A New Film Scanning Machine for Film in a Digital World

By David Corbitt

This paper describes some of the difficulties the design team of Innovation TK (ITK) had to overcome to build a new high-definition telecine based on CRT flying spot technology. It also explains how some old problems in this field were resolved with new concepts.

In the past there have been several basic hardware choices for telecine scanning of film. Each hardware design was intended to create the most accurate translation from film to television within the constraints of the technology of the day. With the current need for high-definition scanning of film, and even higher rate scans for digital manipulation of film images, new techniques have been brought to the marketplace.

Current competing telecine technologies involve three very different basic categories of hardware to get the job done: CRT-based flying spot scanners, CCD-based linear array scanners, and area array CCD scanners. The oldest technique still in widespread use is the flying spot telecine using a CRT as the scanning light source. This concept, developed in the 1930s, has undergone several generations of improvement since then to bring it out of its early primitive days. CRT scanning machines have gone from intermittent movement analog black-and-white scanners to high-resolution digital scanners with continuous film movement.

The next technique with wide market penetration is the telecine utilizing linear array CCDs for scanning film images. This technology was first introduced in the 1970s and has undergone several generations of improvement over the years to open up the bandwidth and improve performance.

More recently, large area array CCDs have been incorporated into a telecine machine using intermittent movement of the film.

There are pros and cons to each technology. Each presents a unique set of problems that design engineers must solve in order to make an economical and practical machine able to scan film in realtime and at high resolutions.

Here is the ITK list of goals for getting the best possible quality out of a film scan:

1. Signal to noise (S/N) must exceed the noise floor of the grain in the film.
2. Colorimetric accuracy and dynamic range must do justice to the film record.
3. Resolution must meet or exceed the limits of the film with no chromatic aberrations.
4. Focus must be uniform across the entire area of the film frame.
5. All film formats in use today must be available: S-8; 16; S-16; 35mm in all its permutations (Academy and Super formats for 2, 3, 4, and 8-perf); and 70mm in various formats up to 15-perf.
6. Resolution independence with up to 4K x 4K native scanning capability and full bandwidth in RGB (refer to 4 above).
7. Stable film transport for all formats.
8. Enough flexibity for use in creative post-production environments.

Which Concept to Choose?

Flying spot, CCD linear array, and CCD area array were examined and flying spot technology was chosen. The reasons were many but most important was the ability to change sample size at will. Both CCD linear and area array devices have a fixed sample size and thus the film can never be scanned at higher sample rates than the fixed sample set of the sensors. Currently available linear array CCDs suitable for telecine machines have up to 1920 pixels per line. We felt this was not adequate for our stated goals. Flying spot techniques, if properly designed, can manipulate the focal size and shape of the spot of light to tailor it to any resolution required.

Spot size and shape can also be manipulated to minimize alias components caused by missed samples in the image. Current high-brightness scanning CRT technology allows a spot size as small as .04 mm at normal operating beam currents. If the scan patch for a 4:3 aspect image is approximately 150 x 112.5 mm, then the maximum number of pixel samples possible with such a raster is 3750 x 2812. Work continues on reducing the spot size even further and increasing the number of samples to approximately 4000 x 3000 for a 1.33 aspect image.

Another major factor in choosing flying spot technology was the goal of having both pin registered non-realtime scanning for high-resolution compositing work and still having the option for realtime continuous motion scanning for everyday jobs.

Film images scanned for compositing work require extremely stable images. These images may be different elements from different camera rolls that will be joined together in a

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graphics workstation. Any differential movement between elements will be a visual clue of the non-real nature of the compositing and is to be avoided to maintain the illusion of the composited image.

Image stability can be quite good with edge-guided film in a continuous motion film scanner, but using a non-realtime pin registered system is preferred and maintains the most accurate placement of each image. Flying spot scanning was chosen in order to keep the options open for both realtime continuous motion transport for realtime film transfers and non-realtime pin registered transfers for those critical applications where absolute positional accuracy is necessary.

Non-realtime pin registration with a linear array is not currently possible. The film must be in motion to create an image since it is the movement of the film that creates the vertical scan of the image. An area array was not considered for our design. An area array can easily scan film in a non-realtime pin registered system, but the difficulties of dealing with realtime with an area array seemed too difficult to try to solve at this time.

Signal-to-Noise Issues

Once the flying spot was decided upon as the basic design choice, there was a need to address the issues of signal to noise (S/N), especially if we wanted to open up our bandwidths to high definition and beyond. Flying spot systems rely on the light from a high-brightness CRT raster being sharply focused on the film emulsion. The light that passes through the film is modulated by the varying dye densities it meets in its path. Spatial "addressing" of the emulsion is taken care of by the scan pattern of the raster. Analog light modulation is detected by sensors beyond the far side of the film, and the signals are then digitized in the color processing channel of the machine.

There are several key factors in optimizing the S/N. There must be enough light in the entire optical chain to allow the sensors to operate quietly; too little light would force the sensors to operate at high gain and generate unwanted noise. The S/N issue is a complex one that will be discussed further.

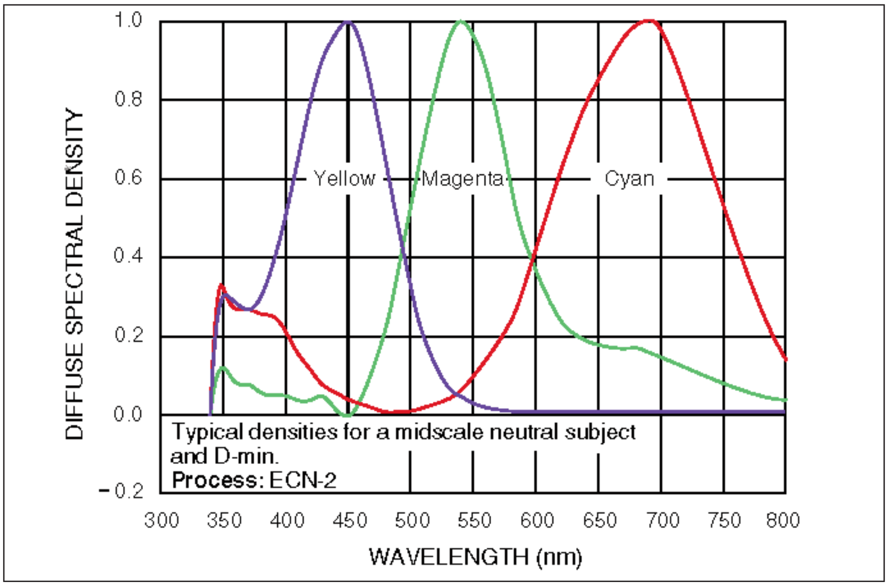

Figure 1. Spectral absorption of Kodak 5274 color negative film dyes. (Graph used with permission of Eastman Kodak Co.)

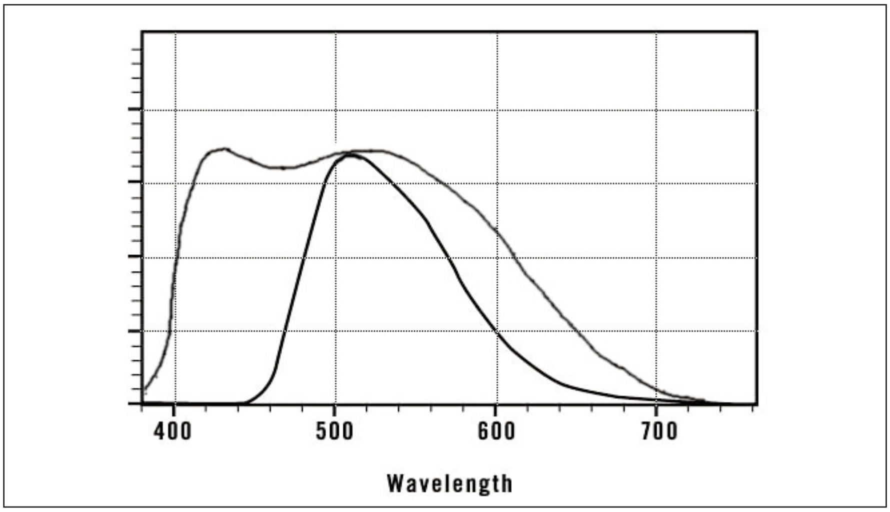

Figure 2. Spectral output of current phosphors used in telecine CRTs.

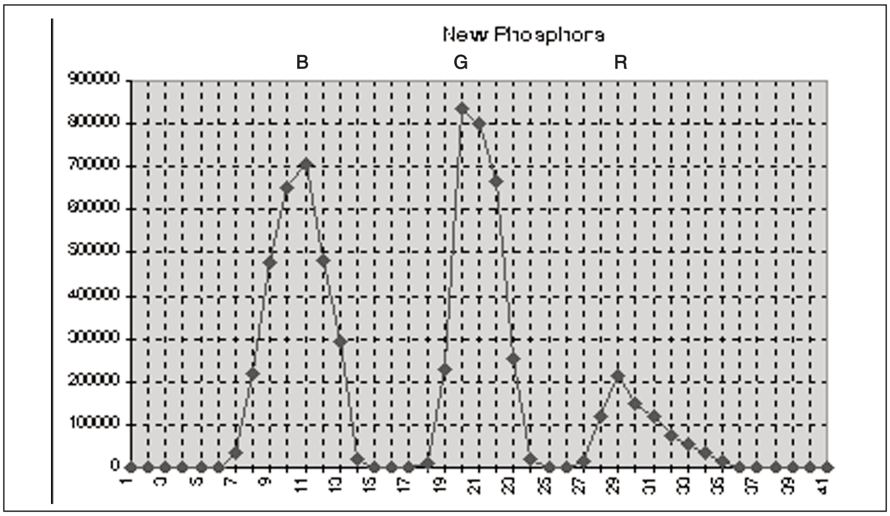

Figure 3. Light transmission through the entire optical path with new phosphor mix. X axis are arbitrary numbers corresponding to short wavelengths on the left, longer on the right.

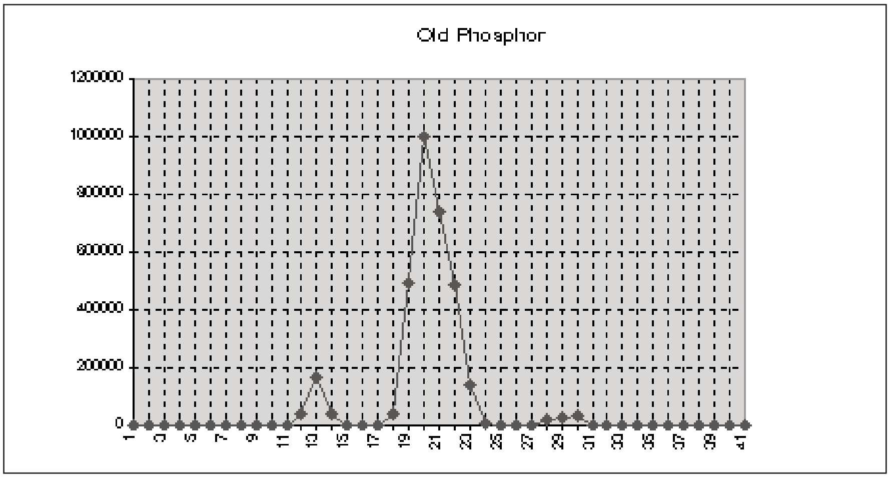

Figure 4. Light transmission through the same optical path but using the earlier phosphor.

Figure 6. Innovation TK's Millennium Machine for scanning multiple film sizes and formats into video or data formats up to 4K resolution.

CRT Design and the Importance of Phosphor Performance

The CRT in a flying spot system must generate light that is broadband enough to be modulated by the three dye layers in color film. Figure 1 is a drawing of the typical absorption spectra of a modern color negative film, Kodak's Vision 200T or 5274 . The dye absorption peaks of this film are similar to several other Kodak film stocks. There must be sufficient light energy near the dye peaks to get a meaningful read of the dye densities. The phosphor material used in the CRT to emit light must also have a very fast decay characteristic to permit reproduction of high-frequency detail in the final signal.

All phosphors have a finite decay characteristic that limits the speed of the detector circuit response. If not corrected, the decay characteristic shows itself as a smearing of the image detail. The shorter the decay, the less correction needed to eliminate smearing and the quieter the images will be. Available fast decay phosphors, up until very recently, were typically narrow in their spectral output. Figure 2 shows a comparison of the spectral energy output of the old phosphors and the newly developed mixture of phosphors. The increase of blue energy is approximately 60 times greater, red increase is approximately 20 times, and green energy remains similar to before.

The graphs in Figs. 3 and 4 compare the amount of energy available in an open gate situation through the optics and color analysis filters with the new phosphor mix compared to the old single phosphor. The new phosphor mix has also been optimized for faster decay characteristics. Another distinctive feature of the new CRT design allows the phosphor to be driven at higher anode voltages resulting in an overall increase in light output.

Other physical characteristics of scanning film were taken into consideration in the design of the new CRT. Film is supported on its edges during scanning. To minimize sag and buck-

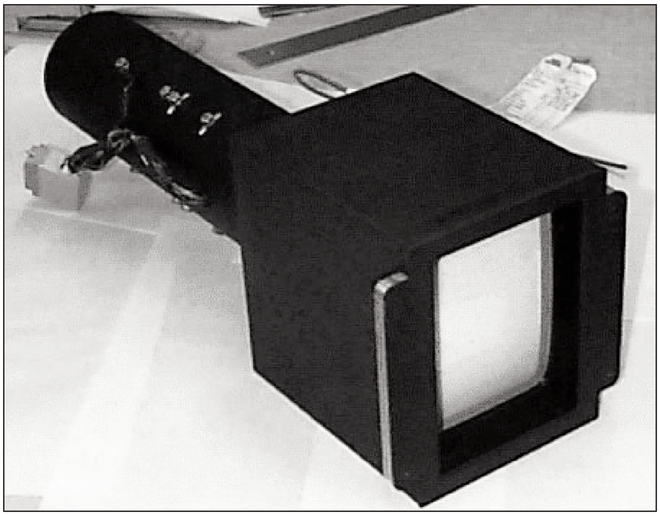

Figure 5. Curved screen CRT mounted in shield and coils assembly.

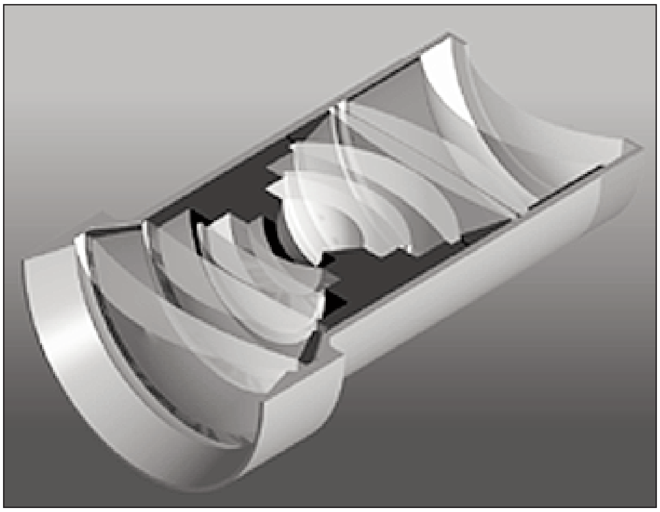

Figure 7. Cutaway drawing of Innovar-80 lens.

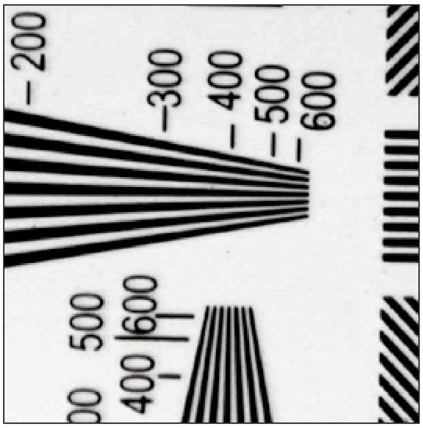

Figure 8. Resolution test for Innovar-80. The number 600 corresponds to 2400 television lines.

le, the film path must have a longitudinal curvature, which causes a focus discontinuity problem if the illumination source (CRT phosphor screen) is a planar surface.

To maximize the light throughput and S/N, a large aperture lens must be used in the film gate. The curvature of the film and the planar surface of the CRT has forced designers in the past to compromise focus or stop down the lens to get an adequately sharp image over the entire film frame. The ITK design team decided early on that both these approaches were undesirable for high-resolution scans and opted for a newly redesigned CRT assembly with a curved phosphor screen to match the curvature of the film plane (Fig. 5). This allows a large aperture lens to function well and still maintain excellent focus over the entire film frame area. Any residual sag in the film is removed by pumping low-pressure air into the gate body in the space between the film and the lens. This low pressure is enough to support the film and keep it very close to the ideal focal point over the full frame.

Lens Design

The gate lens must efficiently focus the CRT light on the film. Design factors will control the resolution, chromatic aberrations or color fringing, depth of field, uniformity of frame illumination, and overall throughput of light.

A new lens for the 35mm film format, with double frame height which can accommodate VistaVision (8-perf 35mm), was designed and fabricated for the new upgrades and the Millennium machine (Fig. 6). The Innovar-80, is a telecentric, 10-element apochromat lens having a focal length of 80mm, operating at a magnification of -0.25, and optimized for the specific faceplate and skid plate curvatures (Fig. 7). The spectral response of the lens is significantly broader than conventional telecine lenses to better match the film and CRT spectrums. Resolution is excellent over the entire film frame.

Figure 8 shows the image of a standard resolution 35mm D.E.L. resolution film frame located at the equivalent of the CRT position. The image was captured with a color CCD cam-

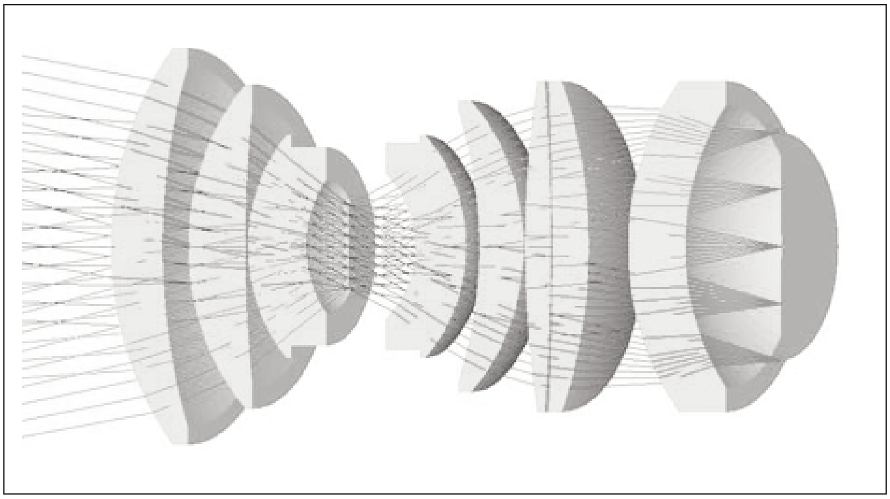

Figure 9. Light paths through Innovar-80 telecentric lens. Light enters on left and exits on right.

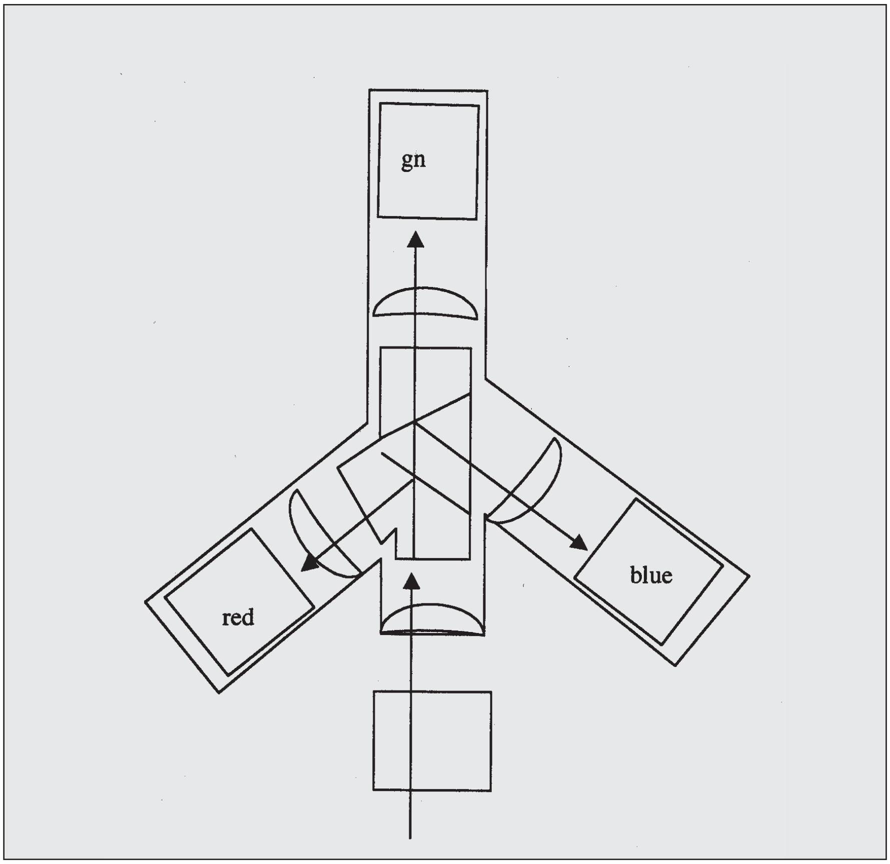

Figure 10. Simplified schematic representation of the Y-Front light path.

era through the Innovar-80 lens for this test only. Normally the CRT raster is the object of the lens and the film in the gate is the focal target. Since the lens' magnification is -0.25, the 600 television lines shown in this test are the equivalent of 2400 telvision lines at the film surface, due to the small size of the test target. The actual CRT raster is much larger than this 35mm film frame. It is evident that the contrast is high and the chromatic correction is excellent.

The lens is rather large (70 mm diameter and 115 mm length) when compared to conventional telecine lenses due to its near-telecentric attribute. A telecentric lens has its exiting cones of light incident upon the film at near-normal angle-of-incidence over the entire film format.

The behavior of the Innovar-80 can be seen in Fig. 9. Regular lenses create steep angles as outer portions of the film are illuminated. In contrast, ITK decided to utilize a telecentric lens to minimize color errors due to widely varying incidence angles on the film, dramatically reduce optically induced shading of conventional telecine lenses, maximize light coupling with the Y-Front, and enhance scratch mitigation.

Sensor Assembly Design

Careful design of the light path after the film gate is essential to maintain an efficient throughput of light to the sensors and minimize the visibility of refraction distortions caused by base scratches, film grain edges, and the matte surface of the film itself. All these irregularities in the film cause a certain amount of light scatter. If the scattered light is not collimated back into the path and gets lost, those surface imperfections will be detected as dark lines or texture by the light sensors. To minimize these refraction artifacts, a new optical sensing assembly has been designed that has a very wide acceptance window and optically folds the refracted light back into the sensing path. The refracted light then adds with the direct light to cancel any losses due to surface imperfections.

ITK chose photomultiplier sensing devices rather than using solid state sensors for several reasons:

- Dynamic range of PMTs is still unmatched by silicon.
- The improved CRT and optical design has permitted sufficient light to overcome dark current noise and random quantum effects in the PMTs.
- The large surface area of a PMT allows for easy gathering of both refracted and direct light from the film surface (essential for scratch and surface texture minimization).
- Low capacitance of PMT elements allows for very wide bandwidth without compensation in the preamplifiers.

The light sensor assembly has been nicknamed "Y-Front" due to its function dictated shape resembling an upside down letter Y (Fig. 10). The design goal was to make the light path as short, simple, and efficient as possible: there are no folded optics (other than dichroic beam splitters). Dimensions are designed for equal transit times from the film to each sensor (for red, green, and blue light).

Analog to Digital (A/D) Conversion

Signals out of the Y-Front are broad bandwidth (up to 60 MHz) and afterglow corrected analog RGB. Prior to A/D conversion, the signals are scaled with a gamma curve of 0.4, allowing the use of 10-bit flash conversion in the A/D stage. A/D conversion is done using 4x oversampling. This permits use of simple bandstop filters before A/D and avoids the ringing associated with steep cutoff "brick wall" type filters. Once the video is digitized it is filtered digitally to limit bandwidth and then linearized. The resulting math of linearization brings the bit count up to 16 bits per channel. All further processing is then full 16 bit until the final output.

Conclusion

Flying spot scanning of film has proven to be a powerful paradigm for today's high-resolution film and data needs and will be valuable for many years to come. Solutions to some old problems formerly associated with this technique have been presented. It is hoped that this paper will help the broadcast engineering community understand that there is still plenty of "state of the art" life left in an old concept if it is optimized by some new thinking.

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