FN-Optiklabor-Buehnenbeleuchtung-EN-v0.1-2026-05-17

Research Note — Stage Lighting

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1. Thesis

Module 11 (Shadow Theatre) treated shadows from point and extended sources separately. Module 08 takes the realistic step: **stage lighting combines several positioned sources with finite extent and different colour simultaneously, and the simple "point source assumption" of school physics is refuted in reality by three different effects at once** — penumbra, multiple shadows, and additive colour mixing. This note examines the three effects in three controlled scenarios (one point source, classical 3-point lighting from photo/film, RGB stage lighting).

2. Assumptions

1. Ray optics (diffraction negligible at stage scales — wavelength $\ll$ source size).
2. Lambert cosine law for reflecting surfaces: illuminance $\propto \cos\theta$ to surface normal.
3. Inverse-square law: intensity $\propto 1/r^2$.
4. Incoherent light sources (no interference).
5. Linear RGB colour space (device-independent).
6. Occlusion test: person blocks ray if line-of-sight passes through cylinder + head sphere.
7. Soft box as disc perpendicular to ray direction; multiple sub-sources for penumbra approximation.

3. Mathematical model

M1 — ideal point source: One source, one hard shadow edge, no penumbra, no colour mixing. Illuminance at wall point (x,y,z_W) to source $\vec{s}$:

$$ E(\vec{p}) = \begin{cases} \dfrac{I_0 \cos\theta}{r^2} & \text{if line-of-sight clear}, \\ 0 & \text{if line blocked by person}, \end{cases} $$

with $r = |\vec{s}-\vec{p}|$ and $\cos\theta = \frac{(\vec{s}-\vec{p}) \cdot \hat{n}_W}{r}$.

M2 — extended source (soft box): Source with finite area A_s produces penumbra region. Numerically: N_s sub-sources distributed across the source, mean visibility:

$$ v(\vec{p}) = \frac{1}{N_s}\sum_{i=1}^{N_s} \mathbb{1}[\text{line to sub-source } i \text{ clear}]. $$

M3 — multiple sources: Linear superposition for incoherent light; multiple sources produce multiple shadows in different directions:

$$ E_{\text{total}}(\vec{p}) = \sum_{k=1}^{N_q} E_k(\vec{p}). $$

M4 — colour mixing: Per RGB channel additive:

$$ E_{\text{RGB}}(\vec{p}) = \sum_k v_k(\vec{p}) \cdot \frac{I_k \cos\theta_k}{r_k^2} \cdot \vec{c}_k. $$

Symbol	Meaning	Unit
$\vec{p}$	point on projection wall	m
$\vec{s}_k$	position of k-th source	m
I_k	source intensity	rel.
$\vec{c}_k$	source colour (RGB)	—
A_s	soft-box size	m
$v(\vec{p})$	visibility (penumbra)	0..1

4. Parameters

Three scenarios, stage geometry: person as cylinder ($r = 0.25$ m, $h = 1.80$ m) + head sphere ($r = 0.12$ m, centre $y = 1.70$ m) at $(0, 0, 2.5)$, wall at $z = 5.0$ m, wall resolution 100×50.

Scenario	Sources
A point source	1 source (−2, 3, 1) m, $I = 10$, warm-white
B 3-point lighting	Key (−1.5, 2.8, 0.5) Soft 0.3 m, $I = 8$; Fill (1.5, 2.0, 0.8) Soft 0.6 m, $I = 3$; Back (0.5, 3.2, 4.0) point, $I = 5$
C RGB	Red (−2.5, 2.5, 1.5), Green (2.5, 2.5, 1.5), Blue (0, 3.5, 1.5), each point, $I = 6$

Tolerance set in advance: $\varepsilon = 5\%$ contrast deviation. Rationale: stage lighting is a visual phenomenon, $\varepsilon = 5\%$ matches the sensitivity threshold of the calibrated eye for brightness differences.

5. Prediction

Scenario	Expectation
A	M1 supported: one sharp shadow, no penumbra, one colour
B	M1 refuted: three shadows, soft edges (penumbra from soft box), no colour mixing
C	M1 refuted: three overlapping coloured shadows, visible RGB mixing in overlap zones

6. Falsification criterion

M1 is refuted if **any** of the following criteria holds: - Observed shadow count > 1 (multiple sources) - Penumbra detected (gradient at shadow edge soft-distributed, not stepwise) - Colour mixing detected (pixels with significant energy in more than one RGB channel)

7. Competing models

- **K1 — one point source (M1):** tested baseline model.
- **K2 — one extended source (soft box):** M2.
- **K3 — multiple point sources:** M3.
- **K4 — multiple RGB sources:** M4.
- **K5 — full radiosity:** with multiple reflections between walls — own module (architectural lighting).
- **K6 — path tracing:** Monte-Carlo image synthesis — separate class (film VFX, architectural visualisation).
- **K7 — geometric optics with refraction:** for transparent stage objects (glass props) — own module.

8. Domain of failure

- **Very close source / person:** inverse-square diverges; numerically stabilised by $r^2 + \epsilon$.
- **Very small aperture:** diffraction becomes visible (Module 03) — irrelevant at stage scales.
- **Highly reflective stage surfaces:** radiosity required, ignored here.
- **Volumetric light** (fog, smoke): scattering in air volume, separate topic.
- **Moving person, moving source:** time dependence; here static image.
- **Wavelength-dependent reflection:** stage costumes have coloured absorption — here assumed neutral.

9. Simulation

Numerical evaluation in `buehnenlicht_simulation.py`:

1. Wall resolution 100×50 pixels over $(-3, 3) \times (0, 3)$ m.
2. Per pixel: Lambert cosine + inverse-square law for each source.
3. Occlusion test: intersection test with person cylinder and head sphere.
4. Soft box: 16 sub-sources on disc, mean visibility.
5. Reinhard tonemapping: $I \to I/(1+I)$ for display.
6. Shadow counting: connected shadow regions via `scipy.ndimage.label`, minimum size 30 pixels.
7. Penumbra detection: gradient magnitude in range 0.03 to 0.2 as fraction of all pixels; $> 2\%$ = penumbra detected.
8. Colour mixing: pixels with all three RGB channels > 0.1; more than 50 such pixels = mixing detected.

Results in `buehnenlicht_results.json`. Plots as `buehnenlicht_A_single.svg`, `buehnenlicht_B_3point.svg`, `buehnenlicht_C_RGB.svg`.

10. Result

Scenario	Sources	Shadows	Penumbra	Colour mixing	M1
A	1	1	no	no	**supported**
B	3	3	**yes**	no	**refuted (penumbra + source count)**
C	3	0 (overlap)	no	**yes**	**refuted (colour mixing)**

Contrast ratios: A: 14.2; B: 8.7; C: 2.03.

11. Assessment

M1 (ideal point source) is refuted in 2 of 3 scenarios — and each time on **different paths**. This is the most important methodological finding: the same hypothesis falls through **three separate falsification modes**.

Scenario A is the textbook limit. One hard shadow edge, one colour, no penumbra. M1 nearly exactly supported — the proof that the model is not generally wrong, only rarely realised in practice. In photo practice this corresponds to a **direct flash without diffuser** or a distant point spotlight.

Scenario B (3-point lighting) is the standard in film and photo studio: Key + Fill + Back. Three shadows in different directions, the main shadow softened through soft-box diffusion. **Penumbra** = numerically detected partial shadow. The lighting ratios 8:3:5 are classical actor lighting (key:fill:rim ≈ 3:1:2 as rough rule of thumb in portrait lighting setup).

Scenario C (RGB stage) is modern theatre lighting — three coloured spotlights from different angles. What becomes visible: no separate shadows (they overlap so much that every pixel is reached by at least one source), but **clear additive colour mixing**. Where all three sources meet: white mixing. Where one is missing: complementary colour (red+green without blue = yellow; red+blue without green = magenta; green+blue without red = cyan). This is exactly the principle of additive screen technology (RGB pixel in monitor), only that here the "pixels" are square meters in size.

Consequence for school physics: The notion of "one light source" is a strong idealisation. In practice (stage, studio, architecture, outdoor with sun + sky light + reflections) there are always at least two sources, and in most cases they are differently coloured. The "hard shadow edge" of the point-source idealisation is the rare exception, not the normal case.

Connection to previous modules: - **Module 11 Shadow Theatre** treated the concept "source size determines penumbra" individually; Module 08 applies it in the realistic multi-source setup. - **Module 05 Lenses (chromatic aberration)** showed that glass refracts different wavelengths differently; Module 08 shows that stage sources of different wavelengths superpose additively on surfaces. - **Module 03 Single Slit** showed that the point-source assumption fails even within a slit; Module 08 shows it fails equally on the macroscopic stage.

12. Next test

Module 09 Colour Mixing as next step: additive (RGB) vs. subtractive (CMYK), metamerism (different spectra = same perception), colour wheel and complementary colours. Requires Module 08.

Module 07 Light Sources as complement: what do halogen, LED, fluorescent, laser actually emit? Spectra, colour temperature, black-body radiation.

Possible extension to Module 08 v0.2: rear-projection screen instead of direct wall; volumetric light (fog, smoke); moving sources (followspot).

Appendix A — Cross-references

- Practice explanation: `PRAXIS-Buehnenbeleuchtung-EN.md` (follows)
- Companion paper: `BEGLEITPAPIER-Buehnenbeleuchtung-EN.md` (follows)
- Tool: `SCAENA.html` (follows) — *Lat. scaena, the stage*
- Code: `buehnenlicht_simulation.py`
- Plots: `buehnenlicht_A_single.svg`, `buehnenlicht_B_3point.svg`, `buehnenlicht_C_RGB.svg`
- Result data: `buehnenlicht_results.json`
- Predecessor modules: Module 11 Shadow Theatre, Module 05 Lenses (chromatic aberration)
- Related modules: Module 07 Light Sources (forthcoming), Module 09 Colour Mixing (forthcoming)

Appendix B — External stocktaking

- **Box (2010)** *Set Lighting Technician's Handbook* — standard reference for film lighting.
- **Brown (2012)** *Cinematography: Theory and Practice* — 3-point lighting theory.
- **Pharr, Jakob, Humphreys (2023)** *Physically Based Rendering*, 4th ed.
- **Cook & Torrance (1982)** *A Reflectance Model for Computer Graphics*.
- **CIE 015:2018** *Colorimetry* — colour measurement and RGB standards.
- **Blender Cycles, Maxwell Render** — path tracers with physically correct light.

What the workshop note adds: three contrasting scenarios in consistent falsification format; explicit connection to stage and studio practice; open-source numerics with shadow counting; bridges to modules 11, 05, 03.

Appendix C — Sources

- Box, H. C. (2010). *Set Lighting Technician's Handbook*, 4th ed. Focal Press.
- Brown, B. (2012). *Cinematography: Theory and Practice*, 2nd ed. Focal Press.
- Pharr, M.; Jakob, W.; Humphreys, G. (2023). *Physically Based Rendering*, 4th ed. MIT Press.
- Cook, R. L.; Torrance, K. E. (1982). A Reflectance Model for Computer Graphics. *ACM TOG* 1(1):7–24.
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