BY **MIKE WOOD**

Etendue

You might try and break this fundamental optical law, but you won't succeed.

THIS ISSUE I WANT TO DISCUSS an optical term that I suspect you have heard used: etendue. It's one of those words that some consultants and engineers, such as myself, bandy around in the vain hope that it makes us appear more knowledgeable than lesser mortals. Etendue is a French word, meaning spread or extent, which makes it sound even more mysterious and ethereal. However, behind this exotic-sounding term, is a concept that is relatively simple and easily understood. It's a fundamental principle that is critical to understanding both what is possible and what is impossible with an optical system. In particular, etendue applies to the optics connected with controlling and directing a light source in a luminaire, but it is relevant to any optical system for any purpose. Some knowledge of etendue can quickly help you distinguish between the salesman with a real product and those offering optical snake oil.

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(*Note: As it is a French word, it is more correctly spelled étendue, but it is common to omit the acute accent on the first e when using it in its scientific sense, if only because many keyboards don't have that character!*)

Etendue as a measure of a light beam has a lot in common with a more familiar unit, the electrical measure of power in watts. Like power, etendue is a product of two other independent variables (volts and amps in the case of power) and, also like power, in an ideal world, is conserved by the system it goes through. In the case of electrical power, we know that an ideal transformer will conserve the power passing through it. The voltage at the output of a transformer is often different from the voltage at the input, but the currents through the primary and secondary windings will adjust such that the product of volts and amps remains constant. For example, a transformer with a 100 V, 10 A input may have a 50 V 20 A output. The product of 100 x 10 is the same as 50 x 20.

If we are talking about a light source, then the two factors that we multiply together to produce etendue are the area of the light emitter and the solid angle of the light beam. *(These are simplified descriptions, but I think they get the point across.)* Etendue, sometimes called throughput, is the product of these two measurements and it represents a measure of the size and angular spread of a beam of light as it passes through an optical system. The larger the beam angle or the larger the source size, the larger the etendue product. Every light source has a size and spread. There is no such thing as a point source and fully collimated zero beam angle in the real world, even a laser beam has a size and a beam angle, albeit a very small one.

Now we get to the interesting part and one of the fundamental laws of physics: **The etendue of a light beam can never decrease as it passes through an optical system.** It can stay the same, or it can increase due to losses—but it will never, ever decrease. Again, this is a little like electrical power. We know that power can be lost as it flows through an electrical system because of inefficiencies and the resistance of less-than-perfect conductors, or, if everything were perfect, it would remain the same. However electrical power can never increase as it flows down a wire. If it did we could build a perpetual motion machine! Etendue follows

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the same conservation of energy principle; however, in the case of etendue, more useful energy is represented by a smaller etendue value, not a larger one, so the equation is reversed. In a perfect optical system etendue will be conserved, but in a real system, with losses from things like scattering, it will always increase as it passes through the system. Etendue is the optical equivalent of entropy as defined in the second law of thermodynamic. As with entropy, a higher etendue means more disorder, and once things are disordered you can't order them again without using energy. Everything in the universe tends towards disorder, just as light tends to scatter.

Let's think of a simple example: a narrow, almost parallel, light beam passing through a frost filter. We know that the angle of the exiting light beam will be larger than the one going in, so even if the source size doesn't change, the etendue has now increased. Unfortunately, as we also know from bitter experience, this is a one-way process. You can't make an inverse frost filter that takes that spread of light and turns it into a nice parallel beam again. Although I'm sure Rosco, in its long history, has tried more than once to manufacture such a filter and would make a fortune if they succeeded, it's just not possible to reduce etendue like that. You may as well argue with the law of gravity as argue with etendue conservation.

A few figures might help get the idea across. **Figure 1** shows a simple source and converging lens.

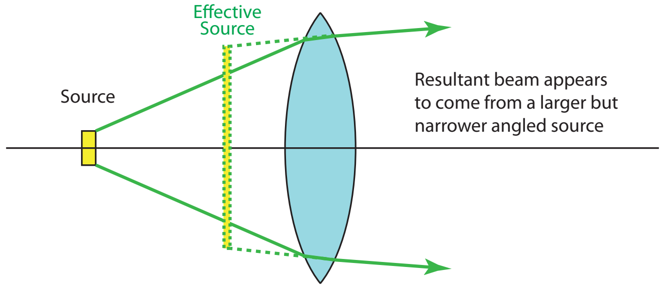

Figure 1 – Etendue conserved

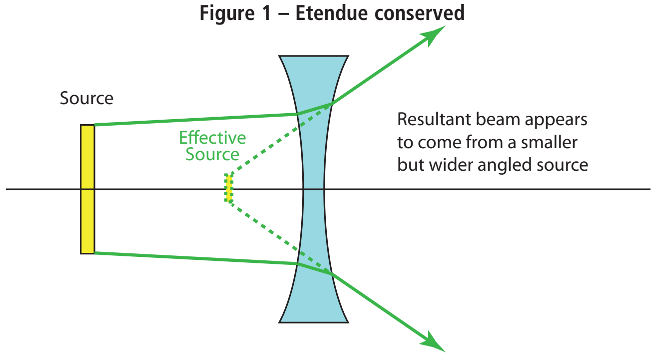

Figure 2 – Etendue conserved

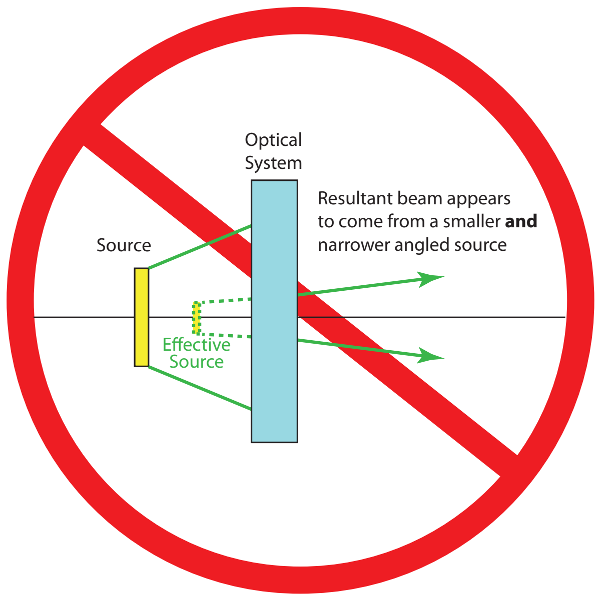

Figure 3 – Etendue decreases – impossible!

The etendue of the source can be represented by its area times the solid angle of the light beam it emits. As it passes through the lens that etendue is conserved. That means that, as the light beam is converged by the lens and becomes more parallel, the size of the effective source increases accordingly. The dotted green effective source shows how much the source increases in this case. Both in to and out of the lens, the product of source size and beam angle remains the same and etendue is conserved.

Figure 2 shows the opposite, this time with a large narrow angled light beam and a diverging lens.

After it passes through the lens the output beam is much wider-angled, but also appears to originate from a much smaller source. Again the product of source size and angle is conserved.

Finally, **Figure 3** shows the system we would all like to make, but can't. This is the one that you can waste years of R&D trying to develop in the forlorn hope that you will find a way to succeed where other, clearly less inventive designers, have failed.

Here we have a very real situation. A large source, perhaps an array of LEDs, with a relatively wide emission angle, and a small gate.

We want to try to do two conflicting things with our hypothetical optical system: shrink the size of the beam and narrow the angle. That way we could get it through the narrow gate or gobo and couple it with lenses downstream. Now we understand something of etendue conservation, we can immediately see that, whatever optics we use, this is just never going to be possible without significant light losses. Reducing beam angle *and* beam size at the same time would mean reducing etendue, and reducing etendue isn't possible. Yes, you'll see optical systems that purport to do this but those systems will have to throw a lot of light away. In its simplest form a gobo with a small hole in it apparently reduces etendue, as the source size reduces with no change in beam angle. However we also know that a small hole in a gobo is incredibly inefficient and wastes most of the light.

This is a particular problem for LED based illumination systems as the source dies often have an inherently high etendue. A common construction is to build a large array of LED emitters where each has a very wide, almost Lambertian, hemispherical light output spread. We now have the worst case: a large source and a large angle, which combine to give you just about as high an etendue as you can get! What you'll typically see immediately after the source is a large, TIR based reflector or lens that collimates that broad beam down to a more usable beam angle. Now you know about etendue, you can immediately understand why the output end of those TIR reflectors has to be so large. It has to be large enough that etendue can be conserved, as a narrower angle beam means you must have a larger emitting area. If the output side wasn't this large then the lens would be very inefficient and waste a lot of light. Unfortunately, this large lens size dictated by etendue conservation puts a limit on how closely together you can cram those LED emitters.

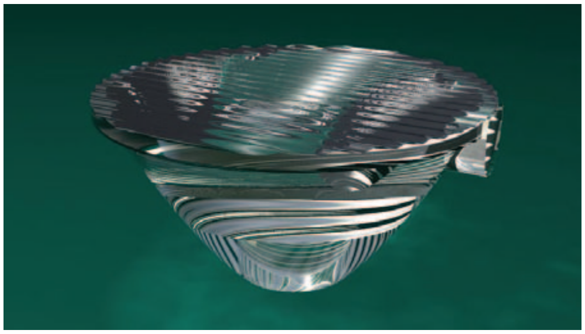

FIGURE 4 COPYRIGHT CARCLO OPTICS

Figure 4 – TIR Lens

Similarly the narrower the angle of the objective lens you install on your ellipsoidal reflector spotlight, the larger and bulkier that lens has to be. A 5° lens that you might use front of house for long throws is huge, and it's etendue that's to blame. Another example is the military searchlights used in WWII. The requirement for a searchlight is that it should have a very narrow beam angle; however we have a large light source with high etendue. The only solution that doesn't violate the conservation of that etendue is to use a vast mirror, over 2 meters in diameter. That way we can parlay our high etendue lamp into the desired narrow beam, with the compromise that it now comes from a very, very large diameter source. It would be much more convenient to use a smaller mirror, but the source etendue does not allow this without losing most of the light.

Things get even more complicated when you are trying to make a projector and need to focus the light onto a device like an LCD or DMD chip. Another consequence of the conservation of etendue is that, in an optical system with a number of optical components, the etendue of the entire system is limited by the device with the largest etendue. If you are fortunate and have a very narrow-angle, very small light source with a low etendue, then you will have no problem controlling and using all that light to illuminate an imaging device with a large etendue. If, however, the situation is reversed, as is more common, and the light source has a higher etendue than the imaging device, then you must waste light in illuminating it—not *might* waste light, *must* waste light.

I hope this article has helped a little in explaining this fundamental optical concept. Etendue is a complex topic, but a basic understanding of its implications can help you evaluate optical systems, and explain the compromises the designer may have had to make. If you see an optical system where large light sources have been made to both appear smaller, and to produce narrow beam angles, be suspicious. This can only have been done by an inefficient process which wastes light. That may be for good reason and good effect, but don't let anyone tell you it's efficient. ■

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Mike Wood runs Mike Wood Consulting LLC which provides consulting support to companies within the entertainment industry on product design, technology strategy, R&D, standards, and Intellectual Property. A 30-year veteran of the entertainment technology industry, Mike is the current chair of the PLASA Governing Body and Treasurer of PLASA North American Regional Board. Mike can be reached at mike@mikewoodconsulting.com.