From Light Bulbs to Leds: How to Measure What We See

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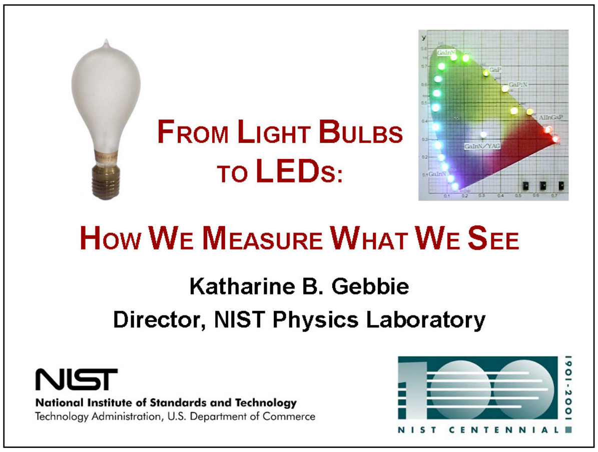

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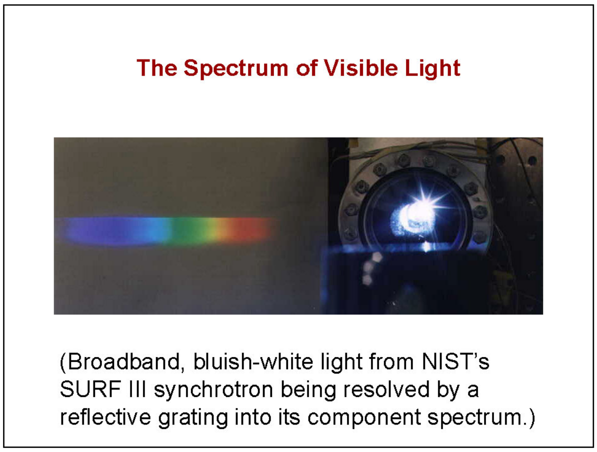

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INTRODUCTION

Bob Scace has just told us about the importance of global standards in the development of semiconductor technology—global standards not only as foundations, but also as the stepping stones for advanced technology development. I am always impressed by the history of NIST's involvement in semiconductor standards. The standards for the microprocessor age are based on work done by NIST in the 1950s and 1960s on single transistors, and the standards for single transistors were based on the work done at NIST on vacuum tubes in the 1940s.

One could continue the "begots and begats" back to the earliest work on the fundamental electrical measurements at NIST in its earliest years. While there had been prior international agreement on "practical" electrical units, in 1921 the world community amended the Treaty of the Meter—the foundation of the international metric system—to include electrical units for the first time.

Now, I want to tell you a similar story that also began in the early days of NIST and also had an important milestone in the early 1920s. It is a story that I think shows that global standards, like fine wine, can improve with age.

We have known since the days of Isaac Newton that white light is composed of a rainbow of wavelengths, each seen as a pure color. We have also known that light is a form of radiant energy, with a power that can be measured in watts. But what we didn't know was the relationship between the visual description of light and the physical description, or as it was then called, the mechanical description of light. Fraunhofer made some of the first quantitative measurements of the response of the eye to different colors in 1817, and Langley made the first real measurements of optical energy in 1823. By 1905, Goldhammer had crystallized the idea that there was perhaps a unique relationship between the brightness as seen by the human eye and the energy at each wavelength of the light. At the young NBS, Nutting introduced the term "visibility curve" in 1908 to relate what the eye saw to the radiant power. But we still didn't know what this visibility curve was, that is, the actual relationship was between the visual and the mechanical description of light. The answer to this question was one of the first challenges and one of the greatest triumphs of the early National Bureau of Standards.

Early NBS Experimenters

William Weber Coblentz

who, with W. B. Emerson, measured the "Relative Sensibility of the Average Eye to Light of Different Colors" in 1917.

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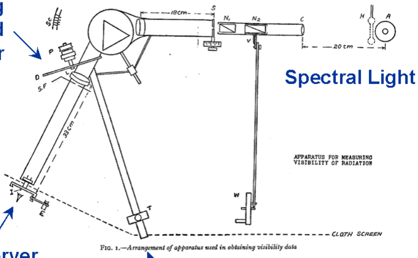
By the early 1920s, there were a number of studies of this relationship going on around the world. The main contribution from the United States came from the laboratories of the noted spectroscopist, William Coblentz, of the National Bureau of Standards. He had developed the art of making sensitive and accurate measurements of optical power by using novel detectors of his own design.

The Flicker Method (from Coblentz and Emerson)

Rotating Slotted Mirror



Spectral Light

Observer

Reference Light

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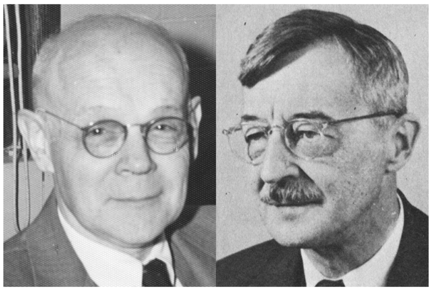
In 1917, Coblentz and Emerson built this instrument in an attempt to find the answer. They used the "flicker" methoda rotating, slotted mirror to let an observer look at two lights of different color in rapid alternation. The lights were adjusted until the flickering appeared to stop, that is, when the lights appeared equally bright. The problem was that these data and others collected from other sources were not consistent. Some of the other experiments also used the flicker method, and others used a split-screen viewing method instead. Their differences seemed irreconcilable. Dr. Edward Hyde of the General Electric Research Labs was President of the United States National Committee of the International Commission of Illumination (the CIE). Seeing the need to bring this to some sort of closure, he proposed to the National Bureau of Standards that they conduct an additional study using the so-called step-by-step method. This form of split-screen matching, where comparisons were made between a series of only slightly different colors, held promise as a means of obtaining more reliable data.

The Fathers of the Visibility Function



K. S. Gibson **E. P. T. Tyndall**

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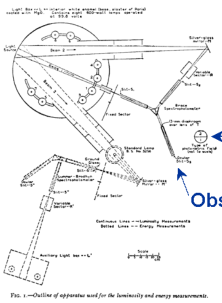
The National Bureau of Standards took on this challenge. The director, then George K. Burgess, appointed a committee to oversee the work, which was carried out by Gibson and Tyndall.

The Step-by-Step Method (from Gibson and Tyndall)



Split Screen View

Observer

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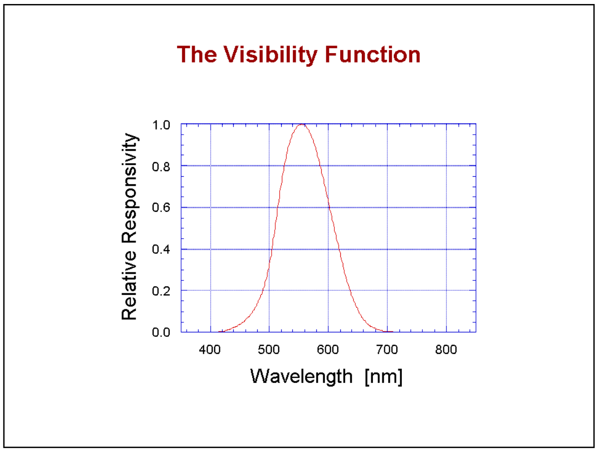
They borrowed equipment from the University of Nebraska, which they incorporated into a quite elaborate apparatus that used some of the National Bureau of Standards' primary standard lamps. They did a careful study and were gratified to see that, in fact, the results were within the uncertainties of the flicker method, but had the precision of the split screen method. Their main contribution, however, was not just in the accuracy of their measurements, but in the very careful analysis and the critical evaluation that they did of all the available data.



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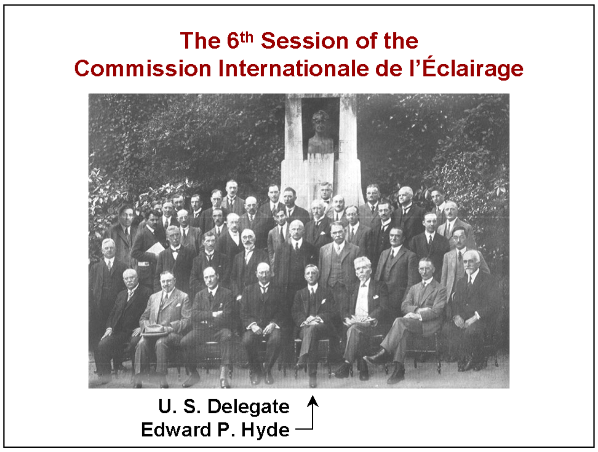
They recommended a consensus visibility function that was based on some 200 different observers who took part in the many separate experiments. This was published in the Scientific Papers of the National Bureau of Standards in 1923, and it is one of the NIST papers that was selected as the most important of the past century in the current celebration of our Centennial.



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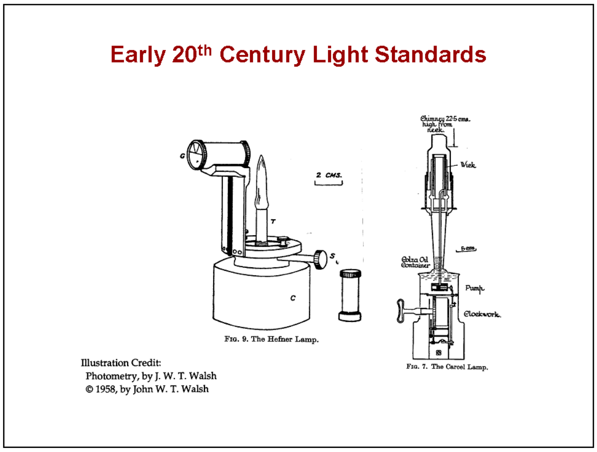
The result had worldwide acclaim, and it was accepted by the CIE at its meeting in Geneva in 1924 as a world standard. In 1933, the International Committee on Weights and Measures followed suit.



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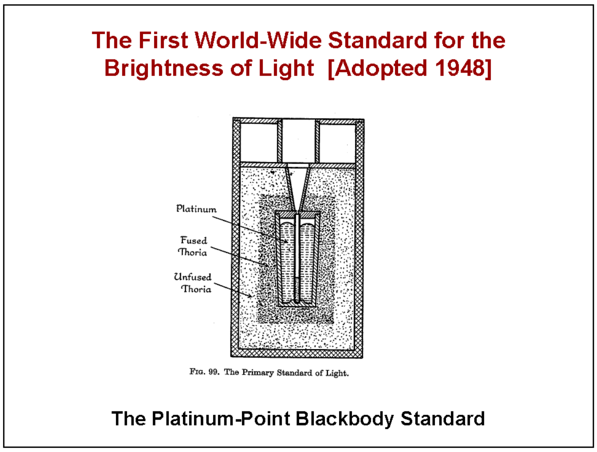
The achievement of Gibson and Tyndall, however, might have remained purely academic had it not been for some changes in the needs of metrology, and advances in technology. As surprising as it seems today, there was until 1948 no unique international standard for the brightness of light. Some countries used gas lamps, and some countries used liquid fuel lamps. Some, like NBS in the United States, used electrical lamps in response to the increasing use of electric lighting at the turn of the century.



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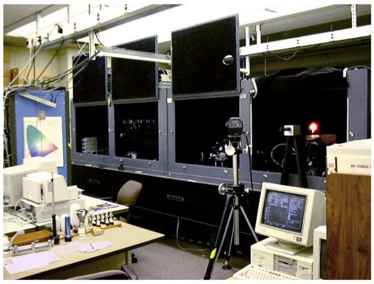
This situation changed with the acceptance in 1948 of the platinum-point blackbody standard as the sole international standard of the brightness of light. The goal in introducing this standard was to improve the stability and uniformity of measurements of light, but in fact it had an unintended consequence in that the behavior of the blackbody could be described using basic principles of physics. This meant that for the first time, unlike with the previous standard lamps, a light standard could be modeled by theory. Suddenly, there was a mathematical model of the entire process of vision, the well-described brightness standard, and the information provided by Gibson and Tyndall on how the eye perceived this light.

Modern Light-Measurement Facility



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This meant that it was then possible to design and build electrical devices that would measure brightness exactly as the human eye would, or at least the ideal human modeled by Gibson and Tyndall 25 years earlier. No longer did people have to look through visual comparators, a process today called "visual photo-

Today's International Standard for the Brightness of Light [Adopted 1979]

The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 x 10^{12} hertz and that has a radiant intensity in that direction of (1/683) watt per steradian.

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metry." The era of "physical photometry" began, in which brightness could be evaluated through electronic sensors, yielding better precision and accuracy.

This became so widely accepted that, in 1979, the current standard was born. It is independent of any artifact—such as a candle, a lamp, or a blackbody. However, it does require the Gibson-Tyndall curve to relate the eye's sensitivity at different wavelengths to the reference frequency within it.

Best Practice Today:
Detector-Based Radiometry

NIST's High-Accuracy Cryogenic Radiometer

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In the last 10 years, or so, this has led NIST and other laboratories to develop quite elaborate detector-based radiometry. Instead of having the lamps as fundamental standards, we now use detectors. This produces accuracy something like a hundred times better than that obtained with the lamps, which was previously limited to about one percent. Slide 3 is the NIST high-accuracy cryogenic radiometer, which today is at the root of our measurements of what we see.

Metrology to Support World Trade:
Key Comparisons in Photometry & Radiometry

- **Photometry**
  - **Luminous Intensity** (directional, from point sources)
  - **Luminous Flux** (total output from lamps)
  - **Luminous Responsivity**
- **Radiometry** [Planned and Underway]
  - **Spectral Irradiance**
  - **Spectral Responsivity**
  - **Spectral Diffuse Transmittance/Reflectance**

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But having the best possible light detectors is not enough. Without a master artifact standard for reference, how do we provide assurance that a measurement is correct? To support world trade, the citizens of each nation need confidence that measurements systems in other countries are equivalent to their own. To achieve this, NIST and other institutes from member states of the Treaty of the Meter adopted a comprehensive Mutual Recognition Arrangement about a year and a half ago. Through Consultative Committees in each technical field—such as in Photometry and Radiometry—and Regional Metrology Organizations geographically, we cross-check our respective measurement capabilities though well-designed "key comparisons." The results are available for inspection in a public database.

Today, All Photometric Measurements Employ the Gibson-Tyndall Result

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Gibson and Tyndall could hardly have imagined in 1923 that, over 75 years later, their work would be an integral part of virtually all photometric measurements of light. The international experts in the CIE have tweaked the curve slightly since then, but despite advances in vision research, they have decided to leave the general form of it unchanged. This says something about the enduring quality of global standards.

However, the world today is very different from the world of Gibson and Tyndall. The world of Gibson and Tyndall in 1923 didn't include the narrow-band light sources so common today, like light emitting diodes, phosphor-based fluorescent lighting, and certain high-efficiency lighting that is used for large facilities and out-of-doors. The methods of photometry of the last century are under great stress now for two reasons. First, the premise that there is a single visibility curve that describes the human vision may no longer suffice. The response of the eye is not linear to very different combinations of narrow band wavelengths—actual perceived brightnesses can differ from the model.

A New Measurement Challenge: Solid-State (LED) Lighting

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Second, even using traditional practice in physical photometry, we are seeing wide variations in measurement results. Instruments calibrated for the spectra and distribution patterns of traditional lighting can give large errors when used with newer lighting technologies.

Industry Directions / Industry Needs

- Advanced source and ballast technologies
  - Solid-state lighting (LEDs, LEPs, ceramics)
  - Two-photon phosphor technologies (advanced fluorescent lamps)
  - High-efficiency point-sources for light-pipes (centralized lighting)
- Clear definitions and standards for lighting quality
  - Uniform set of performance specs
  - Standard formats for energy and economic data

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These are challenges that face us today, as we continue to undergo a revolution in lighting technology. Lighting accounts for nearly one-sixth of the electricity used in the United States, $40 billion annually. Advances in lighting, particularly the use of high-efficiency lighting sources, have the potential to reduce U.S. electricity bills by billions of dollars annually, conserve energy, and reduce power-plant emissions. Industry has responded with new technologies in place and under development. And they have come forward with their needs, including modern standards and specifications.

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With stakes so high, industry and government have set out their goals in a roadmap for the future: Vision 2020. The items on the last slide were strategies pulled from this report. There is barely time today to discuss the report, but the message is clear: As old as this subject is, it is still a vital one. It is a continuing challenge for industry and its partners vision researchers, standardizing bodies, and government to develop better lighting technologies (such as LED and other solid-state sources), and to evaluate them with fair metrics. And global consensus standards will continue to be needed to support success in the marketplace. Into our next century, NIST will continue to work with U.S. industry, the CIE, and the standards community, to help see this vision through.