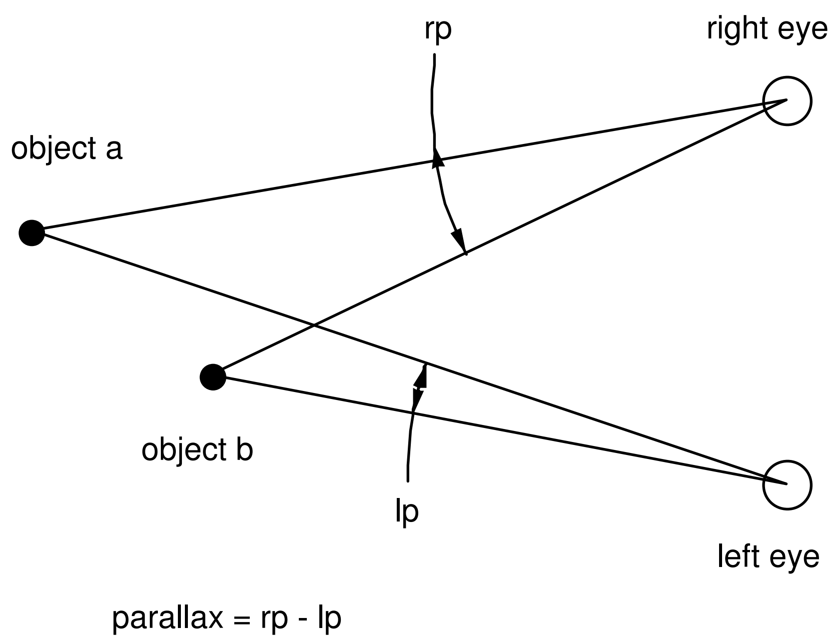
In a stereo view, one can tolerate only so much depth before parts of the scene just won't stay together anymore. At that point, we say the stereo view won't fuse. We can tolerate more depth in real life than in a stereo view, but why is a bit of a mystery. Maybe it has something to do with some things being in focus and some things being out of focus in real life. In a stereo view, conventionally, everything is purposely kept in focus because if everything weren't in focus, your eyes would feel like they were failing you when you looked at an out-of-focus part of the scene. (However, this isn't to say that out-of-focus areas aren't worth experimenting with.)

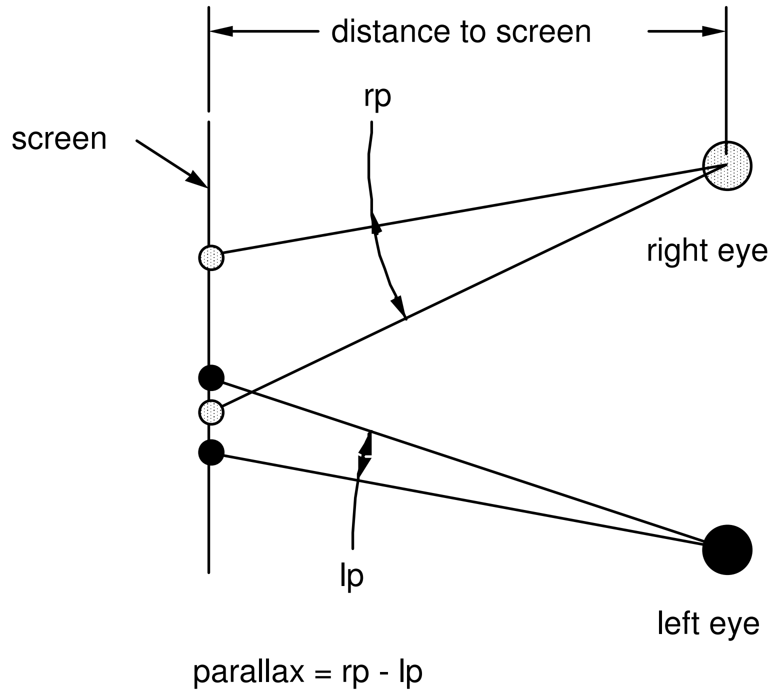
Regardless of the cause, the depth limits of stereo views are real, and quantitatively they are fairly well established. In the simplest terms, the total parallax from front to back shouldn't exceed an angle of one part in thirty. So what is parallax?

As used here, parallax is short for parallactic disparity. There is a disparity between what the left and right eyes see and it is due to parallax. Parallax can be quantified as follows:



<u>Real-life example</u>

The difference between the angles is parallax. Either angle could be larger; it is only the difference which counts. The illustration above is supposed to represent a real-life scene, but when two images of a stereo pair are projected onto a screen, the situation is very much the same:



Projected stereo example

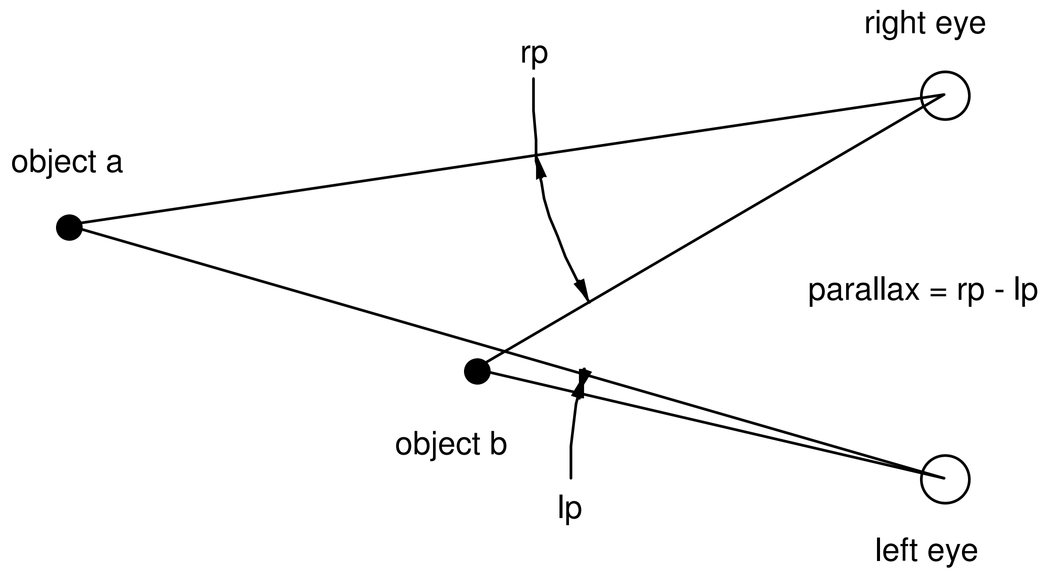
As long as parallax is less than one part in thirty (one part in 30 is about 2 degrees), the projected scene should be fusible by anyone.

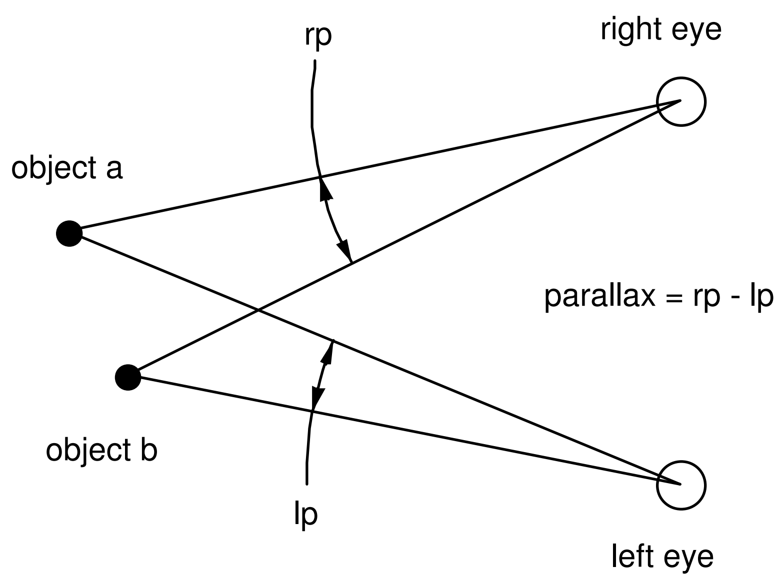
As long as angle lp (as an example) is the same in the projected version as it was in real life, you are sitting the correct distance from the screen (your perspective is correct). If you sit too far away, angle lp decreases and if you sit too close, angle lp increases because the separation of the image points on the screen doesn't change while your distance does. Of course you could substitute any other characteristic angle for lp. I do know what effect sitting too close or too far from the screen has on tolerance for parallax so I specify that we always view images from the perspectively-correct distance.

In order to make lp of the recreated scene equal to lp of the original scene, an image must be viewed from a distance equal to the focal length* of the camera's lens (you will need a lensed viewer to get this close), or if the image is projected or in any other way magnified, from an equivalent distance (= magnification times the focal length of camera lens).

Returning to parallax, where does the 1 in 30 figure come from? In a post to the electronic mailing list called photo-3d, Bob Mannle of New Vision Technology said that the amount of parallax in a stereo pair should be held down to about 1.2 mm for 35 mm stereo (which is usually shot with lenses of roughly 36 mm focal length) and it should be held down to about 2.7 mm for medium-format stereo (which is often shot with lenses of about 80 mm focal length). Note that these figures are each approximately 1/30th of the focal length of the camera's lenses.

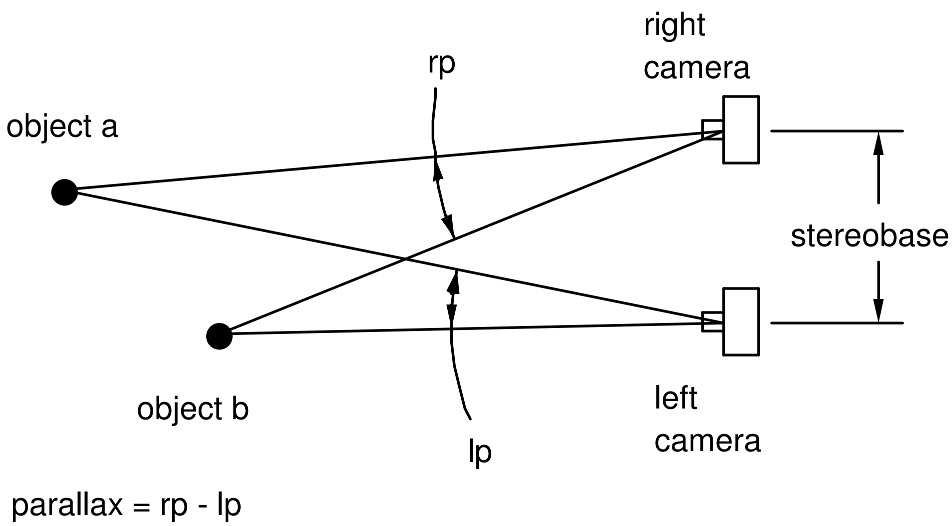
If we accept that holding the parallax down to one in thirty is a reasonable criterion for viewability, then mathematically we can easily determine allowable distances from the stereo camera to the nearest and farthest objects in the scene given the stereobase.

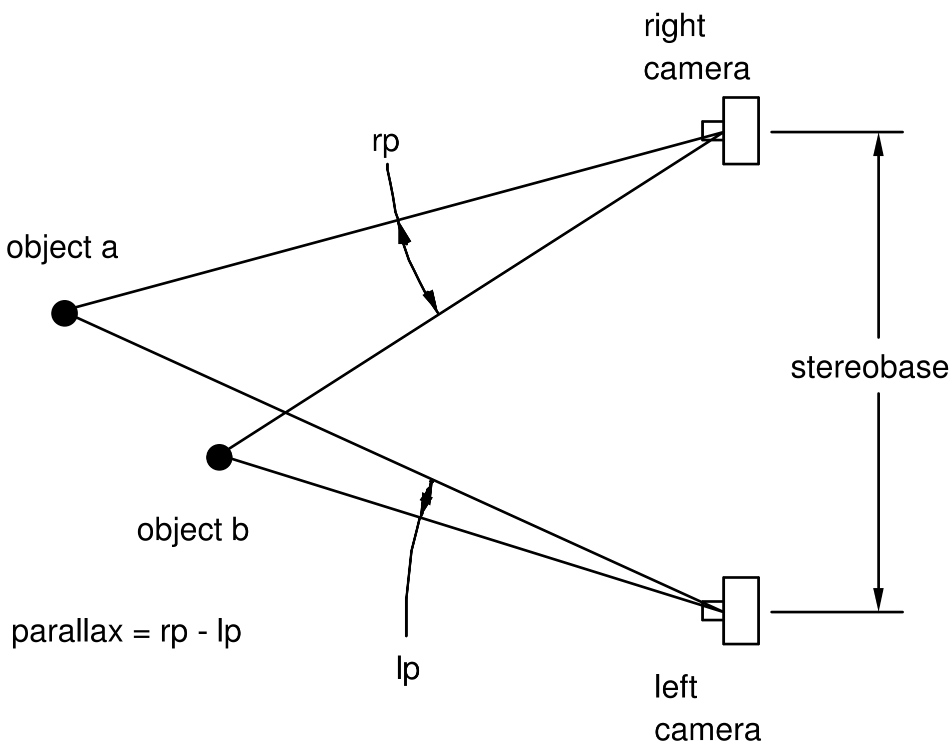




Notice how much greater the parallax is in the upper illustration than in the lower illustration. This is because the distance to the far object is farther and the distance to the near object is nearer in the upper picture than in the lower picture. This increase in parallax is what tells us that the objects in the upper picture are farther apart than the objects in the lower picture.

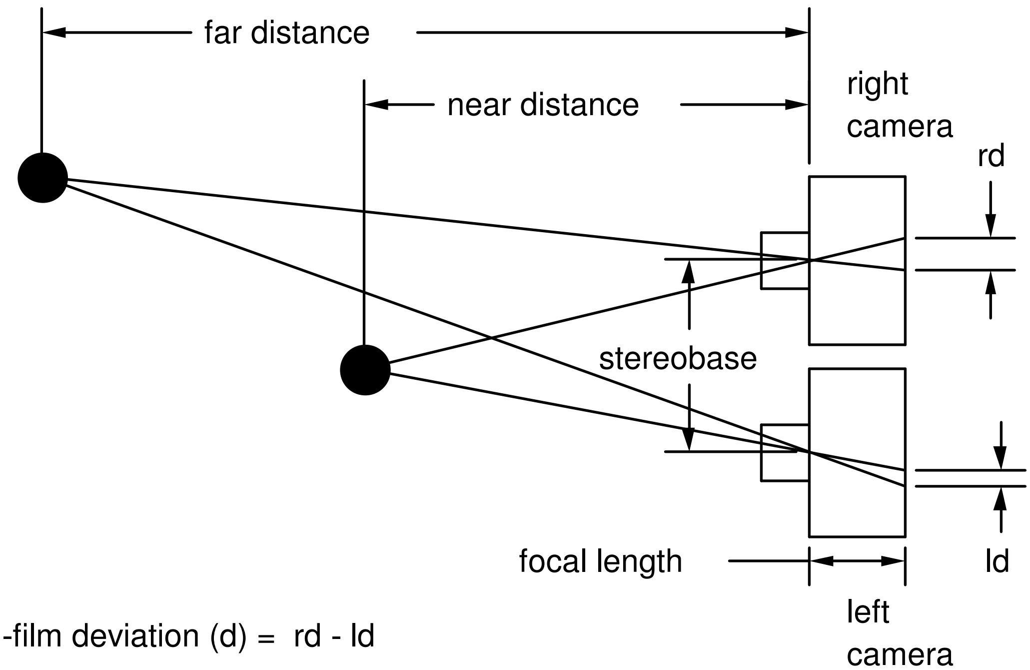
If we substitute cameras for the eyes, we will have an illustration of the situation we have when we take a stereo picture. This illustration is intended to show another effect, the effect of changing stereobase, the distance between cameras.





Notice how much less the parallax is in the upper illustration than in the lower illustration. This is because the distance between the cameras (stereobase) is less in the upper illustration.

We can also look at what goes on inside the two cameras:



On-film deviation (d) = rd - ld

On-film deviation is a measure of parallax, but in linear terms, at the film plane. Without going into the derivation, which is presented elsewhere, the following variables are related by the equations given below them:

sb = the stereobase.

f = the focal length of the camera's lenses.

d = on-film deviation; nominal maximum = f/30

an: distance from camera lens to nearest object in scene.

af: distance from camera lens to farthest object in scene.

a = the distance at which the camera is focused
Best compromise between an and af is when
a = (2*af*an)/(af + an)

It may be shown through geometry and algebra that:

$$sb = d \cdot \frac{af \cdot an}{af - an} \cdot (1/f - 1/a) \qquad (1)$$

This equation may be rearranged to give the following:

$$an = \frac{2 \cdot sb \cdot f \cdot a}{d \cdot a + 2 \cdot sb \cdot f - d \cdot f} \quad \text{and} \quad af = \frac{a \cdot an}{2 \cdot an - a} \qquad (2)$$

If you don't like solving these equations, Excel spreadsheets are available.

The fine print

* When the distance from the object to the film plane is decreased, the distance from the lens to the film plane is increased: the lens moves toward the object. As is clearly shown in the last illustration above, the distance from the lens to the film is what counts, not the actual focal length of the lens. The two equations given above take this into account and keep d at the figure assigned by the user. Why d and not angular parallax? Well, mostly it's for historical reasons. This effort started with on-film deviation and not angular parallax. Although it would be no great trick to reconfigure the equations to use angular parallax instead of on-film deviation, even if this were done, there would be no cure for the fact that many people do not sit at the correct distance from the screen as defined above. So it is probably just as well to leave the equations as they are now. If people do observe from the correct distance, then the equations give the correct angular parallax. The on-film deviation is also useful in the sense that it is easy to measure on the actual images, unlike angular parallax.

Ideally you would use a viewer lens which has a focal length equal to the distance of the lens from the film or, if the image is magnified, you would sit at a distance of the image magnification times the distance of the lens from the film. In practice, occupying approximately the correct position will be good enough.

If the camera lens is extended a lot, as in a close-up or macro situation, then it might be better to plan ahead. For instance, if the idea is to use a 35 mm format camera to take a picture of an object which is only 4 inches (100 mm) away using a lens with a focal length of 35 mm, then it would be good to recognize that the lens will be about 54 mm from the film, not 35 (you will have to rack it out 19 mm from infinty to achieve focus), and so you should sit 54 mm times the on-screen magnification away from the screen, not 35 mm. This is all to the better since the audience for a screening tends to sit at least two but usually three or more times the image height away from the screen. In 35 mm format, three times image height works out to be about 72 times the image magnification away from the screen indicating a lens focal length of 72 mm should be used in that format for proper perspective.

As a specific example, the 35 mm format is 24 mm high on the transparency and, say, 1200 mm (4 feet) high on screen. This is a magnification of 50X. So if the camera's lenses operated at a distance of 54 mm from the film, we should sit at a distance of 54 mm times 50X = 2700 mm or 9 feet to achieve the proper perspective (giving no stretch or squash distortion).

Another caveat has to do with the exact distance of the camera's lenses from the scene. The distance should actually be measured from the entrance pupil since that is the center of perspective. In the equations (1) and (2) above, the Gaussian and Newtonian forms of the lens equation were used to figure the position of the lens from object and image. Fortunately, most lenses are built approximately symmetrical and so we can say that the entrance pupil is where the lens is without causing an error in the equations. For a solution to the problems caused by asymmetrical lenses, see "Image-side Perspective and Stereoscopy" by yours truly, copyright SPIE 1998.

Is one part in 30 a hard limit or a soft limit? I think it is pretty soft. There are plenty of examples of "double depth" stereo pairs which work well. I think the key to having more depth is to have a gradual transition from near objects to far objects. The most gradual transition might be a stereo pair of a lawn. This boring, featureless picture would extend from a few feet away to, essentially, infinity. There would be no "jumps" in depth. A very sharp transition from front to back would be found in a scene showing a flower a few feet away with a mountain for its background. This would be a difficult picture to fuse because of high relative disparity between flower and mountain.