FN-Merge-Signalkette-EN-v0.1-2026-05-17

Research Note — The Signal Chain

Author: Thomas Schüller · forschung@tschueller.com · ORCID 0009-0003-9799-6747 **Affiliation:** privately funded, no institutional affiliation **Licence:** CC BY 4.0 · **Version:** 0.1 · **Date:** 2026-05-17 **Strand:** FORSCHUNG / Merge / M1 Signal Chain **Tool:** CATENA · **Document type:** Research note (Template v1.0) **Status:** completed test with documented assessment **Special feature:** first **merge module** — connects all four strands

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1. Thesis

The workshop has built four strands side by side: optics, mechanics, audio, perception. This module shows that they treat **the same structure**:

$$\text{STIMULUS} \rightarrow \text{TRANSDUCER} \rightarrow \text{PROCESSING} \rightarrow \text{OUTPUT} \rightarrow \text{INTERPRETATION}$$

A photon meets a lens, a pressure wave a membrane, a force a spring, a stimulus a receptor. In all cases what follows is: transduction, processing, output — and at the end stands an interpretation. **At every station information is lost and interpretation is added.**

The tested baseline model M1 reads: "Measuring delivers reality. What comes out is what was there; information loss is a technical shortcoming, not a principle." This module claims that M1 is false in all four strands — **for the same formal reasons.** If so, the cave-allegory core (Module 02), which so far carried the perception strand, is not restricted to perception but holds for every measuring device.

For merge modules the stricter rule applies (merge architecture, section 6): **no analogy without calculation.** "Everything is a signal chain" would be a phrase as long as the commonality is not established numerically. This module establishes it.

2. Assumptions

1. Every measurement chain can be decomposed into the five stations.
2. The transducer maps the stimulus onto an output quantity; this mapping is characterisable (transfer curve).
3. Processing includes at least sampling (temporal/spatial) and quantisation (value range).
4. The output always has **lower dimension** than the stimulus.
5. Reconstructing the stimulus from the output is an inverse problem.

3. Mathematical model

M1 — “measuring delivers reality”: The mapping $\mathcal{K}$ from stimulus s to output y is injective and lossless; s is recoverable from y.

M2 — sampling and quantisation. Quantisation with n bits produces, at full scale, a signal-to-noise ratio of $$\mathrm{SNR} \approx 6.02\,n + 1.76 \ \text{dB}.$$ Sampling at f_s maps frequencies above the Nyquist limit $f_s/2$ onto **wrong** frequencies (aliasing): $$f_{\text{alias}} = \left| f - \operatorname{round}(f/f_s)\cdot f_s \right|.$$

M3 — transfer curve. Four generic forms over the same stimulus range: linear ($y \propto x$), logarithmic (Weber-Fechner, $y \propto \log x$), power (Stevens, $y \propto x^{0.33}$), S-curve (photographic density curve).

M4 — inverse problem. Let the stimulus be a spectrum $s \in \mathbb{R}^{61}$ and the output the cone response $y = A s$ with $A \in \mathbb{R}^{3\times 61}$. Then $$\dim \ker A = 61 - \operatorname{rank} A = 58,$$ that is: a 58-dimensional space of spectra produces **exactly the same** output.

Symbol	Meaning	Unit
s	stimulus (here: spectrum)	—
y	output	—
A	transducer matrix	—
n	quantisation depth	bit
f_s	sampling rate	Hz
$\ker A$	null space (metamerism space)	—

4. Parameters

Scenario	Setup
A sampling	stimulus: sum of three sines (20, 60, 140 Hz); quantisation 16/12/8/4/2 bit at full rate; sampling 1000/400/200/100 Hz at full depth
B transfer curves	stimulus range 4 decades (10^{-2} to 10^{2}), four curves
C metamerism	61 spectral sample points (400–700 nm, 5 nm), 3 cones (Gaussian approximation)

Tolerance: $\varepsilon = 0$ — a single demonstrated loss already refutes M1.

Methodologically important: In scenario A, quantisation and sampling are measured **separately**. Applied jointly, the sampling error dominates the balance and the loss would be wrongly attributed to bit depth. This separation is a precondition for robust statements (see section 11, first version).

5. Prediction

Scenario	Expectation
A	quantisation SNR follows $6.02n+1.76$; below Nyquist

	wrong frequencies appear
B	identical stimulus produces markedly different outputs depending on the curve
C	null space dimension 58; constructible metamer with identical output

6. Falsification criterion

M1 is refuted as soon as (a) information is lost in principle even with flawless technology, (b) the same stimulus produces different outputs depending on the transducer, or (c) different stimuli produce the same output. Any single point suffices.

7. Competing models

- **K1 — naive realism (M1):** tested baseline; measurement as imaging.
- **K2 — information theory (Shannon):** channel capacity as upper bound; loss is quantifiable and principled.
- **K3 — sampling theorem (Nyquist-Shannon):** lossless reconstruction only for band-limited signals at sufficient rate.
- **K4 — inverse problems (Hadamard, Tikhonov):** ill-posedness; uniqueness requires additional assumptions (regularisation).
- **K5 — Bayesian perception:** the system supplies the missing information through priors — exactly what L1 and L5 show.
- **K6 — quantum measurement theory:** there the situation sharpens further; measurement alters what is measured (see wishlist W2).

8. Domain of failure

- **Generic transfer curves.** The four forms in B are model forms, not fitted to concrete devices. The statement is structural (“curves differ considerably”), not device-specific.
- **Cones as Gaussian approximation.** In C, Gaussians are used instead of CIE data. The null space dimension is independent of this (it follows from \(61-3\)); the concrete metamer shape is not.
- **No bit figure for the eye.** Assigning the eye a quantisation depth would be dishonest: its dynamic range arises through adaptation over roughly ten decades, the instantaneous range is small. A direct bit comparison is deliberately **not** drawn.
- **Linear transducers in C.** The inverse problem is formulated linearly here. Real chains are nonlinear; non-uniqueness does not thereby diminish but becomes harder to describe.
- **Interpretation not modelled.** The fifth station (interpretation) is named structurally but not computed — it is the subject of L5 and the planned modules W1/W2.
- **Merge limit.** The commonality of the four strands is **formal**, not physical: the same mathematics, different carriers. It does not follow that optics and perception are “the same”.

9. Simulation

Numerical evaluation in `signalkette_simulation.py`:

1. Scenario A part 1: pure quantisation at full sampling rate, measured SNR against theory.

2. Scenario A part 2: pure sampling at full depth, alias frequency and SNR.
3. Scenario B: four curves over four decades; output values at identical stimulus, spread.
4. Scenario C: SVD of the transducer matrix, null space basis, construction of a positive metamer.

Results in `signalkette_results.json`, plot as `signalkette_szenen.svg` (four subplots).

10. Result

10.1 A — quantisation (measured separately)

Depth	SNR measured	Theory $6.02n+1.76$	Deviation
16 bit	98.85 dB	98.08 dB	+0.77
12 bit	73.76 dB	74.00 dB	−0.24
8 bit	50.34 dB	49.92 dB	+0.42
4 bit	26.16 dB	25.84 dB	+0.32
2 bit	11.46 dB	13.80 dB	−2.34

Agreement is better than 1 dB down to 4 bit. At 2 bit the formula fails as expected (the assumption of uniformly distributed quantisation noise no longer holds at so few levels).

10.2 A — sampling (Nyquist limit for 140 Hz: 280 Hz)

Sampling rate	Nyquist	140 Hz correct?	appears as	SNR
1000 Hz	500 Hz	yes	140.0 Hz	32.36 dB
400 Hz	200 Hz	yes	140.0 Hz	18.81 dB
200 Hz	100 Hz	**no**	**60.0 Hz**	7.64 dB
100 Hz	50 Hz	**no**	40.0 Hz	6.18 dB

Assessment M1: refuted.

10.3 B — transfer curves

Output at an **identical** stimulus (middle of the stimulus range):

Curve	Output
linear	0.010
logarithmic (Weber-Fechner)	0.501
power (Stevens, $n=0.33$)	0.180
S-curve (film)	0.505

Spread: 0.495 — at exactly the same input. **Assessment M1: refuted.**

10.4 C — metamerism as null space

Quantity	Value
spectral sample points	61
output dimension (cones)	3

null space dimension	**58**
metamer constructed	yes (positive)
max. deviation of output	0.00 (machine precision)
relative deviation of spectra	0.17

Assessment M1: refuted.

11. Assessment

M1 (“measuring delivers reality”) is refuted in all three scenarios — and the three refutations concern three different stations of the chain.

Scenario A shows the loss in processing. Quantisation follows the theoretical bound exactly: the loss is not an expression of poor technology but fixed by word length. The second part matters more. **The sharpest finding of this module arose unplanned:** at a sampling rate of 200 Hz the 140 Hz component appears as 60 Hz — and 60 Hz is already a **real** component of the stimulus. The aliasing error falls exactly onto an existing signal. The result is thereby internally consistent, plausible and false, and **from the output alone the error cannot be detected.** The chain does not report that it has lost something. This is a sharper statement than “information is lost”: information can be **replaced by plausible misinformation**, without any trace.

Scenario B shows the imprint of the transducer. The same physical stimulus produces outputs between 0.010 and 0.505 — a spread of 0.495 on a normalised scale from 0 to 1, that is nearly half the output range, purely through the choice of curve. The transducer is not a neutral window. The systematic direction is notable: the sensory-physiological curves (logarithmic, power) compress strongly, the technical one (linear) does not. This is no deficiency of the senses. A linear sensor across four decades squanders almost the entire output range on the upper tenth of the stimulus range; the logarithmic curve distributes evenly. For a system that must work across ten decades of brightness, compression is the better solution — **the curves are not differently good but designed for different tasks.**

Scenario C shows the irreversibility. The result is the formal core of the module: 61 spectral degrees of freedom are mapped onto 3 cone responses, the null space has 58 dimensions. A concrete, physically admissible (everywhere positive) metamer was constructed whose spectrum differs visibly (relative deviation 0.17) while the cone response remains identical at machine precision. **Reconstructing the stimulus from the sensory impression is not difficult but impossible in principle** — not because of noise, but because the mapping is not injective. Every reconstruction needs additional assumptions; this is exactly what the brain supplies with priors (K5), and exactly where L1 and L5 begin.

The merge finding. The three scenarios come from three strands — A from audio/signal processing, B from sensory physiology and photographic technology, C from colorimetry (Module 09) — and establish the same structure with **the same mathematics**. The merge rule is thereby satisfied: the commonality is computed, not asserted.

The substantive consequence reaches further than was foreseeable at the outset. The cave-allegory core (Module 02) — we see interpretations, not things — was so far a statement about **perception**. Scenario C shows, however, that the decisive property (non-injectivity of the mapping) has nothing to do with biology: it follows from $\dim(\text{output}) < \dim(\text{stimulus})$. **Every** measuring device satisfies this condition. A spectrometer with 1024 channels has a smaller null space than the eye, but not an empty one. **The perception strand is therefore not the special case but the well-studied instance of a general structure.**

On the first version. The original version of scenario A applied sampling and quantisation jointly and computed from this an “information loss in bits” relative to the nominal word length. This is unusable: the sampling error dominates the balance, and the loss is wrongly attributed to bit depth (a 16-bit system appeared with “10.7 bit loss” although quantisation was practically error-free). Separating the two mechanisms was necessary; only this permits comparison with theory. The error is documented here rather than silently corrected (workshop line: report corrected predictions honestly).

12. Next test

Module N1 camera vs. eye (CAMERA COMPARATA) as the next step: the signal chain worked through on two concrete systems, with real sensor data instead of generic curves.

Possible extension v0.2: real transfer curves instead of model forms; CIE cone data; nonlinear inverse problems; regularisation (Tikhonov) as a model for priors; the fifth station (interpretation) quantitatively.

Appendix A — Cross-references

- Practice explanation: `PRAXIS-Signalkette-EN.md`
- Companion paper: `BEGLEITPAPIER-Signalkette-EN.md`
- Tool: `CATENA.html` — *Lat. catena, chain*
- Code: `signalkette_simulation.py` · Plot: `signalkette_szenen.svg` · Data: `signalkette_results.json`
- **Modules used:** 09 colour mixing (cones, metamerism), Audio 01 spectrum (sampling), 07 light sources (curves), L1–L5 (perception as inference), 02 cave allegory (core)
- **Planning document:** `MERGE-ARCHITEKTUR-v0.1-2026-05-17.md`

Appendix B — External stocktaking

- **Shannon (1948)** — information theory, channel capacity.
- **Nyquist (1928) / Shannon (1949)** — sampling theorem.
- **Weber (1834) / Fechner (1860)** — logarithmic sensory scale.
- **Stevens (1957)** — power law of psychophysics.
- **Hadamard (1902)** — ill-posed problems.
- **Wyszecki & Stiles (1982)** — metamerism, colorimetry.

What the workshop note adds: the bringing together of these separately established results into **one** chain; the numerical demonstration that all four strands share the same structure; the finding that aliasing can fall onto a real signal component and thereby become undetectable; the generalisation of the cave-allegory core to arbitrary measuring devices.

Appendix C — Sources

- Shannon, C. E. (1948). A Mathematical Theory of Communication. *Bell System Technical Journal* 27:379–423.

- Nyquist, H. (1928). Certain topics in telegraph transmission theory. *Trans. AIEE* 47:617–644.
- Fechner, G. T. (1860). *Elemente der Psychophysik*. Breitkopf und Härtel, Leipzig.
- Stevens, S. S. (1957). On the psychophysical law. *Psychological Review* 64:153–181.
- Wyszecki, G.; Stiles, W. S. (1982). *Color Science*. 2nd ed., Wiley, New York.

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