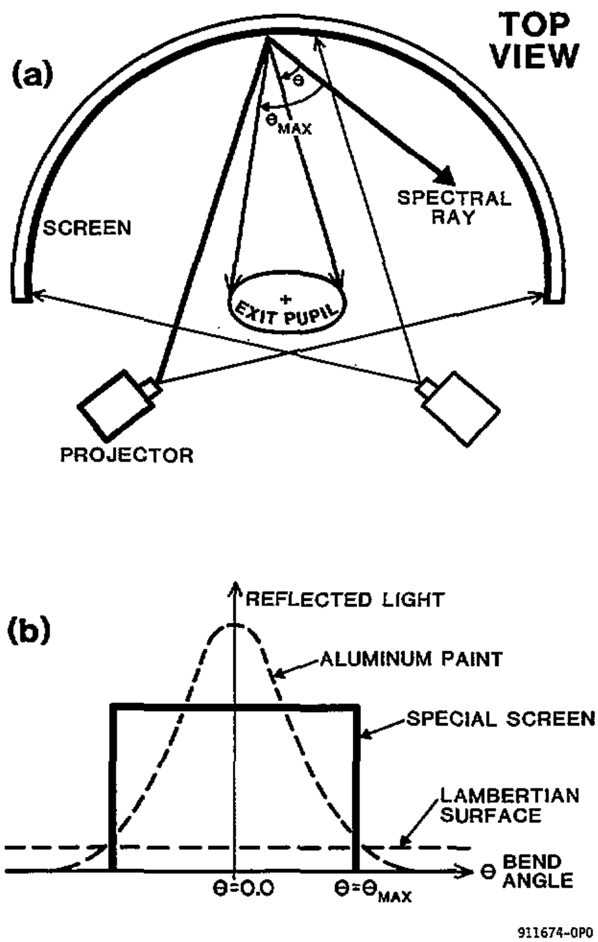

Figure 5. Screen Material Versus Reflected Light Uniformity

By-products Of Quality Edge-blending

After developing a projector system which utilizes electrical edge-blending techniques for quality edge-matching several fringe benefits were realized. These include:

- Non-linear mapping capability in the projector
- Digital convergence and distortion correction
- Real-time interactive control of convergence, edge-matching and brightness uniformity
- Increased brightness capability and a wide exit pupil due to the special screen material
- Closed-loop feedback control of geometry and intensity to maintain quality edge-blending

Conclusions

Both optical and electrical techniques exist for blending multiple projection displays on a dome surface. Electronic techniques are superior because they are inherently more precise and adaptable. When real-time interactive adjustment of edge-blending is done under software control, high-quality edge-matching is possible.

The edge-blending quality of projector systems needs to be quantified so the edge-matching of different projector systems can be compared. By quantifying parameters like: registration accuracy in the overlap region, color-match between adjacent channels, intensity variation across the edge boundary, brightness uniformity across the entire viewing area, and exit-pupil size, edge-blending can be commonly understood. This will facilitate the inclusion of edge blending specifications in contract proposals for multi-channel projector systems. The following minimum specifications are suggested:

- Registration accuracy - same as the required color convergence accuracy
- Color-match - no perceivable color change across the edge boundary
- Intensity variation - not to exceed two percent per degree of overlap
- Brightness uniformity - greater than 0.75
- Exit-pupil size - large enough so quality edge-blending can be viewed from all expected head positions

A special screen material having a flat gain response curve has been developed for dome simulator applications. This screen material can improve the performance of a projector by allowing wide and uniform exit pupils, increasing system brightness capability, and increasing the contrast ratio.

Acknowledgments

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References

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