

SYNTAGMA FORSCHUNG · TEXTBOOK EDITION

Measurability

Framework theory of the measurement chain

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Obtain	syntagma-science.com/werke/messbarkeit/

The parts remain freely accessible. The textbook edition combines them with syntax card, learning path and glossary into a study and working book and is updated with each new version of the work.

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An Information-Based Framework for Physical Measurability and Reconstructability

Version 0.9 · Preprint / Framework Paper · FORSCH-PROV0420 (number provisional) · as of 6 Oct 2026

Field	Entry
Author	Thomas Schüller (researcher), ORCID 0009-0003-9799-6747
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Funding	self-funded

Field	Entry
Conflicts of interest	none
Licence	CC BY 4.0
Data status	no experimental raw data; ten numerical minimal models, reproducible (Section 14, Appendix C)
Source status	50 entries verified (publisher, standards register, full text), 12 flagged as open in Appendix I.2; these concern almost exclusively the edition and ISBN of textbooks and first editions
Track	FORSCHUNG (open channel, feeder). Tools run exclusively on the syntagma-science platform, see Appendix G

This version claims no new fundamental physics. It is an ordering framework for the measurability, reconstructability and falsifiability of physical measurement chains.

0 What changed relative to Version 0.8

Nothing in the work itself. No result, no proof, no figure and no appendix has changed. This version makes the bundle around the work ready for publication; the number is carried along so that work and bundle do not drift apart.

No.	Change	Reason
1	New VEROEFFENTLICHUNG.md in the main folder: the sequence in one place — the seven decisions that block everything, the order platform → deposit → journals, tick-off steps per track	the sequence was spread across the handover, the operations manual and the upload notes; when publishing you need it in one place
2	Landing page extended with legal matters : imprint, terms of use, privacy, separate licences for work and tool, liability note	without these a page is not publishable
3	Landing page extended with the network of brands	whoever cites, cites Syntagma; whoever licenses, buys from the responsible track. That was stated nowhere
4	Citation template in the author register corrected — it still read Version 0.3 — and extended with per-version check points	an outdated citation template produces wrong citations, permanently

The material is finished. What remains are the seven decisions in VEROEFFENTLICHUNG.md Section 1; all of them belong to the author and none can be derived from the material.

0.1 What had changed relative to Version 0.7

This version changes no result and no proof. It draws the disclosure line explicitly instead of presupposing it.

No.	Change	Reason
1	New Appendix G.6: self-protection and the disclosure line per REGEL-PROV0002	the work sits beside a paid offering; leaving that unstated leaves open whether something is being held back
2	For every component it is stated whether it is open and why — including what is not present at all	a claim without evidence would be advertising; evidence without a line would be a build manual
3	Checkability outranks protection is recorded as the precedence	a framework that cannot be refuted supports no offering
4	The choice for the browser tool is made and justified : MESSWERK stays open on the platform page	“in the browser” and “computing core internal” exclude each other; the rule requires a deliberate choice rather than a tacit one
5	REGEL-PROV0002 sits as its own file in the bundle; the adoption block now covers both rules	it governs all tracks, not only this project

Substantively unchanged: measurement chain, Theorems 1 and 2, classification A/B/C, numerics, experimental protocol, references, source checklist, licence levels, active/passive assignment.

0.2 What had changed relative to Version 0.6

This version changes no result and no proof. It anchors a cross-track rule that so far existed only as a decision.

No.	Change	Reason
1	New Appendix G.5: active and passive versions per REGEL-PROV0001	the line for what may go on a deposit was described for this project but not stated as a general rule
2	The borderline case of computation scripts is settled: they are passive and stay on the deposit	without them the work could not be checked, and checkability is the reason for depositing at all
3	The difference between free verification and the licensed tool is stated in G.5 rather than assumed	anyone verifying the numbers here does not need the tool; the tool computes on someone else’s measurement chain
4	The rule sits as its own file in the bundle (regelwerk/), with an adoption block for the central rulebook	it governs all projects, not only this one

Substantively unchanged: measurement chain, Theorems 1 and 2, classification A/B/C, numerics, experimental protocol, references, source checklist, licence levels.

0.3 What had changed relative to Version 0.5

This version changes no result and no proof. It converts the commercial arrangement to a platform-centred one.

No.	Change	Reason
1	Appendix G rewritten: syntagma-science is the destination, the open research channel the feeder	tools now run exclusively on the platform; Zenodo carries no tool, not even a preview build
2	Licence levels L0–L3 and six product classes per LIZ-PROV0001 added as Appendix G.2 and G.3	the assignment existed only as four service levels in the offering, not in the work itself
3	Appendix H reordered: platform → deposit → journals	a reference needs a destination; the platform has to exist before the deposit
4	Zenodo bundle prepared separately (Appendix H.2, folder <code>zenodo-upload/</code>)	the working bundle and the publication bundle are not the same; only the open material belongs on the deposit
5	Every deposit of the preprint carries the reference to syntagma-science	the preprint is a reach channel, not an end in itself

Substantively unchanged: measurement chain, Theorems 1 and 2, classification A/B/C, numerics, experimental protocol, references, source checklist.

0.4 What had changed relative to Version 0.4

This version changes no result and no proof. It folds in the source check that version 0.4 listed as the single remaining open task.

No.	Change	Reason
1	ISO 12233:2023 → ISO 12233:2024 in Section 19.3, Section 19.6 and Appendix D	the fifth edition supersedes the 2023 edition and also carries a changed title: “Digital cameras — Resolution and spatial frequency responses”
2	IEC TR 60825-14:2022 (Ed. 2.0) in place of the undated reference; status of IEC 60825-1 Ed. 4 noted	an undated normative reference is not reproducible in an experimental protocol
3	Mezghani, Antreich & Nossek (2010) : the conference paper WSA 2010, Bremen, 143–150, DOI 10.1109/WSA.2010.5456454 is now the primary source, arXiv:1010.5532 the preprint	the factor $2/\pi$ in class B now rests on the reviewed version
4	Kalman (1963) : journal name corrected to <i>Journal of the Society for Industrial and Applied Mathematics, Series A: Control</i>	<i>SIAM Journal on Control</i> is the later name of the same journal, not yet in use in 1963
5	Six missing DOIs added: Krener & Ide, Galiffi et al., Hansen, Janesick, Stadler, Amari (2016)	these had no identifier in v0.4, or only an unverified ISBN
6	Issue numbers added for ten entries (among them Paris, Bellman & Åström, Berreman, Shannon, Landauer, Hempel)	the page range alone does not identify the volume unambiguously

No.	Change	Reason
7	Appendix D converted into one continuous alphabetical list	the split into “DOI-verified” and “further sources” lost its purpose once the check was done
8	Appendix I restructured into I.1 verified, I.2 still open, I.3 what the check changed in the work	the reader should see the remaining gaps at a glance
9	Open entries reduced from 25 to 12 , verified entries from 23 to 50; those remaining concern almost exclusively the edition and ISBN of textbooks and first editions	the sources that carry content are now fully substantiated

What is still outstanding: the choice of edition for fourteen textbooks and three first editions, the edition status of JCGM 100/200 and EMVA 1288, and the access date of the SEP entry. These are itemised in Appendix I.2 and are to be closed before a journal version.

0.5 What had changed relative to Version 0.3

No.	Change	Reason
1	The gap claim is everywhere tied to the literature strands searched rather than stated absolutely	Integrity: the search was not exhaustive
2	Class C extended by three cases: EMCCD at low gain , quantisation outside the limiting cases, generally heteroscedastic noise	completeness of the classification
3	Section 5.5 extended by the noise coefficient (Chao, Ward & Ober) and the Stam inequality	two further neighbouring concepts requiring demarcation
4	New Section 7.1: Rayleigh and Sparrow as special cases of a threshold on d'	the Fisher information is the sharper criterion; the classical criteria can be placed rather than discarded
5	Convention for the excess noise factor stated explicitly	Robbins & Hadwen define $F_{\text{ENF}} = \sqrt{2}$, other works the squared quantity — without a convention the factors 2 and 1/2 are not traceable
6	Quantum bounds under noise (Escher et al.) and monotonicity of the quantum Fisher information under CPTP maps added	connects Section 13 to the data-processing inequality
7	New Appendix H: publication path , with a venue matrix and the arXiv endorsement rule changed on 21 January 2026	so far only noted in the handover
8	New Appendix I: source checklist with a status per entry	separates verified from unverified references traceably

No.	Change	Reason
9	References extended by twelve entries	Chernoff, Amari (2001), Chao et al., Hyncek & Nishiwaki, Mortensen et al., Escher et al., Paris, Gan & Law, Aspden et al., Worrall, Earman & Norton, Stadler

0.6 What had changed relative to Version 0.2

No.	Change	Reason
1	The core statement is explicitly identified as observational equivalence in the sense of Rothenberg (1971) and no longer framed as an own finding	Literature check: the statement has been standard since 1971. The contribution lies in the transfer to physical measurement chains, not in the statement
2	The separability criterion is formulated as Theorem 1 with an equivalence proof instead of being asserted	On a connected product domain, $\partial^2 \log F / \partial p_i \partial p_j = 0$ is equivalent to the product form
3	Sharper formulation via stage efficiencies $\eta_k = F_k / F_{k-1}$ (Theorem 2)	The telescoping identity $F_n = F_0 \prod \eta_k$ is trivial. The real claim is that η_k depends only on its own stage's parameters
4	Classification of forward models into three classes with evidence and counterexamples (Section 5.6)	The open question from v0.2 is thereby settled for the main channel classes
5	Demarcation from parameter orthogonality (Cox & Reid 1987) and from cascaded-detector theory (DQE)	These are the closest literature strands; the DQE literature explicitly denies the general product form
6	Four new numerical minimal models M7–M10 with Figures 6–9	Stage efficiency, separability map, qubit dephasing, slit experiment
7	Complete experimental protocol for the optical slit experiment (Section 19)	v0.2 named the experiment only as an open item
8	New section Vienna lineage and the philosophy of measurability (Section 16)	Mach, Boltzmann, Bridgman, Vienna Circle, Schrödinger, modern measurement theory
9	New section demarcation from observability theory (Section 17)	Kalman and Hermann–Krener are the closest competing formulation
10	References extended with DOIs; Appendix F states what was not found in the literature	Positioning of the contribution

Abstract

This work formulates an information-based ordering framework for physical measurability and reconstructability. The claim is not to introduce new fundamental physics but to organise established concepts from wave theory, electrodynamics, scattering theory, signal theory, digitisation and quantum measurement along a common measurement chain:

$$X_0 \rightarrow H_{\text{field}} \rightarrow H_{\text{mat}} \rightarrow H_{\text{mix}} \rightarrow H_{\text{measure}} \rightarrow Q \rightarrow Y.$$

The starting point is observational equivalence: if $p(Y|\theta_1) = p(Y|\theta_2)$ for $\theta_1 \neq \theta_2$, unique reconstruction from that channel is excluded. This is not new; it is the definition of identifiability of a parametric model, and its local version has been equivalent to regularity of the Fisher information matrix since Rothenberg (1971). The contribution of this work lies in two points.

First, the diagnostic working quantity K is defined as an effective signal-to-noise ratio and derived exactly from the Fisher information for the scalar Gaussian channel: with $K := \theta^2 F(\theta)$ one obtains $K = \text{SNR} \cdot C^2$. Second, the product form

$$K = \text{SNR} \cdot G(|q|a) \cdot D_{\text{mat}} \cdot \gamma \cdot R_{\text{dir}} \cdot C^2$$

receives a testable validity criterion: on a connected product domain it is exact precisely when $\log F$ is additively separable. Stated more sharply via stage efficiencies $\eta_k = F_k/F_{k-1}$, the claim is that each η_k depends only on the parameters of its own stage. This is decided for three classes of forward models: multiplicative transmission with single-stage noise and Poisson thinning satisfy the criterion exactly; high-gain EMCCDs and low-SNR one-bit quantisation satisfy it asymptotically; multi-stage noise injection, the crossover between shot and read noise, nonlinearity and saturation violate it.

Ten numerical minimal models with a fixed random seed support the statements, among them a separability map over signal level and read noise and a fully computed optical slit experiment. The scientific load-bearing capacity lies in the falsification conditions.

Keywords: measurability; reconstructability; identifiability; observational equivalence; Fisher information; separability; cascaded systems; wave-vector transfer; coherence; inverse problems; quantum measurement.

1 Introduction

Physical measurements are often described through single terms: signal strength, frequency, wavelength, reflection, resolution, noise, detection. These are necessary but not sufficient. A strong signal may say little about the state sought. A local null signal may arise from destructive interference. A digitally crisp result may rest on coarse quantisation or algorithmic priors. A reflected signal may carry energy while having lost direction and phase.

The central question is therefore not whether a signal exists, but:

Which state information is distinguishable in the signal under the given physical and instrumental conditions?

The contribution is not a new law of nature. It is a framework that orders existing physical descriptions along the question of measurability and — since version 0.2 — states the conditions under which the working quantity used is admissible. Version 0.3 answers that question for the main channel classes.

2 Scope of claim

The model claims no new fundamental physics. It replaces neither Maxwell’s equations, nor quantum mechanics, scattering theory, Fourier optics, information theory, nor the theory of inverse problems. It is an ordering framework whose purpose is to make the measurement question explicit:

1. Which state is to be distinguished?
2. Which physical forward chain generates the signal?
3. Which factors preserve or destroy state information?
4. Which states remain distinguishable in the measurement channel?
5. Which states collapse into the same measurement distribution?

3 Measurement chain

$$X_0 \rightarrow H_{\text{field}} \rightarrow H_{\text{mat}} \rightarrow H_{\text{mix}} \rightarrow H_{\text{measure}} \rightarrow Q \rightarrow Y. \tag{1}$$



Jede Stufe kann Zustandsinformation erhalten, umformen oder vernichten.
Every stage can preserve, transform or destroy state information.

Messbarkeitskriterium / measurability criterion: $p(Y | \theta_1) \neq p(Y | \theta_2)$
Das Messergebnis ist nicht der Zustand. / The result is not the state.

Figure 1: Figure 1: Operator sequence of the measurement chain. The result is not the state itself but the outcome of physical and informational transformations.

Symbol	Meaning
X_0	physical initial state
H_{field}	field or wave propagation
H_{mat}	material response: reflection, transmission, absorption, scattering, dispersion
H_{mix}	mixing, multiple scattering, mode coupling, nonlinearity, linear time variance
H_{measure}	measurement process, detector response, measurement operator
Q	quantisation, thresholding, classification, digital decision
Y	registered result

In the linear case $Y = H_{\text{total}}X_0 + N$ with $H_{\text{total}} = H_m \cdots H_1$ (2). If H_{total} has a null space, different states produce the same signal. In the nonlinear case $Y = F_m(\dots F_1(X_0)) + N$ (3), and local sensitivity decides.

4 State distinguishability

A signal carries state information about θ if

$$p(Y|\theta_1) \neq p(Y|\theta_2) \quad \text{for } \theta_1 \neq \theta_2, \quad (4)$$

and unique reconstruction is excluded if

$$p(Y|\theta_1) = p(Y|\theta_2), \quad \theta_1 \neq \theta_2. \quad (5)$$

Provenance of the statement. Equation (5) is the definition of *observational equivalence* of two parameter values; a model is identifiable if no two distinct parameter values are observationally equivalent. Rothenberg (1971) shows that under weak regularity conditions local identifiability is equivalent to non-singularity of the Fisher information matrix. This work adopts that theorem and applies it to physical forward chains. The contribution lies in the transfer and in the stage decomposition, not in the statement itself.

Three levels must be separated:

Level	Criterion	Quantity
measurability in principle	$p(Y \theta_1) \neq p(Y \theta_2)$	identifiability
practical reconstructability	overlap of distributions	Kullback–Leibler divergence, d'
robust technical estimability	achievable variance	Fisher information, Cramér–Rao

In the quantum case the Fisher information is replaced by the quantum Fisher information; Braunstein and Caves (1994) show that the statistical distinguishability of neighbouring states defines a Riemannian metric on the space of density operators.

Appendix S · Syntax card

The card renders the work in Syntagma Syntax 1.0 (specification: syntagma-science.com/syntax/). Levels G0-G5 describe the evidence, T1-T6 the kind of source; every hypothesis names its test, every card its limits.

Element	Level	Statement
F1 Question		Which state information is distinguishable in the signal under the given physical and metrological conditions?
F2 Question		Under which condition may a physical measurement chain be combined into a product form of stage factors?
G1 Object		Physical measurement chain from initial state through field, material, mixing and sensing element to quantisation and the recorded result ebene: statische oder quasistatische Messketten unter Rauschen · ort: Optik, Hochfrequenz, Akustik, Detektortechnik
G2 Object		Quantum stage of measurement: states, measurement operators and decoherence ebene: Quantenmessung, Qubit unter Dephasierung
B1 Term		Observational equivalence := two different parameter values yield the same measurement distribution fach: statistik · bruecke: wissenschaftsphilosophie=Modellpluralismus (Boltzmanns Bildtheorie)
B2 Term		Identifiability := no pair of different parameter values is observationally equivalent fach: statistik · bruecke: regelungstechnik=Beobachtbarkeit nach Kalman und Hermann-Krener
B3 Term		Fisher information := measure of the attainable variance of an estimate of a parameter from the measurement distribution (Cramér-Rao) fach: statistik · bruecke: metrologie=Unsicherheit vom Typ A an der Cramér-Rao-Grenze (GUM)
B4 Term		Working quantity K := effective signal-to-noise ratio of the equivalent Gaussian channel that yields the same Fisher information as the measurement chain fach: signaltheorie
B5 Term		Logarithmic sensitivity C := relative change of the signal per relative change of the state parameter (elasticity of the forward chain) fach: signaltheorie · bruecke: metrologie=normierter Sensitivitätskoeffizient (GUM)
B6 Term		Stage efficiency := ratio of Fisher information after a stage to that before it, between 0 and 1 fach: informationstheorie
B7 Term		Separability := the logarithm of the Fisher information is additive in the stage parameters; all mixed second derivatives vanish fach: mathematik
S1 Statement	G5	Observational equivalence excludes unique reconstruction; under weak regularity conditions local identifiability is equivalent to non-singularity of the Fisher matrix belege: Q2
S2 Statement	G3	In the scalar Gaussian channel $K = \text{SNR} \cdot C^2$ holds exactly; $\log_2(1+K)$ is there the Shannon capacity of the equivalent channel belege: Q1
S3 Statement	G3	Theorem 1: on a connected product domain the product form of the Fisher information is equivalent to the vanishing of all mixed second derivatives of its logarithm belege: Q1
S4 Statement	G3	Stage efficiencies are at most 1; this follows from the data processing inequality for Fisher information, so the telescoping representation carries no content by itself belege: Q3
S5 Statement	G3	Digitisation as pure post-processing creates no state information not contained in the analogue signal, additional data or priors belege: Q3
S6 Statement	G3	Multiplicative transmission with single-stage noise and Poisson thinning satisfy the criterion exactly, high-gain EMCCD and one-bit quantisation at low SNR asymptotically; multi-stage noise coupling, nonlinearity and saturation violate it belege: Q4 Q5 Q6

S7 Statement	G2	Factorisability is a property of the operating point: in the minimal model it holds in the clearly shot-limited and clearly read-limited regimes and breaks in the transition band; at a threshold of 0.05, 58 per cent of the parameter area considered is separable belege: Q1
S8 Statement	G3	In the quantum case indistinguishability is measurement-relative: the classical Fisher information of a measurement can be zero while the quantum Fisher information is positive belege: Q1 Q7
S9 Statement	G3	The DQE of a cascaded detector system is in general not a multiplicative cascade of individual DQEs belege: Q8
H1 Hypothesis	G2	With noise coupled in at the end of the chain the stage efficiency depends on upstream stages and is not a property of the stage alone belege: Q1 · pruefung: P1
P1 Test		Fails if a stage efficiency stays constant under variation of upstream parameters although the noise model shows multi-stage coupling
H2 Hypothesis	G1	In the optical slit experiment the mixed second difference of the Fisher information over exposure and read noise deviates significantly from zero in the transition region, but not in the asymptotes pruefung: P2
P2 Test		Fails if the mixed difference does not deviate from zero in the transition region or the stage efficiencies stay constant across all operating points although the photon transfer curve shows multi-stage noise coupling
H3 Hypothesis	G2	The product form of the working quantity does not hold where the separability criterion is violated belege: Q1 · pruefung: P3
P3 Test		Fails if the product form holds in a system in which the criterion is demonstrably violated
Q1 Source	T5	Derivations and ten numerical minimal models M1-M10 of the work with fixed random seed; calculation scripts in the archive package nachweis: Abschnitte 5 und 14, Anhang C
Q2 Source	T2	Rothenberg: Identification in parametric models nachweis: Rothenberg 1971 · ort: https://doi.org/10.2307/1913267
Q3 Source	T2	Zamir: Fisher information inequality via a data processing argument nachweis: Zamir 1998 · ort: https://doi.org/10.1109/18.669301
Q4 Source	T2	Robbins and Hadwen: noise performance of EMCCDs nachweis: Robbins & Hadwen 2003 · ort: https://doi.org/10.1109/TED.2003.813462
Q5 Source	T2	Mezghani, Antreich and Nossek: one-bit quantisation, WSA 2010 nachweis: Mezghani, Antreich & Nossek 2010 · ort: https://doi.org/10.1109/WSA.2010.5456454
Q6 Source	T2	Friis: noise figure cascade of receivers nachweis: Friis 1944 · ort: https://doi.org/10.1109/JRPROC.1944.232049
Q7 Source	T2	Braunstein and Caves: statistical distance and the geometry of quantum states nachweis: Braunstein & Caves 1994 · ort: https://doi.org/10.1103/PhysRevLett.72.3439
Q8 Source	T2	Cunningham and Shaw: signal-to-noise optimisation of medical imaging systems nachweis: Cunningham & Shaw 1999 · ort: https://doi.org/10.1364/JOSAA.16.000621
M1 Method		Established concepts from wave theory, electrodynamics, scattering theory, signal theory, digitisation and quantum measurement are ordered along a common measurement chain and decomposed stage by stage
M2 Method		Statements are supported with numerical minimal models (Monte Carlo against analytical values) and cast as falsification cases; an optical slit experiment is described as a test plan
X1 Measure		Working quantity K (effective SNR) einheit: dimensionslos · misst: G1
X2 Measure		Stage efficiency of a chain stage einheit: dimensionslos (0 bis 1) · misst: G1
L1 Limit		No new fundamental physics and no new fundamental theory; the core statement is taken over from identifiability theory, the contribution lies in transfer and stage decomposition