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

Research Note — Mirrors

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1. Thesis

Modules 05 (Lenses) and 06 (Prisms) treated refraction. Module 10 takes the **counterpart: reflection.** The intuitive assumption “mirrors always image perfectly” is tested against real mirror geometries and turns out to hold only for the special case of the plane mirror: **the plane mirror is the only perfect imager (virtual image of equal size), while curved mirrors show spherical aberration and their imaging depends drastically on object distance.** Reflection and refraction are dual phenomena — spherical aberration occurs in both, the imaging equation has the same form, and both have their idealisation limits.

2. Assumptions

1. Ray optics (geometrical optics), diffraction negligible.
2. Law of reflection: angle of incidence = angle of reflection, at each surface normal.
3. Spherical mirror surfaces (sphere segment) as realistic model; plane mirror as limit $R \to \infty$.
4. Ideal reflectivity (no brightness loss, no absorption).
5. Monochromatic light (reflection, unlike refraction, is wavelength-independent — no chromatic problem).
6. Point objects or simple arrow objects on the optical axis.

3. Mathematical model

M1 — “mirrors always image perfectly”: Every mirror creates a sharp, undistorted image. The plane mirror as prototype: virtual image of equal size.

M2 — concave mirror with spherical aberration: A spherical concave mirror with radius R has paraxial focal length $f = R/2$. Off-axis rays, however, focus nearer the mirror — the **longitudinal spherical aberration**:

$$\Delta f = f_{\text{paraxial}} - f_{\text{marginal}}.$$

The reflected rays envelope a **caustic** instead of meeting at a point.

M3 — convex mirror: An outward-bulging mirror ($R < 0$ in the convention) always creates a virtual, reduced, upright image with enlarged field of view.

M4 — imaging equation: For object distance g, image distance b, focal length f:

$$\frac{1}{g} + \frac{1}{b} = \frac{1}{f}, \qquad m = -\frac{b}{g},$$

with magnification m (negative = inverted image). Sign: $b > 0$ real (in front of mirror), $b < 0$ virtual (behind mirror).

Symbol	Meaning	Unit
R	radius of curvature	m
f	focal length ($= R/2$)	m
g	object distance	m
b	image distance	m
m	magnification	—
Δf	spherical aberration	m

4. Parameters

Three scenarios:

Scenario	Setup
A plane mirror	object at 1, 2, 5 m; law of reflection at 15°–60°
B concave mirror	$R = 2$ m ($f = 1$ m), parallel rays at heights 0.05–1.7 m
C imaging	$f = 1$ m, object at 3, 2, 1.5, 1, 0.5 m

Tolerance set in advance: $\varepsilon = 1\%$ (0.01 m) for focal deviation and image position. Rationale: 1% is the threshold above which blur becomes visible in the image.

5. Prediction

Scenario	Expectation
A	virtual image of equal size, law of reflection exact → M1 supported
B	off-axis rays focus nearer → spherical aberration $> \varepsilon$ → M1 refuted
C	image position/type strongly distance-dependent (real/virtual, enlarged/reduced) → M1 insufficient

6. Falsification criterion

M1 (“mirrors always image perfectly”) is refuted if **any** holds: - The spherical aberration (paraxial vs. marginal focus) exceeds ε. - Imaging changes with object distance between real and virtual or enlarged and reduced (instead of "always the same"). - A curved mirror creates an image size different from the object (violation of "equal size").

7. Competing models

- **K1 — perfect imaging (M1):** tested baseline model (plane mirror).
- **K2 — spherical concave mirror (M2):** with aberration.
- **K3 — convex mirror (M3):** virtual reduced image.
- **K4 — parabolic mirror:** corrects spherical aberration exactly for axis-parallel rays (telescopes, spotlights).
- **K5 — aspheric / freeform mirrors:** for special corrections.
- **K6 — multi-mirror systems:** Cassegrain, Newtonian telescope — combination of several mirrors.
- **K7 — wave optics of reflection:** diffraction at mirror edges, resolution limit — relevant for small mirrors.

8. Domain of failure

- **Very large aperture:** spherical aberration grows strongly with aperture ratio; at small aperture (paraxial) M1 holds well.
- **Very small mirrors:** diffraction limits resolution (wave optics), geometric model fails.
- **Object at focal point:** image at infinity, imaging equation singular.
- **Obliquely incident bundles:** coma and astigmatism (off-axis aberrations) — not treated here.
- **Non-ideal reflectivity:** real mirrors lose light, especially metal mirrors in UV.
- **Wavelength-dependent reflectivity:** unlike geometry, the brightness of reflection is colour-dependent (gold mirror reflects IR better).

9. Simulation

Numerical evaluation in `spiegel_simulation.py`:

1. Exact ray tracing at spherical mirror surface (circle-ray intersection, reflection at normal vector).
2. Scenario A: plane mirror analytically — virtual image, law of reflection.
3. Scenario B: parallel rays at 30 heights on concave mirror \(R = 2\); axis intersection of each ray; paraxial vs. marginal focus; longitudinal aberration.
4. Scenario C: imaging equation for five object distances; image distance, magnification, image type.

Results in `spiegel_results.json`. Plot as `spiegel_szenen.svg` (four subplots: plane mirror, concave caustic, imaging equation, magnification).

10. Result

10.1 A plane mirror

Object distance	Image distance	Magnification	Image type
1 m	−1 m	1.0	virtual, upright,

			equal size
2 m	−2 m	1.0	virtual, upright, equal size
5 m	−5 m	1.0	virtual, upright, equal size
Law of reflection			exact (incidence = reflection)
Assessment M1			**supported**

10.2 B concave mirror ($R = 2$ m, $f = 1$ m)

Quantity	Value
ideal focal length $R/2$	1.000 m
paraxial focus (height 0.05 m)	0.9997 m
marginal focus (height 1.7 m)	0.294 m
longitudinal spherical aberration	1.294 m
Assessment M1	**refuted**

(Note: the large aperture — ray at 85% of the radius — deliberately exaggerates the effect; at small aperture the aberration is tiny and M1 nearly holds.)

10.3 C imaging ($f = 1$ m)

Object distance	Image distance	Magnification	Image type
3 m	1.5 m	−0.5	real, inverted, reduced
2 m	2.0 m	−1.0	real, inverted, equal size
1.5 m	3.0 m	−2.0	real, inverted, enlarged
1 m	∞	—	object at focal point
0.5 m	−1.0 m	+2.0	virtual, upright, enlarged
Assessment M1			**refuted**

Plot: `spiegel_szenen.svg`.

11. Assessment

M1 ("mirrors always image perfectly") is refuted in 2 of 3 scenarios — supported only for the plane mirror.

Scenario A is the textbook limit, and here M1 is exactly right. The plane mirror creates a virtual, upright image of equal size at equal distance behind the mirror plane. The law of reflection (angle of incidence = angle of reflection) holds perfectly. This is the bathroom mirror: you see yourself at original size, laterally reversed, apparently behind the glass. Notable is the special status: unlike lenses, where even the thin ideal lens presupposes four idealisations (Module 05), the mirror has a **truly perfect** case — the plane mirror.

Scenario B is the central falsification finding: **spherical aberration**. A spherical concave mirror focuses near-axis rays at $f = R/2$, but off-axis rays meet the axis nearer the mirror. At large aperture (here ray at 85% of the radius) the deviation is dramatic — the marginal focus lies at 0.29 m instead of 1.0 m. The reflected rays do not meet at a point but envelope a **caustic** — that bright, heart-shaped light curve seen in a coffee cup, a ring or the bottom of a pot when light enters obliquely. This is exactly the reflection counterpart to the spherical aberration of the lens (Module 05). The solution is the same idea as the achromatic doublet, but geometric: a **parabolic mirror** focuses axis-parallel rays exactly to a point — which is why telescope mirrors and spotlight reflectors are parabolic, not spherical.

Scenario C refutes "always perfect" on another level: even ignoring aberration (paraxial approximation), the image depends **drastically on object distance**. For a distant object (3 m) a small, inverted, real image forms near the focal point. At double the focal length (2 m) an equal-sized inverted image. Between single and double focal length (1.5 m) an enlarged inverted real image (principle of the concave-mirror projector). At the focal point (1 m) the image diverges to infinity (parallel ray bundle — principle of the spotlight). Within the focal length (0.5 m) an enlarged, upright, virtual image — the **shaving and make-up mirror** that shows the face enlarged. Five qualitatively different images from one mirror, by distance alone.

The central methodological lesson: Reflection and refraction are **dual phenomena**. The imaging equation $1/g + 1/b = 1/f$ has the same form for mirrors and lenses. Spherical aberration occurs in both and is corrected in both by asphericising (parabolic mirror or aspheric lens). The essential difference: reflection is wavelength-independent (no chromatic problem), which is why large telescopes use mirrors and not lenses — a mirror has no chromatic aberration and can be built arbitrarily large and supported from behind.

Connection to previous modules: - **Module 05 Lenses:** the same spherical aberration, the same imaging equation. The mirror is the reflection analogue of the lens. Reflection, however, has no chromatic aberration (advantage for telescopes). - **Module 06 Prisms:** refraction fans out colours; reflection does not. Both are the two basic mechanisms of geometrical optics. - **Module 04 Camera model:** single-lens reflex cameras use a mirror for beam deflection; mirror telescopes are the large form. - **Module 11 Shadow Theatre / 08 Stage Lighting:** reflectors (parabolic mirrors) concentrate spotlight light — the practical application of scenario C at the focal point.

12. Next test

Module 12 Telescope and Microscope as a possible next step: combination of lenses (and mirrors) into magnifying systems; Keplerian vs. Galilean telescope; mirror telescope (Newtonian, Cassegrain). Requires Module 05 (lenses) and Module 10 (mirrors).

Possible extension Module 10 v0.2: parabolic mirror in direct comparison (aberration corrected); coma and astigmatism at oblique incidence; multi-mirror telescopes; detailed caustic visualisation.

Appendix A — Cross-references

- Practice explanation: `PRAXIS-Spiegel-EN.md` (follows)
- Companion paper: `BEGLEITPAPIER-Spiegel-EN.md` (follows)
- Tool: `SPECULUM.html` (follows) — *Lat. speculum, the mirror; root of "speculation"*

- Code: `spiegel_simulation.py`
- Plot: `spiegel_szenen.svg`
- Result data: `spiegel_results.json`
- Predecessor modules: Module 05 Lenses (imaging, aberration), Module 06 Prisms (refraction)
- Related modules: Module 04 Camera model, Module 08 Stage Lighting (reflectors)

Appendix B — External stocktaking

- **Hecht (2017)** *Optics*, 5th ed. — mirrors, imaging, aberration.
- **Born & Wolf (1999)** *Principles of Optics* — law of reflection, aberration theory.
- **Jenkins & White (2001)** *Fundamentals of Optics* — mirror imaging.
- **Euclid** *Catoptrica* — historical reflection theory.
- **PhET "Geometric Optics"** — didactic imaging simulation.

What the workshop note adds: three contrasting scenarios in falsification format; the explicit reflection/refraction duality (mirror as lens analogue without chromatics); real ray tracing with caustic demonstration; bridges to modules 05, 06, 04, 08.

Appendix C — Sources

- Hecht, E. (2017). *Optics*, 5th ed. Pearson.
- Born, M.; Wolf, E. (1999). *Principles of Optics*, 7th ed. Cambridge University Press.
- Jenkins, F. A.; White, H. E. (2001). *Fundamentals of Optics*, 4th ed. McGraw-Hill.
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